THE POSSIBILITY OF GENERATION OF HIGH-ENERGY ELECTRON BEAM AT THE SNS FACILITY

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Abstract

The linac of the SNS accelerator facility is considered to produce an electron beam with 300-400 MeV energy and relatively high current. However, the SNS linac is designed and optimized for acceleration of the H^- beam, which creates problems when direct acceleration of electrons is considered. An alternative machine setup for electron acceleration and transport is discussed. Here, we present a study of the optimal electron beam parameters that can be achieved without any significant hardware changes in the SNS accelerator.

INTRODUCTION

The SNS accelerator facility is designed for neutron production via H^- and proton acceleration. In this paper we investigate if it can be used to produce high energy electron beams as well. A multi-species design of the accelerator complex is extremely valuable because of the high price of independent accelerator projects. A possible use of a 300-400 MeV electron source for the fundamental study of electron wave function is discussed in [1]. A successful demonstration of electron production at the SNS can stimulate serious investment for the energy and quality upgrade useful for other studies like FEL.

The normal conducting part of the SNS linac up to 186 MeV is designed for accelerating beam with a fixed charge to mass ratio and cannot be retuned for lighter particles. The superconducting part (SCL) consists of accelerating cavities with independent control of phase and amplitude. We show that there is a set of parameters providing stable acceleration of electrons to 400 MeV with acceptable transmission and output emittance. Currently, there is no an electron source at the SCL entrance. We demonstrate that with only minor hardware upgrade the capability of the SNS laser wire system can be used to generate electrons for a demonstration experiment.

First, we show how to generate electron with a laser wire station. Then we discuss the key problems of electron beam acceleration and how the accelerator is optimized to get the best parameters for the accelerated beam. The acceleration system instability and quality of the beam are studied in the end of the paper.

ELECTRON SOURCE

There is no an electron source, such as an electron gun, at the SNS accelerator. However, there are 9 laser wire stations for H^- beam profile measurements along the SCL [2]. Interaction of the laser pulse with the H^- beam produces a 10 ns FWHM pulse of electrons with velocity equal to the H- beam velocity at the interaction point. Picture 1 shows a convenient laser wire station location between the first and second cryomodules of the SNS superconducting linac. The H^- beam energy is about 190 MeV, which corresponds to about 100 KeV energy for the stripped electrons.

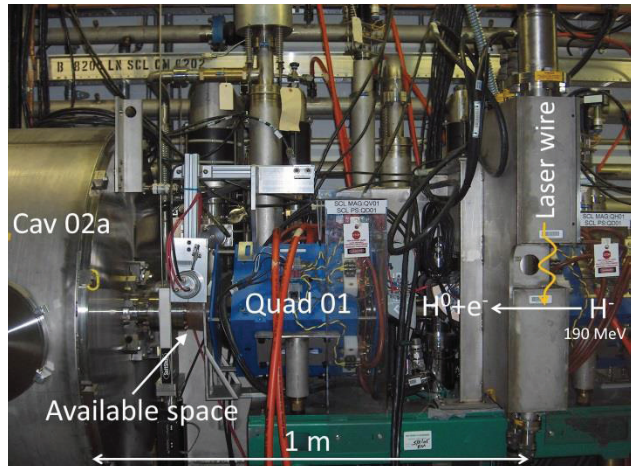

Figure 1: Beginning area of the SNS superconducting linac.

Calculations [3] and experiments show that we can achieve 90% to 100% stripping efficiency for the H^- beam to generate electrons. In this way, the laser wire can be used to produce up to a 30 mA electron source with a pulse length of 10 ns and repetition rate of up to 30 Hz. The approximate design transverse sizes of the H^- beam and the laser beam are 1 mm and 0.2 mm, respectively. Thus, the laser beam size must be optically enlarged to overlap with the H^- beam in order to achieve 90% to 100% stripping. The remaining H^- and H^0 beam is lost, and we do not focus on it in this study. For the following study we can assume electron bunches with up to 0.075 pC charge (for 30 mA), 1 mm transverse, 1 to 2 mm longitudinal size, and 100 keV energy.

