A New Laser-Stripping Method for the Proton Storage Ring of Neutron Science (Double Lasers and Undulator Charge Exchange : DoLUCE)

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Abstract

A new scheme of the charge-exchange injection DoLUCE is reported for the proton storage ring of the next-generation neutron sources of 5 MW-class. In this scheme, periodical magnetic field (undulators) and photon beams from powerful lasers are efficiently used for the ionization of the hydrogen beam in stead of stripping foils. The H^0 beam of the ground level is excited to that of n = 2 and then from n = 2 to n = 4 level which are Stark-shifted by the Lorentz electric field. By the 2-step excitation, the powerful lasers in infrared and visible ranges can be applicable. All the components of this system, the undulators and the powerful lasers, will be realized with advanced technologies.

1. Introduction

Operations of the proton storage ring have been limited by the foil-stripping method in the injection device due to the radioactive damage and the cooling time for keeping safe maintenance. Activation by the beam loss, is the most urgent and important technical problem for the proton storage ring of 5 MW-class, such as ESS, SNS and JAERI–NSP, where the storage ring is indispensable to produce the high power proton beam for the neutron scattering science.

The authors have proposed a new charge-change method LUCE [1]. This system is composed of a neutralizer and an ionizer, which are placed along a straight section of the ring as shown in Fig. 1. The neutralizer strips an electron of H^- beam into H^0 with a tapered undulator. The ionizer is composed of a tapered undulator and a laser system. A laser beam excites H^0 beam resonantly to a Stark state, and the excited beam is ionized by the Lorentz electric field generated with the interaction of the relativistic velocity of the H^0 beam and the magnetic field of the undulator.

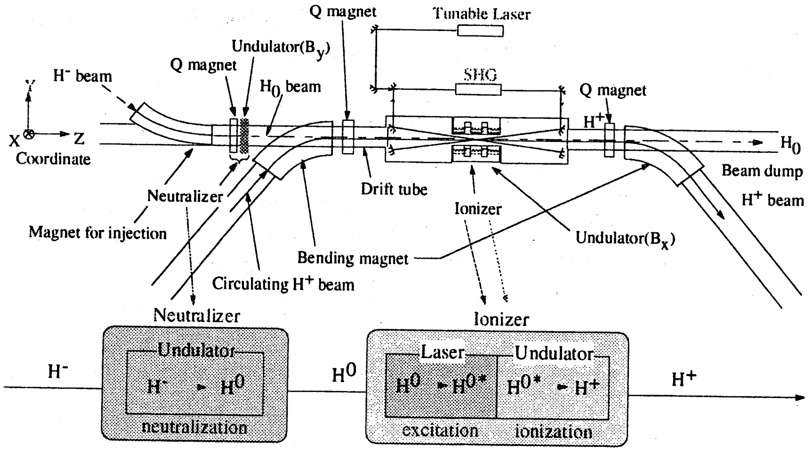


Fig.1 Concept of LUCE (Laser and Undulator Charge Exchang).

2. DoLUCE

DoLUCE is a new version of LUCE in the ionizer, which is modified by 2-step excitation method using the two lasers in the visible and infra-red ranges, for application to the new design of NSP-JHF unified plan (possibly, 0.8 –1.0 GeV H^0 beam injection). If we may try to use the 1-step excitation method to the design, the high power laser in the ultraviolet range is required due to lack of the Doppler shift.

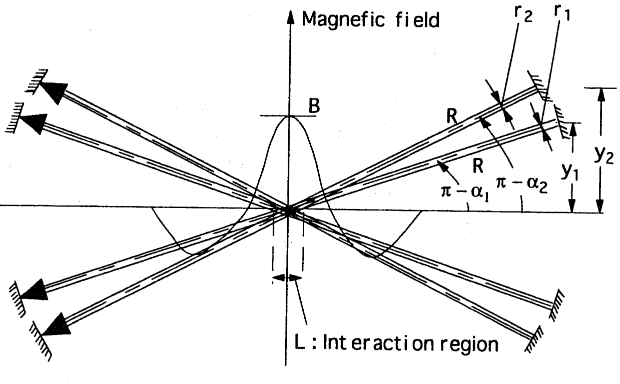


Fig.2 The tapered Undulator and the relative positions of the multi-mirror system.

