LONGITUDINAL LASER WIRE AT SNS

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Abstract

This paper describes a longitudinal H- beam profile scanner that utilizes laser light to detach convoy electrons and an MCP to collect and measure these electrons. The scanner is located in MEBT with H- energy of 2.5MeV and an RF frequency 402.5MHz. The picosecond pulsed laser runs at 80.5MHz in sync with the accelerator RF. The laser beam is delivered to the beam line through a 30m optical fiber. The pulse width after the fiber transmission measures about 10ps. Scanning the laser phase effectively allows measurements to move along ion bunch longitudinal position. We are able to reliably measure production beam bunch length with this method. The biggest problem we have encountered is background signal from electrons being stripped by vacuum. Several techniques of signal detection are discussed.

INTRODUCTION

The Spallation Neutron Source accelerator complex consists of an H- linac where a one mS long train of ~1us mini-pulses is accelerated to 1GeV to be injected into a storage ring. The mini-pulses are accumulated in the ring and extracted to hit a mercury target as an intense ~700nS long pulse. Every mini-pulse is bunched at a 402.5MHz frequency. The SNS accelerator runs at 60Hz with average current of ~1.6mA resulting in over 1MW of beam power on target. Such a machine requires low loss operation, thus careful matching of longitudinal and transverse planes becomes important. The SNS uses several diagnostics devices and techniques for longitudinal profile measurements [1] including classical wire based Bunch Shape Monitor [2] and Laser Bunch Shape Monitor (LBSM) installed in MEBT. Also a method for measuring longitudinal Twiss parameters with Beam Position Monitors (BPM) was recently developed [3]. The LBSM is the only beam dynamics model independent device that allows non-invasive measurements while the accelerator is running at full power in neutron production mode.

THEORY OF OPERATION

A mode-locked laser running at 80.5MHz – in sync with the 5th sub-harmonic of 402.5MHz – detaches the electrons from the 2.5MeV negative hydrogen ions in the MEBT. The detached electrons are deflected by a magnet to be collected by an MCP as shown in Fig.1. While changing the laser phase we effectively move longitudinally along the ion beam and strip the ions that have a corresponding beam phase only. Using the 5th sub-harmonic results in 72° of scanned laser phase for a full sweep of 360° of ion beam phase.

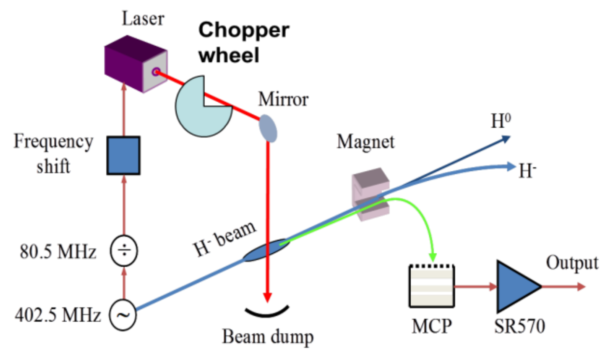

Figure 1: A layout of the Laser Bunch Shape Monitor.

In order to use this technique we need to precisely measure the laser phase vs. the base 402.5MHz carrier. We developed two approaches: frequency offset and phase shift.

Frequency Offset

If we change laser pulse repetition frequency by a tiny Δf on the order of 1kHz it will result in a phase drift with the period of ~1ms. Since the ion pulse length is 1ms it will experience all possible values of laser phase along its length. This will effectively plot longitudinal bunch distribution against time along the macro-pulse where 200us (1ms/5) corresponds to 360° of ion beam phase. Figure 2 shows the bunch profiles for different Δf.

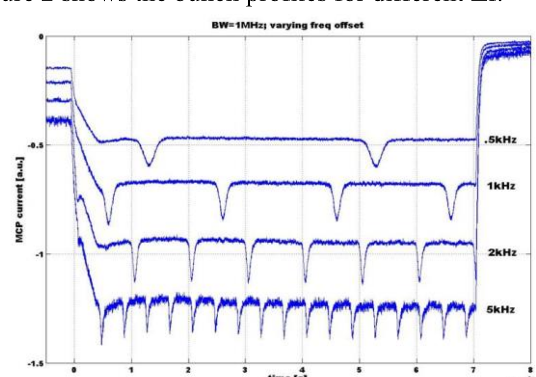

Figure 2: Bunch profile measurements with different frequency offsets in the frequency offset mode.

