EXPERIMENTAL STUDY OF A SIMPLE METHOD TO CHOP PENNING SPS H^- BEAMS*

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Abstract

Accumulator rings proposed for use in high-intensity spallation-neutron sources require a chopped beam with particle-free gaps $\approx$100 ns wide at 1-2 MHz rates with rise and fall times $\leq$20 ns. Chopping the beam directly in the ion source may be an attractive way to provide the desired beam structure. A grounded collar placed in the drift region next to the emission aperture lowers the e^-/H^- ratio in the 8X source H^- beam. We electrically isolated the collar and biased it to modulate the extracted H^- current. Positive collar bias decreases the H^- beam by up to 90%. The fastest H^- current fall and rise times achieved to date are 400 ns and 2 μs, respectively. The fall time is close to the pulser rise time ($\approx$300 ns). The rise time is considerably longer than the pulser fall time ($\approx$500 ns). Negative collar bias lowers the H^- beam by up to 50%.

Introduction

The Los Alamos study of a next-generation spallation-neutron-source driver [1] calls for injection of a cleanly-chopped H^- beam into a proton accumulator ring. Extraction from the ring is accomplished by energizing an extraction-kicker magnet during the passage of the hole (created by the chopping pattern) in the beam stored in the ring. The extracted beam is then transported to the spallation-neutron target. The approximate chopping requirements are to turn the beam off (within 0.01%) for 235 ns every 670 ns with beam fall and rise times $\leq$20 ns [1]. The chopped-beam fall and rise times determine the beam-bunching factor and the injection duty factor, both important parameters for ring stability. The beam modulation fraction determines the power that must be dumped on an auxiliary target at higher energies during the chopped portion of the beam.

Presently the beam chopping at LAMPF is done with a traveling-wave chopper [2]. This device electrostatically deflects the H^- beam onto a beam dump, and allows the unchopped portion to be transported through an aperture in this dump. Experience at Brookhaven National Lab [3] with H^- beams similar to those of future spallation sources shows that when the chopper is placed in a 35-keV low-energy beam transport (LEBT) between the H^- injector and the radio-frequency quadrupole (RFQ) linac, the chopper causes time-varying neutralization in the beam channel. The resulting time-varying beam-phase-space orientations reduce the RFQ output current. Another option is to place the chopper after the first RFQ and add a second RFQ to rebunch the beam into the first drift-tube linac (DTL) accelerator [1]. In this arrangement, it is desirable to pre-chop the H^- beam in the ion source to reduce the power lost in the transfer line [4].

York *et al.* [5] showed that positive or negative bias on the plasma electrode-collar structure in a cesium-free, cusp-field volume H^- source reduces the 2-mA extracted H^- current by 90% (0.2 mA of the original beam remains) with H^- beam fall and rise times $\approx$200 ns. We decided to try modulating the Penning surface-plasma source (SPS) H^- beam by using only a biased collar because, in previous Penning SPS work without collars, we found that plasma-electrode bias does not affect the extracted beam current [6].

Experimental Method

The experimental arrangement is shown in Fig. 1. The 8X source [7], developed at Los Alamos, is a Penning SPS that operates on a hydrogen-cesium discharge. The collar electrode is mounted in the source drift region, 0.5 mm from the emission aperture. The collar is constructed from molybdenum and has thickness L along the beam direction and inner diameter 2R perpendicular to the beam direction. We tested four collars: L = 1.2 mm and R = 1.5 mm, L = 2.4 mm and R = 1.25 mm, L = 2.4 mm and R = 1.5 mm, and L = 6.0 mm and R = 4.6 mm. The H^- are emitted through a 2.6-mm-diam emitter and formed into a beam with a diode extraction system. The extractor aperture is 3.0 mm, the extraction gap is 2.9 mm, and the extraction voltage is 15 kV. The H^- current is measured with a current toroid and a Faraday cup (not shown) that are 4 and 8 cm from the extraction aperture, respectively.

Typical 8X-source parameters are discharge voltage V_d = 90 V, discharge current I_d = 460 A, discharge pulse length = 1.2 ms, repetition rate = 5 Hz, H_2 gas flow = 0.13 Tℓ/s, N_2 gas flow = 0.005 Tℓ/s, and discharge magnetic field = 370 G.

