REAL-TIME LONGITUDINAL PROFILE MEASUREMENT OF OPERATIONAL H$^-$ BEAM AT THE SNS LINAC USING LASER COMB*

Y. Liu[†], C. Long, and A. Aleksandrov
Spallation Neutron Source, Oak Ridge National Laboratory, Oak Ridge, TN 37831, USA

Abstract

We demonstrate a novel technique to measure the longitudinal profile of an operational hydrogen ion (H$^-$) beam in a nonintrusive, real-time fashion. The measurement is based on the photoionization of the ion beam with a phase modulated laser comb – pico-second laser pulses with controllable temporal structure. The measurement technique has been applied to a 1-GeV, 1.4-MW H$^-$ beam at the Spallation Neutron Source (SNS) high energy beam transport (HEBT). A stroboscopic photograph of the H$^-$ beam micro bunch can be obtained by using a phase modulated laser comb. The entire measurement takes only 700 μs.

INTRODUCTION

Short-pulsed laser beam has been proposed to measure the longitudinal H$^-$ beam profiles in the particle accelerators [1, 2]. The measurement is based on the photo neutralization of the ion beam where the electrons are detached from the ions by a focused laser beam, often named as laser wire, and the number or density of the detached electrons leads to the determination of the original ion density. The measurement is generally nonintrusive and can be conducted on operational particle beams. So far, laser wire based longitudinal profile measurements have been conducted on relatively low energy beams. One reason is that for the short-pulsed, high repetition rate lasers, the available peak power is in the range of 1-10 kW, which produces photodetachment yield below 10^{-4}. Detection of such weak signals requires high sensitivity detectors such as photomultiplier tube (PMT) and suffers from the large background noise in the low/medium-energy beam line.

In this paper, we describe the longitudinal profile measurement of 1-GeV H$^-$ beam using a customized light source, referred to as a laser comb, which has multi-layer pulse structure with a peak power of more than 100 MW. The laser pulses can be phase modulated so that each comb tooth has a different phase delay with respect to the ion beam micro-bunches. When a phase modulated laser comb is applied to the ion beam, the photo-detached electrons are detected with a Faraday cup (FC). A stroboscopic photograph of the H$^-$ beam micro-bunch can be obtained from the FC output with the measurement time of only 700 μs. This real-time measurement causes negligible beam loss and therefore was conducted at different locations of the 1.4-MW neutron production H$^-$ beam line.

LIGHT SOURCE DEVELOPMENT

Estimation of Laser Power Requirement

Photo neutralization is a non-resonant process with a very small cross section (~3×10^{-17} cm^2). In laser-based H$^-$ beam diagnostics, the photo-detached electrons are directly proportional to the product between photon and ion beam densities as expressed by

$$n_{det} = c\sigma n_b n_l \tag{1}$$

where c is the light speed, σ the photon-ion interaction cross-section, and n_b and n_l represent density functions of ion and photon beams, respectively.

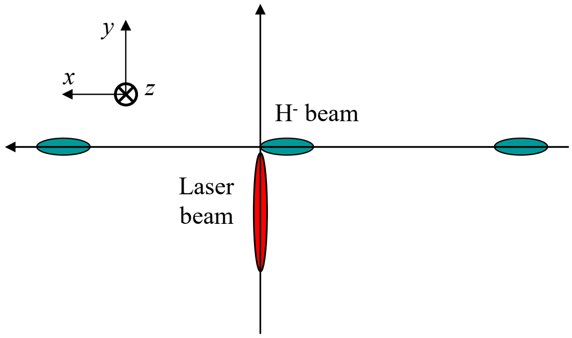

Figure 1: Schematic of laser-H$^-$ beam interaction.

