Controlling the Shape of the ISIS H^- Penning Ion Source Beam Pulse

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Abstract The Penning ion source serving the ISIS Pulsed Spallation Neutron and Muon facility routinely delivers 55 mA beam of negative hydrogen ions (H^-) in 250 µs pulses at 50 Hz repetition rate. The Front End Test Stand (FETS) specifications require 60 mA, 2 ms, pulses at 50 Hz. Extending the ion source discharge pulse length to 2.2 ms will need overcome the observed beam current droop caused by thermal transients in long pulse operation. Recent experiments at 25 Hz have demonstrated square 60 mA beam pulses up to 1.2 ms with the permanent magnet version of the ISIS source and 100 mA pulses up to 1.65 ms with the same source equipped with a double-width extraction slit. Droop was compensated by ramping up the discharge current during the beam pulse. The physical phenomena underlying the droop and its countermeasures are discussed, and further technical developments that are necessary to reach the FETS specifications are described. In addition, various experimental shapes of the ion source discharge pulses and H^- beam pulses were achieved by controlling the ion source discharge current and accelerated through the ISIS 70 MeV linac. The technique allows almost arbitrary shaping of the H^- beam pulses for injection studies into the 800 MeV rapid cycling proton synchrotron.

THE ISIS H^- PENNING ION SOURCE

The ISIS Penning ion source [1] is a cesiated pulsed DC discharge surface plasma source delivering 55 mA beam of negative hydrogen ions (H^-), as measured after a 90° magnetic dipole cold trap and Low Energy Beam Transport (LEBT), in 250 µs pulses at 50 Hz. These are used for charge exchange injection in a rapid cycling synchotron for neutron and muon production.

The H^- ions produced on the caesiated cathode surfaces are believed to undergo resonant charge exchange [2] with slow neutral ground state hydrogen atoms in the discharge volume, i.e. $H^-_{\text{fast}} + H(1s)_{\text{slow}} \rightarrow H(1s)_{\text{fast}} + H^-_{\text{slow}}$. These "second generation" H^- ions are then extracted from the discharge volume through a rectangular extraction slit by pulsing the extraction electrode high voltage. This process was first proposed in Ref [3].

The magnetic field of the operational ISIS Penning source is created by an electromagnet whereas the experimental sources dedicated for ion source physics studies at the VESPA [4] test stand utilize permanent magnets. Figure 1 shows a schematic of the permanent magnet version ISIS H^- ion source.

Meeting the 60 mA, 2 ms, 50 Hz specifications of the Front End Test Stand (FETS) [5] requires extending the ion source discharge pulse length to 2.2 ms, allowing 0.2 ms for discharge breakdown oscillations [6] to subside before extracting the 2 ms H^- beam pulse. Injecting 60 mA beam pulses into the FETS RFQ requires nearly 100 mA of H^- current from the ion source to account for transmission losses through the 90° bend of the refrigerated cesium trap and subsequent LEBT.

H^- CURRENT DROOP AND COMPENSATION

Operating the source in long pulse mode at elevated discharge power (current) has been shown to result in decreasing beam current towards the end of the pulse, referred to as ‘droop’. The droop is caused by local transient increase of the cathode surface temperature [7] affecting its caesium coverage, thermionic electron emission current, and subsequently the volumetric ionization rate of the cesium-hydrogen discharge. The details of the physical model can be found from Ref. [8].

