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PRELIMINARY STUDIES OF LASER-ASSISTED H$^-$ STRIPPING AT 400 MeV

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Abstract

Laser-assisted H$^-$ stripping is very essential to overcome real challenges of short lifetime and machine activation by using solid stripper foil for that purpose. Extensive studies on the laser stripping are in good progress at the Spallation Neutron Source (SNS) of Oak Ridge for an H$^-$ energy of 1 GeV. It is therefore interesting to explore these studies for lower H$^-$ energies. As an example, the 3-GeV Rapid Cycling Synchrotron (RCS) of Japan Proton Accelerator Research Complex (J-PARC) is considered, where H$^-$ injection energy is 400 MeV. The present work is a preliminary study of the laser-assisted H$^-$ stripping at this energy, where a set of optimized parameters are considered in order to realize a same level of stripping efficiency as in the SNS case. The feasibility and real challenges are discussed.

INTRODUCTION

Solid stripper foil is used for several hundred to thousand multi-turn H$^-$ stripping injection in the proton accelerators in order to achieve MW-level beam power [1, 2]. However, lifetime and rapid foil failure due to overheating of the foil are serious concerns to maintain stable operation of the machine [3]. It is therefore a real challenge and may be the biggest limitation to realize a multi-MW user machine. Although continuous efforts on durable foil production made remarkable progress on the foil lifetime [4], it is still unclear how to deal with multi-MW beam. Other than foil lifetime, the residual activation near the stripper foil due to the foil scattering beam loss during multi-turn injection is also another uncontrollable factor and a serious issue for facility maintenance.

It is therefore essential that alternate technologies other than using solid foil for the charge-exchange injection have to be established in order to avoid these issues. The idea of laser-assisted H$^-$ stripping, which is a three-step process of an H$^-$ conversion to a proton (magnetic stripping + laser excitation + magnetic stripping) was originally proposed nearly two decades ago [5]. A schematic view of the concept is shown in Fig. 1. A little modified approach to reduce Doppler broadening in the second process of laser excitation was later proposed and also successfully demonstrated a proof-of-principle (POP) experiment at the Spallation Neutron Source (SNS) in Oak Ridge, achieving 90% stripping efficiency for a short pulse of 6 ns, 900 MeV H$^-$ [6, 7]. Aiming for 3 orders of magnitude improvement by increasing the H$^-$ pulse length 5~10 μs, preparations for the next experiment are in good stage and will be carried out in early 2016 [8, 9].

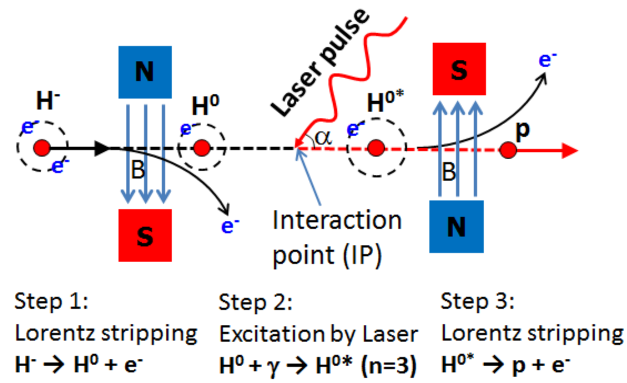

Figure 1: Schematic view of laser-assisted H$^-$ stripping.

The present work is a preliminary study for laser-assisted H$^-$ stripping at an energy quite lower that of SNS. For instance, the 3-GeV Rapid Cycling Synchrotron (RCS) of Japan Proton Accelerator Research Complex (J-PARC) is considered [1]. The injection energy is 400 MeV, while the extraction energy is 3 GeV. The designed beam power of the RCS is 1 MW at a repetition rate of 25 Hz. RCS beam power for the operation is 500 kW at present, while an equivalent beam power of 1 MW beam has already been demonstrated recently [10]. Although no foil failure occurred so far but based on measured foil degradation, it is worried that the real lifetime at 1 MW could be much shorter than expected. In order to realize further more than 1 MW beam power, it is therefor essential to study the possibility of laser-assisted H$^-$ stripping at 400 MeV as foil may not survive beyond 1 MW. The present work has been done in the similar framework as in the SNS. The aim is to give an overview of the optimum parameters to realize laser-assisted H$^-$ stripping at 400 MeV.

