# DESIGN OF A LASER-BASED EMITTANCE METER AT CSNS LINAC*

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## *Abstract*

Following the successful profile measurement of an 80 MeV negative hydrogen ($H^-$) beam using a laser wire monitor at the China Spallation Neutron Source(CSNS), an emittance measurement system with a Low-Gain Avalanche Diode (LGAD) sensor has been developed and is currently under commissioning this year. This system utilizes the LGAD to reconstruct the spatial distribution of neutral hydrogen atoms ($H^0$) generated through laser photodetachment. By combining this distribution with laser wire position, it enables complete phase-space reconstruction and accurate emittance measurement of the $H^-$ beam. This paper focuses on the design and characterization of the LGAD-based $H^0$ distribution measurement system, including $H^0$ energy deposition simulation, LGAD sensor performance characterization, the design of a ceramic PCB readout board, and local signal response tests. The proposed system offers a promising non-interceptive, high-precision solution for negative hydrogen beam emittance measurement.

## INTRODUCTION

The China Spallation Neutron Source (CSNS) linear accelerator (linac) will be upgraded with a superconducting section, boosting the beam energy from 80 MeV to 300 MeV and increasing the Rapid Cycling Synchrotron (RCS) beam power from 100 kW to 500 kW [1–3]. To prevent contamination of the superconducting cavities from broken physical wires, a non-destructive diagnostic method was developed [4, 5]. This method uses a 1064 nm laser to ionize $H^-$ ions into electrons and neutral hydrogen,(binding energy 0.75 eV), with the resulting electrons, proportional to the local ion density, collected to reconstruct the beam profile as the laser scans the beam [6–9]. By detecting the neutral hydrogen distribution 5 m downstream of the laser–beam interaction point, the angular distribution of the beam at the stripping location can be inferred, enabling reconstruction of the transverse phase space of the beam. The Low-Gain Avalanche Diode (LGAD) is a high precision silicon-based timing detector with a typical gain of 10-50. This paper presents test results of an LGAD sensor for $H^0$ detection.Besides, a fluorescent screen is also designed to detect the two dimension distribution of the detached $H^0$ for phase space reconstruction.

## LASER WIRE SYSTEM

Figure 1 provides a schematic overview of the entire laser wire system [10]. The CSNS linac comprises a radio-frequency quadrupole (RFQ) that accelerates the negative hydrogen beam to 3 MeV and four drift tube linacs (DTLs) that further accelerate the beam to 80 MeV. For the upgrade of the emittance monitor [11, 12], the laser wire station is allocated in the linac transport beam line (about 150 m downstream of the DTL), where the beam energy is 80 MeV. The time structure of the pulsed beam in the linac, shaped by an RF chopper cavity for RCS injection, is depicted in Fig. 2. The beam pulse consists of 324 MHz micro-bunches, 550 ns intermediate bunches, and a 750 µs (max.) macro-pulse with a repetition rate of 25 Hz.

A high-power Q-switched Nd:YAG laser, operating at 1064 nm, serves as the light source for efficient photodetachment. This laser has a full width at half maximum (FWHM) of approximately 10 ns and a repetition rate of 1-10 Hz. By synchronizing the timing between the beam and the laser, the laser can precisely interact with a specific intermediate bunch, detaching approximately six micro-bunches per laser pulse. The demonstrated synchronization timing jitter is about 1 ns.

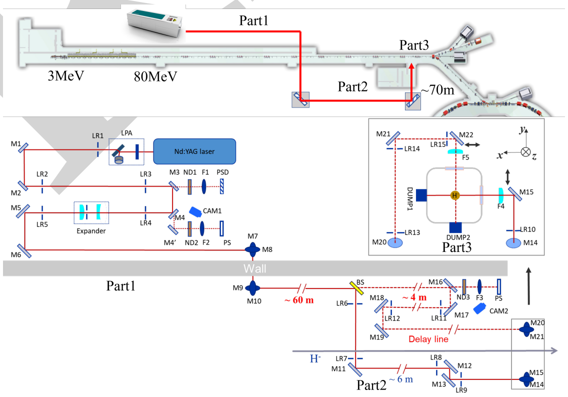

Figure 1: Outline of the laser wire system installed in the CSNS linac.

