SPACE CHARGE COMPENSATION TIME MEASUREMENT FOR A PULSED, HIGH-CURRENT H– ION BEAM

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Abstract

Strong space charge effects in pulsed, high-intensity hydrogen ion beams lead to transport losses in the Low Energy Beam Transport (LEBT) of particle accelerators. The space charge compensation (SCC) process lowers the potential of the beam by trapping compensating particles produced by beam-induced ionisation of residual gas. Significant beam losses during compensation build-up necessitate minimising the SCC time. Quantifying the SCC time and determining optimal conditions to reduce it can be done using time-resolved diagnostics. An optical diagnostic based on a Multi-Pixel Photon Counter has been developed at ISIS Neutron and Muon Source to measure the beam-induced light emission during SCC. The transmission through the acceptance-limited RFQ, measured by beam current transformers at the entrance and exit, can also be used to determine SCC time. These two diagnostics have been used at ISIS to measure the SCC time of the 36 keV pulsed H^- beam during parametric sweeps of residual hydrogen gas pressure, beam current and the solenoid magnet current. As predicted by theory, the beam current did not have an effect on the SCC time but the time reduced at higher gas pressures and was altered by the magnetic field.

INTRODUCTION

As pulsed, high-intensity ion beams are transported through the Low Energy Beam Transport (LEBT), space charge forces cause the beam to diverge which can result in beam losses. The space charge of the beam is reduced through the space charge compensation (SCC) process. This process occurs due to ionisation of the background gas in the LEBT, e.g. $H^- + H_2 \rightarrow H^- + H_2^+ + e^-$ for H^- beams. The secondary particles created are either repelled by the beam potential (electrons for H^- beams) or trapped by it (H_2^+ for H^- beams), reducing the local charge density and the electric field inside the beam.

The potential at the centre of the compensated beam, ϕ_c and the uncompensated beam, ϕ_u, may be used to calculate the SCC degree by:

$$\eta = 1 - \frac{\phi_c(z,t)}{\phi_u(z,t)} \tag{1}$$

Significant beam is lost when the SCC degree is low, making the final SCC degree important to beam transport. It is also important to decrease the SCC time, estimated by:

$$\tau = \frac{\eta}{n_g \sigma(E_b) v_b} \tag{2}$$

where n_g is the gas number density, $\sigma(E_b)$ is the energy-dependent beam-induced ionisation cross section, and v_b is the speed of the beam [1]. This equation assumes that only the primary beam ionises the background gas and that all compensating particles created are trapped by the beam potential and non-compensating particles are repelled and removed from the system. As the mobility of the compensating particle is significantly lower for a negative beam, this assumption is more valid for a negative beam.

As the ion beam species and the ion energy in Eq. (2) are set by the design of the system, reducing the SCC time is typically achieved by changing the gas density (gas pressure) or gas species. In the case of negative beams, the pressure range and species are limited, as an increase in the gas density or mass will lead to beam losses through electron detachment. Changes to the focusing fields used in magnetostatic LEBTs may also affect the SCC time, as the magnetic field will affect the dynamics of the secondary particles relevant to the process [2, 3].

As the SCC process is crucial to beam transport in the LEBT, many diagnostic techniques are applied to its study. To measure the SCC degree, time-resolved measurement of the beam potential is required. The SCC time is more easily measured, with multiple time-resolved diagnostics available. While many of the diagnostics used are invasive, experimental measurements and simulation have found that these diagnostics will not only intercept the beam but will also alter the upstream SCC process [3–5]. This, along with the possibility of continued diagnostic measurement during normal accelerator operation, emphasise the advantage of non-invasive diagnostic techniques for studying SCC. This work uses two non-invasive diagnostic techniques, beam current transformers (BCTs) and an optical diagnostic, to estimate the SCC time or equilibration time and to determine the optimal conditions for compensation of a pulsed H^- beam. The optical diagnostic used to measure equilibration time is a novel technique developed at ISIS, with BCT measurements used as validation.

EXPERIMENTAL SETUP

The ISIS Neutron and Muon Source uses a caesiated Penning surface plasma source to generate a pulsed H^- beam [6]. The 36 keV ion beam pulse length is ~200 µs at a repetition rate of 50 Hz. The Penning source routinely produces 50-55 mA, which is injected into the 3-solenoid magnet LEBT. A diagnostic chamber sits between the second and third solenoid magnet. The LEBT transports ~35 mA

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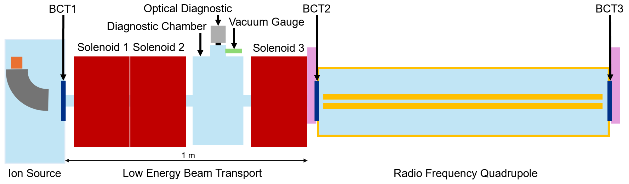

Figure 1: A schematic of the ISIS Neutron and Muon Source H^- ion source, 36 keV LEBT and 665 keV RFQ accelerator.

of H^- beam, which is matched into the subsequent radio frequency quadrupole (RFQ) accelerator for acceleration up to 665 keV. Figure 1 shows a schematic of the ISIS ion source, LEBT and RFQ, with the location of relevant diagnostics indicated.