In principle the H^- beam current droop could be eliminated by suppressing the thermal transient induced by the discharge pulse. Unfortunately the power deposition by ion bombardment is localized within a thin layer of molybdenum at the cathode surface and cannot be overcome by increasing the thermal conductance between the cathode and the water-cooled source body, nor by improving the cooling itself. One approach for suppressing the droop was

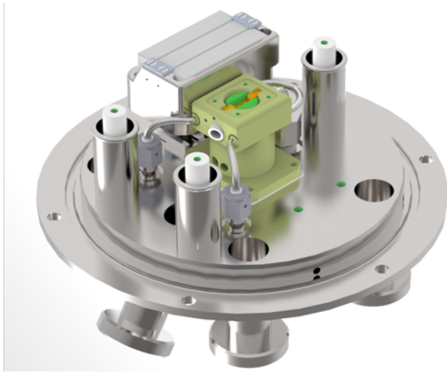

Figure 1. The permanent magnet version of the ISIS H^- Penning ion source. The 5 mm x 10 mm x 2.1 mm discharge volume is surrounded by the cathode (green), hollow anode (orange) and aperture plate with 0.6 mm x 10 mm extraction slit. The aperture plate and one of the permanent magnet blocks are removed for illustration purposes.

Figure 2. On the left is the standard aperture plate, 0.6 mm x 10 mm, to compare with the double width aperture plate on the right, 1.2 mm X 10 mm. The double width aperture plate was used to increase the beam extracted in long pulses.

to increase the size of the discharge volume and extraction aperture. The 2X scaled source [9] was developed with all linear dimensions of the discharge chamber double that of the standard source, resulting in reduced power density at the cathode surfaces. So far, the 2X source has demonstrated flat 60 mA, 2 ms and 150 mA, 700 µs beam pulses at 50 Hz [10]. Scaling the discharge volume by a factor of 8 and the extraction slit area by a factor of 4 comes with a price though. The increased discharge volume implies reduced current density by a factor of 4 (at constant discharge current) whereas the larger extraction slit would be expected to result in horizontal and vertical emittance increasing by a factor of 2. Experimental comparison of the 1X (standard) and 2X sources confirm these trends, i.e. the transverse rms-emittance of the 1X source is typically 0.2–0.5 π·mm·mrad while the corresponding preliminary values for the 2X source are 0.8–1.1 π·mm·mrad. Furthermore, the large extraction slit on the 2X source allows greater caesium leakage, so it typically operates at elevated caesium oven temperature [11]. This could affect the reliability of the source but needs to be confirmed by lifetime tests.

An alternative approach to combat the beam current droop is to tailor the temporal profile of the discharge pulse, thus compensating for the reduced volumetric ionization rate. The discharge is sustained by a pulsed power supply operated in current regulated mode i.e. the discharge voltage (cathode-anode potential difference) is a free parameter, adjusted by the power supply feedback system to maintain the requested discharge current. The discharge power supply readily accepts a 0–10 V control signal which can be adjusted arbitrarily with an external function generator. In particular, the discharge current can be ramped linearly during the discharge pulse as first demonstrated in Ref. [8] where 1.2 ms, 60 mA square H^- beam pulses at 25 Hz were reported for the permanent magnet version of the standard ISIS source at the VESPA test stand where there are no transport losses. The pulse length delivered by the power supply is limited by the temperature rise of the 6 insulated-gate bipolar transistors (IGBTs) of the FETS pulsed power supply capable of delivering approximately 108 mC charge per discharge pulse.

Achieving the square 1.2 ms, 60 mA H^- beam pulses required ramping the discharge current from 50 A to 72 A, which implies that at the end of 2 ms pulses the discharge current would be nearly 100 A. However taking into account the inevitable transport losses it is calculated that achieving 2 ms, 60 mA H^- beam pulses at FETS with the standard ISIS Penning source would require a $\sim$150 A discharge power supply and much improved cooling of the ion source.

A possible solution to relax the power supply requirements is to enlarge the extraction slit of the standard source from 0.6 mm x 10 mm to 1.2 mm x 10 mm, preserving the expected current density of the 1X source while doubling one of the transverse emittances. A photo of the standard and double width aperture slits is shown in Figure 2.

Figure 3 shows an example of a 1.65 ms, 100 mA H^- beam pulse from the 1X source equipped with a double width extraction slit. The beam pulse length is limited by the maximum charge of 108 mC per plasma pulse delivered from the discharge power supply. To achieve this result, the discharge current was ramped from 50 A to 62 A to suppress the droop of the 100 mA H^- beam current pulse at 25 Hz repetition rate.

