

LASER STRIPPING FOR THE PS2 CHARGE-EXCHANGE INJECTION SYSTEM

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Abstract

Laser stripping for an H^- injection system into the proposed PS2 accelerator could provide an attractive alternative to the use of a conventional stripping foil. In this paper possible concepts for a 4 GeV laser stripping system are outlined and compared, using either laser or magnetic initial stripping steps and a resonant excitation of the intermediate H^0 atom, followed by a final magnetic stripping. Issues of laser power, overall efficiency and emittance growth are discussed.

INTRODUCTION

The proposed PS2 [1] will accelerate protons from 4 to 50 GeV. The required beam intensity and brightness requires a multi-turn H^- charge exchange injection. The optics of the long straight section has been designed to accommodate a foil-based stripping section [2], together with the other injection and extraction elements.

A conceptually attractive alternative [3] to foil stripping uses laser photons to excite H^0 into a quantum state H^{0*} which can be stripped by a strong magnetic field. The initial stripping of H^- to H^0 can be accomplished with a strong magnetic field, or possibly also by laser photons. The technical challenges are considerable, with very high laser power required to achieve the required efficiency.

The frequency f_0 of a photon in the laboratory frame is Doppler shifted to a frequency f_i in the atomic frame according to the relativistic β and γ parameters, and the intersection angle θ , as $f_i = f_0 \gamma (1 + \beta \cos \theta)$. For 4 GeV H^- ions with $\beta\gamma = 5.17$, the enhancement factor is ~ 10 for intersection angles below about 45° , Fig. 1. Interestingly, for 4.5 GeV, all quantum states are energetically possible.

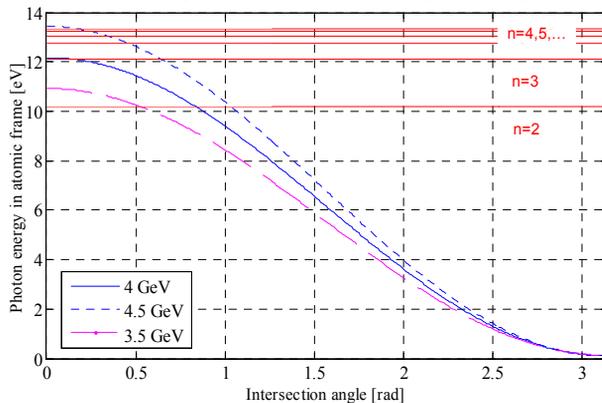
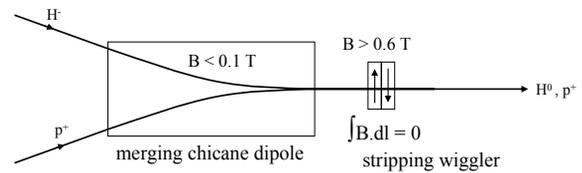


Figure 1: Photon energies in atomic frame for $\lambda=1064$ nm laser as a function of intersection angle and beam energy.

STRIPPING OF H^- TO H^0

H^- Neutralisation with Wiggler Magnet



The lifetime of the weakly bound electron in the H^- ion is a strong function of the external magnetic field and the ion energy. At 4 GeV, magnetic fields above about 0.15 T are sufficient to strip the outer electron. One concept uses a stripping wiggler magnet, with zero $\int B \cdot dl$, arranged in the vertical plane. This strips the full beam without generating extra horizontal angular spread from stripping in the fringe field which would increase the laser power required. However, there is an emittance growth in the vertical plane. For the PS2, unlike other machines considering laser stripping [4], the emittance is small ($2.5 \pi \cdot \text{mm} \cdot 1 \sigma$ normalised). The RMS angle error was calculated for an H^- beam stripped in a magnet fringe field and converted to emittance growth assuming $\beta = 20$ m, Fig. 2. A peak wiggler field of at least 0.6 T is required to keep the error below an acceptable $\sim 1-2 \pi \cdot \text{mm} \cdot \text{mrad}$.

