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A Foil-less Charge Exchange Injection (LUCE) for the Intense Proton Storage Ring

Yasuo SUZUKI
Center for Neutron Science
Japan Atomic Energy Research Institute
Tokai-mura, Naka-gun, Ibaraki-ken 319-11, Japan

ABSTRACT

A new scheme of the charge exchange injection is reported for the next-generation neutron sources of 5 MW-class. Periodical magnetic field (undulators) and photon beam (a powerful laser) can ionize hydrogen beams efficiently in stead of stripping foils.

1. Introduction

LUCE is an abbreviation of 'Laser and Undulator Charge Exchange'. This injection system is composed of a neutralizer and an ionizer, which are placed along a straight section of the ring. The neutralizer strips the electron of H^- beam into H^0 with the magnetic field of a tapered undulator. The H^0 beam is excited to H^{0*} (n=3p) in the ionizer with laser light and the H^{0*} is ionized to H^- with the moderate magnetic field of a long tapered undulator as shown in Fig. 1.

(The parameters in this paper are calculated for a JAERI-NSP2: 1.587 GeV H^- injection)

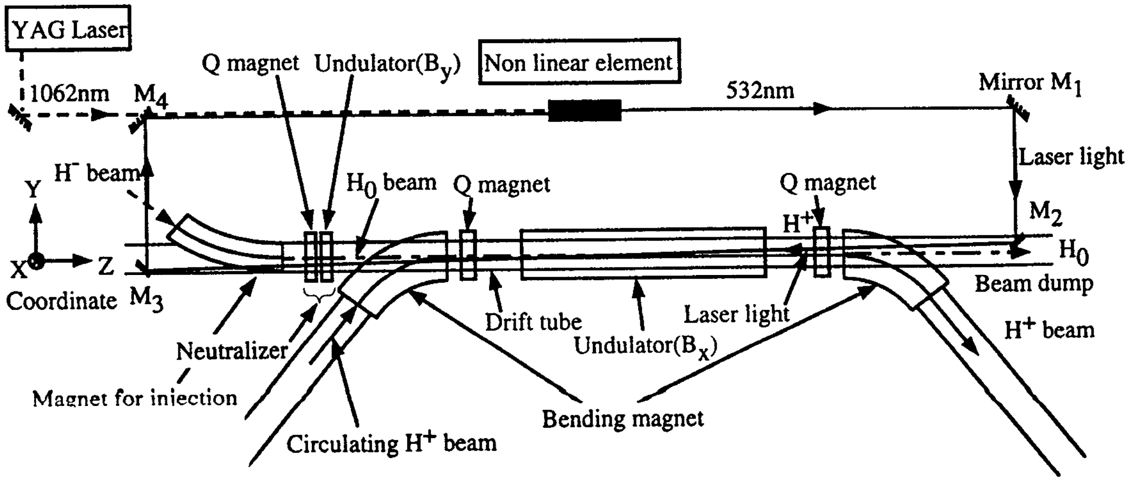
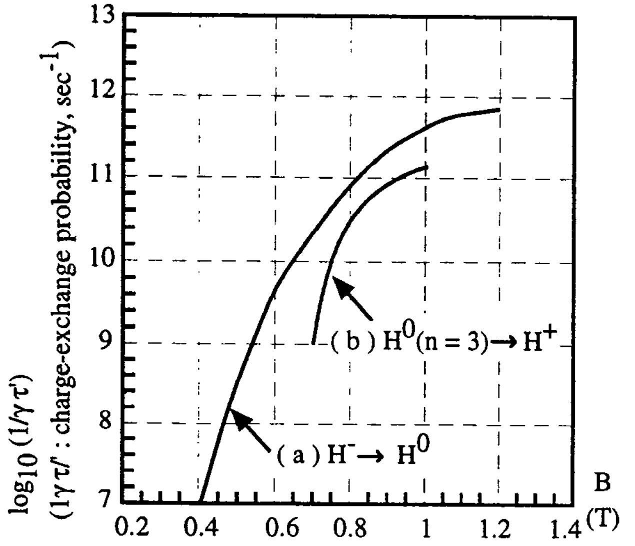


