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A novel longitudinal laserwire to non-invasively measure 6-dimensional bunch parameters at high current hydrogen ion accelerators

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Abstract. Optical methods for non-invasive beam diagnostics of high current H^- ion accelerators have been developed in recent years. Such laserwires typically measure a 1D beam profile and/or 2D transverse emittance from the products of photo-detached ions as a laser beam is scanned across the H^- beam. For laser pulse durations (∼80 ns) longer than the RF period (∼3 ns), the detector integrates many complete bunches, enabling only transverse beam monitoring. This paper presents a new technique to capture a series of time resolved transverse emittance measurements along the bunch train. A fast (∼10 ps) pulsed laser photo-detaches ions within each bunch and is synchronised to sample consecutive bunches at certain longitudinal positions along each bunch. A fast detector records the spatial distribution and time-of-flight of the neutralised H^0, thus both the transverse and longitudinal emittance are reconstructed. We present simulations of a time varying pulsed laser field interacting within an H^- bunch, and estimate the yield, spatial and time distributions of H^0 arriving at the detector. We summarise the design of a recently funded longitudinal laserwire being installed in FETS at RAL, UK.

1. Introduction

Non-invasive laserwires to measure the transverse profile and emittance of high intensity hydrogen ion beams have been demonstrated at several accelerators including SNS [1] and CERN's LINAC4 [2, 3, 4, 5, 6, 7, 8]. Such laserwire systems rely on photo-detachment of H^- ions to neutralise only a narrow slice of the beam, thus permitting an essentially non-destructive measurement. Collection of the liberated electrons by a Faraday cup or similar detector enables the 1D profile to be determined as the laser is scanned across the beam, while a spatially sensitive downstream detector records the neutralised H^0 enabling the 2D transverse emittance (x, x') to be reconstructed.

In 2017, a dual station laserwire system was designed and permanently implemented at LINAC4 [8], with each station consisting of two orthogonal laserwires, an electron detector and a crossed pair of diamond strip detectors. In first commissioning at 160 MeV, 2× 1D beam profiles in orthogonal dimensions were obtained by exploiting a temporal delay in the incident orthogonal laser pulses [9]. Ultimately, each laserwire station will be capable of reconstructing 2× 2D transverse emittance measurements (x, x') & (y, y').

Notwithstanding that such laserwires show excellent agreement with conventional transverse diagnostics (typically <2%), they are limited by the laser pulse duration (∼80 ns) which is longer than the RF period (∼3 ns), thus the detector integrates many entire bunches and allows only transverse beam monitoring. In contrast, much shorter laser pulse durations are achievable and can probe longitudinally within a single bunch, as shown at SNS [10, 11], where the 1D temporal charge profile of the bunch can be measured by short laser pulses (10 ps after the fibre) synchronised with the accelerator RF. Furthermore, in early studies at LAMPF[1], the momentum spread $\Delta p/p$ of a relativistic H^- beam was measured via photo-detachment, by observing the narrow Feshbach resonance and as the incident angle of the laser beam was adjusted to vary the Doppler shift [12, 13].

Therefore, laserwire systems developed so far have been sensitive to individual parameters or correlated pairs of the 6 different dimensions of accelerator phase space (x, x', y, y', z, z'). In this paper we propose a combination of the above techniques with a time-of-flight method, to enable 6-dimensional bunch parameters of high intensity H^- beams to be measured by a single non-invasive laserwire instrument. Moreover, the resulting neutralised particle distributions may be deconvolved to explore correlations between the 6D variables, with the aim of reconstructing the true 6D phase space, similar to other 6D phase space diagnostics [14, 15, 16].

The new laserwire instrument is under construction at the Front End Test Stand at STFC Rutherford Appleton Laboratory, UK. FETS is a high intensity H^- accelerator shown in Fig. 1, designed to deliver a high quality 60 mA, 2 ms pulsed at upto 50 pps, 3 MeV chopped beam.