The given example demonstrates that meeting the FETS specification of 60 mA, 2 ms with the 1X source is feasible by using the double extraction slit and upgrading the discharge power supply, i.e. increasing the number of IGBTs from 6 to 8–10, and modestly improving the cooling of the ion source to allow 50 Hz operation. However, the emittance, beam transport properties and the lifetime of the 1X source with the double width extraction slit still need to be compared to those of the 2X source in long pulse operation.

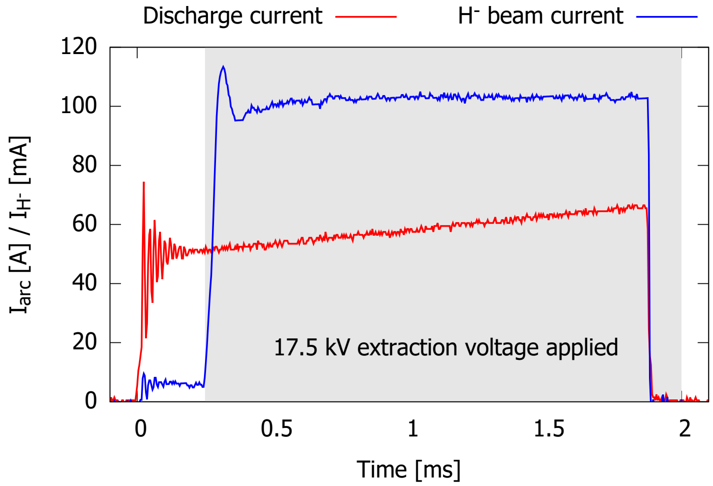

Figure 3. A 1.65 ms, 100 mA H^- beam pulse achieved with the 1.2 mm x 10 mm extraction slit (at 25 Hz). The shaded area indicates the timing of the 17.5 kV extraction voltage pulse. The arc discharge, and therefore also the H- beam stops before extraction because the power supply limits the charge in an arc pulse to 108 mC.

CONTROLLING DISCHARGE CURRENT

The arc power supply takes a 0-10V control signal typically set at a constant level during operation. Ramping experiments were performed with a shaped control signal defined on a function generator. Initial success in implementing the ramps motivated an exploration of how much the arc pulse shape could be manipulated. Manually defining a pulse on a function generator is impractical long term, so a Graphical User Interface (GUI) was written in PyQT, a Python library. An example is shown in Figure 5, where the user may move any of the blue dots, and add and remove them as desired, giving flexibility to easily draw any shape. The PC running this script uses serial communications to configure the function generator to the same pulse. Observing the arc discharge closely following the control signal opened the possibility for further experiments.

