ICANS - XV
15^{th} Meeting of the International Collaboration
on Advanced Neutron Sources
November 6-9, 2000
EPOCHAL TSUKUBA International Congress Center, Tsukuba, Japan

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A New Laser Stripping Method by use of Multi–Photon Resonance Ionization Enhanced with Multi-Mirror System (RIMMS)

Yasuo SUZUKI

IDX Technologies Corporation
1-25-11 Gotanda Tohoseimei Bldg, Higashigotanda Shinagawa-ku Tokyo, Japan

Abstract

A new laser stripping method by use of multi-photon resonance ionization is proposed which is an advanced design of LUCE (Laser Undulator Charge Exchange) and DoLUCE (Double LUCE) for the next generation's proton storage rings. The new method utilizes a magnetic field to generate the Lorentz electric field on an H^- beam and to neutralize the beam. It utilizes also a visible laser light which irradiates the H^0 beam efficiently with a multi-mirror system in the central region of the magnetic field as like in the cases of LUCE and DoLUCE. In this method, the laser beam strips the electron of the H^0 beam almost completely by multi-photon resonance ionization. Thereby, the low emittance growth of H^+ beams after ionization can be achieved. It will possibly be realized with the existing technology.

1. Introduction

Storage of the high power proton beam in the ring is indispensable to promote the neutron or neutrino science. However, operations of the proton storage ring have been limited by the foil-stripping method for charge exchange, because scattering of the high energy beam causes radiation damage and activation around the beam injection section. Therefore, development of an alternative charge exchange method is the most important and urgent issues, in order to reduce a cooling time of the radioactive material and to secure a safe operation and maintenance.

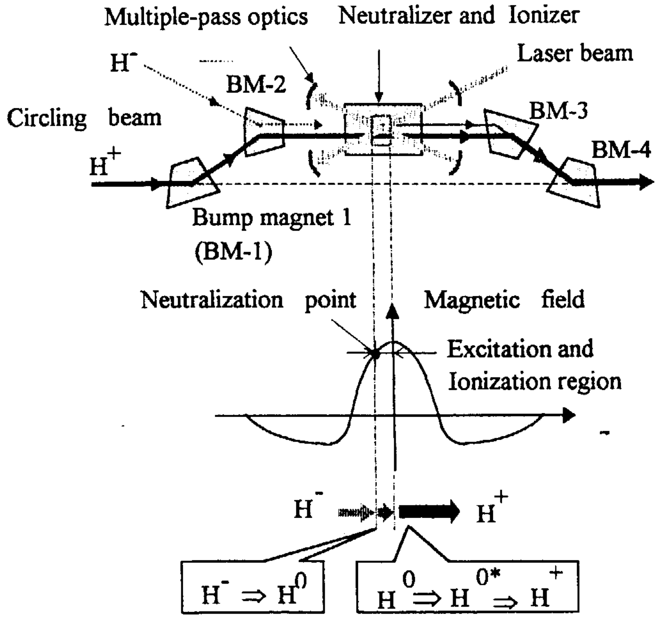

Fig. 1 New configuration of the charge exchange

The authors proposed a charge-exchange methods LUCE and DoLUCE (Double LUCE): Laser and Undulator Charge Exchange[1],[2]. The neutralization and ionization occur about the high intensity region of the magnetic field that is placed at the straight section of a bumped orbit, as shown in Fig. 1.[3],[4] The magnetic field is applied to ensure a trajectory stability of the circulating beam, because the directional deviation of the circulating beam is cancelled out by the experience of the field. The rear half-cycle part of the magnetic field can also control the direction of the ionized beam. The central magnetic field works as both the neutralizer and the ionizer. That is, the H^- beam is firstly neutralized by the intense Lorentz electric field generated by the interaction between the relativistic velocity of the H^0 beam and the magnetic field. Soon after that, the laser light intensified with a multi-mirror system (MMS) excites the H^0 beam resonantly to a Stark shifted state and the excited H^0 beam is ionized by Lorentz electric field near at the peak of the magnetic field in LUCE. When the hydrogen beam energy is less than 1.2 GeV, the one-step excitation by the visible laser can not succeed in due to lack of the relativistic Doppler effect.