The number of stripped electrons is related to the laser energy and is assessed by

$$-\mathrm{d}n = \sigma(E_{\mathrm{cm}}) \times \Phi(x, y, z, t) \times n(t)dt \qquad (1)$$

where $n(t)$ is the number of negative hydrogen beam in an elementary volume element, $\sigma(E_{\mathrm{cm}})$ is the photodetachment cross-section [13], and $\Phi$ is the photo flux. The laser beam is kept at a fixed position and focused into the vacuum vessel with a diameter of approximately 100 µm. Due to the beam quality factor $M^2 = 4$, the laser beam diameter remains nearly constant when interacting with the millimeter-

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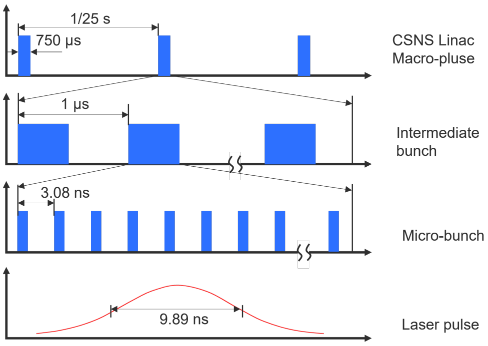

Figure 2: Time structure of the pulses beam in the CSNS linac.

scale particle beam. For an averaged $H^-$ beam current of 10 mA and a laser pulse energy of more than 100 mJ, approximately $10^4$-$10^7$ $H^0$ atoms are detached. The resulting neutral $H^0$ atoms drift unperturbed towards the detector while the majority of the $H^-$ ions are deflected in a downstream bending magnet. The laser beam is scanned using a remotely controlled translation stage. By scanning the laser beam position across the $H^-$ beam and combining it with the downstream $H^0$ distribution, the transverse phase space can be reconstructed. Figure 3 presents a schematic of the laser-wire-based emittance measurement, and Figure 4 is the corresponding detector layout.

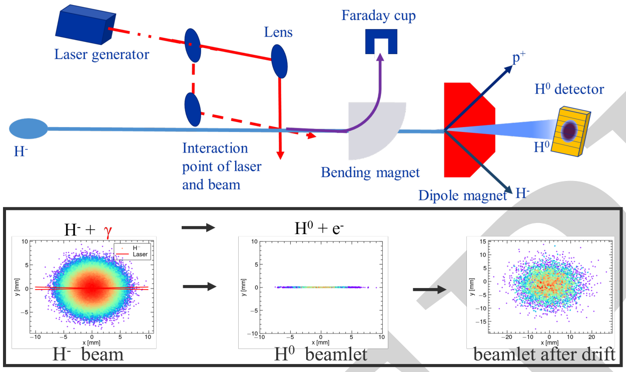

Figure 3: Concept of the laserwire emittance measurement.

## LGAD DETECTOR

To enhance the sensitivity and dynamic range of transverse phase space measurements, Low Gain Avalanche Diode (LGAD) strips are employed to detect the $H^0$ distribution. The LGAD is a new kind of avalanche diode characterized by their low gain, typically in the range of 10-50. Compared with other semiconductor materials such as diamond and silicon carbide, LGAD offers both excellent time resolution (30 ps) and high radiation tolerance (up to $2.5 \times 10^{15} \mathrm{cm}^{-2}$). Based on CSNS beam parameters, the RMS spot size of the $H^0$ distribution at the detection plane is approximately 5–6 mm, and the LGAD strips are accordingly designed with dimensions of $0.3 \times 19$ mm$^2$. At the maximum expected particle count per strip, the corresponding reverse voltage drop is approximately 10 V, significantly lower than the applied bias voltage of 150 V, indicating that gain saturation is negligible. The LGAD position is scanned by a stepper motor with a repeatability of better than 20 μm. For the weak $H^0$ signals, an unsupervised machine learning algorithm (Noise2Noise) is applied to perform automatic denoising. This project plans to utilize existing LGAD strips, whose measured time resolution and signal gain have both been demonstrated to meet the requirements [14]. Figure 5 shows the layout of the $H^0$ detector together with the LGAD sensor.