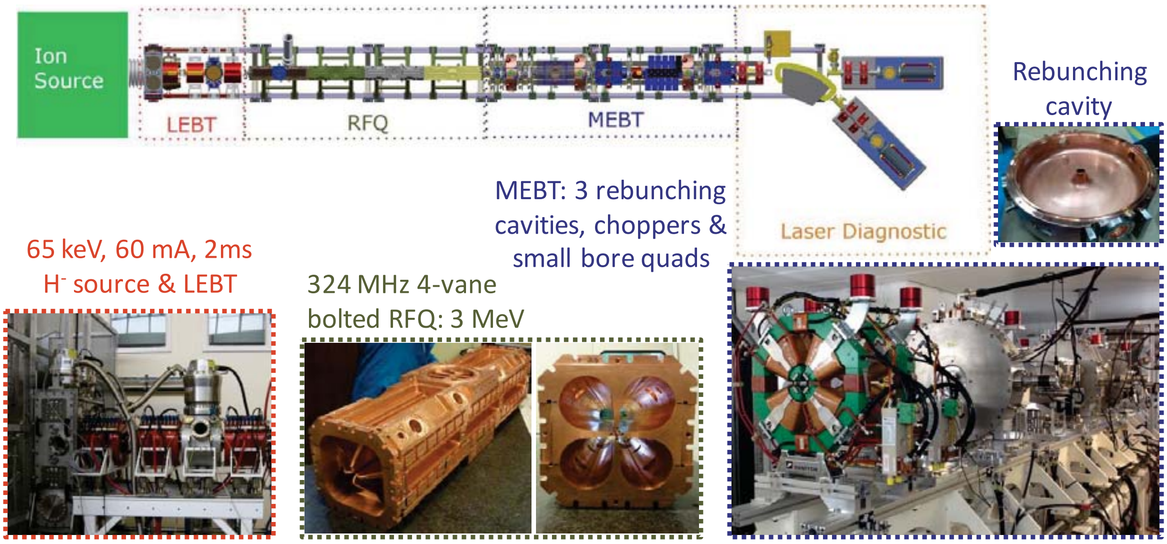

Figure 1. Front End Test Stand at STFC RAL.

This paper presents the concept of the longitudinal laserwire and summarises simulations of the laser pulse interactions with the 3 MeV H^- beam distribution, based on realistic particle beam and laser parameters, to calculate the yield, spatial and time distributions of the neutralised particles that inform the design.

2. Instrument Design

2.1. Longitudinal Laserwire Concept

The fundamental concept of a transverse laserwire diagnostic for FETS outlined above has been detailed previously [17, 18]. The new concept presented here is for a longitudinal laserwire that uses a short pulse (< 50 ps) laser to capture a series of transverse emittance profiles in

[1] Los Alamos Meson Physics Facility [13]

longitudinal slices along the bunch train. When the laser pulses are synchronised to a sub-harmonic of the accelerator RF, this provides the opportunity to understand emittance variations along the pulse train with an unprecedented time resolution. By precisely synchronising the laser pulses such that certain consecutive bunches in a train are sampled at different longitudinal positions along each bunch, then the time-resolved emittance variation along the mean bunch can be determined from multiple measurements.

At each laser time slice corresponding to a certain z position along a bunch, the transverse emittance can be obtained by reconstructing angular information from the neutralised H^0 atoms that reach a 2D spatially sensitive, fast detector, which is placed downstream of a dipole to deflect the main unneutralised H^- beam. The laser beam delivery optics split and steer two beams from a single fibre-coupled MOPA laser source to be orthogonally incident on the ion beam in the interaction chamber. By suitable adjustments to the relative optical path lengths, a time delay is introduced between the orthogonally incident laser pulses, such that interleaved laser pulses interact with alternative bunches at an RF sub-harmonic in the bunch train. The fast downstream detector distinguishes the neutrals generated by each laser pulse and records the spread in arrival time, relative to the relevant laser pulse interaction time. The latter can be determined from the RF synchronisation signals, a laser photodiode at the point of delivery, and by the fast response of a detector near the laser to collect the liberated electrons, with precise synchronisation established via a phase adjustable RF source. Thus for each laser pulse, the arrival time of the neutrals at the detector with respect to the time of the interaction of the laser pulse with the ion beam enables the time of flight and velocity of the neutrals to be calculated, thus determining the longitudinal emittance.