MAGNETIC FIELD STRIPPING

As shown in Fig. 1, the 1st and 3rd steps utilize Lorentz stripping by using high field magnets. In the former step, an H$^-$ is stripped to an H^0, while H^0 excited by the laser is stripped to a proton by the 2nd magnet in the later step. The basic concept is similar to that already designed for 1 GeV H$^-$ at SNS [11]. A detail is thus not discussed here. Figure 2 shows magnetic field configuration together with stripping functions. The magnetic field for each magnet is considered to be Gaussian shape with σ=0.03m for simplicity as shown

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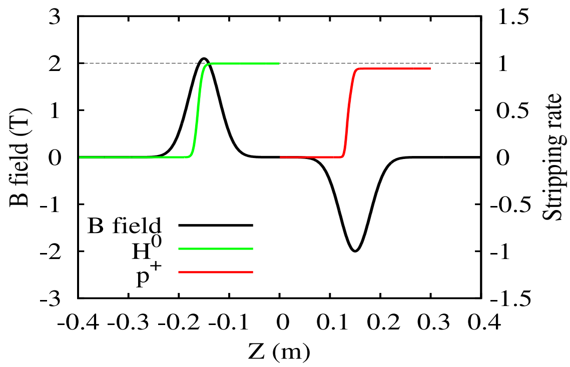

Figure 2: Magnetic field configuration and Lorentz stripping rate of H^- and H^{0*}.

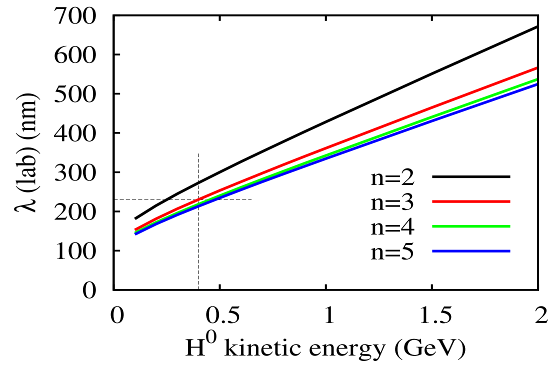

Figure 3: Doppler shift of the transition wavelength of H^0 as a function of its kinetic energy is calculated by using Eqn. 1. n is the principal quantum number of hydrogen atom. Laser wavelength for 400 MeV is required to be 230 nm.

by the black curve. The amplitude of the first and second magnet are 2.1 T and 2.0 T, respectively. The green curves represents the stripping fraction of H^- to H^0 or $\frac{H^0}{(H^0+H^-)}$ ratio in the H^- beam, while the red one represents stripping fraction of H^{0*} to p^+ or $\frac{p^+}{(p^++H^0)}$ ratio in the H^0 along the beam (z) axis through the magnets. Due to disintegration of 3p excited state into the ground state during flight between interaction point (IP) to the 2nd magnet, $H^{0*} \rightarrow p^+ + e^-$ stripping efficiency is obtained to be about 97%. There also remains nearly 2% of the H^0 unexcited and the final stripping efficiency is thus obtained to be 95%.

H^0 EXCITATION BY LASER

All methods for the H^0 beam parameters have also been adopted from the SNS [9]. The basic difference is the beam energy and also some minor differences in twiss parameters.

Optimum Laser Wavelength and Pulse Parameters

The first requirement is to calculate an optimum wavelength of the laser for 400 MeV beam for a typical incident angle of around 36 degree with the H^0 beam. Due to the Doppler effect, laser wavelength, λ in laboratory frame is shifted to λ_0 of the H^0 atom in the rest frame, given by

$$\lambda = \lambda_0(1 + \beta cos\alpha)\gamma \qquad (1)$$

where β and γ are relativistic parameters, α is collision angle between laser and the H^0 beam in the laboratory frame, which is used to be 36.4 degree. Figure 3 shows the laser wavelength as a function of the kinetic energy of the beam for exciting an H^0 to upper states. The dash cross lines represent the required laser wavelength for two level excitation (n=3) of 400 MeV H^0, which is calculated to be 230 nm.

The laser pulse that interacts with H^0 micro-bunch can be characterized by the longitudinal shape and peak power, P_{peak}. The laser pulse width should be at least two times bigger than the H^-. Transverse parameters can be characterized with a waist parameter and distance between waist and IP. Here we will use beam size r and angular divergence α at the interaction point that can be calculated from the first two parameters [9]. In this paper, we will take an optimum laser wavelength of 230 nm with 1 MW peak power in order to obtain a satisfactory excitation efficiency.

H^0 Beam Parameters

An efficient laser excitation also requires optimum transverse and longitudinal parameters of the H^0 beam. Table 1 shows typical transverse parameters used in the present study.

Table 1: Typical Transverse Parameters of the Beam

$\epsilon_{x,y}$ **(norm.)** (π mm mrad)	$\alpha_{x,y}$ (rad)	$\beta_{x,y}$ (m)	$D_{x,y}$ (m)	$D'_{x,y}$ (rad)
0.25, 0.25	0, 0	20, 0.1	0, 0	-2.55, 0

The above parameters are required in order to get minimum beam size, where dispersion parameters are very important and responsible for high efficient excitation.

The longitudinal parameters are used to be as follows:
Relative momentum spread, $\frac{\Delta p}{p}$ = 8.0× 10^{-4}
α_z = 0.0 and σ_z = at least two times smaller than the laser pulse length in terms of time.