The larger cross-sections of resonant excitation can also not be used in the scheme. DoLUCE is a new version of LUCE which is modified by the 2-step excitation scheme to be applied to 0.8 –1.0 GeV H^0 beam injection. The method uses two lasers and two MMS's with visible wavelength and infrared one, respectively. Here, the two sets of the optical system share the ionization potential. Thereby, the required laser power can be reduced.

In the magnetic field B [T], the lifetime of H^- beam τ is given by: $\tau = (A_1/F) \exp(A_2/F)$, where $F = \gamma \beta cB$, $A_1 = 2.47\times10^{-6}$ (V.s /m) and $A_2 = 4.49 \times 10^9$ (V /m) .[5] From the calculation of this equation, the intensity of the magnetic fields is selected to be more than 1.2 T for example to 1.0 GeV beam.

In this paper, following the calculations for LUCE and DoLUCE, a new laser stripping method by two-photon resonance ionization enhanced with MMS (RIMMS) is described. That is, in the RIMMS, the ionization process is in essentially two photon resonance ionization in stead of two photon excitation plus ionization by the intense Lorentz electric field of DoLUCE.

2. Selection of the Stark state and the ionization cross-section

The neutralized H^0 beam is photo-excited to one of the Stark states under the intense Lorentz electric field, which the magnetic field generates in the interaction with the velocity of the H^0 beam. In this paper, the Stark states are denoted by a series of quantum numbers $| nn_1n_2m>$. The main quantum number n has a relation of $n = n_1 + n_2 + m + 1$, and the energy level is expressed as $E| nn_1n_2m>$. Applying the laser light polarized in parallel to the Lorentz electric field, the condition of $\Delta m = 0$ and $m = 0$ (the least energy gap between two Stark states of the different main quantum number) is available as the transition selection rule in this scheme.

The energy level of the Stark state is expressed as follows:

$$E = E_{|n,n1,n2,0>} = (-1/2n^2) + (3/2)n(n_1-n_2)F - (n^4/16)\{ 17n^2 - 3(n_1 - n_2)^2 + 19\}F^2 + (3/32)\, n^7(n_1 - n_2)\{23n^2 - ((n_1 - n_2)^2 + 39)F^3 \cdots,$$

where F is the intensity of Stark electric field ($\gamma\beta cB$) expressed in the unit of 5.13×10^{11} V/m, and the energy E is by that of 27.2 eV. The energy difference between two Stark sates is expressed as follows:

$$\Delta E_{n-n'} = E_{|n,n1,n2,m>} - E_{|n',n1',n2',m'>}.$$

The energy difference is equivalent to a frequency for the resonant excitation ν (= $\Delta E/ h$ where h is Plank constant) from the ground level $|1000>$ to the upper level. The values are expressed by a function of the magnetic field intensity.

The lifetime on the excited Stark state is calculated by the following formula [6]:

$$\tau = h / 2\pi\Gamma_{|n,n1,n2,0>}$$

where $\Gamma_{|n,n1,n2,m>}$ is a resonant width of the excited Stark state. The resonant width of the excited Stark state $\Gamma_{|n,n1,n2,m>}$ is expressed as follows:

$$\Gamma_{|n,n1,n2,0>} = (4R)^{2n2+1} \{n^3 n_2! \, n_2 !\}^{-1} \exp\{(-2R/3) - (n^3 F/4)(34n_2^2 + 46n_2 + (53/3)),$$

where $R = (-2E)^{3/2}/F$. This means the life time staying on the excited state and waiting the next ionization process.

Transition probability between two Stark states, and the excitation cross-section are calculated according to the quantum theory[7]. The calculation results are summarized in Table 1.

