EVALUATION OF LASER-ASSISTED CHARGE-EXCHANGE INJECTION INTO THE ESSNUSB+ PROTON ACCUMULATOR*

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Abstract

Laser-based H⁻ charge-exchange injection offers an attractive alternative to conventional carbon-foil stripping for injection into multi-megawatt proton rings. In foil-based systems, foil heating and degradation, radioactivation, and uncontrolled beam losses are factors limiting the achievable average beam power. In this work, we evaluate the feasibility of implementing laser-assisted H⁻ charge-exchange injection into the 5 MW ESSnuSB (European Spallation Source neutrino Super Beam) proton accumulator. The analysis is based on numerical and asymptotic solutions of the Schrödinger equation for a two-level model describing the interaction of a relativistic hydrogen atom with a Gaussian pulsed laser beam.

INTRODUCTION

Laser-based H⁻ charge-exchange injection offers an attractive alternative to conventional carbon-foil stripping for injection into multi-megawatt proton rings. In foil-based systems, foil heating and degradation, radioactivation, uncontrolled beam losses, and transverse emittance growth are factors limiting the achievable average beam power. It motivated to carry out deep investigations for developing the laser assisted methods [1,2]. In this work, we evaluate the feasibility of the tree-step laser-assisted H⁻ charge-exchange injection into the ESSnuSB (European Spallation Source neutrino Super Beam) proton accumulator [3].

A THREE-STEP SCHEME

We consider a three-step laser-assisted H⁻ charge exchange injection into a proton ring without stripping foils [1,2]. The scheme of the beam – laser interaction is shown in Fig.1. It consists of: i) a first magnet-neutralizer of the H⁻ beam using Lorentz stripping, ii) a colliding system of a high power laser and the H^0 beam to excite H^0 atoms to the 3p state using the Rabi oscillation, and iii) a second magnet to strip the $H^0(3p)$ to a proton beam by Lorentz stripping. In this paper, we focus on the second step - excitation of H^0 from the ground state $(1s)$ to the excited $(3p)$. The excitation energy is $\hbar\omega_0$ =12.10 eV in the rest frame of the atom.

Elliptic Gaussian Laser Beam

We consider a linearly polarized elliptical Gaussian laser beam that crosses the H^0 beam axis at an angle α as shown in Fig.1. The interaction point (IP) is located at a distance z_L from the laser waist. The vertical component of the electric field, E_y, in the rest frame K' of an individual atom in the beam is given by

$$E'_y(t') = \mathrm{Re}\left\{\sqrt{\frac{2P}{\pi\sigma_y\sigma_x c\epsilon_0}}\frac{\omega'}{\omega}e^{-\frac{(t')^2}{2\sigma_{t'}{}^2}+i\left(\omega' t'-\frac{\Gamma(t')^2}{2}+\varphi_0\right)}\right\}, \quad (1)$$

where $\sigma_{t'} = \frac{\sigma_x}{c\gamma\beta sin\alpha}$ is the rms interaction time of the atom with the laser; $\Gamma = \sqrt{\frac{1}{2}\left(\frac{\omega}{c}\theta_{0x}\sigma_x\right)^2 - 1}\Big/\sigma_{t'}^2$ is the frequency sweep rate; ω' is the Doppler shift of the laser frequency ω

$$\omega' = \omega\gamma(1 + \beta cos\alpha). \quad (2)$$

The following values correspond to the laboratory frame K: γ is the relativistic factor; β is the velocity ratio, α is the angle between the laser and the H^0 beam as shown in Fig.1; $\sigma_{x,y} = \frac{w_{0x,y}}{\sqrt{2}}\sqrt{1+\left(z/z_{0x,y}\right)^2}$ is the transverse size of the laser beam at the IP ($z = z_L$); P is the power of the laser micropulse, $w_{0x,y}$, $z_{0x,y}$, and $\theta_{0x,y}$ is the waist, Rayleigh range, and divergence of the laser beam, corresponding to the x and y directions.

