LASER STRIPPING INJECTION FOR THE ESS ACCUMULATOR RING

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Abstract

The injection of an intense H^- beam into a circular machine is limited by the number of foil traversals and the temperature limitations imposed by the foil. This leads to lifetime and reliability problems. An alternative scheme for injection where a laser beam and high field magnets replace the foil is discussed in terms of the expected beam dynamics. It is concluded that "Laser Stripping injection" is a viable alternative to conventional foil injection.

1 INTRODUCTION

The injection of a high intensity H^- beam into any circular machine is difficult when the circulating beam makes many passes through the injection stripping foil. The original design of the ESS ring and foil-injection scheme would have resulted in an excessive foil temperature[1]: foil reliability and lifetime are limiting issues, and are in general the motivation to find an alternative injection scheme.

Stripping of the H^- to form a neutral beam has been demonstrated[2] but cannot be easily used to strip to the proton because of the high binding energy of the H°. The suggestion to use laser resonant excitation of the H° prior to stripping in an intense magnetic field has been made[3,4] and investigated[3-6], under a number of different schemes. The functional elements of the scheme are shown schematically in Figure 1.

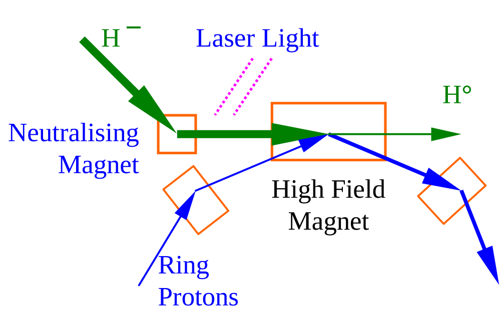

Figure 1: Schematic of the Resonant Laser Excitation and Stripping Process.

The H^- beam from the linac is neutralised in a high field magnet. The neutral beam coasts and joins protons from the accumulator prior to interacting with laser light which resonantly excites a weakly bound state (3P) and a second high field magnet where it can be ionised.

Essentially, there are two problems to be overcome in the stripping/injection process; first that there is sufficient laser power[3-5] (or that the laser power can be sufficiently amplified); and secondly that the emittance of the beam is not increased beyond the acceptance of the accumulator ring into which the beam is being injected[5]. In this paper, we will briefly describe two injection schemes and examine the beam dynamics of these systems.

2 THE NEUTRALISATION PROCESS

In these schemes, the H^- beam is first neutralised by stripping in a magnetic field. This technique has been demonstrated by Jason[1]. The outer electron is weakly bound (<1 eV) and has a short lifetime in the field of a strong magnet. This process introduces a spread in the horizontal emittance of the beam since the magnet is also required to bend the beam and particles are stripped over a finite path length. This effect is shown in Figure 2 where a beam of mono-energetic particles are tracked through a strong magnetic field gradient. Magnet design, e.g. stripping on the rising edge of the magnet field or at the peak field can affect this emittance growth.

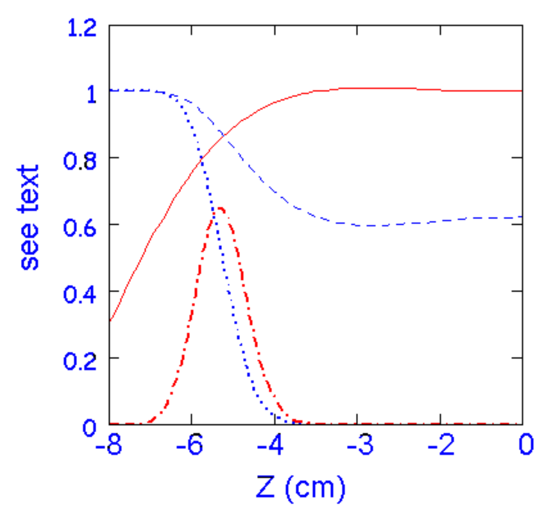

Figure 2: The Neutralisation Process. The magnetic field profile (solid line, in Tesla), the relative beam intensity (dotted line), the relative rate of beam loss (dashed line) and the relative angular distribution (dot-dash) are shown as a function of position in the magnet (centre z=0).

