A QUEST FOR MEASURING ION BUNCH LONGITUDINAL PROFILES WITH ONE PICOSECOND ACCURACY IN THE SNS LINAC

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Abstract

The SNS linac utilizes several accelerating structures operating at different frequencies and with different transverse focusing structures. Low-loss beam transport requires careful matching at the transition points for both the transverse and longitudinal plane. Longitudinal beam parameters are measured using four Bunch Shape Monitors (used at many ion accelerator facilities, aka Feschenko devices). These devices, as initially delivered to the SNS, provided an estimated accuracy of about 5 picoseconds, which was sufficient for the initial beam commissioning. New challenges of improving beam transport for higher power operation will require measuring bunch profiles with 1-2 picoseconds accuracy. We have successfully implemented a number of improvements to maximize the performance characteristics of the delivered devices. We will discuss the current status of this instrument, its ultimate theoretical limit of accuracy, and how we measure its accuracy and resolution with real beam conditions.

INTRODUCTION

Uncontrolled beam loss is the major factor limiting the maximum achievable beam power in high intensity linacs. The SNS accelerator is operating routinely at beam power of about 1 MW with typical levels of uncontrolled beam loss within the design limit of 1W/m. This small level of beam loss, while considered to be acceptable, still creates significant activation of the beam line equipment, which affects the lifetime and complicates maintenance. Moreover, the SNS power upgrade plan requires 50% increase in beam intensity while keeping uncontrolled beam loss at the present level. Understanding and mitigating beam loss mechanisms requires knowledge of beam parameters in 6D phase space. In the absence of practical tools for measuring the bunch distribution in 6D space, devices for measuring 1D projections, or profiles, are commonly used. The SNS accelerator is equipped with seven Bunch Shape Monitors (BSMs) for measuring the longitudinal bunch profile. The BSM principle is based on the coherent transformation of the ion bunch temporal structure into an equivalent temporal structure of secondary electrons emitted from a thin wire inserted into the beam. The resulting electron signal is analyzed using transverse deflection in an RF deflector synchronized with the RF frequency of the linac. Details of the BSM design and its characteristics can be found in [1]; a schematic layout is shown in Fig.2. The BSMs were useful in the initial commissioning of the linac where they helped to identify serious problems [2]. The accuracy of the devices, roughly defined as about 1° at 805MHz, was sufficient for identifying and correcting a significant deviation of the beam longitudinal phase space from design expectations. After transition to operations, the focus of beam study shifted to more delicate matters of beam matching and model verification, which require measurement accuracies of 10-15%. A typical RMS bunch length in the SNS warm linac is about 3° at 805MHz (corresponding to ~10 ps or 1.7 mm). In order for the BSMs to be useful for beam tuning they should provide an accuracy of better than 0.5°, or roughly 1 ps. An example of a beam matching exercise is shown in Figure 1. The red dots show the RMS bunch length measured at four BSM locations along the linac. The blue line is the RMS bunch length predicted by the model with the initial Twiss parameters fit for the best agreement between the measurements and the model. If we assume zero measurement error then the conclusion from the measurement is that beam is mismatched at the entrance, resulting in the longitudinal size oscillations and emittance increase along the linac. If we assume that measurement error is 1°, as shown by the larger vertical bars on the plot, then no definitive conclusion can be made regarding the beam matching quality. Measurements with 0.5° accuracy will provide useful information and thus we have adopted this value as the goal in the device improvement process.

Figure 1: The RMS bunch length evolution along the SNS linac. Red dots – measurements; blue line – model prediction.

LIMITING FACTORS OF THE BSM RESOLUTION

The process of bunch shape measurement is shown schematically in Fig. 2. There are three steps in the process: 1) conversion of the ion bunch shape to the low energy electrons bunch shape via the secondary emission process, 2) transport of the electron bunch to the analyzer entrance aperture, and 3) transport of the bunch through

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the deflector/analyzer. All three steps affect the resolution of the measurement.

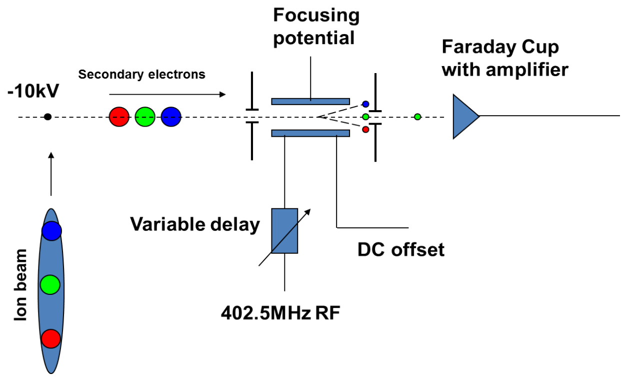

Figure 2: Schematic diagram of the SNS Beam Shape Monitor operational principle.