This method allows measuring bunch profile instantly by capturing one ion beam macro-pulse. It is very convenient because no additional equipment is needed and a scope waveform shows the bunch profile. It also doesn't require any precise measurement of Δf and actually even locking to 402.5MHz is not necessary.

Unfortunately this approach only works for long ion beam pulses. It is impossible to run full-length pulses

ISBN 978-3-95450-141-0

during experimental setups where high loss is expected. Thus this method is applicable for production optics only.

Phase Shift

An alternative way to scan laser phase relative to beam phase is to insert a controllable phase shifter between the base 80.5 MHz clock and the laser. This way one sets the phase and records MCP signal for every phase value. So to obtain a profile consisting of N points it requires N macro-pulses to be measured.

While this method works with any macro-pulse length, implementing it requires a much more sophisticated setup including automated phase shifting and measuring its actual value. Figure 3 shows a typical bunch length measurement with a phase shifter.

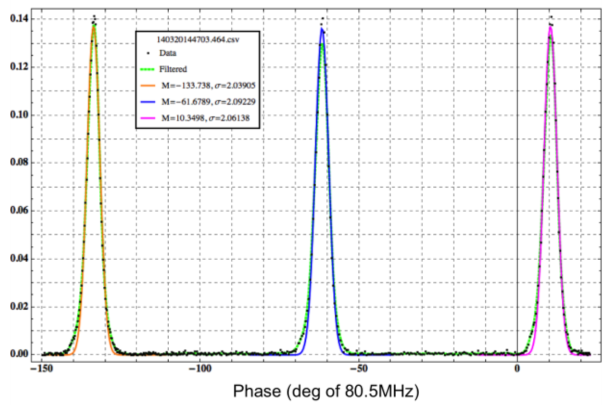

Figure 3: Typical bunch profile taken with phase shift technique. Peaks are distributed 72° apart.

LASER AND TRANSMISSION LINE [4]

SNS uses a Mira 900 Ti:sapphire mode-locked laser (pumped by a 10W Verdi-V10 solid-state laser) as the light source. The laser is synchronized to a stable external radio frequency (RF) source at 80.5MHz with a Coherent Synchro-Lock controller. The laser has pulse width (FWHM) of 2.5pS. The laser's peak power is variable up to 5kW.

The laser itself is located on the third floor of SNS front end building, so the light has to be transported to the beam line from there. Initially a free propagation transport line was used, but it was adding significant vibration and temperature effects. So it was replaced with a 30 m long polarization-maintaining LMA fiber (PM-LMA) from Nufern. The fiber significantly increases laser beam stability in the interaction point but broadens the laser pulse to ~10 ps. With the current laser spec (800nm wavelength/0.6W average power/80.5MHz rep. rate) and ion beam spec (2mm transverse and 80ps longitudinal, all of sigma size), the photoionization efficiency was estimated to be about 3×10^{-6} at the MEBT. For a typical SNS ion beam macro-pulse, the photo-ionized electron charge over one macro-pulse was estimated to be about 10pC.

A chopper wheel is used to intercept the laser beam and collect the background signal of the MCP with no laser present. We also experimented with a shutter instead of the chopper in order to have full control of the number of background measurements.

A motorized stage allows transverse scans in the horizontal plane, so it's possible to build 2D distribution in the X-Z plane.

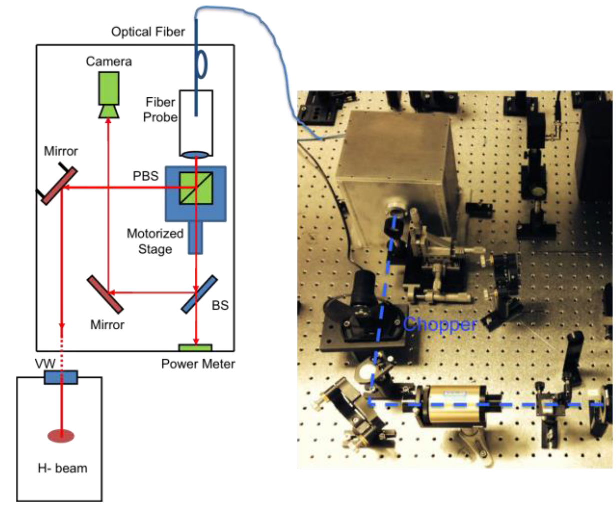

Figure 4: Laser transport line layout.