3. THE EXCITATION AND STRIPPING PROCESS

Resonant excitation of neutral atoms by laser light is a well understood process, however there are two treatments of the problem which lead to different equilibrium solutions. The process of excitation by an electric field [Eo · Sin(ω·t)] of an ensemble of particles in which there are two quantum states available (Φo - the ground state, and Φx - the excited state with energies Eo and Ex (Eo<Ex) and Ex - Eo = ω) results in the well known Rabi oscillation of the population between the two states with a well defined frequency. In this case it is possible to have a complete population inversion after one half cycle. However, this requires that the atoms all see the electric field in exactly the same phase. A bunch of particles of length τ=360 ns travelling close to the speed of light (β=0.91, for the ESS linac) will see many different phases (τ × β c = 98 m). In this case, it can be argued that a treatment in terms of individual atoms, where the absorption of a photon is treated as a fixed rate of transition probability is more appropriate and exponential solutions are then obtained for the population of the two states. In the case considered here, these states are the 1S (ground-) and 3P (excited-) states. The equilibrium population at most allows 50% of the atoms to be in the 3P state since the laser induces both absorption and emission and the equilibrium is dynamic.

In addition to the absorption and stimulated emission, spontaneous decays to the ground and excited 2S states can occur. The level scheme is shown in Figure 3. Spontaneous decays from the 3P- to the 2S-state lead to losses since the latter is not able to decay quickly to the ground state.

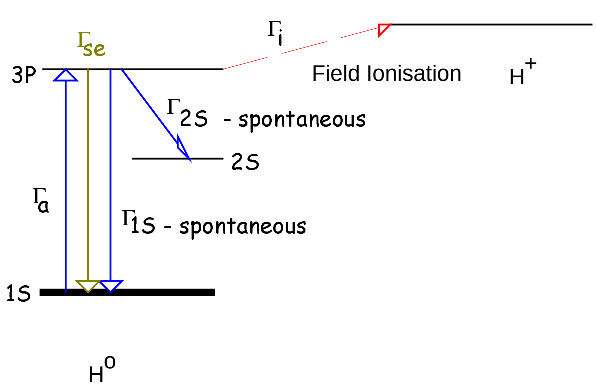

Figure 3: The excitation and decay scheme for laser ionisation.

4 FACTORS AFFECTING PERFORMANCE

4.1 Momentum Spread

As a general comment, the power required in the laser beam depends on the momentum spread of the beam from the linac, assuming that the laser beam width is narrow. In this case the momentum spread of the linac beam should be as narrow as possible to minimise The present work has assumed a $\Delta p/p$ of 10^{-5}.

4.2 Beam Energy

Although the energy of transition in the hydrogen atom is fixed, in a head on interaction between the neutral atom and the laser beam, the frequency of the laser seen by the particle beam is highly Doppler shifted to higher energies, making the use of a laser more practical. Lasers in the wavelength range of 470 nm are required at ESS Energies (1.33 GeV).

4.3 Beam Size and Divergence

The probability of interaction of the laser and the particle beam depends on the energy density of the laser and the density of the particle beam. Hence the beam size is a factor which can increase the required power from the laser. Similarly, a high divergence on the beam gives rise to an angle between the laser and individual beam particles which can knock the particles out of resonance and increase the required laser power.

4.4 Multi-Pole-Undulator System

In this scheme, an undulator magnet and a laser beam are used to form a periodic structure where the process of resonant excitation and stripping occur at different parts of the system and are repeated. The undulator is such that there are field free regions between the poles. At each period a fraction of the neutral atoms can be excited to the 3P state (<50%). This occurs in a field free region prior to entering the magnetic field. In the magnetic field, the 3P excited state is split into its non- degenerate Stark states. Two principle negative factors exist for this system; each of the Stark states is stripped at a different point in the magnetic field since each has a different binding energy. Since the device is fairly long (typically 2 m) an emittance growth occurs because of this distributed stripping. Since the undulator bends both clockwise and anti-clockwise, two beams are also generated. (see Figure 4). Unfortunately, the proton beam circulating in the ring can only follow one of them. Tracking of particles through an 8 half-period device shows that, in the case of the ESS, the two beams are outside of the acceptance of the accumulator ring, (Figure 5).