A typical laser-ion interaction scheme is shown in Fig. 1. Both n_b and n_l are assumed to have a Gaussian function distribution as

$$n_b = \frac{N_b}{(2\pi)^{3/2}\sigma_{bx}\sigma_{by}\sigma_{bz}} \exp\left[-\frac{(x-\beta ct)^2}{2\sigma_{bx}^2} - \frac{y^2}{2\sigma_{by}^2} - \frac{z^2}{2\sigma_{bz}^2}\right], \tag{2}$$

$$n_l = \frac{N_l}{(2\pi)^{3/2}\sigma_{lx}\sigma_{ly}\sigma_{lz}} \exp\left[-\frac{x^2}{2\sigma_{lx}^2} - \frac{(y-c(t-s))^2}{2\sigma_{ly}^2} - \frac{z^2}{2\sigma_{lz}^2}\right]. \tag{3}$$

Here N_b and N_l are ion and photon numbers, respectively, $\sigma_{bx,y,z}$ ($\sigma_{lx,y,z}$) represents the RMS size of the ion (photon) beam along the ion beam propagation, photon beam propagation, and vertical direction, respectively, and s denotes the phase delay in longitudinal profile scan. For pulsed beam with low duty factor, the overall photodetachment yield over one micro bunch of the ion beam can be calculated by integrating n_{det} over an entire space and time as

$$\eta = \frac{c\sigma}{N_b} \iiint_{-\infty}^{+\infty} n_b n_l dxdydzdt$$

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[†] liuy2@ornl.gov

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$$= \eta_{max}\exp\left[-\frac{s^2}{2\left[\tau_{bx}^2+(\sigma_{lx}/\beta c)^2+\tau_{ly}^2+(\sigma_{by}/c)^2\right]}\right]. \tag{4}$$

with

$$\eta_{max} \cong \frac{\sigma\lambda E_l}{2\pi h\beta c\sigma_{bz}\sqrt{(\tau_b^2+\tau_l^2)c^2+\sigma_{by}^2}} \tag{5}$$

where λ and E_l are laser wavelength and pulse energy, h is the Planck constant, βc is the ion beam speed, τ_b ($=\sigma_{bx}/\beta c$) and τ_l ($=\sigma_{ly}/c$) are ion and laser pulse width. For typical H$^-$ beam parameters in the SNS linac for neutron production, $\eta_{max} \sim 0.01$ is required to achieve sufficient dynamic range in the measurement, which leads to a laser pulse energy of ~ 10 µJ.

Laser Comb

To measure the longitudinal profile of H$^-$ beam micro bunches, laser pulse width needs to be at the picosecond order. Such laser pulses are normally generated from mode-locked lasers with typical pulse energy at a 10 nJ order. Therefore, a power amplification with a gain of at least three orders of magnitude is required.

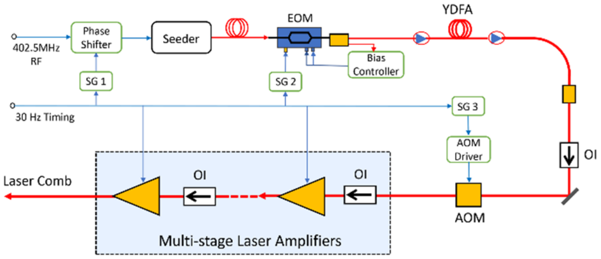

Figure 2: Laser system schematic. EOM: electro-optic modulator, AOM: acousto-optic modulator, YDFA: ytterbium-doped fiber amplifier, OI: optical isolator, SG: signal generator.

Recently, we developed a laser system that has a multi-layer pulse structure [3]. The system has been modified in this work by including a new mode-locked seed laser with the RMS pulse width of ~5 ps. Figure 2 shows a schematic of the laser system that consists of a mode-locked seed laser, pulse picking components, and multi-stage amplifiers. Each macropulse of the laser is referred to as a laser comb as it contains multiple mini-pulses (comb teeth). The comb parameters, i.e., comb duration, width and spacing of individual comb teeth, are produced by a combination of high-bandwidth, high-extinction-ratio EOM, a fiber-based pre-amplifier, and an AOM. The laser combs are amplified by three stages of double-pass, diode-pumped Nd:YAG amplification modules with a total gain greater than 10^6. The seed laser and the control electronics of the EOM have been properly conditioned to achieve high quality pulse generation and efficient power amplification.

