ACCUMULATION IN A RING WITH LASER PHOTO-IONIZATION INJECTION

CHIHIRO OHMORI and SHIGENORI HIRAMATSU*

Institute for Nuclear Study, University of Tokyo, Tanashi-shi, Tokyo, 205, Japan
(*) National Laboratory for High Energy Physics, Tsukuba-shi, Ibaraki, 305, Japan

ABSTRACT

Beam Accumulation by photo-ionization injection in a ring is described. The ionization efficiencies are estimated for two cases; the case using a standard laser and the case using a FEL.

1. INTRODUCTION

Multi-Turn Injection using the charge exchange reaction is one of the most available methods, to accumurate a high intensity beam in a synchrotron, and is used at many accelerators. In the charge exchange injection, the beam loss and emittance growth by the carbon foil can not be neglected and several pulse bump magnets with high magnetic field are necessary to make the bump orbit.

One of the striping methods without foil is that by photo-ionization[1,2,3]. For this high energy H^- beam injection scheme, high intensity lasers are necessary. We describe the photo-ionization method in section 2. In sections 3 and 4, the schemes of the laser injection by a standard high power argon laser and a FEL(Free Electoron Laser), respectively.

2. PHOTO-IONIZATION OF HYDROGEN BEAM

A simple method of ionizing hydrogen by photon is irradiation with ultra-violet light at 13.6 eV. However the ionizing cross section of the hydrogen atom in the 1S state is very small ($\sim 10^{-17}cm^2$) and a high power laser with a short wave-length of $\lambda \sim 100nm$ is not available. Therfore, we propose a two-step ionization method, that is, an optical pumping from the 1S state to the the 2P state and an ionization of hydrogen from the 2P exicited state. The cross sections of the 1S-2P transition and the ionization of the 2P state are given as follows,

$$\sigma_{1S\rightarrow 2P} = \frac{\lambda_{12}^2}{(2\pi)^2}\frac{A_{12}}{\Delta\nu_D}\frac{g_2}{g_1} \sim 2.3\times 10^{-15}cm^2 \qquad (1)$$

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

In these expressions, $\lambda_{12} = 121.6nm$ is the photon wave-lengthfor optical pumping, $A_{12} = 1/1.6nsec$ is the probability of a spontaneous transition 2P → 1S, $\Delta\nu_D$ is the Doppler broadning of an absorption line associated with the momentum spread of the beam, g_2/g_1=2 is the ratio of statistical weights of the ground and excited levels, $h\nu_{ion} \geq 3.4eV$ is the energy of the ionization from the 2P state and r_0 is classical electron radius. The Doppler broadning is equal to $\nu_0\beta\Delta p/p \sim 2\times 10^{12}$Hz, where $\nu_0 = c/\lambda_0$ and the momentum spread of hydrogen is $\Delta p/p = 10^{-3}$.

The transition probability w in the particle rest frame is given by,

$$w = \frac{\sigma}{h\nu}Q_0. \qquad (3)$$

where, $h\nu$ is the photon energy; w is the transition probability in the particle rest frame. When w_{12} is $(0.8nsec)^{-1}$, $Q_{12} \sim 2\times 10^5 W/cm^2$[1]. In this calculation, we assume a 0.1% spread of the photon wave-length for optical pumping to cover the Doppler broadning due to the momentum spread. For a hydrogen beam with a velocity of $v = c\beta$ and a collision angle of θ, the wave-length in the laboratory frame (λ_{Lab}) is larger than the wave-length in the particle rest frame(λ_0) by the Doppler shift as follows,

$$\lambda_{Lab.} = \lambda_0\sqrt{(1+\beta)/(1-\beta cos\theta)}. \qquad (4)$$

For example, the transformed wave-length of optical pumping is 471.0nm at 1 GeV. The photon flux density in the particle frame is larger than in the laboratory frame, since the photon flux density is transformed as,

$$q = Q_0(1+\beta)/(1-\beta). \qquad (5)$$

In this expression, q and Q_0 are flux densities in the laboratory frame and in the particle rest frame, respectively.