Secondary Emission Temporal Response

We do not have reliable experimental data on the secondary emission temporal response. It is assumed to be on the order of 1 ps or faster [1]. The only way we can estimate the upper limit in the existing device is to create and measure as short a bunch as possible. The fastest bunch RMS fall time we have been able to measure so far is ~1.5°, as shown in Fig. 3, which is a convolution of the unknown ion bunch length, the unknown secondary emission response and the deflector/analyzer resolution of ~.5°.

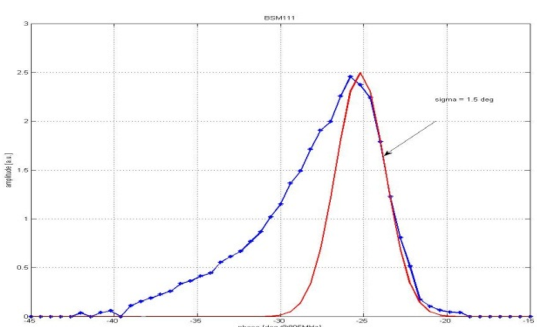

Figure 3: The fastest measured fall time. Blue – measurement, red – Gaussian fit to the falling edge.

Space charge effect in the accelerator pipe

The peak current of the measured ion bunch is typically about 1A. The electric field of the ion bunch acting on the low energy electrons travelling from the wire to the analyzer/deflector can distort the electron bunch shape. This effect is clearly observed in the measurements shown in Fig. 4 and Fig. 5. Fig.4 shows a 100mA bunch profile measured at three locations of the wire: 1) in the ion beam center, 2) offset by +1mm and 3) offset by -1mm. The measured profile does not depend on the wire position as expected. Fig. 5 shows the same measurements but with a 1A ion beam bunch. There is a significant difference in the profile shape caused by the varying degree of space charge force at different wire locations.

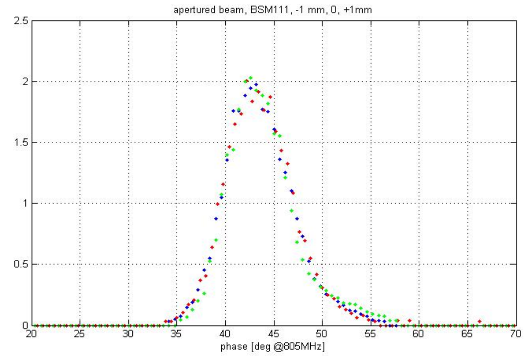

Figure 4: Low current bunch profile measured at different positions of the wire: -1mm, 0, +1mm.

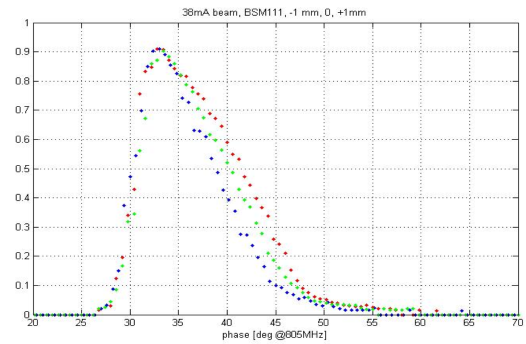

Figure 5: Nominal current bunch profile measured at different positions of the wire: -1mm, 0, +1mm.

The effect of the ion beam space charge appears to be the dominant source of measurement error and can be a fundamental limiting factor. We plan to explore the dependence of the error on the energy of the electrons and the position of the wire. Placing the wire at a significant distance from the ion beam center can reduce the space charge effect and the measurement error, assuming there is no correlation between the horizontal and longitudinal charge distribution within the bunch.

Resolution of the deflector/analyzer

The resolution of deflector/analyzer can be estimated using the following equation:

$$\delta\varphi = \frac{\delta x}{a_{\max}} \approx \frac{\sqrt{d^2 + \sigma^2}}{a_{\max}} = \frac{\sqrt{d^2 + \sigma^2}}{g \cdot V_{RF}} \quad , \quad (1)$$

where d is the analyzer slit width, σ is the transverse size of the electron beam, V_{RF} is the RF field amplitude in the deflector, and g is a constant. It is clear from (1) that in order to improve the resolution we should focus the electron beam, reduce the slit width and increase the deflecting voltage. In practice, increasing the RF voltage is beneficial to only some extent. At higher levels non-linear effects increase the electron beam size and the net effect can be detrimental. Reduction of the analyzing slit size was the easiest option to implement and resulted in

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an improvement of the resolution as confirmed by the measurements described below.