An example of the laser output is plotted in Fig. 3. A laser comb used in this measurement contains 75 comb teeth and the width and spacing of comb teeth are 30 ns and 9.45 µs, respectively. The laser comb repeats at 30 Hz. As shown in Fig. 3(b), each comb tooth further contains certain number of micro-pulses generated form the mode-locked seed laser. Such a micro-pulse structure of the laser comb minimizes the required laser average power. For example, the peak power of the micro-pulse in Fig. 3 is 20 MW while the average power is only about 6 W in this case.

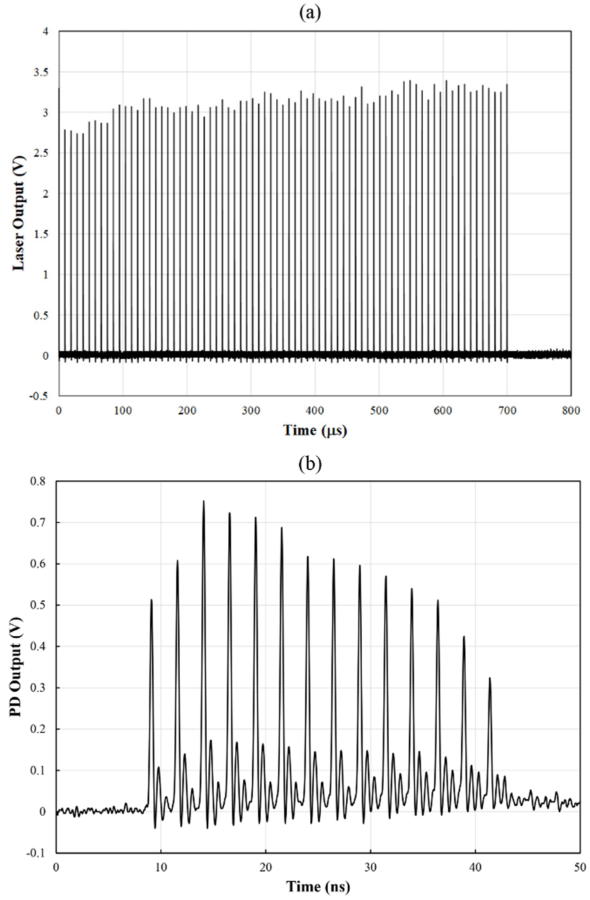

Figure 3: (a) A laser macro-pulse (laser comb) consisting of 75 mini-pulses (comb teeth). (b) Micro-pulses inside a single laser comb tooth.

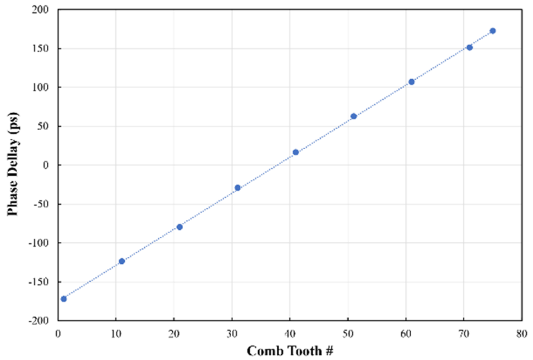

Figure 4: Phase delay vs. individual comb tooth as a result of phase modulation.

As illustrated in Fig. 2, the phase of individual micro pulses can be controlled with a phase shifter. In this work, we controlled the phase shifter with a 30-Hz sawtooth signal so that each comb tooth has a different phase delay with respect to the H⁻ beam bunches. An excellent linearity between the phase delay and comb teeth has been measured as shown in Fig. 4.