EXPERIMENT SETUP

In order to implement the phase shifting scheme we used a custom built analog chassis that relies on two RVPT0003MAC phase shifters. The shifters are connected in series to provides more than 400° at 80.5MHz. The base 402.5MHz is down converted to 80.5MHz and connected to the phase shifting chassis. The output of the chassis is sent into the laser synchronization module.

The phase shifter's dependence on bias isn't linear (Fig. 5). Chaining two phase shifters also adds non-linearity due to amplitude variations for differing bias, so phase readback is necessary.

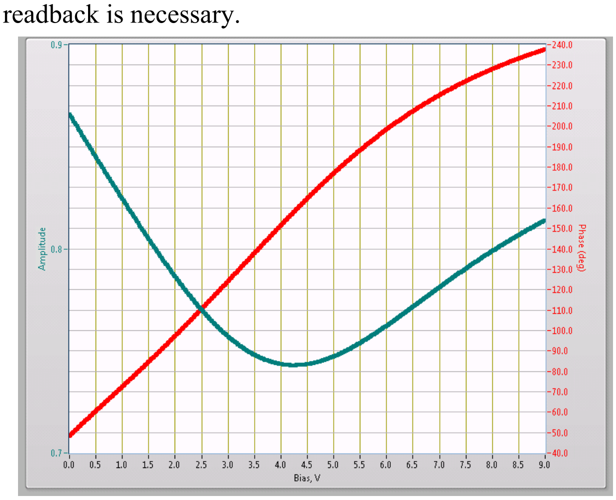

Figure 5: Phase shifter output vs. controlled bias.

The actual laser phase is monitored from an internal photodiode by an SR844 lock-in amplifier that is locked

ISBN 978-3-95450-141-0

to the same 80.5MHz. We found out that we needed to buffer the shifter's inputs with ZFL-500LN amplifiers to avoid reflections that contaminated the base frequency of the lock-in amplifier – Fig. 6.

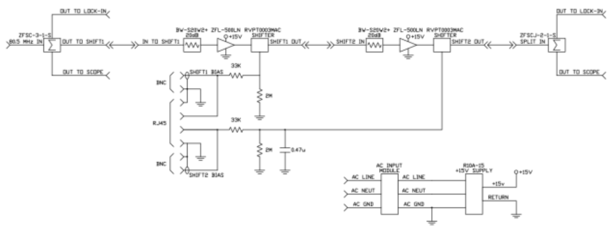

Figure 6: Schematics of phase shifter chassis.

Collected electrons are amplified by an MCP (Photonis APD 1 MA 40/12/10/8 D 60:1) and further amplified with an SR 570 current amplifier. The signal bandwidth is ~ 1MHz. The amplified signal is digitized with an NI 5105 card. The MCP's high voltage is controlled by a custom made HV power supplied that is controlled by an NI 6229 card and typically runs at negative 2.3kV.

The chopper wheel is synchronized to the ion beam trigger, so every even pulses have laser-induced signal and odd ones are used for background (that is subtracted in software). This effectively halves the ion beam repetition rate, as two ion pulses are required for each data point taken.

Everything is controlled form LabVIEW based software that manages data acquisition, background subtraction, phase scanning, and phase read back measurements. It also provides control over the MCP HV and magnet current.

Background Considerations

The laser signal is ~20% of the background in the maximum of bunch profile. The main source of background signal is from H- stripping on residual gas. It makes measurements extremely sensitive to background pulse to pulse deviations. Fig. 7 shows the typical signal in phase shifting measurement in the middle of the bunch.

