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Laser wire beam profile monitor in the spallation neutron source (SNS) superconducting linac

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ABSTRACT

The spallation neutron source (SNS) at Oak Ridge National Laboratory is an accelerator-based, neutron-scattering facility. SNS uses a large-scale, high-energy superconducting linac (SCL) to provide high beam power utilizing hydrogen ion (H^-) beams. For the diagnostics of high-brightness H^- beams in the SCL, nonintrusive methods are preferred. This paper describes design, implementation, theoretical analysis, and experimental demonstration of a nonintrusive profile monitor system based on photodetachment, also known as laser wire, installed in the SNS SCL. The SNS laser wire system is the world's largest of its kind with a capability of measuring horizontal and vertical profiles of an operational H^- beam at each of the 23 cryomodule stations along the SCL beam line by employing a single light source. Presently 9 laser wire stations have been commissioned that measure profiles of the H^- beam at energy levels from 200 MeV to 1 GeV. The laser wire diagnostics has no moving parts inside the beam pipe, causes no contamination on the superconducting cavity, and can be run parasitically on an operational neutron production H^- beam.

1. Introduction

The spallation neutron source (SNS) commissioned recently at Oak Ridge National Laboratory (ORNL) is the world's most powerful short-pulse, neutron-scattering facility. SNS is an accelerator-based neutron source, and its linac consists of a combination of a room temperature linac and a high-energy pulsed superconducting linac (SCL) [1]. The current SCL consists of 23 cryomodules with 81 superconducting cavities and is designed for acceleration of pulsed hydrogen ion (H^-) beams from 187 MeV to 1 GeV with a peak beam current of 38 mA. The design beam power is 1.44 MW in 1-ms pulsed mode with repetition rates of up to 60 Hz. In the SNS upgrade plan, an additional nine cryomodules will be added to the SCL to boost the H^- beam energy to 1.3 GeV with a beam power reaching 3 MW.

Measurement of H^- beam profiles along the acceleration path in the SCL is important to minimize the beam loss. The profile monitor system for the SCL was originally envisioned to be a carbon wire scanner system [2,3]. However, linac designers were concerned about the possibility that carbon wire ablation, or broken wire fragments, could find their way into the superconducting cavities and cause them to fail [3,4]. A search for nonintrusive methods was performed in collaborations with Los Alamos National Laboratory and Brookhaven National Laboratory [4,5]. After initial experiments on H^- beam profile measurements using a Nd:YAG laser, the final decision was made to replace the carbon wire scanner system with a laser profile measurement system, also referred to as laser wire, in the SNS SCL [6]. The advantages of the laser profile monitor system over the conventional wire scanner system are: (1) H^- beam profiles can be measured during normal operations, as opposed to the 100 μs, 10 Hz duty factor restriction [2,3] needed to prevent damage to carbon wires; (2) there are no moving parts inside the vacuum system, thus reducing the possibility of a vacuum system failure; (3) the profile measurement can be conducted in a parasitic manner for an operational neutron production beam; and (4) a longitudinal beam scan can be conducted by using a pico-second pulsed light source such as a mode-locked laser and adjusting the phase between ion and laser pulses [7].

An outline of the SNS laser wire system is shown in Fig. 1. The SNS SCL consists of 23 cryomodules where each of the first 11 cryomodules houses 3 medium-beta cavities and each of the remaining 12 cryomodules houses 4 high-beta cavities. The SCL beam line was designed to have a laser wire station after each cryomodule. Currently, 9 laser wire stations have been commissioned along the SCL beam line. The first 4 stations are located after each of the first 4 medium beta cryomodules, the next 4 stations after the first 4 high beta cryomodules 12 through 15, and the last station at the end of the SCL. In this way, the profiles of the H^- beam at different energy levels (200 MeV–1 GeV) can be measured.

Compared with the laser wire systems implemented in other facilities [8–13], the system installed at SNS has a number of unique features. First, the SNS laser wire beam profile monitor consists of 9 measurement stations and can be readily extended to

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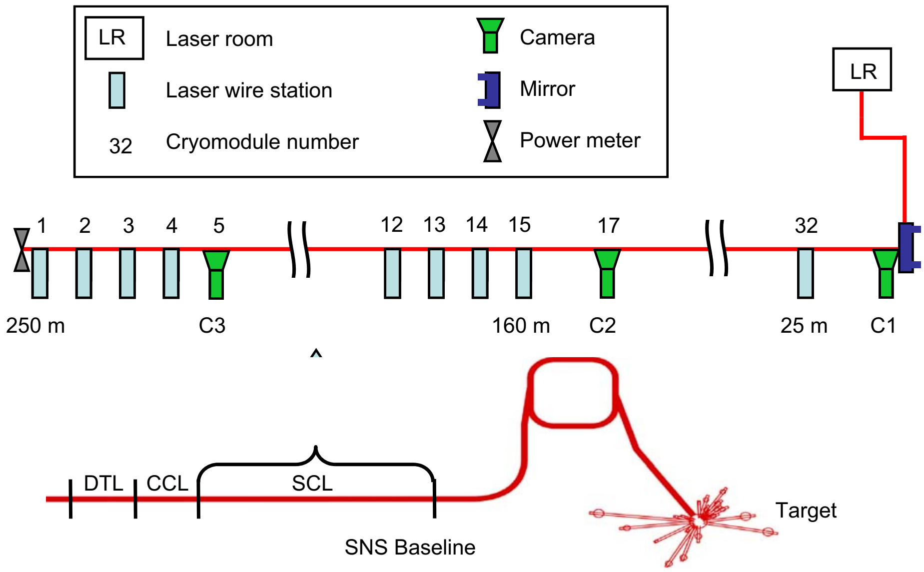

