ISBN: 978-3-95450-232-5 ISSN: 2673-7000 doi:10.18429/JACoW-NAPAC2022-WEPA33

LASER STRIPPING FOR 1.3 GeV H- BEAM AT THE SNS*

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Abstract

A realistic full duty factor laser stripping charge exchange injection scheme for a future 1.3 GeV beam at the SNS is considered. Different schemes of laser stripping involving combinations of photoexcitation, photoionization and magnetic field stripping are calculated. The laser power and magnetic field strength needed for different approaches are estimated and compared. The most practical scheme of laser stripping is selected for development.

INTRODUCTION

Laser assisted charge-exchange injection of H^- beam has been studied theoretically and experimentally at the Spallation Neutron Source (SNS) in Oak Ridge. This novel method can replace foil assisted charge exchange injection. High beam power destroys stripping foils quickly due to beam heating [1].

A detailed review of laser stripping development can be found in a recent paper [2]. The first proof of principle experiment has been carried out at the SNS for a 900 MeV beam energy [3] using a three step laser stripping scheme [4]. A proof of practicity experiment has been performed for 1 GeV energy [5]. The main goal of laser stripping development is to optimize lasers, magnets and other tools so it would be practically reasonable to build the system. Lasers must have small average power and stripping magnets must be preferably non-superconducting. Recently we developed a sequential scheme of laser stripping that could reduce laser power by a factor of 10 and simplify the project [2]. J-PARC is considering using lasers only without stripping magnets for their low energy 400 MeV beam [6].

The choice of laser stripping scheme and its optimization depends mainly on the beam energy and other parameters of the beam. SNS is planning to upgrade the beam energy to 1.3 GeV within the PPU project [7]. In this paper we present all possible schemes and parameters for the 1.3 GeV beam using realistic expected parameters of the beam distribution. Based on these schemes we will select the most simple and practical method to consider for further development.

* This manuscript has been authored by UT-Battelle, LLC, under Contract No. DE-AC05-00OR22725 with the U.S. Department of Energy. The United States Government retains, and the publisher, by accepting the article for publication, acknowledges that the United States Government retains a non-exclusive, paid-up, irrevocable, world-wide license to publish or reproduce the published form of this manuscript, or allow others to do so, for United States Government purposes. The Department of Energy will provide public access to these results of federally sponsored research in accordance with the DOE Public Access Plan (http://energy.gov/downloads/doe-public-access-plan).

MAGNETIC STRIPPING

High energy H^- ion beam as well as H^{0*} excited state beam can be easily stripped/ionized in a strong magnetic field through Lorentz ionization. The first and the last step of the three step laser stripping have been performed by using non-superconducting electromagnets [3] or permanent magnets [5] of 1.5-2.0 Telsa. The beam energy was 0.9-1.0 GeV and H^{0*} was excited into the 3p state for easy magnetic field stripping. The first step $H^- \rightarrow H^0 + e^-$ for 1.3 GeV ion beam can be performed by a simple permanent magnet with field of the order of 1 Tesla. The 3s, 3p and 3d excited states of the Hydrogen beam $H^{0*} \rightarrow p + e^-$ can be stripped by the same order of magnetic field.

In this section we will estimate stripping of the 2p excited state in a 1.3 GeV beam. The magnetic field profile $B_x(z)$ along z-direction of a beam for a typical magnet can be characterized by a Gaussian shape:

$$B(z) = B_0 \exp\left(-\frac{z^2}{2\sigma^2}\right) \quad (1)$$

The ionization lifetime of the 2p excited state of the hydrogen atom in electro-magnetic field has been calculated from this work [8]. The stripping efficiency of single particle is calculated by integrating the stripping probability over *B(z)* Eq. (1). Figure 1 represents the stripping efficiency of the beam as a function of $B_0$and σ.

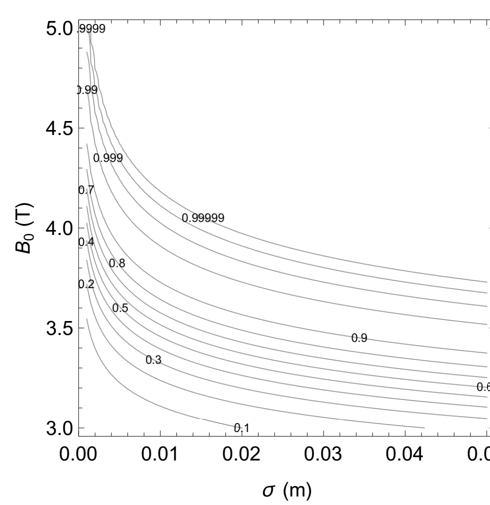

Figure 1: Stripping efficiency of 2p excited state in a 1.3 GeV hydrogen beam in a magnetic field (1).