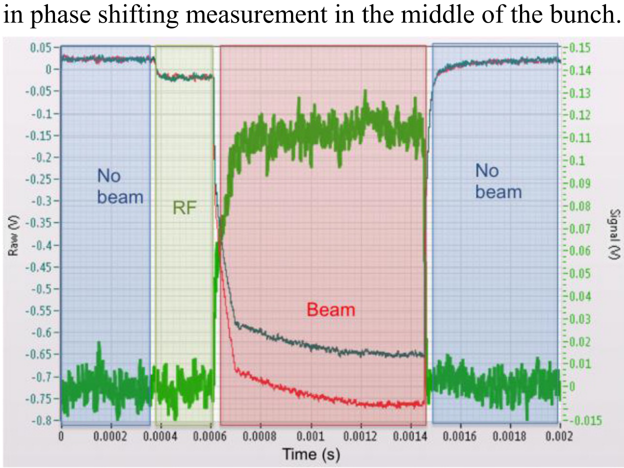

Figure 7: Macro-pulse structure during production. Red trace shows the MCP signal with laser hitting the ions and the grey-blue trace represents signal with laser being blocked by chopper. Green trace is the difference.

The first "step" of the waveform corresponds to cavities switching on and generating x-rays. The second step is actual ion-beam induced signal.

For a better understanding of the noise structure we collected 10 minutes of waveform data at 60Hz during beam production. The data was partitioned into batches of 1000 subsequent pulses and waveforms were averaged over every batch – Fig. 8. From this we obtained a slow evolution of the background waveform over time and concluded that it makes sense to average over several macro-pulses as it decreases signal deviation according to 1/√N.

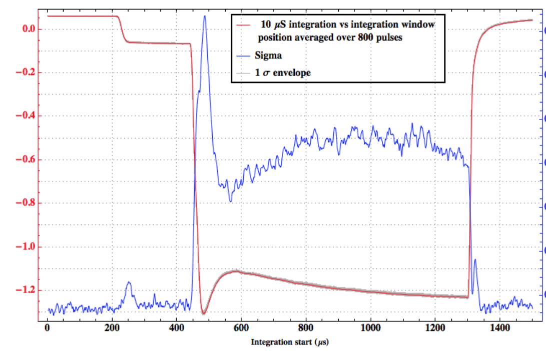

Figure 8: Background waveform averaged over 1000 macro-pulses. Sigma refers to standard deviation of every waveform point for one batch statistics.

The Fig. 9 demonstrates how 10 pulse averaging works for production beam.

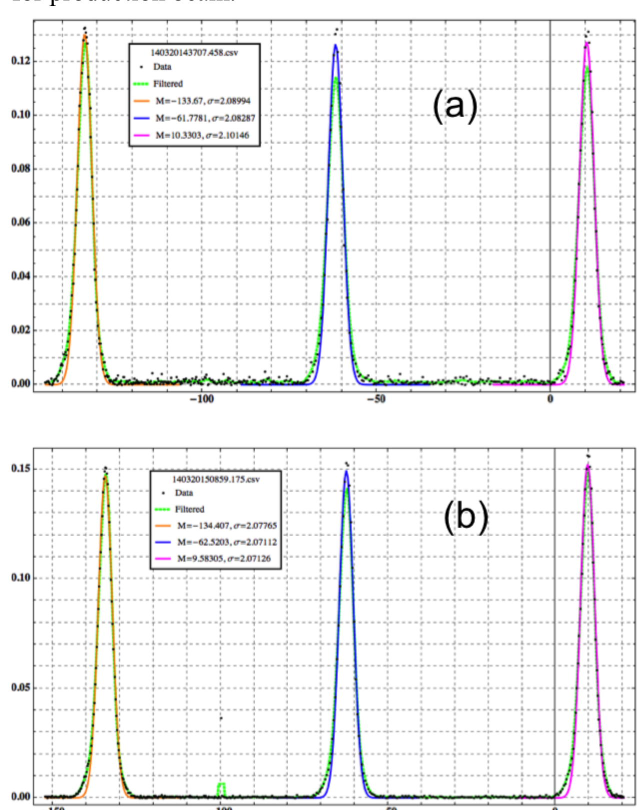

Figure 9: (a) no averaging, (b) averaged over 10 macro-pulses.

ISBN 978-3-95450-141-0

We experienced significant problems with the short ion beam pulses that are used for accelerator studies – 50 uS length. We considered several ways of statistically improving the profiles. One can either increase the ion beam length up to 50 us and run scans at 1 Hz repetition rate or alternatively we can run 10 us beam at 5 Hz rate to stay below dangerous beam power levels. In the first scenario we can average along macro pulse (in the beam window) and in the second scenario we can average over several macro-pulses. Unfortunately we weren't able to obtain conclusive results of which technique is better. We observed that the pulse-to-pulse background deviation is significantly higher than during production. Figure 10 demonstrates an example noise pattern during a 50 us scan.

