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AN INTENSE POLARIZED BEAM BY A LASER IONIZATION INJECTION

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ABSTRACT

Accumulation of protons and polarized protons by photo-ionization injection are described. This method consists of (1)producing the neutral hydrogen beam by Lorentz stripping, (2)excitation of the neutral hydrogen beam with a laser, and (3)ionization of the hydrogen beam in the 2P excited state with another laser. When the laser for the excitation is circularly polarized, we can get a polarized proton beam. An ionization efficiency of 98% and a polarization of 80% can be expected by an intense laser beam from a FEL(Free Electron Laser).

INTRODUCTION

To accumulate an intense proton beam in a synchrotron, multi-turn injection using the charge exchange reaction is one of the most available methods, and is used at many accelerators. In this charge exchange injection, generally, beam loss and emittance growth from multiple scattering on a thin foil are severe problems for accumulating the very intense beam. For example, the beam loss becomes to be few μA for a beam current of a few hundred micro amperes even if the loss rate is less than 1%.

To store such an intense beam, a new accumulation method by photo-ionization injection has been proposed to eliminate the charge exchange foil[1]. The scheme is shown in Fig. 1. The first step of this ionization process is neutralization of the negative hydrogen beam with Lorentz stripping. The second step is excitation of neutral hydrogen with a intense laser flux. The final step is ionization of the 2P-excited hydrogen with another intense laser flux. The reason why we don't use the simple one-photon process is that the cross section of this two photon process is much larger than that of one photon($13.6 eV$) absorption.

At the same time, we can obtain an intense polarized proton beam if we use an intense and circularly polarized photon flux for the excitation(optical pumping)[2]. It is difficult to obtain such an intense and polarized photon flux with a commercially available laser. In a case of FEL with a helical wiggler, we can expect an intense circularly polarized photon flux. The laser amplification gain and obtainable flux density in the FEL are estimated with a one-dimension calculation.

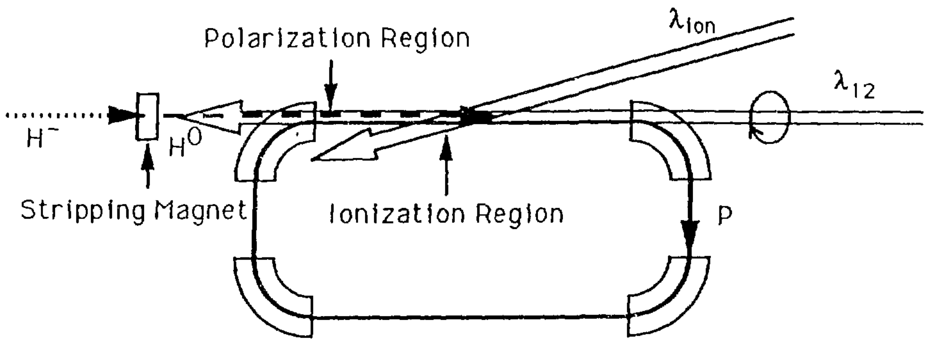

Fig. 1. The H^0 beam(dashed line) is excited and polarized by the laser with a wavelength of λ_{12} in the polarization region. Then, it is ionized with simultaneous irradiation by another laser (λ_{ion}) in the ionization region.

PRINCIPLE

The required wavelengths of the photons for the optical pumping to the 2P excited state and ionization in the H^0 rest frame, are $121.6nm$ and $365nm$, respectively. These required wavelengths in the laboratory frame are lengthened with Doppler shift for the head-on collision, as shown in Fig. 1[2]. For a 1GeV H^0 beam, the required wavelengths in the laboratory frame are $470nm$ and $1.4\mu m$ for the optical pumping and ionization, respectively. The wavelength in the laboratory frame($\lambda_{Lab.}$) is given by

$$\lambda_{Lab.} = \lambda_0 \gamma/(1 - \beta cos\theta), \tag{1}$$

where λ_0 is the wavelength in the H^0 rest frame and θ is the collision angle between the laser light and H^0 beam. The wavelengths in the laboratory frame are listed in Table 1.

Table 1. The wavelengths λ_{12} and λ_{ion} in the laboratory frame for the 1S-2P excitation and ionization of the 2P excited state hydrogen, respectively.