Fig. 1 A new scheme of injection

2. Magnetic field strength versus charge exchange probabilities

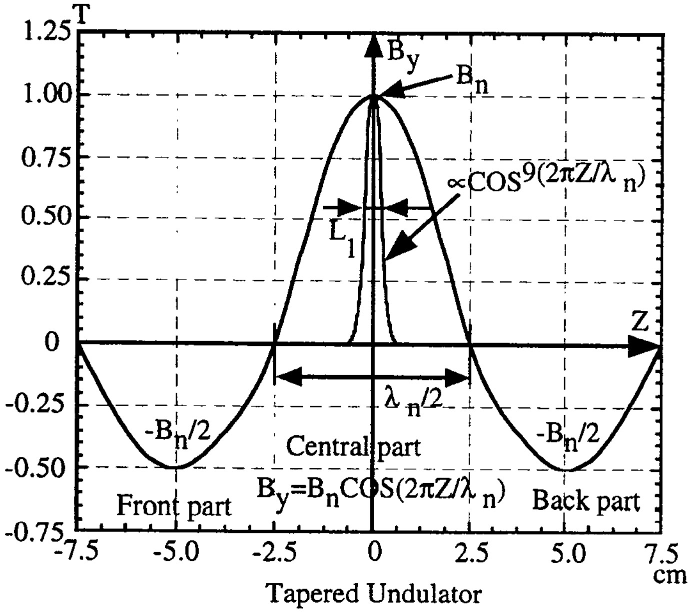
The Lorentz electric field generated by the interaction between the relativistic velocity of particle beam and the magnetic field, deforms the atomic potential and lets the electrons free from the atom (neutralization and ionization). The charge exchange probabilities versus the magnetic field for H^- and H^0 are obtained from the quantum theory[1,2] for 1.587 GeV beam as shown in Fig. 2.



(a) caluculated from the paper of A. J. Jason et al. [1)]
approximate eq. (~1T)
$1/\gamma\tau' = 2.8 \times 10^{11}\, B^9$

(b) caluculated from the paper of D. S. Bailey et al. [2)]
approximate eq. (~0.8T)
$1/\gamma\tau' = 3.1 \times 10^{11}\, B^{11}$

Fig. 2 Magnetic field strength vs. charge-exchange probabilities.



Tapered Undulator
(λ_n=10cm, B_n=1T, 1/2 wave length)

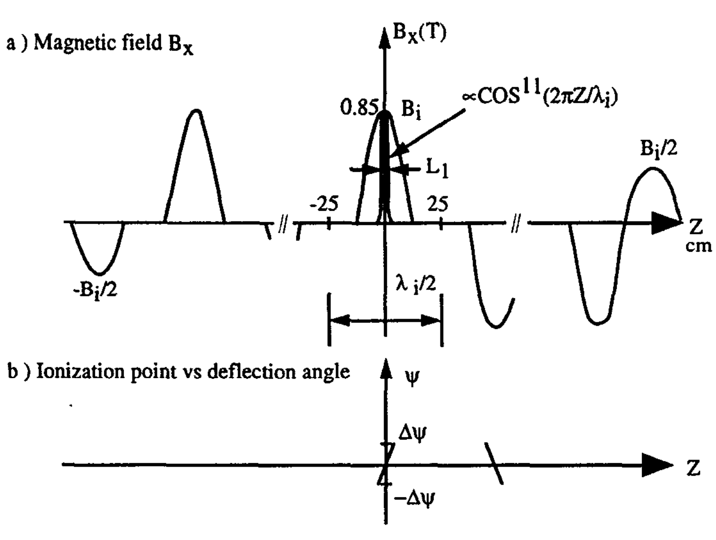
Fig. 3 Undulator magnetic field

3. The tapered undulator for the neutralize

A half period tapered undulator is applied for the neutralizer. The length of period is 10 cm and the maximum field strength is 1 T as shown in Fig. 3. Tapered magnets are facilitated to strip the electron of the H^- beam mainly around the peak position of the magnetic field strength and to let the H^0 beam go straightforwardly into the ring. The deflection angle of H^- beam can be analyzed from the equation of motion and the half width of the deflection angle $\Delta\Psi$ is expressed as:

$$\Delta\Psi = -\,(em_p\gamma\beta c)\, B_n L_l/2,$$

where L_l is the effective length of neutralization zone. The deflection angle become ~0 owing to adjustment of the tapered section of the undulator, and its width is minimized (.≤0.8 mrad)[3].