Experimental Results and Discussion

In our initial parametric studies we reduced the H^- beam from the 8X source to 10% of its original value by applying positive bias voltage to the L = 2.4 mm, R = 1.5 mm collar. The collar-voltage pulser is identical to the one that drives the 8X-source Penning discharge; its rise and fall times are $\approx$10 μs. The source discharge is switched on at time t = 0.1 ms for 1.2 ms (Fig. 2). At time t = 0.9 ms the extraction voltage (not shown) is switched on and 25 mA of H^- current (I_{H^-}) extracted. Fig. 2e shows I_{H^-} recorded in the Faraday cup. The collar voltage V_c = 38 V (48 V above the -10 V floating voltage) and current I_c = 100 A after the collar pulser is switched on at time t = 1.05 ms. This reduces I_{H^-} to ~2.5 mA. The collar pulse does not affect the operation of the discharge. The collar pulser is switched off at t = 1.2 ms, and I_{H^-} returns to 25 mA. When the pulser is off, the collar floats. At t = 1.3 ms the extraction voltage and the discharge are turned off and I_{H^-} drops to 0.

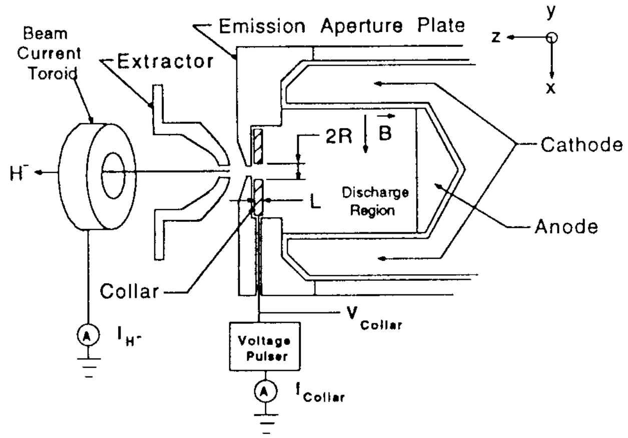

Figure 1. Schematic of the 8X source showing the collar mounted in the drift region adjacent to the emission aperture.

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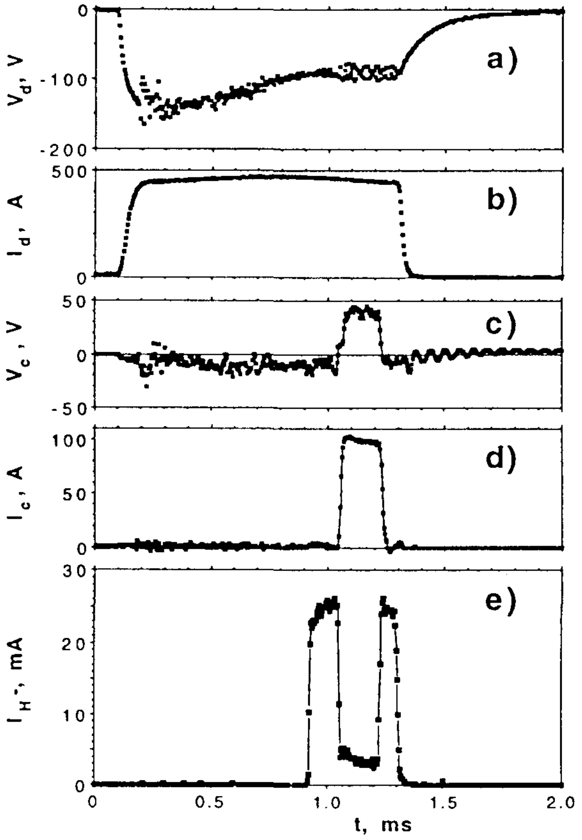

Figure 2. a) V_d, b) I_d, c) V_c, and d) I_c waveforms for the e) modulated H^- beam current I_{H^-}.