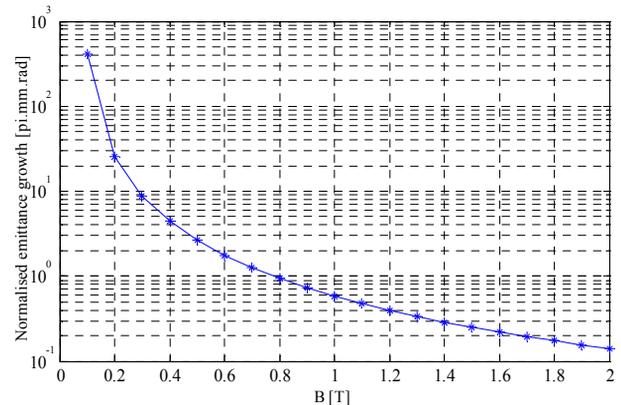
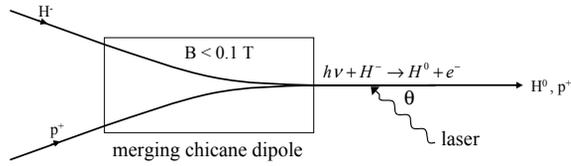


Figure 2: Normalised emittance growth as a function of wiggler peak field, for 4 GeV H^- stripping to H^0 .

H^- Neutralisation with High-Power Laser

Neutralisation of the H^- beam with a laser is potentially attractive since there are no issues of emittance growth or wiggler integration. The cross-section Σ_0 for photo-dissociation of the H^- ion [5] has a broad peak at about 840 nm or 1.5 eV, with a maximum of $4 \times 10^{-17} \text{ cm}^2$ (the cross-section for double-electron ejection (direct photo-ionisation) peaks at $1.1 \times 10^{-19} \text{ cm}^2$ at 60 nm or 20 eV).



The fraction of ions neutralised by an intersecting laser beam as a function of intersection angle θ depends both on the geometrical and temporal overlap of the two beams (the ‘luminosity’) and frequency (i.e. angle) dependent cross-section. For an individual laser micro-pulse length σ_{ls} longer than the ion micro pulse, the neutralisation degree can be expressed [6] as

$$\eta_0 \approx \frac{E_l \lambda}{2\pi \cdot h \cdot c} \frac{(1 + \beta \cos \theta)}{\beta \sin \theta} \frac{\Sigma_0}{\sigma_{ls} \sigma_{bz}}$$

where E_l and λ are laser pulse energy and wavelength and σ_{bz} the vertical interaction region size. Using cross-sections from [5], the fraction of remaining H^- was calculated taking account of saturation, for different laser pulse energies and intersections angles, Fig. 3. Even with laser photon recycling which might reduce the laser power by a factor of 100 or above, the laser macro-pulse energies $E_m = f_{rf} \cdot \tau_{inj} \cdot E_\mu$ required to reach 99% efficiency for such a scheme are very large – for example at a 140° intersection angle the laser would need to provide 60 mJ per micro pulse, or 60 μ J with a factor 1000 from photon recycling, corresponding to 21 J in the laser macro pulse with $f_{rf} = 352$ MHz and $\tau_{inj} = 1$ ms.

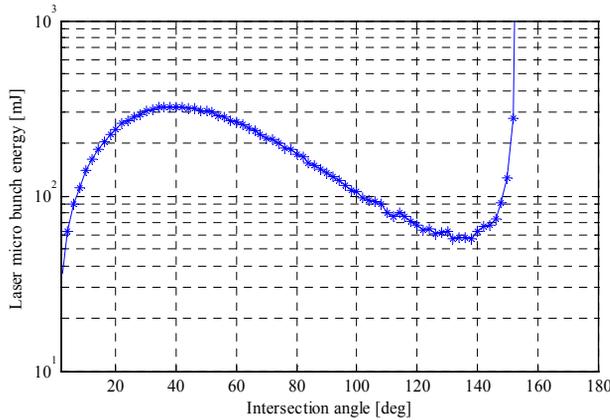


Figure 3: Laser micro bunch energy required for 99% neutralisation as a function of intersection angle.