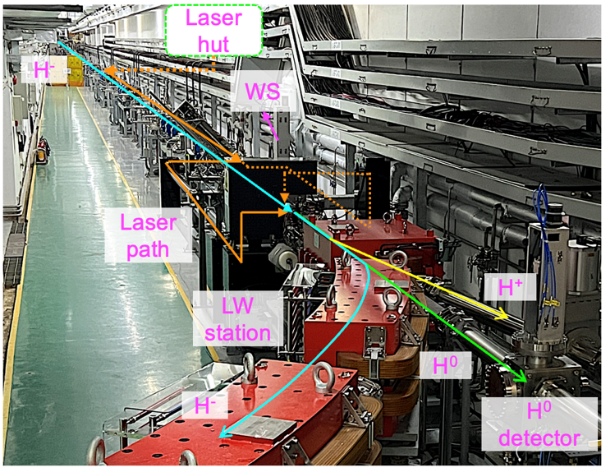

Figure 4: Layout of the laserwire emittance detector.

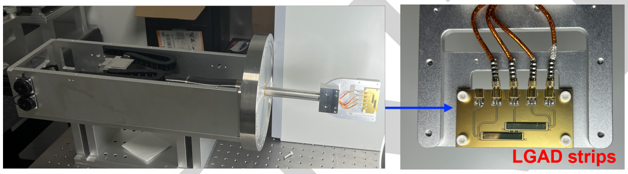

Figure 5: Layout of the $H^0$ detector LGAD sensor.

To characterize the particle detection performance of the strip LGAD sensors, a test system utilizing an Am-241 alpha source was developed. Signals were read out using a single-end readout scheme, with the LGAD strips connected at both ends. The readout board is a two-layer PCB endowed with an approximate bandwidth of 2 GHz and a trans-impedance preamplifier with a resistance of 50 Ω. This setup is powered via a Keithley 2410 source meter, ensuring full depletion during measurements. Signals induced by alpha particles were first amplified by the on-board preamplifier and subsequently by a commercial amplifier providing an additional 20 dB gain. The fully amplified signals were then digitized using a high-speed oscilloscope with 3.2 GHz analog bandwidth and a sampling rate of 20 GS/s per channel, enabling detailed waveform analysis of the LGAD response.

Figure 6 shows typical waveforms recorded from the four readout channels of the strip LGAD's surface when illuminated by the alpha source. Assuming a Gaussian transverse distribution for the $H^-$ beam at the laser interaction point with an RMS beam size of 2 mm and an angular divergence of $\sigma_{x'} = 1$ mrad, a single bunch at a beam current of 15 mA contains approximately $3 \times 10^8$ particles. The laser is expected to photodetach around $6 \times 10^6$ neutral hydrogen atoms

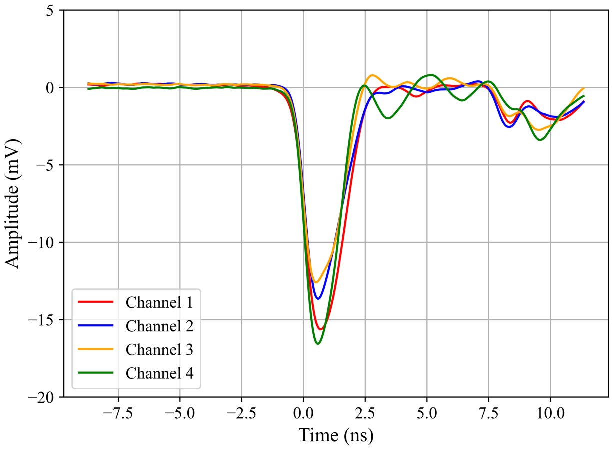

Figure 6: Waveforms read out from the four channels of LGAD.