For measuring the electron beam size on the slit we switch off the RF voltage on the deflector and scan the electrons across the slit by applying DC voltage on the deflector plates. A typical scan is shown in Fig. 6. The focusing is adjusted to minimize the profile width.

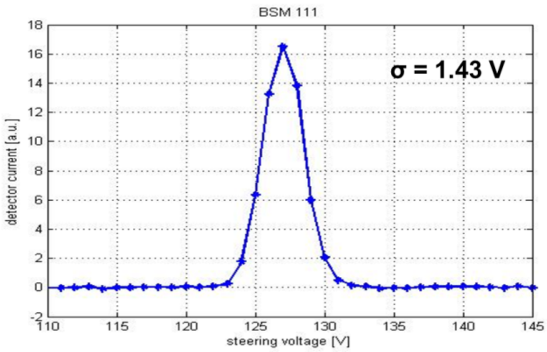

Figure 6: Measured electron beam profile on the analyzing slit plane.

For measuring the relative RF deflector strength we make two bunch length scans with different DC biases applied to the deflector plates. The profile shift, in degrees per volt, is inversely proportional to the RF voltage amplitude.

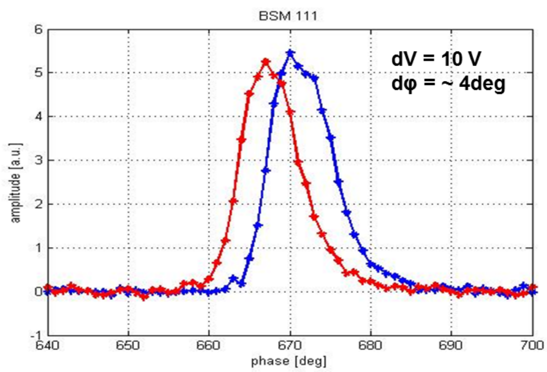

Figure 7: Measurement of the RF deflector strength.

We calculate the RMS impulse response of the deflector/analyzer system by multiplying the measured phase shift in degrees per volt by the RMS electron beam profile width in volts. The results of measurements for unmodified and modified BSMs are shown in Table 1. A reduction of slit size from 1mm to .3mm improved the resolution of BSM111 by 50%. This modification will be applied to all remaining BSMs.

Table 1. Measured properties of the SNS BSM

	BSM107	BSM109	BSM111
σ_V [V]	2.28 old slit, 1 mm	1.94 old slit, 1 mm	1.43 new slit, .3 mm
$d\phi/dV$ [°/V]	.36	.47	.38
$\delta\phi$ [°]	.83	.85	.54

The above measurements do not include the effect of additional focusing and aberrations from the RF voltage. In order to estimate the BSM resolution including all effects except for the space charge, we create as short bunch as possible by adjusting the linac parameters. Profile measurements shown in Fig. 8 demonstrate that an overall resolution of the system better than .5° is achievable.

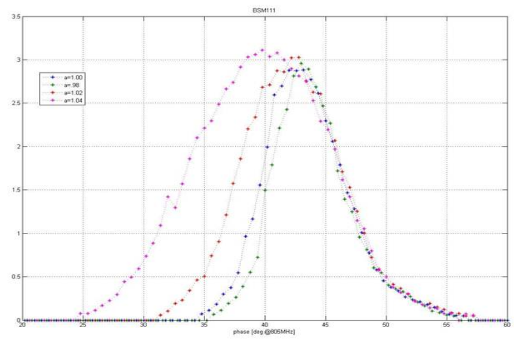

Figure 8: Bunch profiles measured at different linac gradients. The RMS bunch widths of the consequent profiles are 5.8°, 4.1°, 3.3°, and 2.9°.

We also found that it is important to verify the device settings with the above set of measurements before every beam study. A stray magnetic field from the adjacent magnets affects electrons trajectories, and any change in the linac quad set point can cause the BSM tuning to change. The new software tools [3] make the retuning process much faster.

SUMMARY

The required accuracy of longitudinal size of the ion bunch in the SNS linac of about 0.5°, or 1 ps, was not satisfied with the existing Beam Shape Monitors installed in the SNS linac. We are investigating possibilities of improving the accuracy through small hardware modifications and tuning of the devices. We demonstrated that reduction of the analyzer slit size and careful tuning of the device improves the resolution of the analyzing part of the device to the required level. It appears that the influence of the ion beam space charge is the strongest remaining factor limiting the accuracy. We are continuing efforts to better understand it and to develop a mitigation strategy.

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