An ionization concept of the DoLUCE is illustrated in Fig. 2. The H^0 beam is injected into the ionizer. The neutralized beam of the ground state goes directly around the peak magnetic field of the undulator and there, is excited to one of the n = 4 Stark states, that is from $|nn_1n_2m> = |1000>$ to $|nn_1n_2m> = |4030>$ within interaction length L, where $|nn_1n_2m>$ is a series of quantum numbers representing the Stark states.

The one and a half period tapered undulator is applied for minimizing the effect on the beam trajectory of the re-circulating beam in the ring. The peak magnetic field works as the ionizer for the excited H^0. The rear half-cycle part of the magnetic field controls the orientation of the ionized beam.

The peak intensity of the magnetic field should be selected sufficiently to ionize the excited H^0 beam instantly, that is, so that the rest-frame life time of the excited H^0 beam may be 1 ps. The life times versus the magnetic field

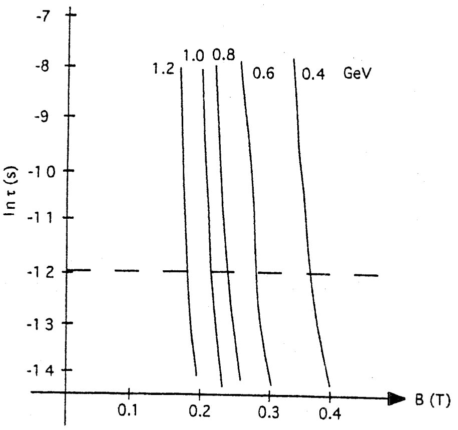


Fig.3 The rest-frame life times of stark state |4030> vs. the magnetic field intensity, where parameters mean beam energies.

intensity are shown as a function of the beam energy in Fig. 3 which is calculated by using the reference [2] and are selected 0.22 T for 1.0 GeV and 0.25 T for 0.8 GeV.

In order to adopt the 2-step excitation method, the most profitable two transitions between the Stark states are selected as |1000> to |2010> and |2010> to |4030>. The energy differences and the corresponding frequencies are :

$$E|2010> - E|1000> = 27.2\,(3/8 - 3F)\ \mathrm{eV} = h\nu_1'$$

$$E|4030> - E|2010> = 27.2\,(3/32 - 15F)\ \mathrm{eV} = h\nu_2',$$

where h is the Plank constant and suffixes " ' ", " $_1$" and " $_2$ " denote the values of the rest frame, of the first excitation and the second one, respectively. An energy level of Stark state $E|nn_1n_2m>$ is approximated as the function of Lorentz electric-field intensity $F = \gamma\beta cB$ by a unit of 5.13×10^{11} V / m as shown in Fig.4 [3].

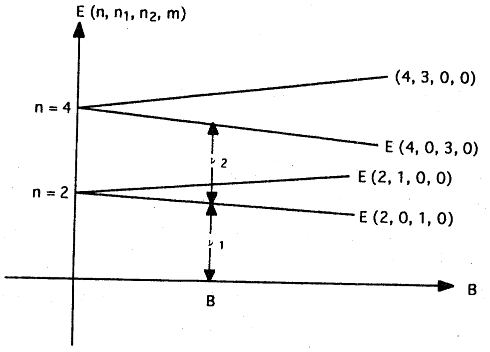


Fig.4 Selected Stark States and the energy levels.