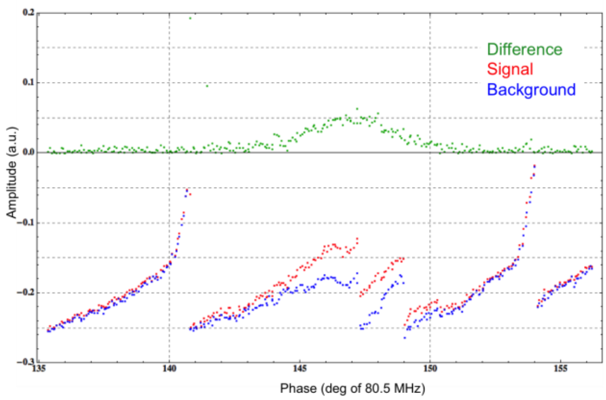

Figure 10: Short pulse scan.

Currently there is no understanding what mechanism can cause such background behavior.

We also tried to detect the 80.5 MHz component in MCP signal hoping that this component won't be prone to noise issues, but we failed since the bandwidth of our existing MCP appeared to be significantly lower.

REBUNCHER SCAN

In order to see if we can achieve meaningful results that can be predicted by beam dynamics models, we successfully applied the well known quadrupole scan technique [5]. Normally it is used to measure transverse emittance by plotting transverse size vs. quadrupole field strength and fitting it with a parabola.

The same technique can be used for plotting the longitudinal size vs. RF amplitude. The results of scanning upstream rebuncher amplitudes are shown on Fig. 11. They provide a good sanity check that the device produces physical results, but couldn't be used for emittance calculation because of space charge. Attempt to perform similar scan with lower beam current (no space charge effects) was unsuccessful due to background issues mentioned above.

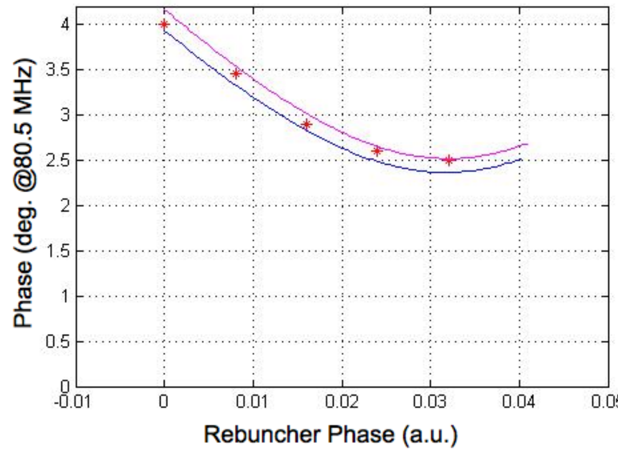

Figure 11: Experimental results compared to model generated for two different input Twiss parameters.

CONCLUSIONS

The SNS LBSM scanner is operational and can be used for reliable measurement of production beam longitudinal size. The measured beam size is around 10°, but the reference design size is ~15°. Currently there is no explanation for this discrepancy, although it's hard to imagine a flaw in the measurements that could lead to smaller beam size.

Significant background signal and its time deviation currently limit the use of this device for short pulses and low current setups. We plan to consider replacing the MCP with a high bandwidth detector and also investigate the bending magnet's ability to reject background electrons.

ACKNOWLEDGEMENT

ORNL/SNS is managed by UT-Battelle, LLC, for the U.S. Department of Energy under contract DE-AC05-00OR22725.

REFERENCES

[1] A. Aleksandrov, *et al.* Proc of IBIC2013, p. 163.
[2] A. Feschenko, *et al.*, Proc. PAC2001, p. 517.
[3] A. Shishlo *et al.*, Phy. Rev. Lett. 108, 114801, (2012).
[4] C. Huang, *et al.*, Applied Optics / Vol. 52, No. 19, p.4462-4467, (2013).
[5] M.G. Minty, F. Zimmermann, "Measurement and Control of Charged Particle Beams", Springer, (2003).

ISBN 978-3-95450-141-0