2.2. FETS Beam Considerations

The laser pulse duration necessary to adequately sample the H^- bunch depends on the beam energy and lateral dimensions of the ion beam under study. For the ion beam at FETS, consideration must be given for the time required by the short laser pulse to traverse the width of the H^- beam, as in Fig. 2. At the exit of the FETS 324 MHz RFQ the bunch σ (rms bunch length) is predicted to be $\sigma \sim 12^\circ$ or 103 ps, with a total bunch length including halo and tails of 45° or 386 ps. In the following simulations a laser pulse with a Gaussian temporal profile of FWHM (2.35σ) of 50 ps and 1 μJ pulse energy was applied, as generated by a Nd:YVO_4 oscillator at 1064 nm mode-locked to the fifth sub-harmonic of the FETS RF, with pulse stretched, multi-stage fibre amplification.

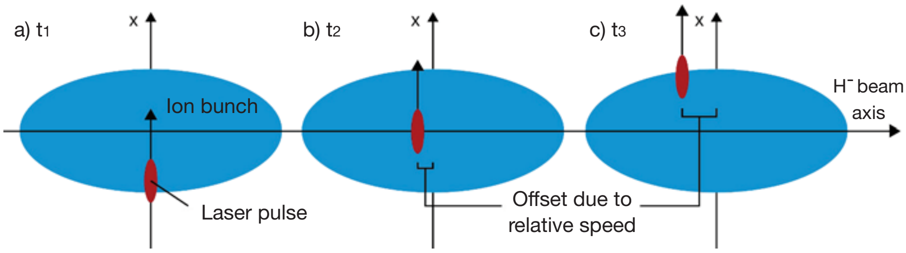

Figure 2. Laser pulse interaction with travelling H^- beam.

3. FETS LASERWIRE SIMULATIONS

A model of the laserwire interaction with the FETS beam was developed for transverse and longitudinal configurations. The laser focus coincides with the bunch and is modelled by Gaussian beam optics having an intensity characterised by

$$I(r,x) = \frac{2P}{\pi w(x)^2} e^{\frac{-2r^2}{w(x)^2}} \quad (1)$$

where P is the total laser power, r is the radial distance from the centre of the laser axis, x is the distance in the laser propagation direction, and $w(x) = w_0\sqrt{1 - \frac{x}{Z_R}}$, for which w_0 is the waist and Z_R is the Rayleigh distance. This static intensity distribution, however, only applies when the laser pulse is much longer than the time required for a photon to traverse the ion beam, as for a transverse laserwire.

For the longitudinal laserwire, the photon density within the H^- bunch also varies with time as the short temporal profile of the laser pulse traverses the optical focus. The time varying photon density $\rho(x, y, z, t_i)$ was calculated at each step i of the simulation, by applying various temporal pulse profiles: a rectangular function, Cauchy-Schwartz and Gaussian profiles were simulated. The results here are for a FWHM = 50 ps Gaussian temporal profile, truncated at $\pm 2\sigma$ as the head and tail of the laser pulse.

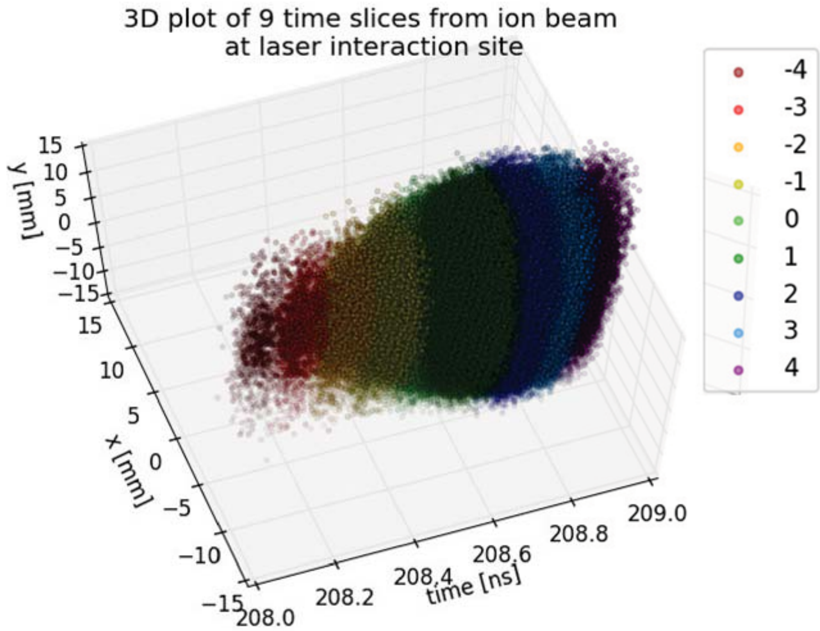

Figure 3. Distribution of H^0 neutralised in a FETS bunch by a vertical laser beam, translated horizontally in $\Delta x = 1$ mm steps, for 9 longitudinal time slices of the H^- bunch.