Beam Current Transformers

BCTs are used for non-invasive measurement of the time-resolved ion beam current along the H^- injector. The BCTs are located at the entrance of the LEBT (BCT1 on Fig. 1, at the entrance of the RFQ (BCT2) and at the exit of the RFQ (BCT3). BCTs at the entrance and exit of an acceptance-limited component, such as the ISIS RFQ, may be used as an SCC diagnostic by measuring the period of low transmission through the RFQ. As the LEBT solenoid fields are optimised for transport of the steady-state of the beam pulse, low transmission through the RFQ will result from the divergence and emittance growth of the ion beam prior to reaching compensation. This period will therefore provide an estimate of the SCC time described in Eq. (2).

Optical Diagnostic

As the H^- beam is transported through the LEBT, it excites the H_2 gas and hydrogen atoms of the residual gas, producing light emissions in the visible range. The secondary electrons produced by ionisation reactions and then repelled by the negative beam potential will also produce light emissions. As the light intensity is dependent on the gas density and the H^- beam energy or the electron energy distribution, the SCC process will affect the resulting light emission. The time-resolved measurement of the light can therefore provide details on the equilibration time of the system.

A non-invasive diagnostic based on a multi-pixel photon counter (MPPC) has been developed at ISIS to measure the beam-induced and electron-induced light emission from an H^- beam [7]. The optical diagnostic system includes the MPPC, a silicon photomultiplier to count photons at visible wavelengths and low light levels, with a driver board and a Redpitaya Single Board Computer [8]. Adjustments to a bias voltage (gain of up to 3.6×10^6) and a thermoelectric cooling voltage are made via an Experimental Physics and Industrial Control System (EPICS) control screen. The board is housed in a metal box to shield from external signals and connected to the MPPC, which sits in a light-tight SM1-threaded lens tube. An uncoated CaF_2 viewing window with an SM1-thread mounting is installed on a vacuum flange of the ISIS LEBT diagnostic chamber for attachment of the optical diagnostic system. The location of the diagnostic chamber is shown in Fig. 1.

RESULTS AND DISCUSSION

To better illustrate the period of low transmission through the RFQ, the signals from BCT2 and BCT3 are normalised to match the steady state of the beam current pulse and the difference between the two is taken. This signal difference is used in this work as an estimation of the SCC time, allowing comparison during parametric sweeps.

A transient peak is often visible in the measured light pulse as the ion beam is compensated. However, changes to the beam pulse shape can alter the shape of the light pulse. Therefore, to directly compare changes during parametric sweeps, the light pulse is normalised to the H^- beam pulse. Ideally, the beam current would be measured at the location of the optical diagnostic measurement. However, ISIS does not have a BCT at this location, so the beam current is measured using the BCT at the entrance of the RFQ. The resulting peak may be used to estimate the equilibration time of the LEBT system.

To examine the effect of beam current changes to SCC time, the arc discharge current of the Penning source was scanned to change the beam current by 20%. No effect was seen on either the BCT or the light signal, as predicted by Eq. (2). This shows that both diagnostic methods are not affected by beam current.

As the gas density is the most direct method of reducing SCC time, the residual gas pressure in the LEBT was adjusted and the effect was measured using the BCTs and optical diagnostics. The LEBT pressure was adjusted using the H_2 gas pressure in the ion source. Figure 2 shows the reduction in SCC time measured by both diagnostics over a pressure range of 1.0×10^{-5} mbar to 1.4×10^{-5} mbar, measured by the vacuum gauge in the diagnostic chamber indicated in Fig. 1. While the pressure at the diagnostic chamber is quoted, the pressure in the LEBT will be a gradient from the ion source pressures (4.3×10^{-5} mbar to 6.6×10^{-5} mbar in this scan) to the lower pressures achieved at the entrance of the RFQ. The SCC time measured during the scan ranged from ~50 µs at low pressures to ~35 µs at the higher pressures. Using Eq. (2), this corresponds to a LEBT pressure of 1.7×10^{-5} mbar to 2.5×10^{-5} mbar, which are in the range of the LEBT and ion source pressures.

Finally, the current setting on the second solenoid magnet of the ISIS LEBT (typical operating value of 20.9 A) was scanned while maintaining the typical operating values of 365 A on the first solenoid and 471 A on the third. Figure 3 shows the resulting signals from the BCTs and optical diagnostic. The range of the solenoid settings scans the on-axis magnetic field inside of the second solenoid from 0.03 T to 0.3 T. However, the scan results in negligible difference in the magnetic field at the location of the optical diagnostic.