It is worth mentioning that both transverse and longitudinal parameters of the beam can be achieved in order to demonstrate a POP experiment at 400 MeV. As an example, Fig. 4 shows a typical simulation results for the longitudinal beam size of the H^- plotted from the entrance of the ACS (annular-ring coupled structure) Linac. The IP considered at this stage for a POP experiment is ~40 m upstream from the present stripper foil location. The advantage of using this point is that all three charge fractions in the H^- beam can be simultaneously measured in the downstream branch beam lines. The longitudinal beam size at the IP for a relatively lower beam current can be reduced to about 24 ps (rms) by optimizing two debuncher parameters. The present value is very reasonable and is similar to that already obtained at SNS [9].

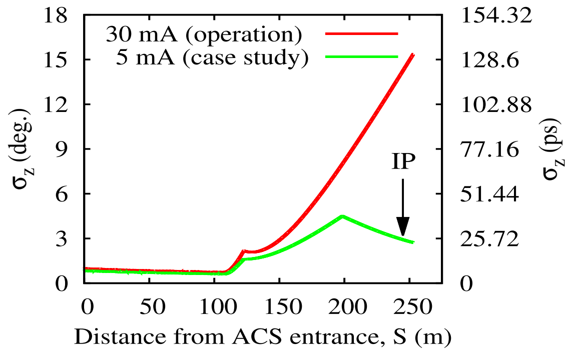

Figure 4: Simulation results for the 400 MeV longitudinal H^- beam size in the J-PARC Linac.

Laser Stripping Model of Excitation

In order to estimate laser excitation of H^0, simple model of two level atom 1s→3p and time dependent Schrodinger equation like for most of the previous calculation for the SNS laser stripping is used [6, 9]. The H^0 bunch has been simulated as a Gaussian beam in (x,y,z) planes consisted of 1000 particles. The error of laser stripping excitation is obtained to be 0.001. Fig. 5 shows the laser stripping efficiency as a function of the laser beam radius, r and its angular divergence, α. A maximum excitation efficiency of 98% was obtained for r and α of 0.26 mm and 0.39 mrad, respectively. These parameters are important to design the laser system for 400 MeV H^- beam.

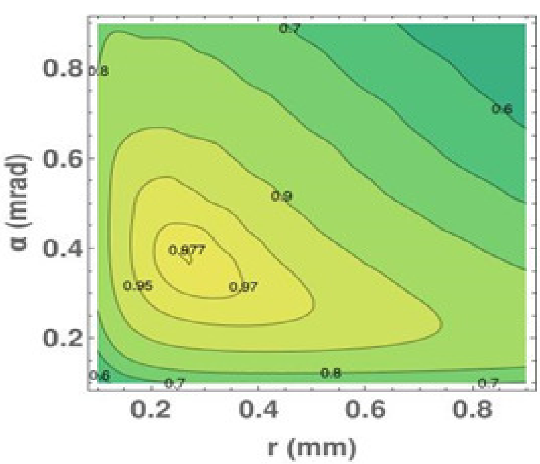

Figure 5: Laser excitation efficiency as function of r and α of the laser beam parameters. The maximum excitation locates at 0.26 mm and 0.39 mrad for r and α, respectively.

There exist UV lasers of wavelength nearly 200 nm but it is very hard to achieve 1 MW peak power as required for the 400 MeV. The 3rd harmonic of Nd:YAG laser (basic wavelength 1064 nm) is used for the required 355 nm wavelength for 1 GeV beam at SNS, where a peak power of more than 1 MW with 10 μs pulse length has already been achieved [12]. If we take 5th harmonic, it gives 212 nm but the peak power will decreased. An improvement of the laser technology is thus very essential in order to realize laser-assisted H^- stripping at 400 MeV.

SUMMARY AND OUTLOOK

A preliminary study of laser-assisted H^- stripping has been done for the J-PARC RCS injection energy of 400 MeV. RCS already demonstrated 1 MW beam acceleration and has a capability of achieving further more than 1 MW even by keeping the injection energy same as 400 MeV. However, lifetime of the stripper foil is the most concerning issue to realize routine operation. The present work basically gives a set of optimum parameters in order to carry out a POP experiment first. The transverse and longitudinal parameters of the H^- beam can be tuned for satisfactory parameters in order to achieve maximum stripping efficiency. An optimum laser pulse of wavelength in the UV region of 230 nm with a peak power of 1 MW may be the real challenge at this moment.

However, the demand and rapid progress in the laser technology in the present days may made it possible to reach the goal in near future. The present result is very preliminary and we should studied all parameters in detail. For example, the angular spread in the first stripping magnet can grow significantly but it has not been taken into consideration at this stage. Further detail simulations have to be carried out in order to proceed step-by-step.

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