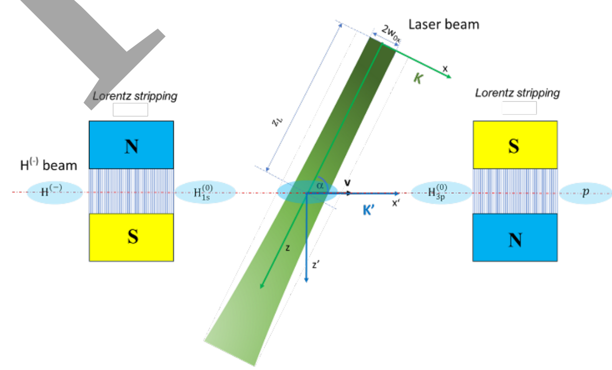

Figure 1: Three-step laser-assisted H⁻ charge exchange injection. K - laboratory frame, K' - rest frame

Doppler Broadening

The relativistic factor γ and angle α of an atom of the bunch with energy spread σ_γ and divergence σ_α in the transfer line between the linac and the IP with the values of dispersion function D_x and derivative D'_x, can be expressed in terms of the deviations $\Delta\gamma$ and $\Delta\alpha$ (correlated and uncorrelated) from γ_0 and α_0 of the reference particle

$$\gamma = \gamma_0 + \Delta\gamma,\ \ \alpha = \alpha_0 - D'_x\frac{\Delta\gamma}{\beta_0{}^2\gamma_0} + \Delta\alpha_{uncor}. \quad (3)$$

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This leads to the appearance of the Doppler broadening of the absorption linewidth $\Delta\omega'$, so that Eq. (2) can be given

$$\omega' = \omega_0 + \Delta\omega', \tag{4}$$

where $\omega_0 = \omega\gamma_0(1+\beta_0\cos\alpha_0)$ is the resonant frequency in the rest frame, $\Delta\omega'$ in the linear approximation is

$$\Delta\omega' \approx \omega[\beta_0 + cos\alpha_0 + D'_x sin\alpha_0]\frac{\Delta\gamma}{\beta_0} - \omega\gamma_0\beta_0 sin\alpha_0\Delta\alpha_{uncor}. \tag{5}$$

TWO-LEVEL MODEL OF H$^{(0)}$ ATOMS

The solution of the Schrödinger equation for two-level hydrogen atoms $\Psi(\vec{r}',t') = c_1(t')\psi_1(\vec{r}')e^{-i\frac{E_1}{\hbar}t'} + c_3(t')\psi_3(\vec{r}')e^{-i\frac{E_3}{\hbar}t'}$, is found from the simplified equations (for example, see [2])

$$\frac{dc_1}{dt'} = -\frac{\Omega_R}{2i}c_3 e^{-\frac{(t')^2}{2\sigma_{t'}{}^2}+i\left(\Delta\omega'-\frac{\Gamma}{2}t'\right)t'+i\varphi_0'}, \tag{6}$$

$$\frac{dc_3}{dt'} = -\frac{\Omega_R}{2i}c_1 e^{-\frac{(t')^2}{2\sigma_{t'}{}^2}-i\left(\Delta\omega'-\frac{\Gamma}{2}t'\right)t'-i\varphi_0'}, \tag{7}$$

with the initial conditions: $c_1(t=-\infty)=1$, $c_3(t=-\infty)=0$. Here $c_1(t')$ and $c_3(t')$ are the probability amplitudes of being in the 1s or 3p state, respectively; $\Omega_R = \frac{\mu_{1,3}}{\hbar}\sqrt{\frac{2P}{\pi\sigma_y\sigma_x c\epsilon_0}}\gamma_0(1+\beta_0 cos\alpha)$ is the Rabi frequency, $\mu_{1,3} = \left(\frac{3}{4}\right)^3\frac{ea_0}{\sqrt{2}}$ is the transition dipole moment of the hydrogen atom, a_0 is the Bohr radius.

The excitation efficiency of the ensemble of H^0 atoms can be found as the asymptotic solution of Eqs. (6, 7)

$$\eta_\infty = \frac{1}{\sqrt{2\pi}\sigma_{\omega'}}\int_{-\infty}^{\infty}|c_3|^2 e^{-\frac{1}{2}\left(\frac{\Delta\omega'}{\sigma_{\omega'}}\right)^2}d\Delta\omega' \approx 1 - e^{-\frac{\pi\Omega_R^2}{2\Gamma}}, \tag{8}$$

where the frequency sweep rate Γ satisfies the condition

$$\left(\frac{\sigma_{\omega'}}{\sigma_{t'}\Gamma}\right)^2 = \left(\frac{\eta_\infty}{\chi}\right)^2 \ll 1, \tag{9}$$

and the rms frequency spread, $\sigma_{\omega'}$, is obtained from Eq. (5)

$$\sigma_{\omega'} = \omega\sqrt{[\beta_0 + cos\alpha_0 + D'_x sin\alpha_0]^2\frac{\sigma_\gamma{}^2}{\beta_0{}^2} + \left(sin\alpha_0\frac{\epsilon_{n,x}}{\sigma_x}\right)^2}, \tag{10}$$

where $\epsilon_{n,x}$ is the horizontal normalized emittance, $\chi \approx 3.4$ is the empirical coefficient found from numerical calculation of Eqs. (6, 7).