Kinetic Energy	(GeV)	0.44	0.8	1.0
λ_{12}	(nm)	309.5	414.9	471.7
$\lambda_{ion}(Max.)$	(nm)	922.6	1245	1413

The cross section of the 1S-2P transition is given as follows[2],

$$\sigma_{12} = \frac{\lambda^2}{(2\pi)^2}\frac{A_{12}}{\Delta\nu_D}\frac{g_2}{g_1} \sim 2.3\times 10^{-15} cm^2. \quad (2)$$

In this expression, $\lambda(= 121.6nm)$ is the wavelength for the 1S-2P transition in the H^0 rest frame, $A_{12}(= 1/1.6ns)$ is the probability of a spontaneous transition of $2P \rightarrow 1S$, $\Delta\nu_D$ is the Doppler broadening of an absorption line associated with the momentum spread of the beam, and g_2/g_1 is the ratio of statistical weight of the ground and excited levels. As the band width of the absorption, $1/A_{12} = 6.6\times 10^8 Hz$, is usually much smaller than the Doppler broadening width, the wavelength spread of a laser should be as large as the momentum spread. Such a wide line spread is difficult for a commercially available laser, but the FEL has a natural wide wavelength spread of about $10^{-3} - 10^{-2}$.

The 1S-2P transition probability w_{12} in the H^0 rest frame is given by,

$$w_{12} = \frac{\sigma_{12}}{h\nu}\frac{1+\beta}{1-\beta}q_{12}, \quad (3)$$

where $h\nu(= 10.2eV)$ is the photon energy and q_{12} is the power flux in the laboratory frame. At $1GeV$, for example, the required flux density of $470nm$ light for the optical pumping is $33kW/cm^2$ by assuming $w_{12} = 5A_{12}$, as listed in Table 2. Such an intense flux is necessary to obtain a polarized beam as described in the next section.

The excited hydrogen beam can be ionized with $\lambda \leq 364.8nm$ light. The ionization cross section from the 2P state is given as follows using the Born approximation,

$$\sigma_{ion} = \frac{\pi}{60}4\sqrt{2}\alpha^6 r_0^2 (\frac{mc^2}{h\nu_{ion}})^{\frac{9}{2}} \times \frac{5}{3} \leq 1.2\times 10^{-15} cm^2. \quad (4)$$

In this expression, $\alpha(= 1/137)$ is the fine structure constant and r_0 is the classical electron radius. The required photon flux for ionization, to obtain the probability of $w_{ion} = 2A_{12}$, is in Table 2. This probability means that 98% hydrogen can be ionized in the 2m ionization region. However, it should be noted that Eq.(4) gives a too large cross section by a factor of several times at the wavelength in the vicinity of the threshold. Therefore, the required flux must be larger than the listed value. In Table 2, the required power flux of the YAG laser($\lambda = 1.06\mu m$) is also listed, which will be available for ionization of the 800MeV and 1GeV H^0 beam.

Table 2. The required power flux. q_{12} means the required power flux in the laboratory frame assuming the 1S-2P excitation assuming the probability of $w_{12} = 5A_{12}$. q_{ion} and q_{ion}^{YAG} mean the power flux for the ionization assuming the probability of $w_{ion} = 2A_{12}$ at the threshold wavelength and at YAG laser's one, respectively.

Kinetic Energy	(GeV)	0.44	0.8	1.0
q_{12}	(kW/cm^2)	72	43	33
q_{ion}	(kW/cm^2)	84	50	39
q_{ion}^{YAG}	(kW/cm^2)		90	120

BEAM POLARIZATION

When the H^0 beam is irradiated in the long flight region with circularly polarized laser radiation for optical pumping, the hydrogen atom proton is polarized[2]. The polarization of protons depends on the power flux of irradiation photon and irradiation time as shown in Fig. 2. When the probability is A_{12}, the $10m$ polarization region is necessary to get the 80% polarized proton beam. When the transition probability is $5A_{12}$, it can be obtained in the $5m$ polarization region. However, a flux intensity several times larger than saturation($w \sim 5A_{12}$) flux is not so effective for the polarization since the polarization time is governed by the spontaneous transition.