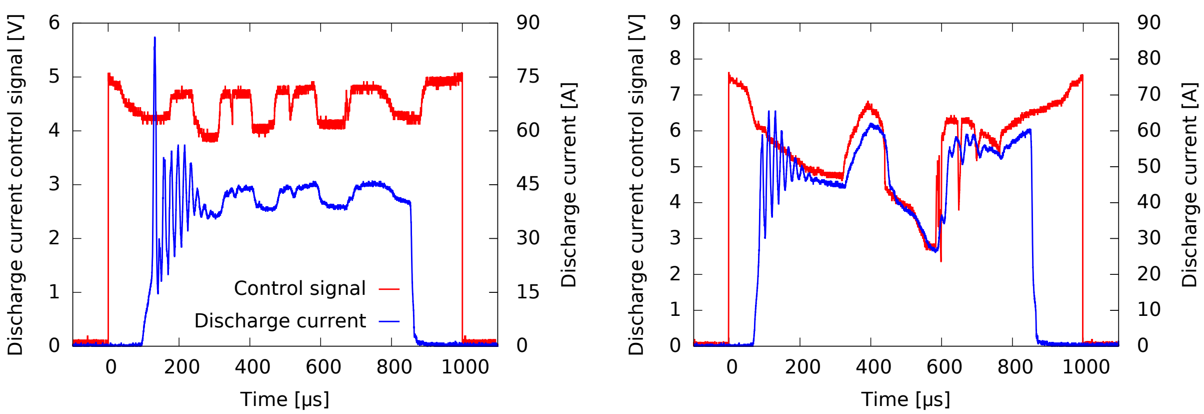

Figure 4. Two examples showing how closely the discharge current follows the control signal, even when arbitrary shapes are drawn. Beam current was observed to closely follow arc discharge.

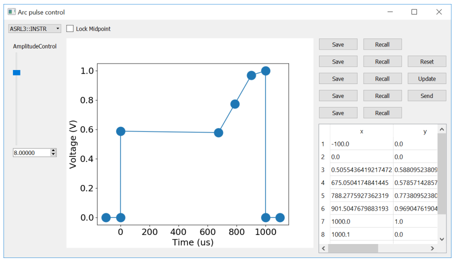

Figure 5. A screenshot of the Graphical User Interface used to define the control signal for the arc power supply. The blue dots can be moved around, created, and destroyed by the user, allowing flexibility for any shape. The program is written in pyQT and communicates using pyVISA.

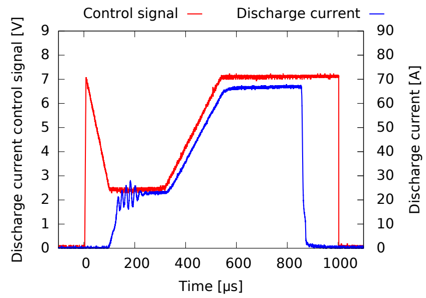

Figure 6. A plot of the control signal sent to the arc power supply and the resulting arc discharge in the ion source. The signal is low during the initial oscillations but high where beam is extracted. Operating in this mode could improve source lifetime by reducing erosion during oscillation period.

REDUCING PRE-EXTRACTION SECTION OF ARC DISCHARGE

Having modified the arc during beam extraction, attention turned to the noisy portion of the arc discharge. The arc discharge is longer than the beam pulse to allow time for these oscillations and noise to subside. The arc current causes erosion of the ion source, and is thought to be the key factor limiting lifetime. In particular, charged particles forming the oscillations are likely to contain Cs^{2+} ions as indicated by VUV spectroscopy [12], which is present in much lower quantities outside this period, and which sputter a lot more than other species [6]. Therefore, minimising the arc current for the duration of the oscillations should significantly reduce erosion. This scheme was tested, and the successful result is shown in Figure 6.

The oscillations in this test are at 20 A with an amplitude of around 10 A peak to peak, much smaller and at a lower current than the typical oscillations of 20 A amplitude at 60 A. To verify this effect, extensive lifetime tests and erosion evaluations should be performed, and observations of oscillation behaviour and Cs balance over long term operation should be studied.

SHAPING THE H^- PULSE INJECTED INTO THE ISIS SYNCHROTRON

Arc discharge current closely follows even unusually shaped control signals, as shown in Figure 4. Similarly, beam current responds to arc discharge very rapidly. Therefore, in addition to combating the beam current droop in long pulse operation, controlling the temporal profile of the ion source discharge pulse allows tailoring the shape of the short (250 μs) beam pulses accelerated by the 665 keV RFQ and the 70 MeV drift tube linac injecting the beam into the 800 MeV rapid cycling proton synchrotron. Tailoring the beam current pulse shape, i.e. inducing a downward slope, but maintaining the total injected charge makes it, in principle, possible to control the transverse distribution of the space charge within the synchrotron beam bunches, which is discussed in the next section. In the ideal case, the space charge force is linear.