A GPT particle tracking simulation of the FETS beamline generated a 6D input distribution for the laserwire simulation. At each laserwire position, the probability that an H^- ion is stripped was calculated for n discrete steps, given by

$$P_s = 1 - e^{\sigma(\lambda) t \sum_{i=1}^{n} \rho(x,y,z,t_i)} \tag{2}$$

where $\sigma(\lambda{=}1064\,\text{nm})$ is the photo-detachment cross-section and t is the time the particle spends in the laser pulse at each step. The resulting neutralised particles are plotted in Fig. 3, for a vertical laser beam, which is stepped transversely across a bunch, for nine time slices. The FETS bunch charge is 10^9, so space-charge effects were simulated by 10^6 macro-particles. The input distribution had 889842 H^- ions at the laserwire and a scale factor of 10 applied to the stripping probability. Thus the results shown must be multiplied by 112 to estimate the true yield for a FETS bunch.

The transverse emittance for each of the nine time slices is reconstructed based on the spatial distribution of neutralised after a 2.0 m drift to the downstream detector, as shown for (x, x') and (y, y') in Fig. 4.

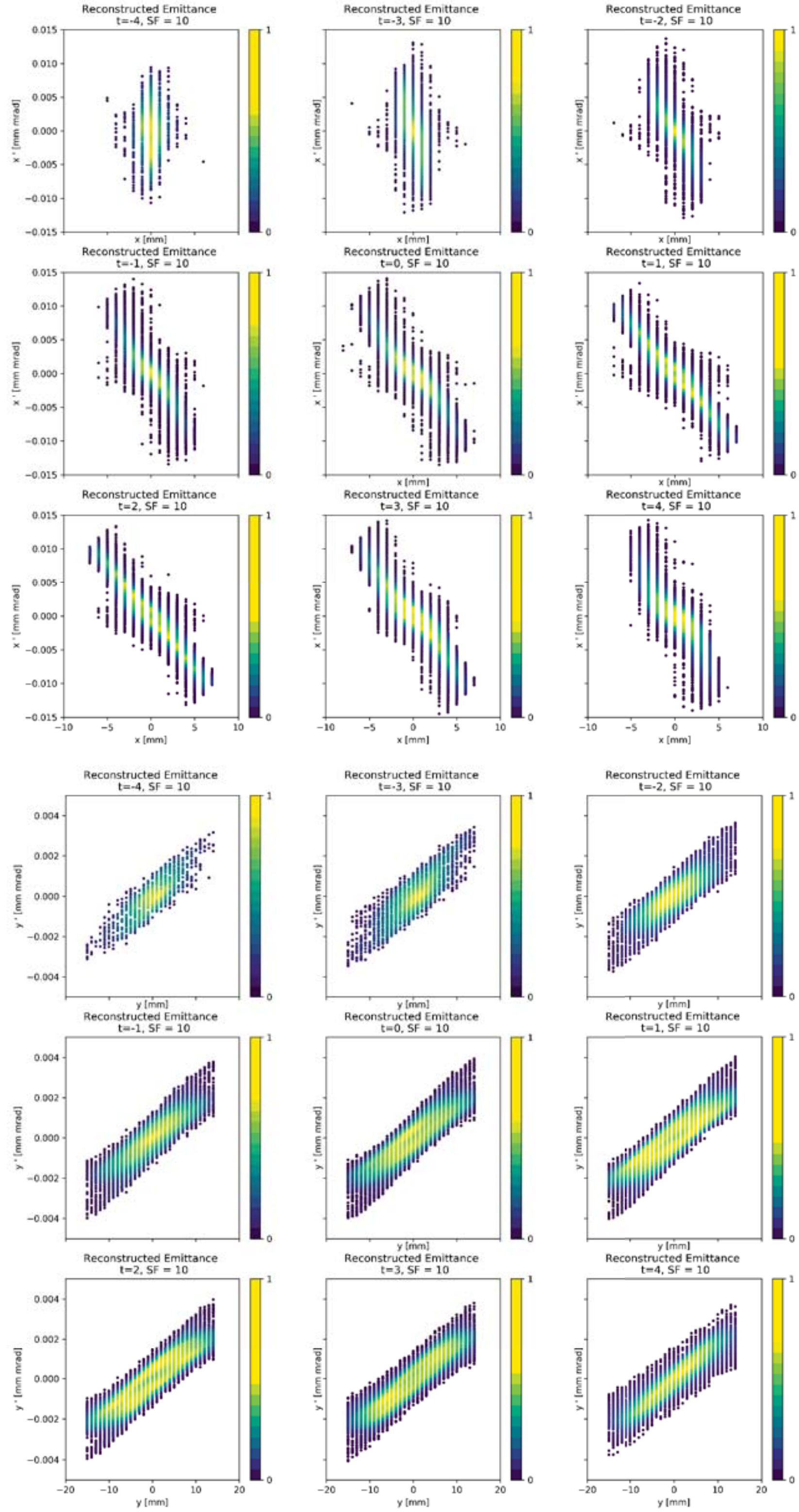

Figure 4. Reconstructed transverse emittance in (x, x') and (y, y') for 9 longitudinal time slices of the H^- bunch.

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Finally, Fig. 5 shows the temporal profile of the neutrals yielded by the laserwire for each time slice and after drift to the detector, where the wider distributions relate to the velocity spread of the bunch. The true longitudinal emittance is reconstructed based on the arrival time at the fast detector and the synchronised laser pulse timing. The technique also explores the correlations of (z, z') with (x, x') and (y, y').

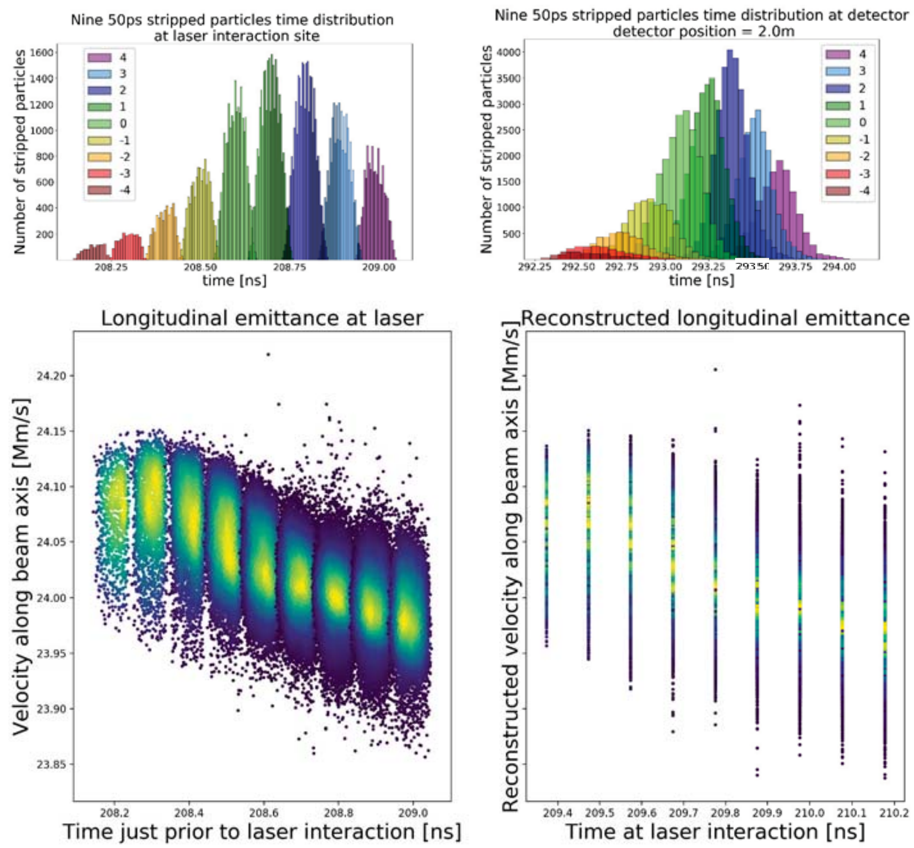

Figure 5. Longitudinal emittance reconstruction using 9 time slices of H^0 particles. Upper plots: time profiles at the laser and after a 2.0 m drift to the detector. Lower plots: true and reconstructed longitudinal emittance.