Undulator for ionizer

(λ_i=1m, B_i=0.85T, number of periods 7)

Fig. 4 Undulator magnetic field for the ionizer

4. The tapered undulator for the ionizer

A 7 periods tapered undulator is applied for the ionizer. The maximum strength of the magnetic field is 0.85 T. The length of period is 1 m but the free space of 25 cm is inserted between every half wave-form. The free spaces are used as the excitation region of H^0 beam by the laser light. Total length of the undulator is 7.75 m including the tapered magnets. The width of the deflection angle is estimated to 3 mrad after similar caluculations described in preceding section.

5. The optical system for the excitation of the H^0 beam

By relativistic Doppler shift, the 2nd harmonics wave (532 nm) of the Nd:YAg laser can be applied to excite H^0 beam resonantly as a Lyman series line L_β(102.5 nm).The optical resonator (a ring resonator in this case) is used to store the laser light and to interact multi-fold times with the H^0 beam. The ring resonator is estimated to amplify the photon density up to 100 times of the laser's. The wave-lengths of lasers to be applicable to the high power neutron sources are listed in Table 1, where the wave-length λ' in the frame of reference moving with H^0 beam, becomes shorter as $\lambda' = \lambda/\gamma(1+\beta)$ in the laboratory frame of reference by the relativistic

$$\frac{dN_1}{dt} = \gamma_1 N_3 + (N_3 - N_1)\Gamma,$$

$$\frac{dN_3}{dt} = -(\gamma_1 + \gamma_+)N_3 - (N_3 - N_1)\Gamma,$$

$$\frac{dN_+}{dt} = \gamma_+ N_3$$

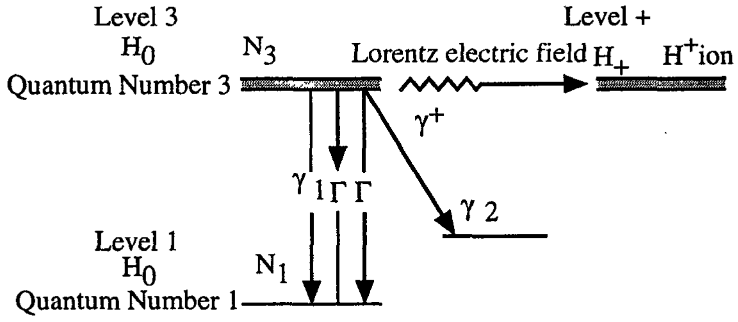


Fig. 5 Four level and the rate equations

Doppler shift.

From calculation of the rate equation of excitation (see, Fig. 5 and 6), the excitation ratio to the injected H^0 is obtained by N_1^2 / N_1^0 and the charge exchange ratio R after passing 14 halves periods of the undulator is expressed as follows:

$$R = 1 - \cosh^{14}(\Gamma T_1)\exp(-14\Gamma T_1),$$

Region I

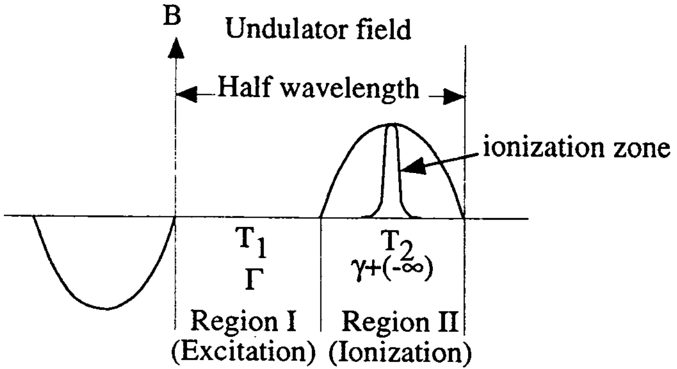
$$N_1^1 = N_1^0 (1+e^{-2\Gamma T1})/2,$$
$$N_3^1 = N_1^0 (1-e^{-2\Gamma T1})/2,$$
$$N_+^1 = 0,$$