In general, decreasing the solenoid current decreased the time to reach equilibrium for both the BCT and optical diagnostic measurements. However, differences between the

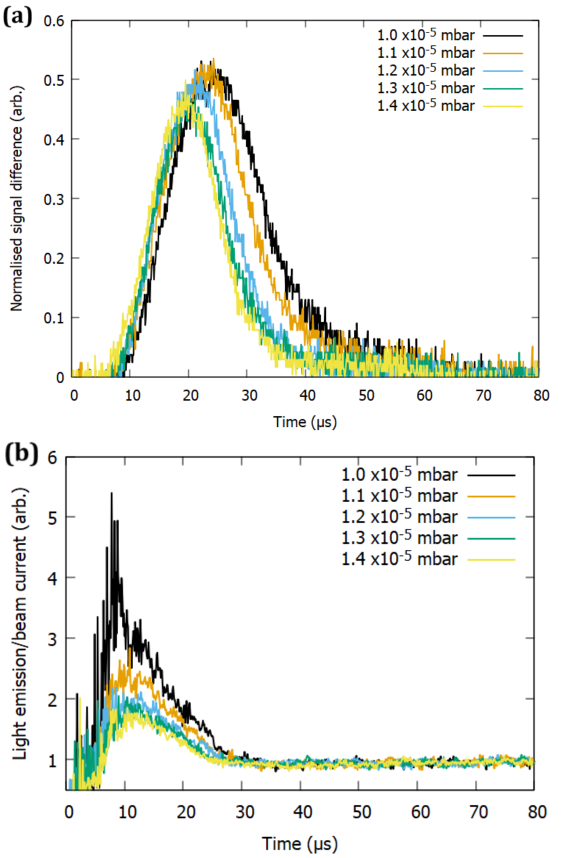

Figure 2: The (a) difference in BCT signal at the entrance and exit of the ISIS RFQ and (b) normalised optical signal/ beam current for a range of LEBT background pressures.

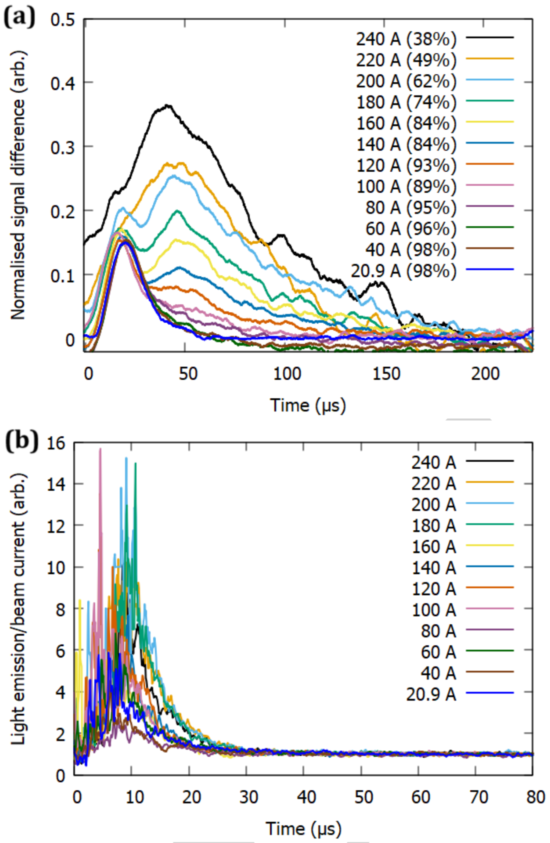

Figure 3: The (a) difference in BCT signal at the entrance and exit of the ISIS RFQ and (b) normalised optical signal/ beam current for a range of current settings on the second solenoid magnet of the ISIS LEBT.

two methods are apparent at the higher solenoid currents. This is likely largely due to poor transport and matching of the beam through the RFQ, resulting in a decrease in overall transmission of the ion beam at some solenoid settings. The transmission values are indicated in the legend of Fig. 3a). The increased equilibration time at higher solenoid settings may be due to the dynamics of the secondary electrons in the system. These electrons will quickly leave the system with low axial fields but at higher axial fields will be confined for longer and may lead to slower compensation due to the accumulation of negative charge in the magnetic bottle between the solenoids.

While the overall trend of all parametric scans are comparable, differences observed between the equilibration time measured by the BCTs and the optical diagnostics are due to multiple differences between the diagnostic techniques. The BCTs measure the time period prior to the beam reaching the size accepted by the RFQ; if compensation proceeds beyond this point it will not be measured. Additionally, as the space charge forces are strongest at the end of the bunching section of the RFQ, the RFQ acceptance will vary slightly with the beam current. The optical diagnostic is not a direct measurement of the SCC time but rather the effect of multiple processes related to the process, including changes in the gas density and in the electron-induced light emission as the beam potential, and therefore electron energy, change. Finally, the BCTs will measure the cumulative change to the SCC time in the LEBT while the optical diagnostic can only measure changes to the compensation process occurring within the MPPC field-of-view. Both diagnostic techniques provide estimated SCC time measurements but also provide reliable information on optimal settings for SCC.

CONCLUSION

BCTs and an ISIS-developed non-invasive optical diagnostic were used to determine the effects of parametric sweeps in the ISIS ion source and LEBT to determine optimal settings to reduce SCC time. Effective methods of SCC time reduction on ISIS included small residual gas pressure increases and a low current settings on the second solenoid of the LEBT. These techniques will be used for further parametric sweeps and monitoring in the ISIS LEBT and the optical diagnostic will be tested on other LEBT systems, including those for H^+ beams.

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