ELECTRON BUNCH ACCELERATION

Acceleration of the available electrons is the most difficult part of this project. The electrons have approximately 1800 times smaller mass than the H^- ions. Hence, the space charge has a huge effect that will blow up the electron bunch quickly in the 1 m drift between the laser wire station and the first accelerating cavity Cav 02a (see Fig. 1). In this scenario, most of the electrons will be lost in the vacuum pipe of 42 mm radius. The available quadrupole magnet Quad 01 will not help because it focuses only in the vertical plane and defocuses in the horizontal plane.

The space charge effect can be reduced by reducing the H^- and electron current. In addition a small focusing solenoid can be installed in the available space between Quad 01 and Cavity 02a (see Fig. 1). A simple estimation for the focal length of a solenoid can be done using:

$$\frac{1}{f} = \frac{q_e^2}{4p_z^2}\int B_z^2 dz = \frac{q_e^2}{4p_z^2}\frac{3i^2\pi^3}{2r}10^{-14} \qquad (1)$$

Here p_z and q_e are electron momentum and its charge correspondingly. It shows that a solenoid with the strength of the order of i=1500 Ampere×Turns is required to focus the electron beam at the distance f=0.5 m from the solenoid to the accelerating cavity Cav 02a. 3D field of a ring of current with a r=10 cm radius is used in simpualtions. Next, there is a superconducting module consisting of three cavities, Cav02a, Cav02b, and Cav02c, located 0.85 m, 2.1 m, and 3.2 m, respectively, from the solenoid. The electron beam must be accelerated as quickly as possible because of the space charge and be focused at the same time. The acceleration of the electron beam with the first three cavities is the most challenging problem.

The default amplitudes of the RF cavities for the H$^-$ production are too high, and the 100 keV electron beam will be destroyed quickly by the transverse fields. We used numerical optimization to solve this complicated self-consistent problem of finding 7 parameters (amplitudes and pahses for 3 cavities and solenoid strength) providing a stable solution for the electron beam acceleration and focusing. Figure 2 presents a solution for the rms size of the electron beam for the first cryomodule using 5 mA current of the input electron beam.

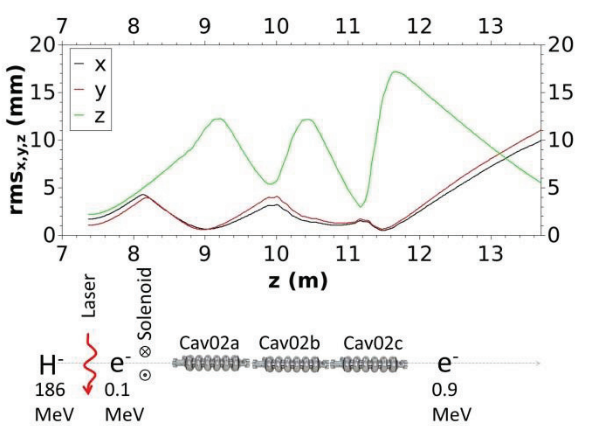

Figure 2. Optimized solution for the electron beam acceleration in the first cryomodule.

For our simulations we used the PyOrbit accelerator code [4], Runge-Kutta tracking of the electron beam, and the 3D FFT method to calculate the space charge. We also used exact 3D cavity fields. The output energy of the electron beam was 0.9 MeV. Subsequent acceleration of the electrons can be performed by the default cavities with high amplitudes of 20 to 30 MV/m designed for H$^-$ beam acceleration. Table 1 shows the default linac optics parameters of the H$^-$ beam and the optimized parameters for electron beam acceleration.