A possible alternative could be to make use of the resonances which appear in the H^- photodissociation spectrum [4]. The Feshbach resonance at 113.49 nm, 10.93 eV, is accessible by a 1064 nm laser with an intersection angle of 37° . For this resonance the cross-section is given as $\sim 1.39 \times 10^{-15}$ cm², and the laser micro pulse energy required to reach 99% neutralisation is reduced to 190 μ J. However, this resonance has a linewidth $\Delta\lambda/\lambda$ of about 5.2×10^{-6} , much smaller than the beam Doppler spread of about 2×10^{-3} , which increases the laser power required to neutralise the full beam by a factor of 5×10^2 , making the total 73 mJ per micropulse.

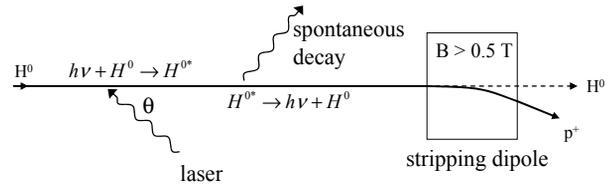
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The $n=2$ shape resonance at 112.95 nm, above the $n=2$ threshold, for the reaction $h\nu + H^- \rightarrow H_{(n=2)} + e^-$, has a cross-section of $\sim 9.8 \times 10^{-17}$ cm². This requires a laser micropulse energy of 2.8 mJ to reach 99% stripping. The linewidth for this resonance is much larger, at 1.8×10^{-4} , closer to the Doppler spread, for a total micropulse energy of 31 mJ. This also results in the production of an already excited neutral hydrogen atom, which could then be resonantly excited from the $n=2$ state to a higher lying level, with the dual advantages of a relatively long lifetime for spontaneous decay and a short lifetime for stripping to p^+ in a magnetic field.

STRIPPING OF H^0 TO P^+

Resonant Excitation in Field-free Region Followed by Field Stripping in a Magnet



The schemes outlined in [3,4] and tested experimentally at SNS use a resonant excitation of the ground-state H^0 atom in a field-free region, followed by a stripping of the excited electron in a magnetic field. There is a large spread of effective resonant frequencies due to the Doppler broadening from the beam momentum spread. Achieving a population inversion in the excited state is achieved by Adiabatic Rapid Passage, where the laser frequency is swept across the resonance by varying the angle of incidence using a divergent beam. High laser power is required to saturate the resonance, since the power is spread across a large bandwidth to cover the Doppler spread. The laser energy required [3] is:

$$E_l = \frac{\ln(1/\delta) \hbar^2 \epsilon_0 c^2 \kappa \omega \tau_l \hbar \sin \theta}{2\mu_{1n}^2 \gamma (1 + \beta \cos \theta)}$$

where $\delta \ll 1$ is the ratio of unexcited to excited atoms, $2h$ the vertical beam size, ω the laser frequency in the laboratory frame, $k \approx 6\Delta\lambda/\lambda$ the full relative frequency change, $\tau_l \approx 50$ ps the laser micropulse duration and μ_{1n} is the dipole transition coefficient. For excitation from the ground state to the $n=2$ or $n=3$ state the laser micro pulse energy is 360 and 92 μ J respectively.

The use of an efficient optical cavity to recycle the laser photons is possible with $\sim 1 \mu$ m laser wavelength. A Q value of 100 or higher should be possible.

An elegant method to cancel the Doppler broadening by arranging a compensating dispersion derivative at the interaction point has been proposed [4], to provide a correlated interaction angle with momentum. For the PS2, however, this requires a dispersion derivative of about 2.0 rad. The dispersion in the injection region is \sim zero, and the emittance growth from such a mismatch would be huge. The tolerable Dp_x mismatch for PS2 is ~ 0.02 rad.

Spontaneous decay of H^{0*} will reduce the efficiency; 1.7 % of $n=3$ decay in 25 cm drift from the laser interaction region to the stripping point, for $\beta\gamma=5.17$.