Region II

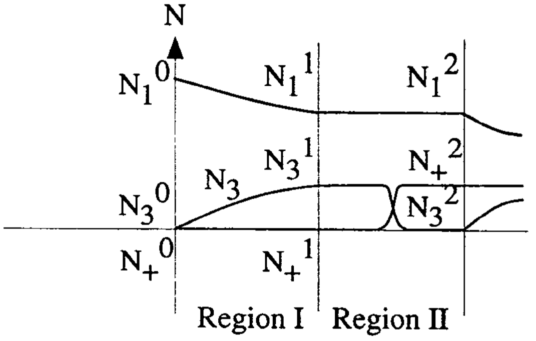
$$N_1^2 = N_1^1 \exp(-\lambda_2 T_2) = (N_1^0/2)(1+e^{-2\Gamma T1})$$
$$N_3^2 = 0,$$
$$N_+^2 = N_1^0 - N_1^1 \exp(-\lambda_2 T_2) = N_1^0 - (N_1^0/2)(1+e^{-2\Gamma T1})$$

Non-charge-exchange ratio during passing a half period of the undulator is as follows :

$$N_1^2/N_1^0 = (1+e^{-2\Gamma T_1})/2 = \cosh(\Gamma T_1)\exp(-\Gamma T_1)$$



a) a half period and the regions



b) Solution of rate equation

Fig. 6 Ionization process

where Γ is the induced transition probability and T_1 is the traveling time of particles in the free space (Lorentz shrinked) of the undulator. The required laser power is obtained 400W in average, 2.2 kW in peak. This power is within the practical level of development.

The momentum dispersion of H^0 beam is estimated to be 0.2 %. The resonant frequency of the beam absorption depends upon the momentum. The resonant condition, however, can be kept because the absorption frequency shifts by the Stark effect due to the Lorentz electric field which is generated by the interaction between the beam velocity and the weak magnetic field ($\leq$15 Gauss) in the free space of the undulator. The shifted frequency of absorption of particles coincides with the line of laser light at a certain point in the free space. So, the line profile of laser light may be narrow as it is.

Beam nergy(GeV)	γ	β	$\gamma(1+\beta)$	Wave-length λ_α corresponds to L_α(121.52nm)	Wave-length λ_β corresponds to L_β(102.2 nm)	Wave-length λ_γ corresponds to L_γ(97.215nm)
$\sigma / \Delta\upsilon'$ $cm^2 s^{-1}$				0.0105	0.00208	0.000771
1.587 JAERI-NSP2	2.691	0.9284	5.189	630.6	531.9 YAG-2nd	504.4
1,5 JAERI-NSP	2.599	0.9234	4.999	607.5	512.4 Cu-Vapour(511)	486.0
1.334 ESS	2.422	0.9108	4.628	562.4	474.4	450.0
1,00 SNS	2.066	0.875	3,874	470.8	397.1	376.6
0.816 LANSCE1	1.870	0.845	3.45	419.2	353.6 YAG-3rd	335.4
0.797 LANSCE2	1.849	0.841	3.404	413.7	348.9 YLF-3rd	330.9

Table 1 Beam Energy & Laser Wave-length

6. Conclusion

Even if unionized neutral hydrogen beams may remain through the ionizer, they go to the beam dump straightforwardly. No uncontrollable scattering will occur and, the production of radioactives around the ring will minimized. Moreover, this device has no effect on the trajectory of the circulating proton beam in the ring.

We can expect a high performance of the charge exchange efficiency, a beam spill-less , a lower beam loss (1/1000 loss to beam dump), and a smaller growth of beam emittance owing to the width of deflection angle in this method. This scheme will be one of the optimal charge exchange methods for the next-generation neutron source.

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