From this picture it is seen that magnetic field of normal longitudinal size σ=1 cm requires 4.0-4.5 Tesla to strip more than 99% of the beam.

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PHOTOIONIZATION

J-PARC is considering using only lasers for photoionization of the H^- beam and H^{0*} excited states without using any stripping magnets because of their small beam energy. Using a superconducting magnet of 4.5 Tesla seems to be complicated so it is good to estimate and compare stripping of the 2p excited state by direct laser photoionization. The photoionization crossection is very small for a hydrogen atom and has a maximum value when the photon energy E_γ matches a "resonance" of photoionization from n^{th} excited state into continuum i.e. $E_\gamma = 1/2n^2$ [9]. Using this factor and assuming that a realistic bunch and laser pulse have Gaussian density distributions we can formulate three criteria for the most optimal photoionization scheme that requires minimum laser power (see Fig. 2):

- The transverse H^0 beam size r_b and corresponding laser beam size be as small as possible in order to provide the highest power density and photon flow for the most effective photoionization.
- The incidence angle α between the laser and H^0 beam must be optimal in order to provide the highest photoionization crossection for the photon energy $h\nu = 1/2n^2$ a.u. in the particle's rest frame accounting for relativistic Doppler effect.
- The H^0 beam must be tilted at the optimal angle φ due to the beam dispersion in order to provide the best overlap with the laser beam for highest photoionization efficiency. This scheme is called the Crab-Crossing scheme [10].

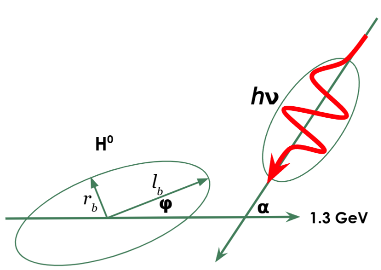

Figure 2: Crab-crossing scheme of H^0 beam photoionization by laser pulse.

1s *Photoionization*

Here we estimate photoionization for a non-excited hydrogen atom in $1s$ state. The photoionization energy in the particle rest frame is 0.5 a.u. or 13.6 eV which requires UV laser with 355 nm wavelength for a 1.3 GeV beam. The photoioniation crossection for the 1s state equals $\sigma = 6.3 \times 10^{-22}$ m^2. We will use an elliptical Gaussian H^0 beam with realistic achievable size parameters for the SNS accelerator. We assume transverse size $\sigma_x = \sigma_y = r_b$=0.5 mm, longitudinal size $\sigma_z = l_b$=100 ps and an incidence angle α=45^0. The photoionization efficiency can be calculated by numerical integration of two Gaussian beams. Optimization of the laser pulse for photoionization of the 99% of the beam gives the optimal transverse size of the laser pulse to be: $r_l = \sigma_l$=0.85 mm. The laser pulse energy is Q=35 mJ. The photoionization efficiency does not depend much on the longitudinal laser pulse width because of the integration properties but the shorter laser pulse is preferable. The total laser pulse energy has a quadratic dependence on H^0 transverse beam size $Q \sim r_b^2$.

2p *Photoionization*

The photoionization crossection for the 2p excited state of hydrogen equals $\sigma = 1.7 \times 10^{-21}$ m^2 which is only 2.6 times bigger than for the 1s state but smaller ionization energy will allow us to use an infrared laser λ=1064 nm that is much more powerful than UV laser. The optimized transverse laser size in this case equals $r_l = \sigma_l$=0.8 mm and the pulse energy equals Q=4 mJ. The optimal angle is α=75.5 deg. Figure 3 shows the photoionization sensitivity as a function of the incidence angle of laser. The photoionization crossection drops down for smaller angle α because the photon energy increases in the beam frame due to the relativistic Doppler effect. In any case, the photoionization efficiency does not change much because of the increasing power density and photon flow in the beam frame due to the relativistic transformation.