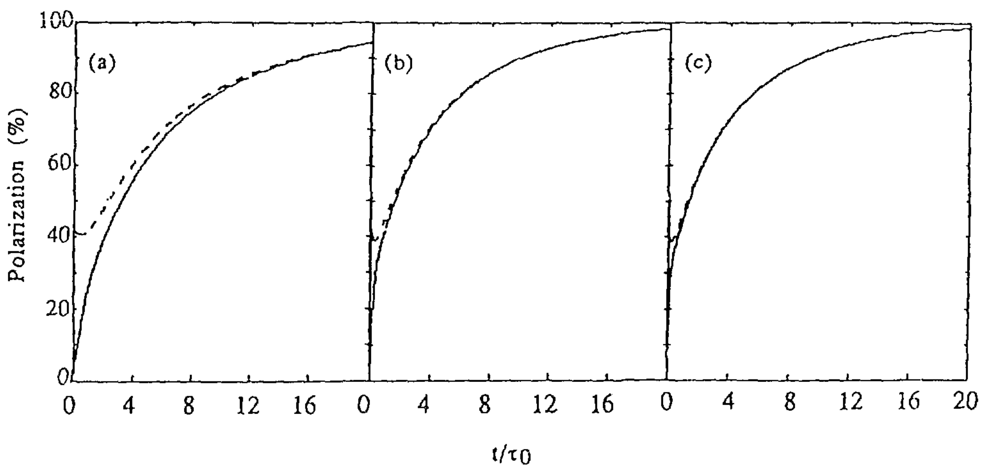

Fig. 2. Time dependence of the polarization of protons. $\tau_0(= A_{12})$ means the life time of the excited state. Figures (a),(b) and (c) are at the transition probabilities of A_{12}, $5A_{12}$ and $10A_{12}$, respectively. The solid lines refer to the ionization of beam atoms from both ground and excited states with a foil, the dashed lines from the excited state only with the laser ionization injection.

SCHEME

To obtain the high power laser flux, the interaction region is included in the optical cavity as shown in Fig. 3. In the optical cavity of the YAG laser with a $1kW$ output peak power, about $200kW/cm^2$ power flux will be expected even for beam size of $10mm^2$. This power flux is enough to ionize the hydrogen beam in the 2m interaction region.

We estimated the laser power of the FEL which is driven by a conventional linear accelerator and a helical wiggler as shown in Fig. 3 and Table 3, with one dimensional approximation model[3]. The maximum average flux in the cavity is expected to be $2.4MW/cm^2$, when the hydrogen beam size and the laser beam size are $10mm^2$. Even though, the estimated flux by the simplified one dimensional calculation may be too large by a factor of several times, it will be enough to get a high degree of polarization.

Table 3. FEL parameters

Drive linac	
Energy	$52.7MeV$
Current	$10A$ (Bunch peak)
Normalized emittance	$\leq 3\pi cm \cdot mrad$
Energy spread	$\leq 0.2\%$
Phase angle of beam bunch	$2.5deg.$
Wiggler	
Wiggler length	$1.5m$
Wavelength of wiggler	$1cm$
Magnetic field	$4.22kG$
Wiggler type	helical
Beam size in the wiggler	$1mm$
Output radiation	
Wavelength	$470nm$
FEL gain	4.4%
Intercavity power flux	$2.4MW/cm^2$
Beam size in the interaction region	$3.6mm$

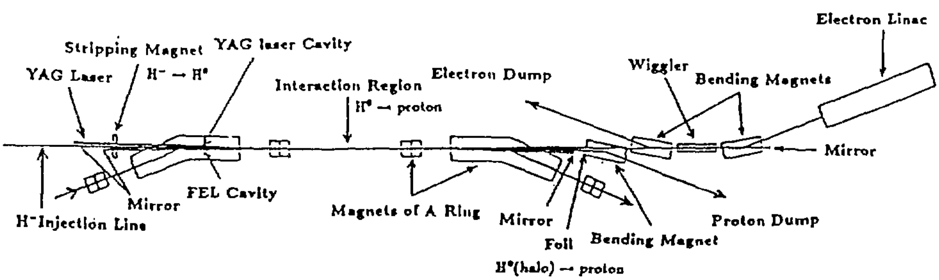

Fig. 3. Injection scheme by a FEL and YAG laser. The FEL system consists of an electron linac, two bending magnets, a wiggler and two mirrors. The electron beam, which is deflected by the magnet, passes through the wiggler which radiates photons. The photons are accumulated in the cavity between the two mirrors and excite the hydrogen atoms in the several meter interaction region. The excited hydrogen beam is ionized by the light in the YAG laser cavity.

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