per bunch. After drifting 5 m downstream, the maximum number of $H^0$ particles incident on a single LGAD strip (with dimensions of $19 \times 0.3 \times 0.05$ mm$^3$) is estimated to be approximately $1.7 \times 10^5$. The Stopping and Range of Ions in Matter(SRIM) simulations indicate that an 80 MeV proton incident on a 50 µm thick silicon target deposits an energy of 79.354 keV. Considering a mean ionization energy of 3.6 eV per electron-hole pair and an internal gain of 10, the theoretical signal amplitude induced by a single $H^0$ is approximately 1 mV. The final expected signal range is between 10 mV and 100 V.

However, after the LGAD detector was installed on the beamline and the vacuum was established, it was not possible to apply the required high voltage, and no signal was observed. The underlying cause is currently under investigation and will be diagnosed during the next scheduled machine shutdown.

## FLUORESCENT SCREEN DETECTOR

Due to difficulties in applying high voltage to the LGAD detector under vacuum conditions, a new $H^0$ detector based on a fluorescent screen is scheduled for installation this year. For the detection of 80 MeV $H^0$ atoms, a fluorescent screen with an effective area of $142 \times 100$ mm$^2$ is placed 5 m downstream of the laser–beam interaction point, oriented at a 45° angle to the beamline in the vertical plane. The screen is imaged through a 150 mm diameter vacuum viewport located 280 mm away, using a Bi-telecentric lens positioned at the working distance of 320 mm from the screen, onto a high-sensitivity, high-resolution sCMOS camera. This optical system provides a final spatial resolution of approximately 50 µm. Because the fluorescent screen is tilted at 45°, the recorded images require geometric projection correction to accurately reconstruct the transverse $H^0$ distribution. The overall design of the fluorescent screen detector together with the LGAD detector is shown in Figure 7.

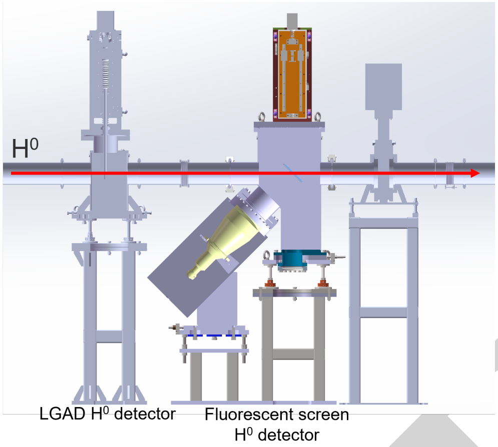

Figure 7: The design of LGAD detector and fluorescent screen detector.

## CONCLUSION

A prototype laser-wire profile monitor has been successfully designed and commissioned at the CSNS LINAC to provide non-invasive transverse beam diagnostics. The monitor demonstrates a temporal resolution of less than 40 ns, enabling the detection of intra-pulse beam centroid drifts and size variations that are otherwise averaged out by conventional wire scanner or ionization profile monitor. To extend the laser-wire system to emittance measurements, two types of $H^0$ detectors have been designed: a Low-Gain Avalanche Diode (LGAD) strip detector and a fluorescent screen detector. Comprehensive characterization tests and simulations were performed for the LGAD sensor, while the design of the fluorescent screen detector has been completed. However, after installation on the beamline, the LGAD detector could not be biased under vacuum and produced no signal; the root cause is under investigation. Following the planned installation of the fluorescent screen detector this year, the emittance measurement experiment will proceed.

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