From Eqs. (8, 9) and Rabi frequency definition, we can obtain the power of the laser micropulse in a more general form, compared to the similar one obtained in [2]

$$P = \epsilon_0\left(\frac{\hbar c}{\mu_{1,3}}\right)^2\frac{\chi}{\eta_\infty}ln\left(\frac{1}{1-\eta_\infty}\right)\sigma_y\sigma_{\omega'}\gamma_0\beta_0 sin\alpha_0\left(\frac{\omega}{\omega_0}\right)^2. \tag{11}$$

LASER POWER REDUCTION

As follows from (10) the dispersion-function at the IP with derivative $D'_x = -\frac{\beta_0+cos\alpha_0}{sin\alpha_0}$ eliminates the Doppler broadening due to the bunch energy spread [2]. In this case the Doppler broadening is caused by the uncorrelated beam divergence (see Eq. (10)). The laser power Eq. (11) becomes

$$P = \epsilon_0\left(\frac{\hbar c}{\mu_{1,3}}\right)^2\frac{\chi}{\eta_\infty}ln\left(\frac{1}{1-\eta_\infty}\right)\frac{\sigma_y}{\sigma_x}\epsilon_{n,x}\gamma_0\beta_0\omega^3\left(\frac{sin\alpha_0}{\omega_0}\right)^2. \tag{12}$$

Using the obtained analytical relation Eq. (12), for the selected beam sizes at the IP, $\sigma_x = 1\,mm$, $\sigma_y = 0.7\,mm$, we can obtain a family of curves of the efficiency as a function of the power at different values of the beam emittance (see the Fig.2). It can be seen that an excitation efficiency of $\eta_\infty = 0.95$ $(\pm0.1\%)$ can be achieved at a realistic laser power of $P = 1.3$ MW $(\pm 0.4\%)$ for the H^0 beam with horizontal emittance $\epsilon_{n,x} = 0.33$ μm·rad.

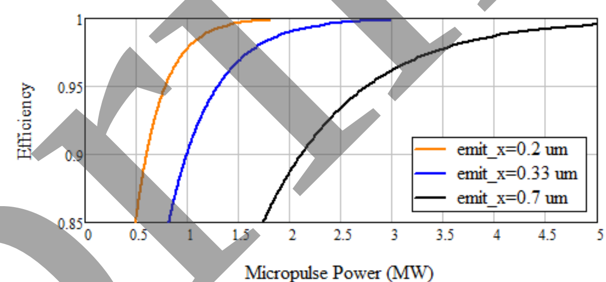

Figure 2: The excitation efficiency versus the micropulse power for the different values of the rms transverse (horizontal) normalized emittance.

LASER ENERGY REDUCTION

In the linac-to-ring transfer line [3], nearly 270 m long, H$^-$ bunches expand dramatically from 3.2 ps to 27.7 ps due to velocity debunching and space-charge forces. This requires very high laser energy and prohibitively high average laser power. To avoid this drawback of the long drift space, the "crab-crossing" scheme (CCS) was proposed in [4] (see Fig. 3).

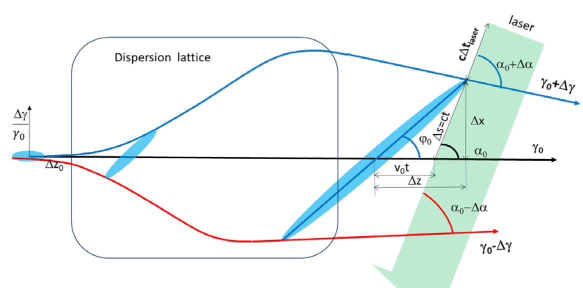

Figure 3: Geometry of the crab-crossing collision.

The angle φ_0 of the bunch rotation is chosen to ensure synchronous motion of the laser pulse and the bunch

$$tg\varphi_0 = \frac{\sin\alpha_0}{\beta_0+cos\alpha_0}. \tag{13}$$

The dispersion function at the interaction point (IP) can be expressed in terms of the longitudinal position Δz of a particle within the bunch and its relative momentum deviation δp_z as

$$D_x \delta p_z \approx \Delta z tg\varphi_0. \tag{14}$$

The CCS allows the laser micropulse duration (FWHM) to be reduced to twice the interaction time with an individual atom $2\sigma_t = \frac{2\sigma_x}{c\beta sin\alpha}$. In this case, taking into account Eq. (12), energy of the laser micropulse is given by

$$J_{mic} = c\epsilon_0 \left(\frac{\hbar}{\mu_{1,3}}\right)^2 \frac{2\chi}{\eta_\infty} ln\left(\frac{1}{1-\eta_\infty}\right) \sigma_y \epsilon_{n,x} \gamma_0 sin\alpha_0 \frac{\omega^3}{\omega_0^2}. \tag{15}$$