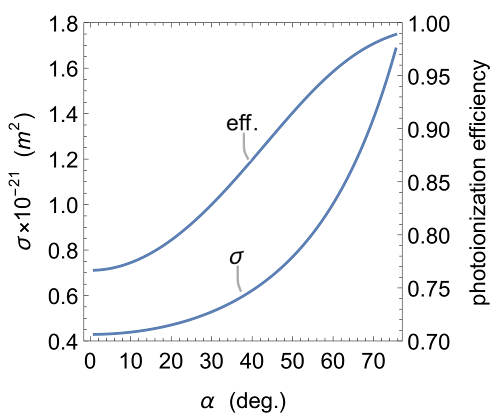

Figure 3: Photoionization efficiency of 2p state as a function of incidence angle of laser α.

Photoionization Option for J-PARC

J-PARC uses a low energy 400 MeV beam for which it is difficult to employ magnetic stripping both for H^- and H^{0*} beams. Here we estimate pure laser photoionization of the 3p excited state [6]. A preliminary estimate has been done in [11]. The crossection equals $\sigma = 3.37 \times 10^{-21}$ m^2. For $\sigma_x = \sigma_y = r_b$ = 1.5 mm transverse and 100 ps longitudinal rms H^0 bunch size we calculated the laser pulse energy to be 15 mJ for 99% efficiency assuming the crab-crossing scheme of interaction. The transverse laser size equals $r_l = \sigma_l$=2.2 mm. The most optimal angles of interaction are α=97^0 and φ=59^0 but can be made smaller if needed.

RESONANCE EXCITATION

Here we consider different schemes of resonance excitation of an H^0 atom by laser for a 1.3 GeV beam in order

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to figure out what is the most optimal and feasible scheme that requires the lowest laser power. Table 1 represents the optimal achievable parameters for a 1.3 GeV beam. The laser beam lies in the horizontal plane with the H^0 beam.

Table 1: Emittance Parameters for 1.3 GeV Beam at the SNS

Parameter	Vertical	Horizontal
Emittance	0.4 mm×mrad	0.4 mm×mrad
α (Twiss)	0	0
rms size	0.5 mm	-
rms angle	-	0.3 mrad
Dispersion	0 m	0 m

We represented the transverse Twiss parameters of the beam in terms of the vertical rms size and horizontal angular rms spread because the minimization of these two parameters provides the maximum efficiency of excitation. The emittance at the SNS is a given value and cannot be minimized without reducing the beam current. Longitudinal momentum spread can be minimized down to σ_p/p=1.5×10^{-4}.

One Step Excitation

Here we consider one step 1s→3p excitation [4]. In this case we can use only UV laser with 355 nm wavelength with incidence angle α=60.2^0. Table 2 shows laser peak power needed for beam excitation for different parameters of horizontal dispersion derivative D′=$\partial D_x/\partial z$ and different excitation efficiencies.

Table 2: Laser Peak Power for 1s→3p Excitation

D′ = 0	**D′ = -1.62**	**Excitation efficiency**
8 MW	6 MW	90%
12 MW	9 MW	95%
37 MW	25 MW	99%

Sequential Excitation

Here we consider scheme of [2] for 1s→2p→3d sequential excitation. Table 3 shows laser peak power for different wavelengths and different parameters D′ of the beam. The bold highlighted values denote the minimum laser power required for the beam excitation with the most optimal D′. It is seen from the Table 3 that the beam dispersion derivative cannot be optimized for both steps 1s→2p and 2p→3d simultaneously. Anyway, it is possible to choose some intermediate value -1.0 < D'_z < -4.7 that would be optimal for excitation 1s→2p by a green laser and 2p→3d by an infrared laser. The laser peak power for each step is about 1MW which corresponds to a 0.25 mJ pulse energy for σ=100 ps laser pulse width.

SUMMARY

We considered different schemes and methods of laser stripping for a 1.3 GeV beam at the SNS. Among all methods the most realistic and practical scheme seems to be the sequential excitation scheme 1s→2p→3d by using a green laser with λ=532 nm and α = 22.8^0 for 1s→2p step and an infrared laser with λ=1064 nm and α = 110.6^0 for the 2p→3d step.

Table 3: Laser Peak Power in MW Required for 99% Excitation of the 1.3 GeV Beam with Emittance from Table 1.

D′	**0**	**-0.1**	**-1**	**-1.2**	**-2**	**-3**	**-4**	**-4.7**
1s→2p								
355 nm	9	9	7.5	**7.5**	8.5			
532 nm	-	-	1.3	1.1	0.6	0.4	0.35	**0.3**
2p→3d								
355 nm	6	**6**	7	7	13			
532 nm	3	**3**	3	3	3.5	5		
1064 nm	0.6	0.6	**0.6**	0.6	0.8	1.0	1.3	1.5

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