Figure 7 shows a comparison of three H^- beam pulses, one produced from a square, two from ramping down discharge pulses, as measured at 36 keV by a current transformer in the LEBT and another at 70 MeV after the linac at the entrance to the synchrotron. All result in approximately the same charge per pulse at the synchrotron injection. Note the standard pulse plotted in red has an initially lower current due to space charge compensation in the LEBT. During this time the phase space orientation of the beam is changing and is not matched to the RFQ input acceptance. Therefore some beam is not transported by the RFQ at the start of the pulse.

These examples demonstrate two features which are relevant for the injection of the beam into the synchrotron. Firstly, increasing the discharge current at the beginning of the extraction pulse and then ramping it down to the nominal level (plotted in blue) counters the slow increase of the H^- beam current both in the LEBT and after the linac and makes the accelerated beam pulses square. This allows shortening extracted beam pulse while achieving the same

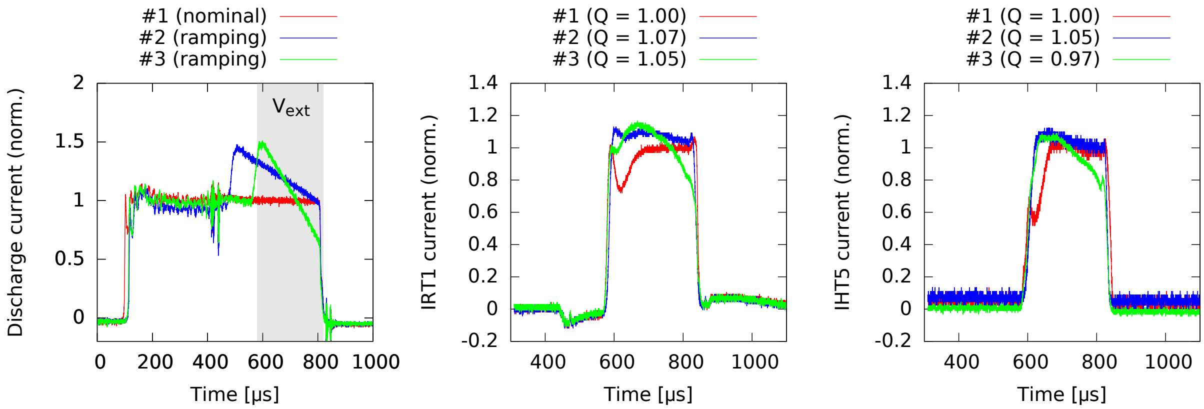

Figure 7. Examples of the ion source discharge pulses with constant and ramping current during the extraction voltage pulse (left) and corresponding H^- beam current pulses in the LEBT at 36 keV (middle) and after the ISIS drift tube linac at 70 MeV (right). In all cases the charge Q delivered to the synchrotron injection is approximately the same.

charge injected into the synchrotron. Secondly, a more aggressive ramp of the ion source discharge current (plotted in green) results in a downward ramp of the accelerated beam current, which is relevant for the injection studies aiming at controlling the transverse distribution of space charge of the synchrotron beam bunches.

MOTIVATION FOR SHAPING PULSES

The ISIS synchrotron and its possible upgrade, use H- charge exchange injection to accumulate high intensity proton beams. In both machines two of the key operating metrics are beam loss, resulting in machine activation, and the number of injection foil hits, leading to reduced foil lifetime or damage. Both can be controlled by manipulating the transverse painted beam to minimise space charge and thus minimise beam emittance. Controlling the temporal injector current adds an extra degree of freedom to this highly constrained process.

These studies, in which the injector current is reduced over injection, are a first attempt to show if correlated small to large amplitudes painted in both the horizontal and vertical planes, could minimise final painted emittances. This scheme generally has the lowest foil hits but potentially suffers from large incoherent tune spreads in the beam, leading to emittance growth, when the painting is small and the intensity is too high. Starting at a lower injector current and then increasing current with painted amplitudes could mitigate this problem.