4. CONCLUSION

An extension of the state-of-the-art in H^- laserwires has been proposed to non-invasively measure the transverse emittance in longitudinal slices along a high intensity H^- bunch train and simultaneously reconstruct the longitudinal emittance by time of flight methods, enabling correlations of 6D bunch parameters to be probed. Studies of beam transport through the FETS accelerator and new simulations of a longitudinal laserwire with temporal pulse profile interaction indicate a realistic laser pulse of 1 μJ and FWHM 50 ps will yield sufficient neutrals to measure the correlated bunch parameters at FETS. These studies inform the optimisation of the laser-H^- interaction region and detection system design.

Acknowledgments

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References

[1] Liu Y et al., 'Laser wire based parallel profile scan of H^- beam at the superconducting linac of Spallation Neutron Source', *THOAB101, Proc. of IPAC 2013, Shanghai, China.*

[2] Gibson S M et al., 'A fibre coupled, low power laserwire emittance scanner at CERN LINAC4', *THPME190, Proc. of IPAC 2014, Dresden, Germany.*

[3] Hofmann T et al., 'Design of a laser based profile-meter for LINAC4 commissioning at 50 MeV and 100 MeV', *TUPB055, Proc. of IBIC 2015, Melbourne, Australia.*

[4] Hofmann T et al., 'Demonstration of a laserwire emittance scanner for hydrogen ion beams at CERN', *Phys. Rev. ST Accel. Beams*, **18** 122801, p1–11 (2015).

[5] Raich U et al., 'Beam instrumentation performance during commissioning of CERN's LINAC4 to 50 MeV and 100 MeV', *MOPMR026, Proc. of IPAC2016, Busan, South Korea.*

[6] Hofmann T et al., 'Experimental results of the laserwire emittance scanner for LINAC4 at CERN', *Nucl. Instr. Meth. Phys. Res. A* **830** 526–31 (2016).

[7] Gibson S M et al., 'Experimental Results of a Compact Laserwire System for Non-Invasive H^- Beam Profile Measurements at CERN's Linac4', *TUPG77, Proc. of IBIC 2016, Barcelona, Spain.*

[8] Hofmann T, 'Development of a Laser-based Emittance Monitor for Negative Hydrogen Beams', *Ph.D. thesis, Erlangen - Nuremberg U. 2017, CERN-THESIS-2017-136.*

[9] Hofmann T et al., 'Commissioning of the Operational Laser Emittance Monitors for LINAC4 at CERN', *WEPAL074, Proc. of IPAC 2018, Vancouver, Canada.*

[10] Huang C, Liu Y and Aleksandrov A, 'Fiber optic picosecond laser pulse transmission line for hydrogen ion beam longitudinal profile measurement', *Appl. Opt.* **52** 4462–67 (2013)

[11] Zhukov A, Aleksandrov A, Liu Y, 'Longitudinal laser wire at SNS', *MOCYB3, Proc. of IBIC 2014, Monterey, CA, USA.*

[12] Quick C R et al., 'Photodetachment of the H^- ion', *Nucl. Inst. Meth. Phys. Res. B* **56/57** 205–10 (1991).

[13] Harris P G et al., 'Measurement and reduction of momentum spread in the LAMPF Linac Beam', *Nucl. Inst. Meth. Phys. Res. A* **292** 254–58 (1990).

[14] Cathey B, Aleksandrov A, Cousineau S, Zhukov A, '6D phase space measurement of low energy, high intensity hadron beam', *FRA1CO04, Proc. of NAPAC 2016, Chicago, IL, USA.*

[15] Cathey B, Aleksandrov A, Cousineau S, Zhukov A, '6D phase space measurement of low energy, high intensity hadron beam', *TUPVA146, Proc. of IPAC 2017, Copenhagen, Denmark.*

[16] Cathey B, Aleksandrov A, Cousineau S, Zhukov A, 'Technical Workings of the 6D Phase Measurement at SNS', *TUPAL044, Proc. of IPAC 2018, Vancouver, Canada.*

[17] Kruchinin K et al. 'Simulation results of the FETS laserwire emittance scanner', *THPME191, Proc. of IPAC 2014, Dresden, Germany.*

[18] Kurup A, Pozimski J, Savage P; Gibson S M, Kruchinin K; Letchford A, 'Simulation of the FETS diagnostic', *TUPB071, Proc. of IBIC 2015, Melbourne, Australia.*