LONGITUDINAL PROFILE MEASUREMENT

Measurement Results

The longitudinal profile measurement was conducted at the end of the SNS linac as shown in Fig. 5. The laser was placed outside the accelerator tunnel and the laser beam was delivered to the measurement station through a free-space laser transport line. The laser beam had an RMS pulse width of about 5 ps with a peak power of ~10 MW. The electrons detached by the laser comb are detected by the FC. Although there were multiple micro-pulses within an individual laser comb tooth as shown in Fig. 3, due to the bandwidth limitation of the detectors, all electrons generated from one laser comb tooth were detected as one pulse. During the profile measurement, individual laser comb teeth interacted with different time sheets of the H⁻ beam micro-bunch. The FC output signals were gated to the laser comb so that the electrons from individual temporal slices of the H⁻ beam were properly processed to reconstruct the profile.

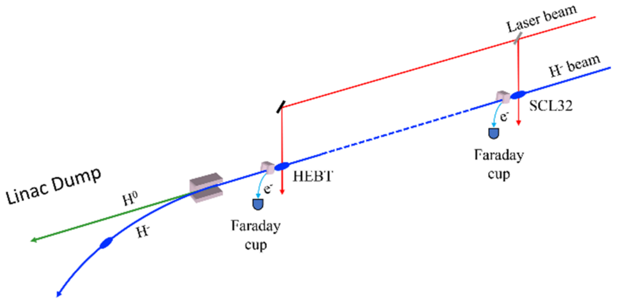

Figure 5: Longitudinal profile measurement locations. First measurement is conducted before the linac dump and second measurement is conducted at the end of SNS superconducting linac (SCL).

As a result of the phase modulation, each laser comb tooth interacts with the ion beam bunch at a different phase. The FC output of all 75 comb teeth can be visualized in a two-dimensional graph as shown in Fig. 6. Since each laser comb tooth corresponds to a different phase delay, the graph represents a stroboscopic photograph of the H⁻ beam bunch. It is noted that the entire photograph was taken within a time period of 700 µs. By integrating the FC output and plot it as a function of the phase delay, we obtain the longitudinal profile the H⁻ beam as shown in Fig. 6(b). The estimated RMS bunch width is about 50 ps.

Another longitudinal profile measurement was conducted at the end of SCL which is about 45 metres upstream of the first measurement location. The measurement is shown in Fig. 7. The RMS bunch width is ~30 ps from the Gaussian fit.

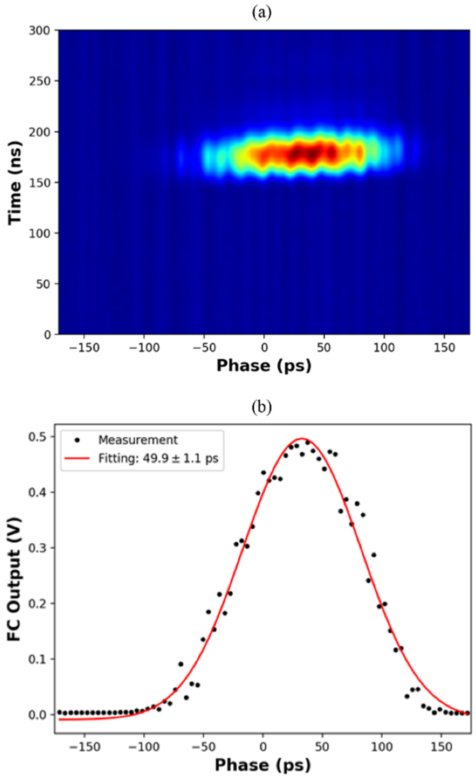

Figure 6: (a) Stroboscopic photograph of H⁻ beam bunch and (b) longitudinal profile before the linac dump.