Table 1: Linac parameters for acceleration of H$^-$ and e$^-$

RF cavities and magnets	H$^-$	electrons
Quad 01 (T/m)	4.4	0.0
Solenoid 01 (A×Turns)	0.0	1800
Cav 02a (MV/m z-axis peak field)	18.0	0.611
Cav 02b (MV/m z-axis peak field)	22.0	2.800
Cav 02c (MV/m z-axis peak field)	20.0	4.547
Quad 02 (T/m)	4.3	0.0
Solenoid 02 (A×Turns)	0.0	4200
Quad 03 (T/m)	5.0	0.0
Quad 04 (T/m)	5.0	0.0135
Quad 05 (T/m)	5.0	0.05
Quad 06 (T/m)	5.1	0.09
Quad 07 (T/m)	5.1	0.1
Quad 08 (T/m)	5.1	0.25
Quad 09 (T/m)	5.0	0.38
Quad 10 (T/m)	5.0	0.47

The RF amplitudes of the first cryomodule are significantly lower for the electrons. Our study shows that it is reasonable to install a second solenoid after the first accelerating cryomodule instead of using FODO quadrupoles in Quad 02.

Figure 3 shows optimized electron beam optics through the full SNS superconducting linac beginning from the laser stripping point down to the last accelerating cavity. Figure 4 presents the output electron beam current and emittance as a function of the input current.

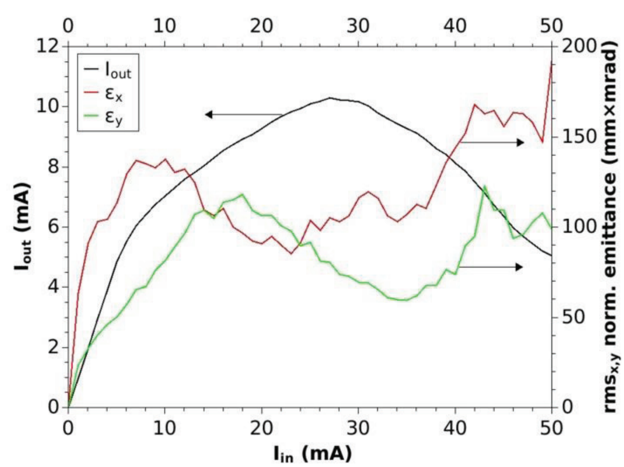

Figure 4. Output electron beam current and emittance as a function of input current.

The maximum current of the electrons that can be achieved is about 10 mA. A bigger input current leads to a bigger space charge and more loss of the output beam. The normalized rms emittance grows significantly at the beginning of the acceleration because of the space charge and reaches 100 mm×mrad at the end of acceleration. The longitudinal momentum spread is $\sigma_p/p = 1.5\times10^{-2}$ for i_{out}=10 mA output beam. Experiment [1] requires relative momentum spread $\sigma_p/p = 1.0\times10^{-3}$ or better that can be achieved by reducing output electron beam current to 1 mA or less.

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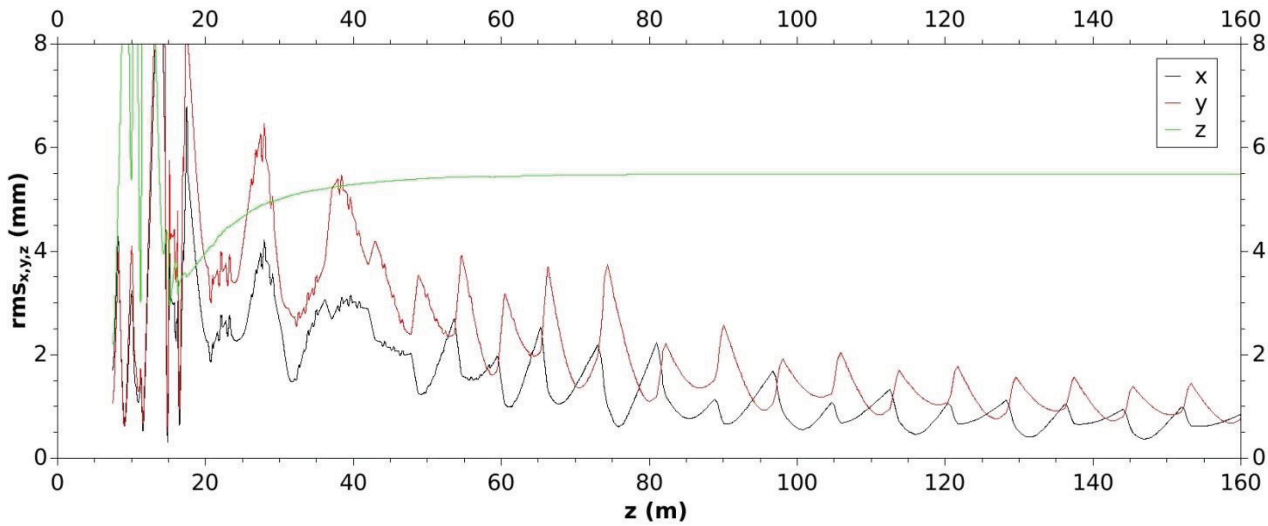