Conversely ISIS injection is a fast process, 133 turns in 200 μs, so these emittance growth rates may be too slow to notice. If this is the case then reducing injector current over injection allows smaller amplitude core beams more turns to distribute into a stable distribution and larger amplitude painted beams injected under lower currents leading to smaller halo formations. The ISIS experiment could only show small to large horizontal and constant vertical paint due to hardware control limitations. In this case high efficiency, >98%, was achieved in injection but high beam losses were observed during ring acceleration. Future studies will concentrate on matching the injector current temporal distribution to the correlated painted amplitudes.

Studies on the ISIS 2 ring are initially concentrating on a linearly increasing injector current ramps where 1.3×10^{14} protons are accumulated over 785 turns (600 μs). These longer injection times may allow incoherent tune driven emittance growth rates to drive beam losses. Increasing, 28.5 mA to 85 mA vs constant 57 mA injector currents for correlated, small to large, paint amplitudes have been simulated. Beam evolution of RMS and 99 % emittance occupancy over injection for each case are compared in Figure 8. Increasing injection current significantly reduces horizontal emittance whilst modestly increases vertical emittance. Foil recirculations, per injected proton, also reduce from 3.2 to 2.6.

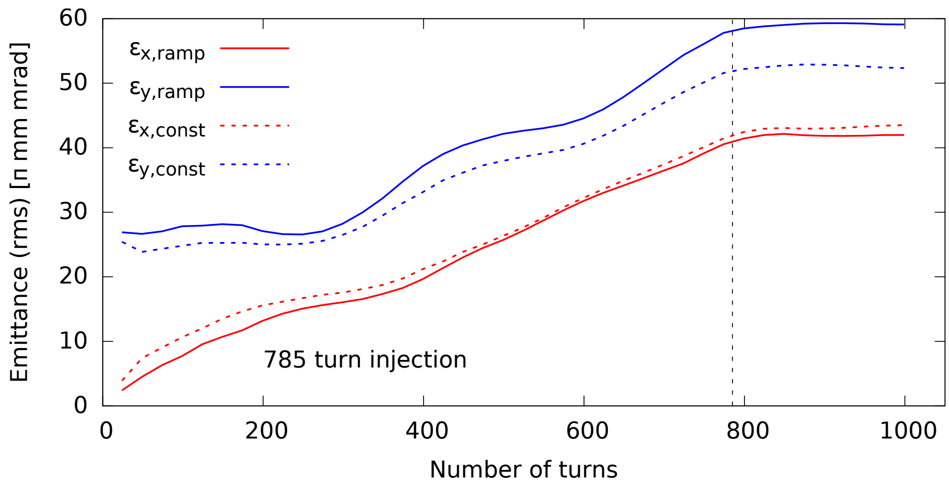

Figure 8. Evolution of beam emittance at 99 % occupancy over 785 turns into a candidate ISIS 2 ring for linear ramped (28 to 85 mA) and constant current (57 mA) injection currents

CONCLUSION

Challenging the typical operation of a flat beam pulse and arc discharge has revealed potential for improvement of ion source performance on many fronts. Higher beam pulse lengths have been achieved by ramping the arc discharge during extraction, offering a low engineering effort path to satisfying FETS requirements. Oscillations in the arc discharge have been significantly reduced without compromising the beam pulse, potentially improving source lifetime. Beam lost to space charge compensation in the linac has been cancelled out by extra production at the beginning of the extracted pulse, reducing the required pulse length at beam extraction. Finally, intentionally changing the beam pulse shape may improve charge exchange injection into the synchrotron by optimising phase space painting.

Further experiments are required on all fronts to verify that these apparent advantages translate into real improvements to ion source performance. If successful, operational arc discharges and beam pulses may look different in the future. Though these experiments have been performed on a Penning source, all ion source technologies should permit some tuning of pulse shape, and there may be potential for interesting results at all ion source laboratories.

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