Table 1 Calculated excitation cross-section between two Stalk states (by linear-polarized light)

Initial Stark state	$|1000>$	$|1000>$	$|2010>$	$|2010>$	$|2010>$	$|1000>$
Final Stark state	$|2010>$	$|4300>$	$|3020>$	$|4300>$	$|4030>$	$|3020>$
$\sigma /L(\Delta \nu)10^{-3}$ cm^2/s	16.2	0.99	36.4	0	8.10	3.15
$\sigma\ 10^{-15}$ cm^2/s	3.09	0.15	37.4	0	6.39	0.50

The excitation cross-section depends on the profile function $L(\Delta\nu)$ of laser spectrum width or the absorption spectrum one, which is a function of Doppler shift due to the momentum dispersion of the accelerated beam. Here, the spectrum width is assumed the order of 10^{-3}.

One of the most important items for developing the DoLUCE and RIMMS, is to select an optimal laser for the Stark excitation. Obtaining sufficient output power, suitable pulse structure synchronized with that of H^0 beam, and oscillation performance of the resonant wavelength for the transition are essential key technology. For the purpose, high power lasers and the multi-mirror system (see Appendix) are selected in the region of visible or infrared

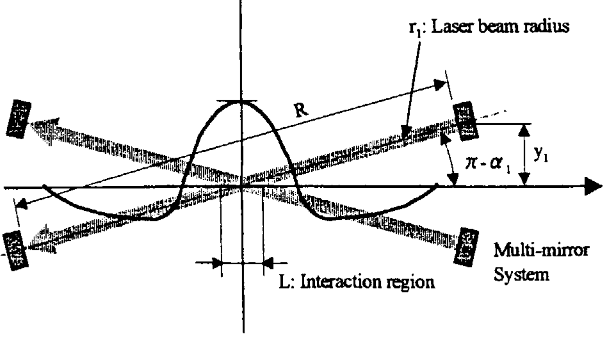

Fig. 2 Tapered undulator and relative positions of multi-mirror system in LUCE

wavelength.

On the other hand, generally speaking, the laser light of 100 nm range is necessary to excite resonantly the hydrogen gas. Considering the effect of the relativistic theory (Doppler effect) on the encountering process of the H^0 beam and photon one, the ultra-violet light is also required for the resonance transition in H^0 beam. Actually, the beam energy lower than 1.2 GeV is necessary to use the two step excitation due to lack of the Doppler shift effect. In the DoLUCE, the two lasers of a visible wavelength and an infrared one are used to excite two Stark states, the wavelength regions of which are preferable from the stand of view of high power laser.

The Doppler-shifted wavelength is expressed in the rest frame as follows: $\lambda_l' = \lambda_l / \gamma(1 - \beta \cos \alpha_l)$, where α_l is a crossing angle between the laser and H^0 beam. Geometrical and Optical parameters are shown in Fig.2, which illustrates the concept of multi-mirror system. Taking account of synchronization with H^0 beam frequency of 200MHz, the distance between the mirrors R is selected to be 1.5 m. In this configuration, for example, the Lyman α line (121.5 nm, the resonance wavelength of the transition from |1000> to |2010> in 1.0 GeV H^0 beam) becomes 469.0 nm (blue light) in the laboratory frame.

3. RIMMS

In the RIMMS the same Stark state of |2010> is used as the first excitation, and the ionization is also carried out by the light of the same laser. Let's summing up the ionization scheme of the LUCE, DoLUCE and RIMMS.

	Neutralization	Ionization
LUCE	Lorentz electric field	Photo-excitation to a Stark state and the field ionization, | 1000> to | 3020> for more than 1.33GeV beam ,
DoLUCE	Lorentz electric field	2 color photon-excitation to Stark states and the field ionization | 1000> to | 2010> and | 2010> to | 4030>,
RIMMS	Lorentz electric field	2 photon ionization via excitation to a Stark state Excitation | 1000> to | 2010> and photo-ionization.