Fig. 1. Outline of laser wire setup at SNS superconducting linac.

measure profiles at each of the 23 cryomodules (or 32 cryomodules in the upgrade project) in the SCL, which makes it the world's largest system of its kind. Next, a single light source is used to perform the profile measurement at all laser wire stations. To track the H^- profiles along the acceleration path, it is necessary to measure beam profiles at multiple locations in the SCL. Using a single light source proves to be economically and operationally more efficient than installing multiple lasers. Furthermore, while the laser wire system has a number of advantages over the conventional wire scanners, a disadvantage is that the laser is not as radiation-resistant as a wire scanner actuator. This issue was overcome in the SNS laser wire system by placing the laser source far away from the beam line in the HEBT Service Building and using a laser transport line (LTL) to deliver the laser beam to each measurement station.

Since the laser beam must be transported as long as 250 m to cover all the measurement stations, and the laser room is located at a different building from the SCL, the laser beam parameters (pointing stability, beam quality, and beam size) as well as the mechanical vibration and temperature instability of the LTL will inevitably affect the laser beam size and position at the measurement point. Thus, it is critical to investigate how the laser beam uncertainties influence the performance of the laser wire measurement.

In the following sections, we start with a theoretical analysis of our laser wire system by including realistic laser beam parameters in the photoneutralization modeling. The numerical simulation clearly reveals the influence of the key laser beam parameters on the performance of the profile measurement. In Section 3, we describe the implementation of the laser wire system including the light source, laser transport line, laser wire station, detection, software platform, and diagnostics. Section 4 describes experimental results of profile measurement at different energy levels. Dependence of the measurement on the ion beam minipulse position is experimentally investigated. Finally, the paper is summarized in Section 5.

2. Laser wire modeling and influence of laser parameters

2.1. Photoneutralization with a realistic laser beam

The principle of the laser wire profile measurement is based on a light–ion interaction process called photodetachment or photoneutralization. The irradiation of the ion beam with a laser light at a certain wavelength range causes photodetachment of electrons from negative ions and the measurement of the resulting electron density leads to the determination of the negative ion density. Fig. 2 shows a schematic of the laser–ion beam geometry. We assume that the ion beam propagates along the x-direction, the laser beam propagates along the y-direction, and the ion beam profile scan is conducted along the z-direction. To achieve spatial resolution, the laser beam is focused by a lens L1 with a focal length f before the light–ion interaction.

The photodetachment process has been studied in a number of previous works [12–14] where the photodetachment yield was expressed as a product of the photon and ion densities. Based on the notations in Refs. [12–14], we can describe the variation of the detached electrons by

$$\frac{\partial n_{\mathrm{det}}(x,y,z,t)}{\partial t} = c\Sigma_0 n_l(x,y,z,t) n_b(x,y,z,t) \tag{1}$$

where $n_{\mathrm{det}}(x,y,z)$ is the number of photo-detached electrons per unit volume, c the light speed, Σ_0 the photodetachment cross-section, and n_l and n_b the photon and ion densities, respectively. As the number of ions decreases when electrons are detached, the ion beam density will change at a rate

$$\frac{\partial n_b(x,y,z,t)}{\partial t} = -\frac{\partial n_{\mathrm{det}}(x,y,z,t)}{\partial t} = -c\Sigma_0 n_l(x,y,z,t) n_b(x,y,z,t). \tag{2}$$

In previous models, both ion and laser beams were assumed to have a Gaussian distribution, i.e.,

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

$$n_l(x,y,z,t) = \frac{N_l}{(2\pi)^{3/2}\sigma_{lx}\sigma_{ly}\sigma_{lz}} \exp\left[-\frac{x^2}{2\sigma_{lx}^2} - \frac{(y-ct)^2}{2\sigma_{ly}^2} - \frac{z^2}{2\sigma_{lz}^2}\right] \tag{4}$$

where N_b (N_l) is the total ion (photon) number, $\beta = v/c$ the ion beam relativistic factor, and σ the RMS beam size. In this paper, we revise Eq. (4) by considering the realistic laser beam parameters. Major revisions in our modeling include: (i) the laser beam is well collimated on the surface of L1. This assumption is reasonable since the laser beam needs to be delivered to targets of up to 250 m away and the beam divergence angle should be sufficiently small; (ii) there exists a defocus Δy between the laser