Space charge compensation of pulsed high-current H^- and H^+ ion beams

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Pulsed high-current hydrogen ion beams (H^- and H^+) are used in many large scale accelerator facilities for discovery science and applications, such as high energy particle physics (e.g. at CERN) and spallation neutron production (e.g. at ISIS). The 10-100 mA current / 0.1-10 ms pulses / $10 - 100\,\mathrm{keV}$ energy beams are produced by plasma ion sources, and transported through a Low Energy Beam Transport (LEBT) section before further acceleration. The pulse repetition rate is 1-100 Hz depending on the accelerator facility. The LEBT section, which is typically 1-3 m long, consists of ion optical focusing elements, e.g. solenoid magnets. The focusing is required for matching the beam into the subsequent accelerator, in particular, for counteracting the repulsive space charge force between the beam particles.

Space Charge Compensation (SCC) is a process that lowers the space charge of the ion beam. The SCC occurs when the H^- or H^+ beam ionises the background gas and traps either positive ions or electrons to the beam potential forming a peculiar "beam-plasma". Significant amount of the beam is lost during the SCC build-up at the beginning of each beam pulse because the beam optics are set to optimise the beam transport at steady-state following the SCC transient. Thus, it is desirable to minimise the SCC time. The beam loss is demonstrated in Fig. 1(a) showing an example of the (normalised) LEBT beam current and the beam current transported through a Radio-Frequency Quadrupole (RFQ) accelerator at the Front End Test Stand (FETS) at ISIS. Unlike the LEBT beam pulse, the RFQ beam current pulse is not square. The initial transient of 75 µs is empirically attributed to poor space charge compensation.

The SCC time τ can be estimated [1] by considering the final SCC degree η, often assumed ~0.9 for high-current beams, the beamline gas density n_{H_2}, the energy-dependent ionisation cross section $\sigma(E_b)$ of the reaction $H^+ + H_2 \rightarrow H^- + H_2^+ + e$ (for H^- beam) or $H^+ + H_2 \rightarrow H^+ + H_2^+ + e$ (for H^+ beam), and the beam velocity v_b:

$$\tau = \frac{\eta}{n_{H_2}\sigma(E_b)v_b}. \tag{1}$$

The beam energy and, hence, the cross section of the beam-induced ionisation are set by the accelerator design, which means that the minimising the SCC time requires increasing the beamline gas pressure. Alternatively, heavier gas with larger ionisation cross section can be injected into the beamline [1]. However, in the case of H^- beam the increased gas pressure or heavy gas injection would lead to increased electron detachment rate or "stripping losses" in $H^- + H_2 \rightarrow H_{\text{fast}} + H_2 + 2e$. The apparent simplicity of the SCC by beam-induced ionisation of the background gas is deceiving. There are no reported cross sections for the H^- induced ionisation of H_2 at relevant energies, which dictates using the H^+ cross section for modelling. The SCC time of H^- beam tends to be overestimated by Eq. 1 as; in the case of Fig. 1 the H^- beam energy in the LEBT is 65 keV and the average beamline gas pressure along the beam path approximately $4 \times 10^{-6}\,\mathrm{mbar}$. With σ of $2.2 \times 10^{-20}\,\mathrm{m}^2$ [2] the predicted SCC time is 130 µs, which is significantly longer than the experimentally observed 75 µs.

As the SCC process is crucial for the LEBT but cannot be predicted precisely with a simple model, we have launched a campaign to better understand the mechanism. This involves development of bespoke diagnostics for the beam-induced low-density plasma, and a comparative study of H^+ and H^- beams with experiments and Particle-In-Cell (PIC) simulations. The purpose of the comparison is to resolve the uncertainty arising from the use of H^+ ionisation cross section for the H^--driven reaction, and to probe the relevance of different compensating particles (electrons for H^+ and positive ions for H^-) on the SCC dynamics and degree. Furthermore, in the H^- case it is conceivable that the electron impact ionisation, i.e. $e + H_2 \rightarrow H_2^+ + 2e$, affects the SCC time as the electrons liberated by the beam-driven ionisation are propelled to energies corresponding to the beam potential (10-100 eV order of magnitude). Figure 1(b) shows a time-resolved measurement of the beam-induced light emission (obtained with a Multi-Pixel Photon Counter diode) exhibiting a peak that matches the SCC time determined from the RFQ beam current. The transient is presumably due to initially low SCC degree resulting in high beam potential, which then tapers off towards the equilibrium SCC degree and low beam potential. Figure 1(c) demonstrates that the magnitude of the light emission transient depends on the LEBT beam current, which implies that the beam potential and the electron impact reactions are relevant for the beam-induced light emission. We are currently commissioning a Retarding Field Analyser (RFA) [3] to correlate the beam transport and light emission signals with the dynamics of the beam potential through time-resolved measurement of the energy distribution of the electrons repelled by the H^- beam.