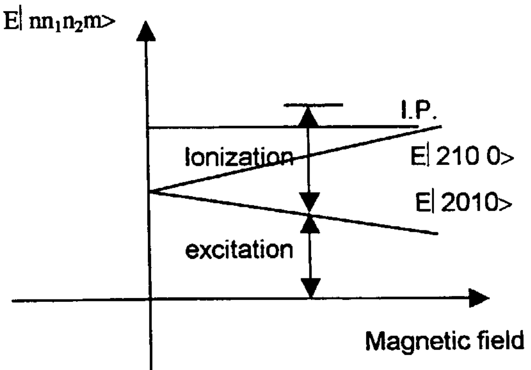

Fig. 2 Selected state and energy levels

The equation of the excitation rate in the laboratory frame is given by:

$$dN / dt = -N n_p \sigma c$$

where N is the number of excited H^* particle in a beam bunch, c is a light velocity, and n_p is the photon density. The absolute value of the left-hand side means an ionization rate per a unit time.

In the rest-frame, the ionization rate is defined as follows:

$$\partial N / \partial t' = -N n_p' c \sigma' ,$$

where σ' is a rest-frame ionization cross-section (unchanged in the laboratory frame), and n_p' is a photon density in the rest fame and is expressed as follows: $n_p' = n_p \gamma (1 - \beta \cos\alpha)$, due to the Lorentz shrinkage where α is a crossing angle between the laser and H^0 beam. In the laboratory frame, the above expression becomes: $\partial N / \partial t' = - \gamma(1-\beta\cos\alpha) N n_p c\sigma$ .Here, putting $\delta t' = \delta z / \gamma v$, the equation is rewritten as follows:

$$\delta N / N = = -(1-\beta\cos\alpha) n_p \sigma \delta z \ / \beta \ \cong - 2n_p \sigma \delta z \quad \text{or} \quad \delta N / N_0 = 1 - \exp(-2n_p \sigma \delta z),$$

where v is the velocity of H^0 beam, and δz is the length of the irradiation region. The length δz is determined by the cross-section of the laser beam and the crossing angle.

The secondary photo-ionization probability governs the total ionization rate from H^0 to H^+, because the large resonance probability in the first excitation is so high in comparison with the second. Let's assume the ionization probability is one–hundredth of the resonance probability about 10^{-17} cm^2, then, the sufficient high photon density for ionization becomes from the following equation:

$$\delta N / N_0 = 1 - \exp(-2n_p \sigma \delta z) \ \cong \ 1 - 10^{-4}$$

Now, we assume that the laser beam is injected to the multi-mirror system at the repetition rate of 1 MHz. The photon bunch is synchronized with the pulses of H^0 beam with the flight time repetition in the multi-mirror system. Here, the interaction frequency is kept at 200 MHz with the distance of 1.5meter between the mirrors. By the multi-mirror system, the photon ca continue the interaction for more than 1 μs. Assuming the pulse duration of 2 ns, that is, the reaction region length of 60 cm, the required peak power I(W) is given by the following equation:

$$I = h \nu n_p c S / A_F = 7.7c^2 S / \sigma \lambda A_F \quad [W],$$

where S is a cross-section area of laser beam.

Under the conditions that the H^0 beam energy is 1.0 GeV, S is 1 cm^2, and A_F =1, the required laser power I for the ionization, becomes 22 MW at the peak. By the way, the excitation to the first resonance level by this laser power, takes less than 20 ps[2]. The same photon density can be accumulated by the injection of the laser power 74 kW, with the frequency 200MHz owing to the accumulation function $A_F = 300$ of MMS. The minimum laser power for the ionization is thus calculated from that of the resonance excitation.

