A New Scheme of Charge Exchange Injection for High Intensity Proton Storage Ring with High Injection Energy

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Abstract

A new charge-exchange injection scheme has been proposed which makes it possible to design a small beamloss proton storage ring. The charge-exchangers are composed of a magneto-neutralizer($H^- \rightarrow H^0$) which is a kind of the tapered half wave-length undulator, and an opto-magneto-ionizer($H^0 \rightarrow H^+$) which is composed of a ring laser used for resonant excitation of atoms and a tapered undulator used for ionization of the excited atoms.

These devices could effectively exchange the charges of the injected beam with the Lorentz electric field generated by the interaction between the relativistic beam and the magnet field. The relativistic Doppler-shift and Lorentz-contraction effects can lighten very much the burdens of power and wave-length required to the laser specification.

1. INTRODUCTION

The pursuits of countermeasures against the beam loss and the production of radioactivities are one of the most important problems in the design work of the intense proton ring of the next generation neutron source.

We propose a new concept of the charge -exchange injection, which is free from the beam spill, using the magnetic field and the available laser light, aiming at realizing a high performance of the charge-exchange efficiency, a lower beam spill, and a smaller growth of beam emittance[1 '4)].

2. NEW CONCEPT OF THE CHARGE-EXCHANGE METHOD

The concept is typically illustrated in Fig. 1, where the neutralizer is located at an extension of a straight section of the ring. The H^- beam is injected into the neutralizer that is, an undulator, the magnetic field of which can strip an electron from H^- ion due to the deformation of the atomic potential by the intense Lorentz electric field. The neutralized beam goes into the ring straightway and interacts coherently with the photon beam circulating in the optical resonator. The wave-length of the photon beam is selected to be able to excite the neutral beam resonantly, taking into account the relativistic beam velocity (Doppler shift). The up-to-date technology of the laser can be applicable to this purpose. The H* beam then experiences the periodical magnetic fields of the undulator and is efficiently ionized by the same process in the neutralizer.

The charge-exchange probabilities of 1.587 GeV H^- and H* beams as an example are shown in Fig. 2 which are obtained by calculations from papers written by A. J. Jason et al[5)] and D. S. Bailey et al[6)]. The maximum strength of the undulator magnetic fields is decided by taking into account these probabilities.

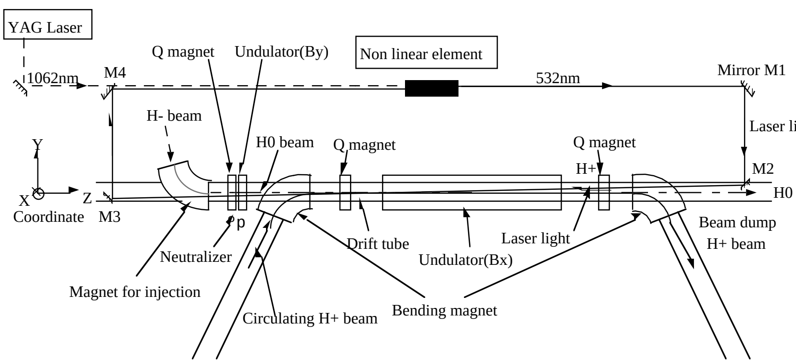


Fig. 1 @A new scheme of injection

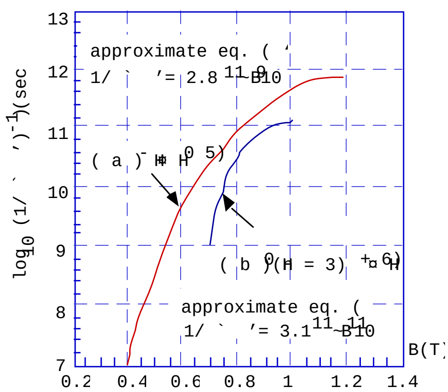


Fig. 2 @Magnetic field strength vs. charge-exchange probabilities

3. UNDULATOR FOR NEUTRALIZATION

A typical magnetic field of the undulator is shown in Fig. 3. This is a half period tapered undulator of the modest magnetic field.

The deflection angle of H^- beam can be calculated in the coordinates X, Y, Z shown in Fig. 1. From the equation of motion,

m_p `dv_x /dt = - e cB$_y$,

we get

= v_x / c = -(e /m_p ` c) $B_y$dz,

where c is the velocity of H^- beam, v_z and v_x is the x-component of the velocity deflected by the magnetic field. The integral region of above equation is from the entrance of the undulator to the neutralization point.