If the excitation rate at the second step is sufficiently high by the powerful laser, the total excitation rate is governed by that of the first step. So, comparing with the rest-frame life time 1 ps, the excitation time of the second is also assumed more than 1 ps and the first excitation 10 ps.

Relativistic Doppler shift makes it possible to use the visible light for the excitation. Doppler shifted wave-length is expressed in the rest frame of reference as :

$\lambda_1' = \lambda_1/\gamma(1-\beta\cos\alpha_1)$ where $\lambda_1 = c/\nu_1$ and α_1 means the crossing angle. The crossing angles between the H^0 beam and the laser beam are here R = 1.5 m, y_1 = 0.1 m, y_2 = 0.15 m, r_1=1.0 mm, r_2=1.5 mm and L=60 mm in Fig. 2.

The rest-frame life time τ' is defined by the excitation equation as :

$$dN/dt = Nn_\nu'c\sigma' \text{ and } \tau'^{-1} = n_\nu' c\,\sigma'$$

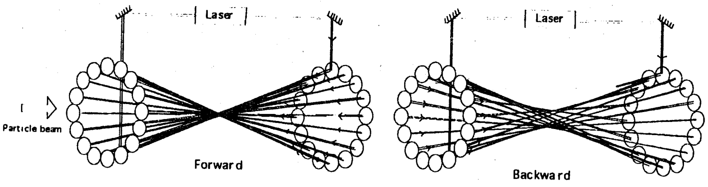
where N is particle density, $n_\nu' = n_\nu\gamma(1 - \beta\cos\alpha_1)$ which is photon density in the rest frame, c : light velocity, and σ' is the rest-frame excitation cross-section (unchanged in the laboratory frame). For the hydrogen beam, $\sigma'/L(\Delta\nu')$ is given from the calculation of the quantum theory [3] and listed in Table 1, where $L(\Delta\nu')$ is, so called, the line profile function, Gaussian and $\Delta\nu'$ is the maximum spectrum broadening among those of the laser light itself, the absorption cross-section or the momentum dispersion of the H^0 beam. The spectrum broadening is here assumed 0.1 % at the maximum, and so $L(\Delta\nu')$ becomes $0.47/(\Delta\nu') = 470/\nu'$.

Initial Stark state	|1000>	|1000>	|2010>	|2010>
Final Stark state	|2010>	|4300>	|4030>	|4300>
$\sigma/L(\Delta\nu)$ 10^{-3} cm^2/s	10.8	0.66	5.4	0
$\sigma \times 10^{-15}$ cm^2/s	2.06	0.10	4.26	0

Table 1 The excitation cross-section between two Stalk states. The circular polarized light is assumed.

3. Multi-mirror systems and Laser powers

In DoLUCE scheme, an optical system, that is, a multi-mirror system, is adopted for the efficient use of laser beam energy. The ray traces are shown in Fig. 5 and the laser beam can interact with H^0 beam multi-times during the flight time. That is, it can accumulate photon density at the central part of the system. Accumulation factor A_F is here assumed to be 300 (see Appendix) [4].



Now we can get n_ν's to make τ_1 =10 ps and τ_2 = 1 ps and n_ν's are given from the formula of Lorentz shrinkage $n_\nu = n_\nu'/\gamma(1-\beta\cos\alpha)$.

A mode-lock laser of 200 MHz (synchronized with H^0 beam), 200 ps (6cm) duration and the peak power I (W) is considered. The required peak power is given as follows :

$$I = h\nu n_\nu cS/A_F\lambda = n_\nu' h c^2S/A_F\,\lambda\gamma(1-\beta\cos\alpha)$$

$$= n_\nu' h c^2S/A_F\,\lambda'\gamma^2(1-\beta\cos\alpha)^2,$$

where S is the cross-section area of light beam. The light columns of r_1 = 1 mm in radius is assumed in Fig. 2 for the first excitation and then, We obtain the required laser power :

I = 0.56 kW which corresponds to 0.11 μJ /pulse.