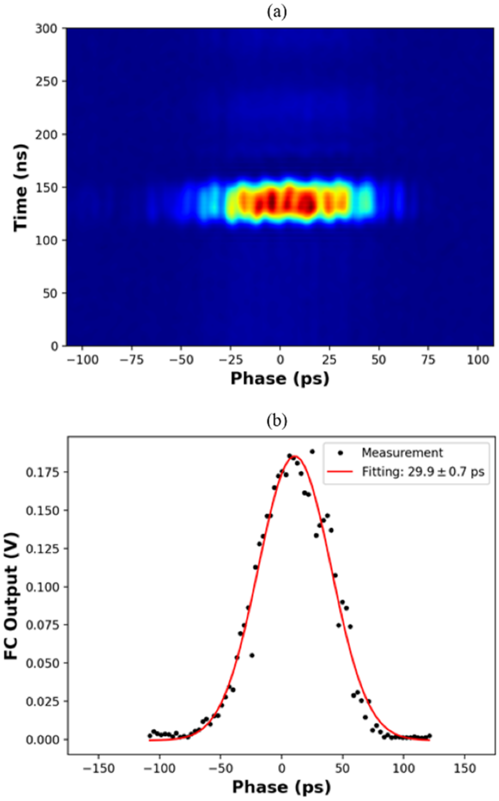

Figure 7: (a) Stroboscopic photograph of H⁻ beam bunch and (b) longitudinal profile at the end of SCL.

Discussions

As shown in Eq. (4), the measured bunch width is a convolution of the actual value with the contributions from the transverse beam width of the H^- beam, the longitudinal and transverse beam widths of the laser beam. In the above measurement locations, those parameters are measured to be σ_{by}/c = 4~8 ps, $\tau_l \approx 5$ ps, $\sigma_{lx}/\beta c \approx 0.4$ ps. Based on that, the actual RMS bunch width are estimated to be about 49 ps and 29 ps for the two measurement locations. Obviously, the effect of those parameters is negligible for large RMS bunch widths. On the other hand, for the measurement of longitudinal profiles in the SCL where typical RMS bunch width is around 10 ps, precise ion beam size and laser pulse width are important to achieve accurate measurement results. It is noted that the ion beam size at SCL can be measured by our laser wire profile monitors. The measurement accuracy will also be affected by the laser pulse intensity jitter and laser beam pointing stability.

If we assume the pulse broadening is homogeneous between the two measurement locations described above, the energy spread can be estimated from the pulse broadening as

$$\frac{\Delta E}{E} = \gamma(\gamma + 1)\frac{\Delta t_0}{t_0}, \qquad (6)$$

where γ is the Lorentz factor of the H^- beam, t_0 is the propagation time between the two measurement locations, and Δt_0 is the growth of the bunch width. For $\gamma = 2.07$, $\Delta t_0 =$ 20 ps, t_0 = 170.85 ns, we calculated $\Delta E/E \approx 7.5 \times 10^{-4}$. Both the measured RMS bunch width and estimated energy spread are close to the design values.

A number of new beam instrumentation systems could be conceived at the SNS accelerator by employing the laser comb based longitudinal profile measurement technique. First, the current longitudinal profile measurement can be applied to 8 cryomodules along the SCL beam line. The longitudinal phase space can be reconstructed from the measurement at different cavity phases. The measurement can only be performed on low-repetition-rate, narrow-pulsed ion beam in this case. Measurement of longitudinal phase space of an operational beam could be realized if the energy spread of each longitudinal slice of the neutralized hydrogen beam can be measured in the linac dump. The longitudinal phase space could also be measured by taking advantage of the large beam dispersion in the end of the HEBT and measuring longitudinal profiles of different transverse portions (corresponding to different energy segments) using a laser comb.

Finally, a nonintrusive high-dimensional beam diagnostics can be realized by combining the longitudinal profile scan with the existing laser wire transverse emittance measurement. This capability was recently demonstrated in a time-resolved emittance measurement [3]. Using the current laser comb system with pico-second laser pulses, we can perform more investigations about the emittance variations within a bunch on the neutron production ion beam.

CONCLUSION

We have described a novel technique of longitudinal profile measurement of the H^- beam by using a laser comb. The proposed technique has been applied to the emittance measurement on the 1-GeV, 1.4-MW neutron production H^- beam at the SNS high energy beam transport. We have experimentally demonstrated that a stroboscopic photograph of micro-bunch can be obtained within a time period of 700 µs. Our experiment strongly supports that the laser-based nonintrusive beam diagnostics can provide unique information about the high-energy, high-power particle beam.

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