The transformed optical pumping wave-lengths ($\lambda_0 = 121.6$ nm) and of ionization ($\lambda_0 = 364.8$ nm) are listed in Table 1, at some energies.

Table 1
The ransformed wave lengths and the flux densities to obtain the transition probability of $w = 0.8nsec$.

Kinetic Energy (GeV)	0.8	1.0	1.6
λ_{12} (nm)	414.9	471.7	633.8
λ_{ion} (nm)	1245	1413	1901
q_{12} (kW/cm^2)	17.2	13.3	7.4
q_{ion} (kW/cm^2)	49.6	38.5	21.3

3. LASER INJECTION SCHEME BY THE STANDARD LASER

In this scheme, a very intense photon flux density is necessary as listed in Table 1. Such an intense flux density can be obtained in the optical cavity of a laser as shown in Fig.1.

For a 1GeV hydrogen beam, a pulsed YAG laser(λ=1.06,1.32 μm) with an output power of more than 2kW is commercialy available for ionization from the 2P state. The transition probability (w_{ion}) is expected to be more than $(0.2nsec)^{-1}$ when the beam cross section is 0.1cm^2.

For the 1S-2P transition, a high power pulsed laser which has an output flux of more than $100W$ at the peak is necessary. In this case, the photon flux in the optical cavity of $\sim 2\times 10^3 W$, the total flux density of $q \sim 2\times 10^5 W/cm^2$ and a transition probabity $w_{12} \sim (0.8ns)^{-1}$ can be expected at 1GeV. Therefore, the ionization probability in the two-step ionization scheme is mainly determined by w_{12} and is 98 % in the 2m interaction regeon. The most available standard laser which has the maximum output at λ=480nm is an argon laser and the output is of the order of 10W. Therefore, ten laser systems are necessary for this scheme. In order to cover the frequency spread due to the momentum spread, these lasers must be set at different collision angles and a somewhat complicated optical system will be required as shown in Fig.1.

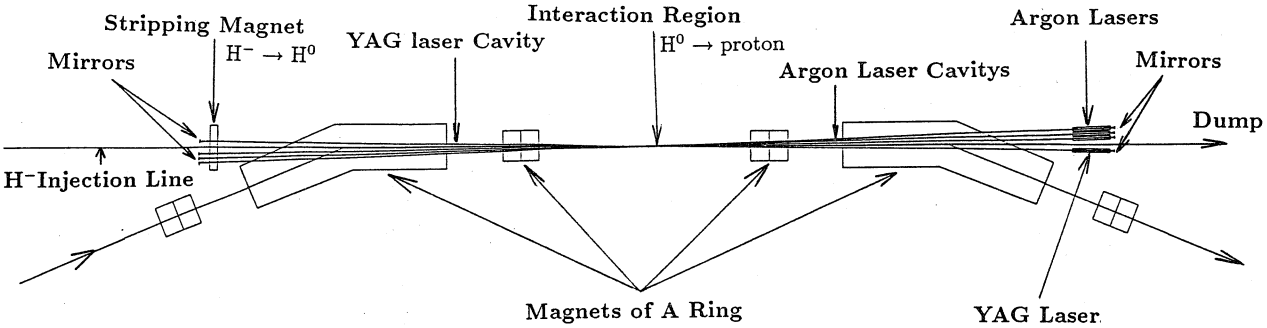

Fig.1. Injection scheme by standard lasers. The H^0 beam which was converted from H^- beam in a stripping magent interacts with the photons in the argon laser cavities and the H^0 is excited to the 2P state. After that, the exicited H^0 beam converted to a pronton beam by photons in the YAG laser cavity. The proton beam is accumulated in the ring without loss and the emittance grothe by a material. The halo H^0 beam which is not converted to proton beam goes to a beam dump. The argon lasers are set at different collision angles in order to cover the frequency spread of 0.1%.