On the other hand, we can rewrite the laser peak power as follows: $I = h\,\nu\, n_p\; cS/\,A_F = n_p'\, h\, c^2S/A_F\, \lambda\gamma(1-\beta\cos\alpha)$ $= n_p'\, h\, c^2S/A_F\, \lambda'\gamma^2(1-\beta\cos\alpha)^2 \quad = I'/\gamma^2(1-\beta\cos\alpha)^2$ [W]. This means that the relativistic effect reduces the required laser power by the amount of $1/\gamma^2(1-\beta\cos\alpha)^2$ by the relativity theory.

4. Discussions

We have firstly selected the resonance wavelength for 1 GeV H^0 beam and calculated the laser power for excitation and ionization through |2010> level in RIMMS. The laser of 469nm in wavelength and 74 kW/pulse in power is required for the two-photon ionization of 1 GeV H^0 beam The practicability for RIMMS depends on the laser which satisfy the required laser performance.

Comparing with LUCE and DoLUCE, RIMMS has an advantage of the simple system and can be applied to the comparatively low energy acceleration beam as large as 1 GeV. In respect with the required laser power, RIMMS is regarded to be most efficient as it uses the largest excitation cross-section of H^0 beam, that is, Lyman α line. Other countermeasures to reduce the required laser power in RIMMS, are to increase the interaction length between H^0 beam and photon one, and to increase the photon accumulation factor A_F by MMS, which is assumed to be about 300 in this paper. In order to improve the factor, mirrors with higher reflection and the optical switch with higher transmittance are needed to be installed. Mirrors with the reflection rate of 99.99 % are commercially available for the visible light. By improving the light accumulating system, it is possible to obtain the factor A_F of more than 10^3. Thereby, the required laser power can easily become less than the value mentioned above.

Taking account of the synchronization between laser beam pulses and the H^0 beams ones, a mode-locked laser is considered as the most suitable type of laser for the system. The tunable high power lasers, such as a Ti-sapphire laser, and OPO laser, are in great progress recently and are capable of a mode-locked operation. Repetition rate of more than 1MHz, jitter of less than 1ps are reported, and various modifications of the pulse structure is also available to such as the 200Mhz operation through the MMS function.

Conclusions

The two photon resonance ionization via the lowest Stark state is proposed as a new charge exchange method. The scheme is effective to hold down the emittance growth of H^+ beam after the ionization, and enables the largest excitation cross sections to be utilized. The process from neutralization to ionization is carried out in the same common magnet and one laser and one MMS, so that the system configuration can be extremely simplified and be compact, compared with the previously mentioned methods, such as LUCE and DoLUCE.

The light accumulation optics combining with the multi-mirror system has been tested to increase the photon density in the reaction region. Use of the visible laser beam enables the accumulation rate to be several hundreds, because of the high reflection rate of mirrors. Thereby, the intensity of the injected laser beam can be reduced to practical level, and various types of laser are available. In conclusion, the new charge exchange method, RIMMS, which we have conceptually designed, is an epochal and practical method of using only magnetic field and photon beam instead of solid materials, such as foils. We expect that uncontrollable scattering and radioactive products will be minimized.. Research and Development on the components of this system should be continued, and experimental tests are needed to justify this concept finally.

Acknowledgments

The authors would like to thank Drs. M, Kinsho and H. Yokomizo for their helpful discussions and for their encouragement. Many people contributed to our studies through the technical meeting about laser stripping, who include Drs R. J. Macek, A. J. Jason, J. B. Donahue and other members of LUCE collaboration group at LANSCE, Prof. H. C. Bryant of New Mexico University, and Drs I. Gardner, G.H. Rees, P. Drumm and others at ISIS. The authors would heartily like to acknowledge useful discussion with these people.