The rest-frame length of interaction region is 60 /γ mm (L = 60 mm)and the life time is 10 ps (3 mm). The total non-ionization rate becomes $\exp(-20/\gamma) = 6.3 \times 10^{-5}$.

The minimum laser power for the second excitation is also calculated with the same way of the first excitation and under the light column of $r_2 = 1.5$ mm.

4. Conclusion

The conclusive results are listed in Table 2 where laser specifications are described for both 1.0 and 0.8 GeV cases.

The average power of the laser is rather high in comparison with the exsiting technology although the interaction region is minimized as small as possible to get high photon density. The interaction region is regarded as a cylinder of L=60 mm and 2 mmϕ. The detailed analysis of the beam optics is necessary to obtain the sufficient interaction between H^0 beam and the laser-light region.

The rationalization of the required laser power is possible to optimize the A_F, S and by taking account of the duty cycle of laser oscillation and the time structure of the laser pulse.

The 2-step excitation method lightens remarkably the burden of development to get higher laser power, and the intense Lorentz electric field allows us to use the modest magnetic field strength of the undulator. The growth of beam emittance at the charge exchange is minimized by limiting the Stark states to be excited [5].

For comparative study, let's consider the 1-step excitation. The energy difference between Stark states $|1000>$ and $|4030>$ is : $E|4030> - E|1000> = 27.2\ (15/32 - 18\ F)$ eV which corresponds to so called, Lyman γline (97.25 nm) and the required wave-length of the laser is 376.7 nm. In this case, the 3-rd harmonics (354 nm) of Nd:YAG laser can be applied but the sufficient photon density is not easy to obtain with the poor accumulating factor due to the large mirror loss and with the small excitation cross-section.

If the 2-nd (532 nm) or 3-rd harmonic wave of Nd:YAG laser which we can expect to be of high power is applied to the first excitation, the energy of H^0 beam should be 1.22 GeV or 0.589 GeV, respectively.

Acknowledgments

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Appendix

The accumulation factor A_F is conducted from the following block diagram of the accumulation, where diffraction loss is negligibly small and only reflection loss is considered.

From the feedback theory, we get :

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

Where means the power generated in the second harmonics generator (SHG).

Defining the accumulation factor $A_F = MI_{out} / I_{in}\,\alpha T$, then, we get $A_F = M/[1 - (1 - 2RM)T]$

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

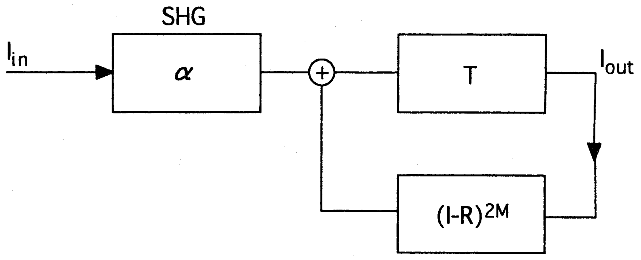

Fig.6 The Block diagram for calculation of photon accumulation.

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

GeV	γ/β	$\gamma(1-\beta\cos\alpha_1)/$ $\gamma(1-\beta\cos\alpha_2)$	λ_1'(Liman α) / λ_2'(Balmer β)	λ_1 / λ_2 nm	n_{v1}'/ n_{v2}' $\times 10^{21}$ /m^3	I_1 / I_2 kW	I_1 / I_2 μJ/pulse
1.0	2.066 /0.87	3.860/ 3.854	121.5 / nm 503.4	469.0 / 1,940	1.63 / 7084	0.56 / 1.47	0.11 / 0.29
0.8	1.85 3/0.84	3.406/ 3.360	121.5/ 503.4	413.8 / 1,691	1.631 / 7.84	0.72 / 1.93	0.14 / 0.39

Table 2 The required laser powers and the wave-lengths for 1.0 GeV H^0 and 0.8GeV.