3. INJECTION SCHEME BY FEL

The method with the standard laser needs a long interaction region and ten argon laser systems. There is another posibility of laser injection by the optical FEL(Fig.2). We estimated the laser power of the FEL which is given by a conventional linear accelerator and a helical wiggler as shown in Table 2 with the one dimmensional apporoximation model[4]. The FEL gain and power flux are calculated with the parameters listed in Table 2. The maximum average flux in the cavity is expected to be 460kW. If the beam size at the interaction region is 0.1cm^2, the flux density is 4.6MW/cm^2 and a transition probability(w_{12}') of $(0.02\text{nsec})^{-1}$ will be expected. In this case because of the large transition probability w_{12}, the two-step ionization effeiciency depends on the intensity of the laser for ionization of the 2P state hydrogen and is lager than $w_{ion} \sim (0.2nsec)^{-1}$ of the YAG laser.

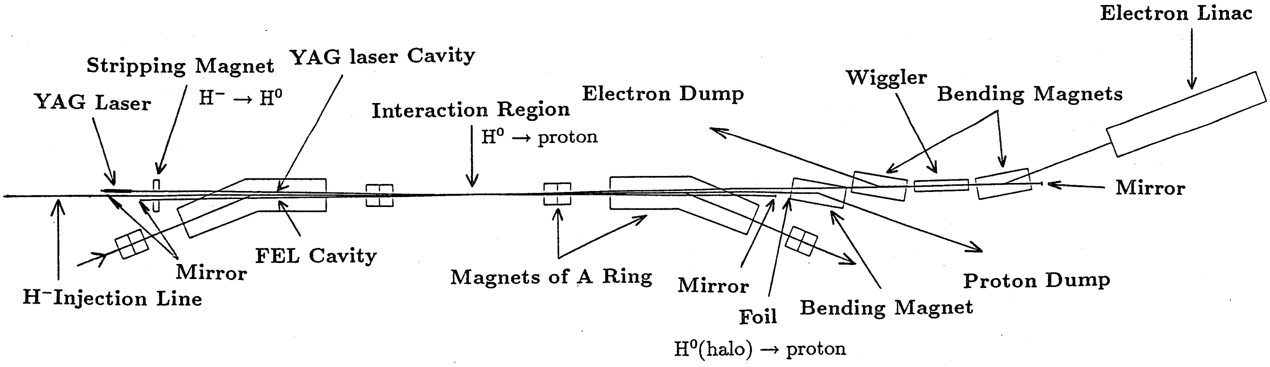

Fig.2. Injection scheme by FEL and YAG lasers. The argon laser cavities in Fig.1 are replaced with a FEL cavity. The FEL system consists of an electron linac, two bending magnet, a wiggler and two mirrors. The electron beam which is bent by the magnet passes through the wiggler with radiating the photons and is bent to the beam dump by another magnet. The photons are accumulated in the cavity between the two mirrors and excite the H^0 in the beam to the 2P state. The excited H^0 beam is ionized by the photons in the YAG laser cavity.

Table 2
Characteristics of the linac and the wiggler

Energy	52.7 MeV
Current	140mA
Normalized Emittance	5-10 cm mrad
Phase Angle of Beam Bunch	2.5 degree
Wave-Length of Wiggler	1cm
Magnetic Field	4.22kG
Wigler Type	Herical

If we use the helical wiggler, the intense polarized photon from the FEL polarizes proton of the hydrogen atom[1]. Therefore, we can get a very high intensity polarized proton beam in this scheme.

Furthermore, we can get much more laser power than a YAG laser by installing another wiggler for the ionization before the wiggler for the optical pumping.

CONCLUSION

A new charge exchage injection scheme employing a high power laser is proposed, where the laser light strips the electron of a H^0 beam. We estimated ionization efficiencies with a standard laser and with a FEL. For a standard laser, we need a complicated optical system to cover the frequency spread. On the contrary, the intrinsic spread of the FEL beam covers this frequency spread. In this scheme, an intense polarized proton beam will be obtained by polarized laser light.

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