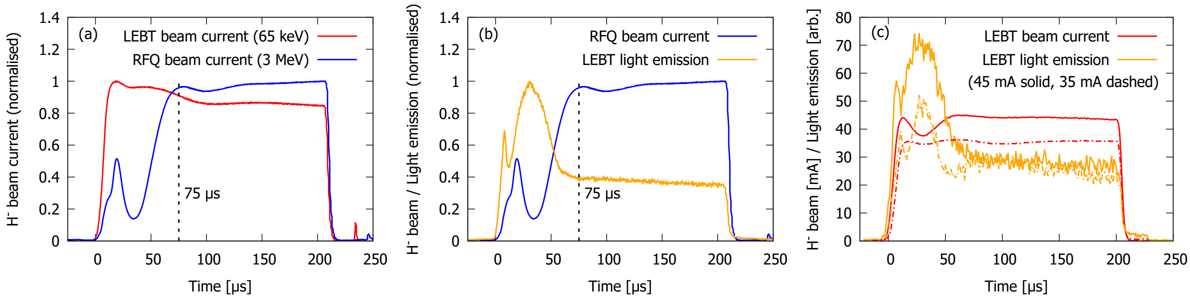

Fig. 1: An example of the space charge compensation. (a) H^- beam pulses in the FETS LEBT and after the RFQ, (b) a comparison of the RFQ beam pulse and LEBT beam-induced light emission, and (c) the effect of the LEBT beam current on the dynamics of the beam-induced light emission.

Figure 2 shows initial PIC simulation results of H^- SCC with PICLas code [4]. The ratio of compensating H_2^+ ions and beam H^- ions in the simulation domain vs. time is plotted for (a) different H_2 pressures (at $0.35\,\mathrm{T}$), (b) different axial magnetic fields (at 1×10^{-5} mbar), and (c) w/wo including the electron impact ionisation and H^- detachment reactions and corresponding electron energy distributions [2] (1×10^{-5} mbar, $0.35\,\mathrm{T}$). When the given ratio is one, the beam potential is zero. The simulation correctly reproduces the neutral gas density dependence of the SCC time and suggests that the previously overlooked LEBT magnetic field could affect the SCC time and final degree. Finally, the PIC simulation implies that the electron impact ionisation has only a small effect on the SCC dynamics, which contradicts the qualitative explanation offered for the light emission transient. The following steps with the PIC simulations include a comparison of the SCC process with H^- and H^+ beams and implementation of wavelength-resolved light emission as an output. Finally, we are exploring the possibility of minimising the SCC time with an external plasma generator producing the compensating particles before the beam pulse. The required plasma density is on the order of $10^8\ \mathrm{cm}^{-3}$, which is attainable with various plasma generator types at relevant H_2 pressures. The effect of the ”pre-generated” plasma on the SCC dynamics will be studied first with PICLas simulations and, if found promising, later with experiments.

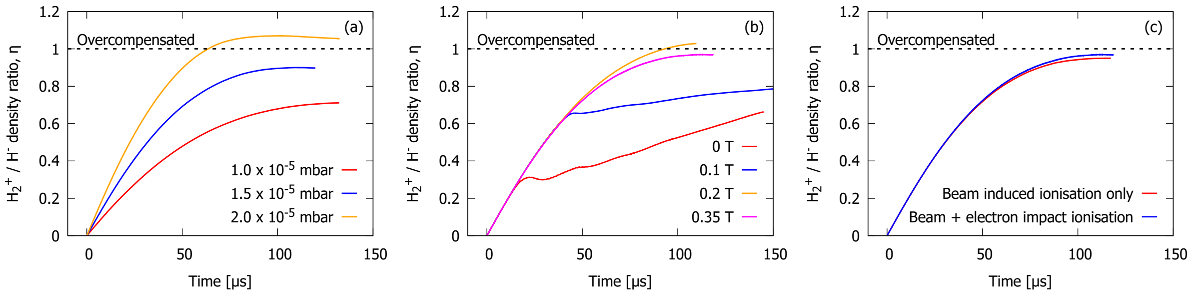

Fig. 2: An example of the PIC simulations of H^- beam SCC. The ratio of compensating H_2^+ ions and beam H^- ions vs. time at (a) different H_2 pressures, (b) axial magnetic fields, and (c) w/wo electron impact ionisation.

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