From the above equations, we can obtain the half width of the deflection angle:

¢ = -(e /m_p ` c)$B_n L_1$ / 2 ,

where B_n is the maximum magnetic field and L_1 is the effective length of neutralization region (typically 12.8 mm). Due to the sharp dependence of the charge-exchange probability on the magnetic field strength (almost proportional to B^9, see Fig. 2), the neutralization points are localized at the position of the peak magnetic field B_n , resulting in ¢ =0.8 mrad when B_n= 1 T and $_n$= 0.1 m where $_n$ is the period of the undulator.

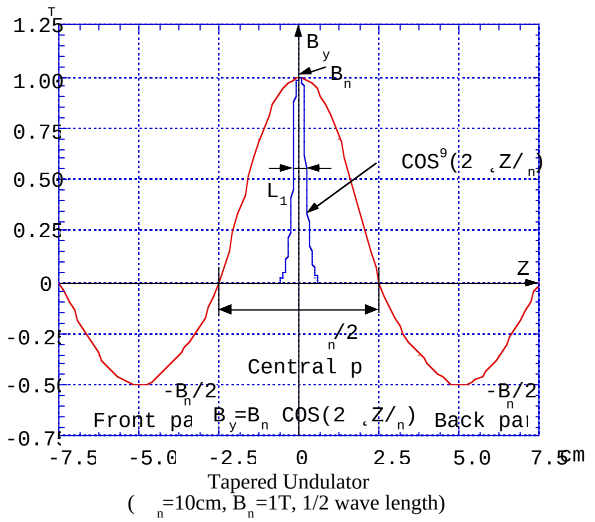


Fig. 3 @Undulator magnetic field

4. UNDULATOR FOR IONIZATION

The magnetic field of the undulator for ionization is shown in Fig. 4. This is also a tapered undulator but a long length (7 periods). The period is 1 meter including the free space of 50 cm and the wave-form is a half sinusoidal of 25 cm long. The free space is provided for avoiding the Stark broadening of atomic absorption spectrum by the intense Lorentz electric field. After the similar calculations described in the preceding section, we obtain ‘0 , ¢ ‘3 mrad and L_1 ‘5.6 cm.

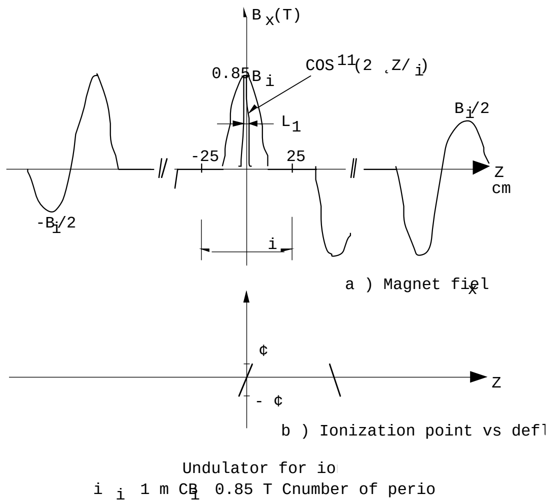


Fig. 4 @Magnetic field of the undulator

5. OPTICAL SYSTEM FOR EXCITATION

5.1 The Laser

The laser of this system should be powerful and tunable for the resonance excitation of H^0 beam. After intensive researches of the present technology of lasers, the wave-length of the 2nd harmonics(λ=532.1nm) of Nd:YAG laser has been chosen as a practical laser which has recently been developed up to the order of one kW in CW mode.

On the other hand, the necessary wave-length to excite H^0 from n =1 to n = 3p level is well-known the Lyman series L (λ’=102.5 nm). The relativistic Doppler shift of the wave-length solves this difference gap by

λ’ = λ / `(1+ $\beta$ cos $\theta$), where $\lambda$' is the wave-length in $H^-$ frame of reference moving with the speed of Hydrogen beam and $\theta$ is the crossing angle between $H^0$ beam and photon beam. Putting cos$\theta$= 1, we can get 1.587 GeV $H^0$ beam, that is, `= 2.691 and β = 0.928

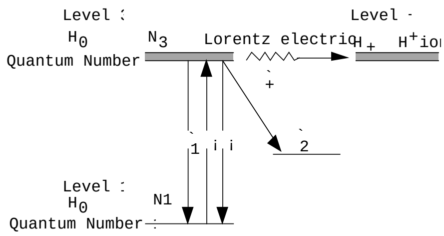
5.2 Rate equation for excitation

Let’s consider the four-level scheme of H^0 beam; ground-level, n =2, 3 levels and ionized state. The rate equations for this scheme are shown in Fig. 5, where `’s are the probabilities of spontaneous transition and ¡ is that of induced transition. The rate equations can be solved as shown in Ref.7.