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Apendix: Multi-mirror system[8]

In order to utilize a laser power effectively, a multi-mirror system is being developed in JAERI. Figure 4 shows ray path in the multi-mirror system. In the optics, an image-relay is utilized to minimize a distortion of laser beam. The focal length is selected at half of the distance between the mirrors. If the properly diverging beam is injected at the first reflection mirror, the reflected beam becomes the forward beam in Fig. 4 with a parallel beam (constant cross-section beam) and travels to the next mirror through the central region of interaction. The reflected light at the next mirror, the beam focuses at the off-center point and becomes the backward beam. The backward beams do not interact with H^0 beam and the forward beam converges at the central region of interaction but only the cross-sectional area is controllable by MMS. The laser beam density can not only be increased with the number of round-trip. In addition to these effect, rotational reflections among the alternative mirrors cancels the diffraction loss at the reflections and can accumulate the high power light under decreasing the thermal pressure.

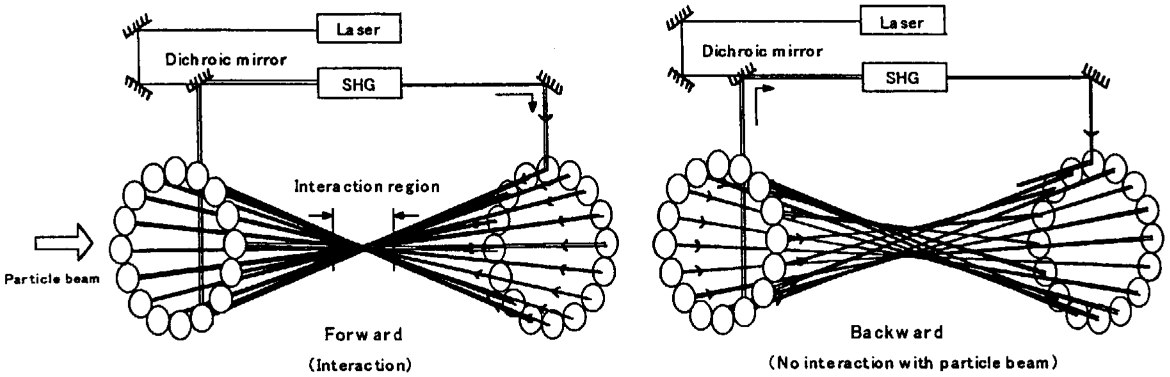


Fig.4 Ray traces in the multi-mirror system and configuration of light accumulation system

Additionally, an active or passive optical switch, such as a Pockels cell or a second-harmonic generator, is combined in order to reuse the laser beam effectively. Thereby, it is estimated that the photon density at the central region becomes approximately 300 times of that of incident beam.

As shown in Fig 5, a photon accumulation factor A_F is defined by a feedback theory. Since the image relay enables the diffraction loss to be negligibly small, the factor A_F is calculated by taking account of only reflection loss.

The equation of power balance is given by:

$$\{I_{in}\,\alpha T + (1-R)^{2M} I_{out} T\} = I_{out}.$$

Here, $I_{in}\alpha T$ means the laser power generated in the second harmonics generator (SHG).

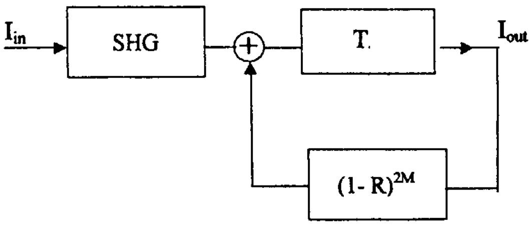
Defining the accumulation factor A_F as follows:

$$A_F = MI_{out} / I_{in}\,\alpha T,$$

and the following equation is conducted :

$$A_F = M / [1 - (1 - 2RM)T]$$

For the parameters of T = 1, M = 40 and R = 0.001 then $A_F = 500$ and for T = 0.95, R = 0.001 and, then $A_F = 317$.



α : Energy Conversion rate of SHG
T : Transmittance in SHG
R : Mirror loss per one reflection
M : Number of mirrors on each side
I_{in} : Injected power into the multi-mirror system
$AF = MI_{out}/I_{in}\alpha T$

Fig.5 Block diagram for calculation of photon accumulation