Dispersion Function for CCS

Taking into account the growth of the beam energy spread in the L2R line due to space-charge fields, as shown in Fig.4 [3], we can estimate the dispersion function as:

$$D_x(L) \approx \frac{L}{\gamma_0^2} \frac{\sigma_E(0)^2 + [\overline{g(L)}]^2}{\sigma_E(0)^2 + \overline{g(L)} g(L)} tg\varphi_0, \tag{16}$$

where $g(L) = \sqrt{\sigma_E^2(L) - \sigma_E^2(0)}$, $\overline{g(L)} = \frac{1}{L}\int_0^L g(s')ds'$, σ_E is the rms energy spread of the bunch.

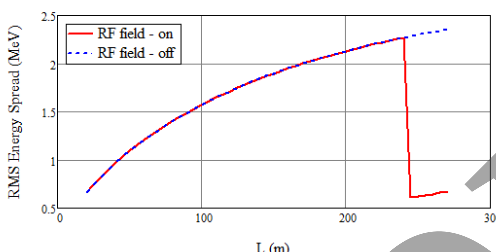

Figure 4: Energy spread along the L2R line with four cavities operated at the zero-crossing (the red line) [3].

Figure 5 shows the dependence of the required dispersion function on the L2R line length. It can be seen that, in order to significantly reduce $D_x(L)$ at the end of the L2R line, the RF field in the four cavities must be turned off.

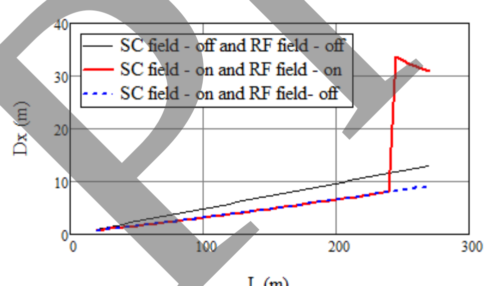

Figure 5: The required dispersion function at the IP versus the length of the L2R line.

Evaluation of Laser-Assisted Injection

By implementing CCS through the creation of the required dispersion function of $D_x(L) = 9.2\ m$ at the IP Eqs. (13, 14) and achieving $D_x' = -ctg\varphi_0$ to eliminate the Doppler broadening due to the energy spread, we have evaluated parameters required for the laser-assisted injection into the ESSnuSB+ accumulator which are summarised in Table 1. It should be noted, the parameters shown in green indicate acceptable values, whereas those shown in red should be significantly reduced; values marked with * are estimates. The last column shows the best results, but they require a halving of the horizontal emittance compared to the current one (from 0.7 to 0.33 μm·rad).

Table 1: Parameters for Laser-Assisted Injection

$H^{(0)}$ bunch parameters	Eliminated σ_E	Eliminated σ_E, & CCS	Eliminated σ_E, & CCS
Average power, (MW)	5	5	5
E (GeV)	2.5	2.5	2.5
σ_E (MeV)	0.6	2.7	2.7
rms duration, $\sigma_{b,t}$ (ps)	27.7	44*	44*
rms size, σ_x/ σ_y (mm)	1.0/0.7	1.0/0.7	1.0/0.7
$\varepsilon_{nx}/\varepsilon_{ny}$ (μm·rad)	0.7/0.33	0.7/0.33	0.33/0.33
D_x/D_x' (m /)	0 / -1.546	9.2/-1.546	9.2 / -1.546
rotation angle φ_0 (deg)	0	32.9	32.9
Laser parameters			
wavelength, (nm)	532	532	532
Angle, α (deg)	64.4	64.4	64.4
Efficiency, η (%)	95	95	95
Power, P (MW)	2.75	2.75	1.3
FWHM of pulse, (ps)	121.7	10.9	10.9
Pulse energy J_{mic} (μJ)	334.2	30.0	14.1
Average f, (MHz)	15.7	15.7	15.7
Average power, (W)	5232	467	220
θ_{0x} (mrad)	1.0	1.0	0.49

CONCLUSION

An asymptotic solution of the Schrödinger equation for an ensemble of relativistic hydrogen atoms interacting with a Gaussian pulsed laser beam has been obtained. This solution provides general analytical relations for the laser power and pulse energy required to estimate the H^0 beam and laser parameters suitable for laser-assisted charge-exchange injection.

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