The stripping of the final excited state from H^{0*} to p^+ in a fringe field will also lead to emittance growth. The lifetime of the H^{0*} atom in a magnetic field depends on the quantum state, applied field and ion momentum [7]. The lifetimes were calculated as a function of magnetic field for 4 GeV H^{0*} and a simulated fringe field from a simple 50 mm gap dipole without field clamp, and a numerical integration carried out to obtain the RMS angle error and hence emittance growth as a function of peak stripping magnet field \hat{B} , Fig. 4. The $n=3$ state gives $\Delta\epsilon$ of between 2 and 4 μm for $\hat{B}\approx 1$ T, depending on magnetic sublevel. This is rather large; careful fringe field design with pole tip chamfers and clamping will be necessary.

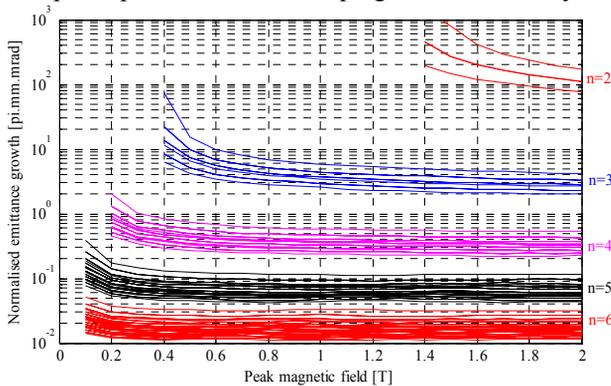


Figure 4: Normalised emittance growth for different H^{0*} quantum states as a function of peak magnetic field.

Excitation and Stripping in High Field Region

A suggestion [8] to overcome the Doppler broadening is to place the interaction region in a magnetic field so that the Stark broadening of the transition is large. A single frequency can then excite the resonance for all atoms. The application of an electric field F causes a linewidth Γ broadening, measured experimentally using 800 MeV H^- [9]. Theoretical expressions exist for estimating the linewidth in the high field regime, e.g. [7]:

$$\Gamma_F = \frac{(4R)^{2n_2+m+1} e^{-2R/3}}{n^3 n_2! (n_2 + m)!} \times \left(1 - \frac{n^3 F}{4} \left(34n_2^2 + 34n_2 m + 46n_2 + 7m^2 + 23m + \frac{53}{3} \right) \right)$$

where n , m , n_1 and n_2 are parabolic quantum numbers and $R = (-2E_0)^{3/2}/F$. Calculated linewidths are shown in Fig 5. To reach the Doppler width of $\Delta\lambda/\lambda \approx 2 \times 10^{-3}$ would require a field of 0.3 T for the transition to $n=3$, where the lifetime of the resulting H^{0*} atom is only 10^{-10} seconds. The required laser micropulse energy is slightly higher than that for the previous method [10]. Another disadvantage of this otherwise promising scheme is that the $H^0 \rightarrow H^{0*}$ takes place over about 0.5 m in a high field region which introduces a large angle between injected and circulating protons which make it difficult to integrate into a real injection geometry.

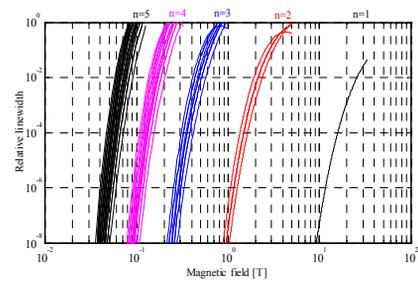


Figure 5: Stark-broadening of quantum levels as a function of applied magnetic field for 4 GeV H^0 atoms.

CONCLUSIONS

Some of the possibilities and issues concerning a laser stripping system for PS2 (or other machine with 4 GeV H^- injection) have been outlined. The scheme with a stripping wiggler after the merging dipole, a resonant excitation to the $n=3$ level and final stripping in the 3rd chicane dipole seems feasible, although excitation to the $n=3$ level is required to avoid large emittance growth, which implies an intersection angle of 8.4° and precludes operation below 4 GeV. The fringe field of the H^{0*} stripping dipole also needs careful design. The main issue remains the laser power required to saturate the resonant step. The other options described have interesting features and should still be studied in more detail, in particular the possible use of the $n=2$ shape resonance for laser stripping of H^- and resonant excitation from this level.

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