4.5 Single -Pole-Magnet System

In this scheme, the interaction between the magnet and the atomic states occurs before the laser interaction, while the laser is tuned to excite a particular Stark state. Further, since the process of excitation and stripping occur simultaneously, with the rate of stripping much greater than that of excitation, the beam can be fully stripped in a single interaction over a fairly compact length. Since the laser interaction occurs with a single Stark shifted state, the emittance growth seen in the multi-pole undulator scheme does not materialise.

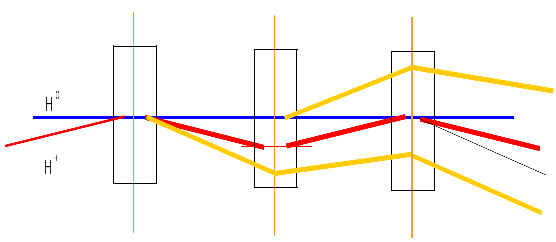

Figure 4. Schematic of the beam path for part of the multi-pole undulator system. Each pole produces its own beam, since odd and even half periods of the magnet bend the beam in opposite senses.

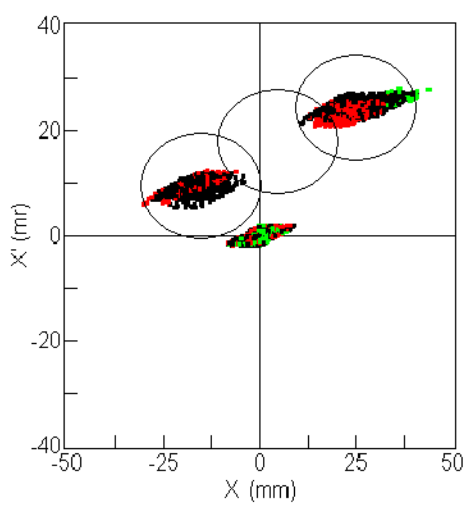

Figure 5. Calculated emittance for the multi-pole wiggler system shown in Figure 4. The calculated emittance is compared to the acceptance of the machine (150 π.mm.mr).

6 CONCLUSION

Solutions have been presented which show the practicality of using intense laser beams and strong magnetic fields to effect injection. Compared to the use of a foil in a machine designed to have a low number of foil transitions, the method is extremely costly and has a certain degree of risk as an untested technique. However, where beam powers rule out the use of foil injection, laser resonant excitation can be considered as a viable alternative. The main development needed is for high power, high duty cycle lasers at wavelengths suitable for beams in the few GeV range.

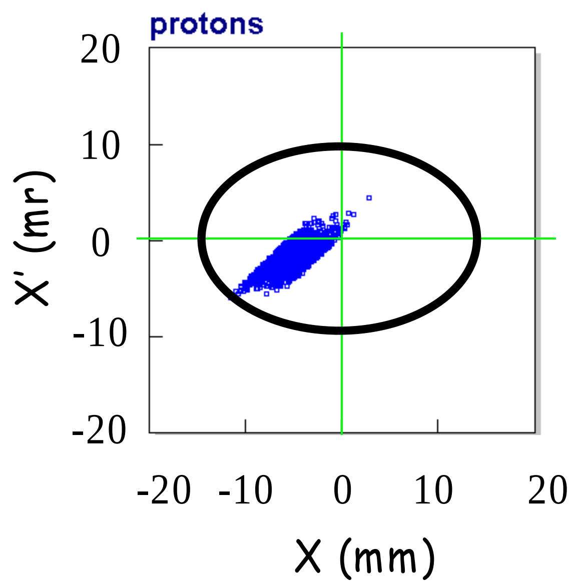

Figure 6. Particles traced through a single pole magnet system. The ellipse represents an emittance of 150 π.mm.mr.

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