Figure 3: Designed electron beam optics at the SNS superconducting linac for 5 mA electron beam current.

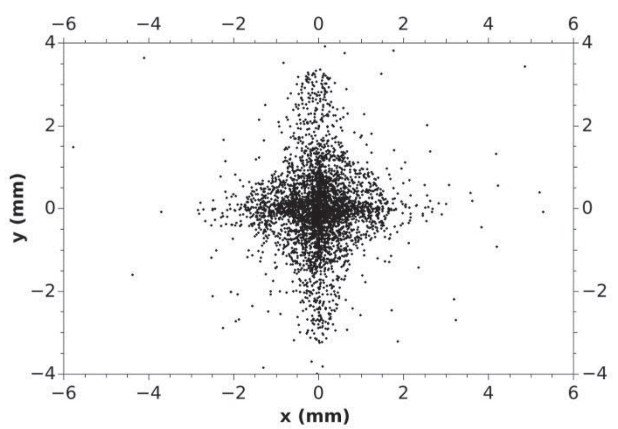

Figure 5: Transverse distribution of the electron beam at the end of the SNS superconducting linac.

Figure 5 shows the output transverse distribution of the electron beam. The output electron energy is 405 MeV. The energy in experiment is expected to be the same because the longitudinal acceleration model works well for H- with known RF amplitudes. The H- beam can be accelerated up to 1 GeV because SNS cavities are designed for lower relativistic factor β=0.61 and β=0.81 while the electron beam has β=1. Thus, the electrons have lower accelerating efficiency approximately by a factor of 2 compared to the H- beam.

An important part of this work is to study the stability of the solution as a function of the uncertainty of the accelerator parameters. This is related mainly to the first acceleration module because some uncertainty in RF amplitudes and cavity phases can completely mismatch the dynamic of the electron bunch leading to its loss. Figure 6 presents the output current of the beam as a function of energy and phase shift of the input beam. The beam seems to have stable acceleration within a wide range of uncertain parameters.

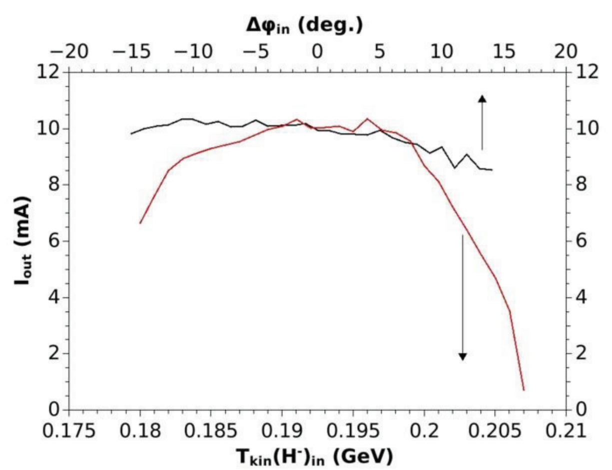

Figure 6: Output current of the beam as a function of energy and phase shift (in terms of RF frequency) of the input beam.

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