Non-charge-exchange ratio after passing through the half period of the undulator is expressed as

N_1^2/ N_1^0 = cosh ¡T_1 exp (- ¡T_1),

where N_1^2 is the particle density of the ground level H^0 at the end of the half period, N_1^0 is its incident value and T_1 is the traveling time of the particles in the free space.



$\frac{dN_1}{dt}$ `1N3 + (3N- 1N) ¡ A

$\frac{dN_3}{dt}$ |(`1 + +)N3 |(3N - 1N) ¡ A

$\frac{dN_+}{dt}$ `+N3

Fig. 5 @Four level and the rate equations

5.3 Required transition probability of induced transition

Non-charge-exchange ratio, that is, non-ionization ratio after passing through the total undulator magnetic fields is expressed as

$$I / I_0 = \cosh^{2M} (¡ T_1) \exp (-2M ¡ T_1)$$

where M is periods of the undulator.
For satisfying the condition $I / I_0 = 10^{-5}$, we get a required transition probability

$$¡ = 1.73 \times 10^9 \ (sec^{-1}).$$

The transition probability ¡ is expressed by cn ¸' — which gives the required laser power, where n ¸' is the photon density of a laser in the H - frame and — is the induced transition cross-section of H^0.

For the hydrogen beam, — is given from the calculation of the quantum theory by — =h ¸'B / (c ¢ ¸') where ¸' is the frequency of laser light in the H - frame, h is the Plank constant, B is the Einstein constant of induced transition and ¢ ¸' is a absorption spectrum width of H^0 due to the momentum broadening ¢p / p of H^0 beam. When ¢p / p is assumed to be 1×10^{-3}, we get a large cross-section

$$— = 0.766 \times 10^{-15} \ (cm^{-2}).$$

5.4 Required laser power

Generally, the photon density n ¸0 of a laser power (I_0 W) is expressed by :

$$n_{¸0} = 1.68 \times 10^5 \ I_0 / S,$$

where is the wave-length of laser light in nm and S is the cross-section of laser light.

This photon density can be amplified with an optical ring resonator by $1 / (1 - R_1R_2R_3R_4)$ ‘100, where R_1, R_2, R_3 and R_4 are the reflectivity of mirrors, respectively. That is, the photon density in the resonator n ¸ is amplified by

$$n_{¸} = n_{¸0} / (1 - R_1R_2R_3R_4).$$

In the H - frame, the photon density n ¸' becomes large owing to, so - called, the Lorentz shrinkage by `(1+). So, we obtain a following formula, assuming the cross-section of the laser light $S = 1 \times 10^{-4}$ (m^2):

$$n_{¸'} = `(1+)n_{¸0} / (1 - R_1R_2R_3R_4)$$
$$= 8.7 \times 10^7 \ I_0 \ (cm\text{-}3).$$

From the relation n ¸' = ¡ / c —, We get

$$I_0 = 1.64 \text{ kW (peak)},$$

and

$$= 300W \text{ (average)},$$

taking into account that a required duty cycle of the laser operation is 0.18.

6. CONCLUSION

In the present concept of the charge-exchange injection method, undulators (magnetic fields) and a powerful laser (photons) are used and materials like stripping foils are not used. We can expect that no uncontrollable scattering will occur and the production of radioactivities will be minimized.

The relativistic velocity of accelerated particles is made full use of : Relativistic Doppler shift makes it possible to use the second harmonics wave of Nd:YAG laser to this injection method, Lorentz shrinkage can amplify the photon density of laser light and lighten 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 application of the resonant excitation to n = 3p level makes it possible to use a large cross - section of induced transition. The optical ring resonator can amplify the photon density and reduces the required laser power. The application of the tapered undulator makes it possible also to minimize the deflection angle and its half width of the H^0 beam.

The efficiency of charge- exchange is very high and the beam emittance growth is very low. Moreover, the magnetic field of the tapered undulator has no effect on the circulating proton beam. Accordingly, this method will be optimal for painting of the beam in the injector.

7.REFERENCES

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