One possible interpretation of Fig. 2e is that the collar voltage dramatically disturbs the H^- emission surface, defocusing the beam at the Faraday cup. Two experimental facts argue against this explanation. First, I_{H^-} in the toroid (Fig. 1) is similar to that in Fig. 2e. Second, the current in the extraction gap (the drain current) drops dramatically, from 91 to 12 mA, when the collar voltage is applied. Because the drain current is $I_e + I_{H^-}$, I_{H^-} must have decreased from 25 mA to <12 mA during the collar pulse.

The variations of I_c, I_{H^-}, and I_e with V_c are shown in Fig. 3 for the L = 6.0 mm, R = 4.6 mm collar with a 100 line per inch (lpi) tungsten mesh. When the collar pulser is off, the collar floats at ≈-9 V. If the collar is grounded (V_c = 0 V), I_{H^-} drops from 25 to 12 mA and I_e drops from 66 to 13 mA. For the L = 2.4 mm, R = 1.5 mm collar (no mesh), I_{H^-} drops from 32 to 15 mA and I_e drops from 90 to 12 mA when the floating collar is grounded, in approximate agreement with our previously-published work on grounded collars (Fig. 3 of [8]). Figure 3 shows the qualitative parametric dependence of I_c, I_{H^-}, and I_e on V_c for all the collar geometries we tested.

When high negative bias is applied to the collar, the H^- current in the Faraday cup is reduced by only 50%: I_{H^-} drops from 22 (collar floating) to 13 mA at V_c = -230 V (Fig. 3). Note also that I_e increases from 40 (collar floating) to 167 mA at V_c = -230 V (Fig. 3). Compared to the positive-collar-bias case, negative collar bias leads to smaller H^- current modulation (50% vs 90%) and larger extracted electron current (150 mA vs 10 mA). This makes positive collar bias more attractive for modulating the H^- beam in the 8X source.

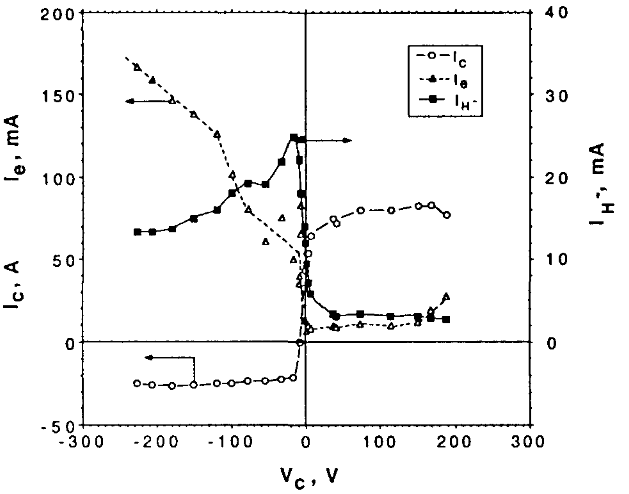

Figure 3. I_c, I_{H^-}, and I_e as a function of V_c for the L = 6.0 mm, R = 4.6 mm collar with a 100 lpi tungsten mesh. The collar floats at ≈-9 V.

To measure the I_{H^-} fall and rise times that can be achieved with positive voltage, we use an intermediate-speed voltage pulser [9] that uses integrated-gate base transistors to supply the pulsed current. For the impedance of the 8X source plasma (≈0.25 Ω) and the series limiting resistor (3.3 - 5.6 Ω), the pulser rise and fall times are ≈300 and ≈500 ns, respectively. A 10-µs-wide portion of a 32-mA, 400-µs-long H^- beam that is chopped with a +10-V (20 V above the floating voltage), 135-A, 2.5-µs-long pulse applied to the L = 1.2 mm, R = 1.5 mm collar is shown in Fig. 4. At 2.2 µs I_c turns on and rises to its full value in 300 ns. There is a delay of 250 ns between the turn-on of I_c and the start of the I_{H^-} drop. After this delay, the I_{H^-} fall time is 450 ns. At 3.6 µs I_c begins falling (V_c rises slightly) because of plasma depletion. The pulser is switched off at 4.7 µs; I_c has a 600-ns fall time. The H^- current begins increasing at about 4.7 µs with a 2.6-µs rise time.

The minimum H^- current fall and rise times, 400 ns and 2 µs, respectively, and the maximum modulation, 90%, achieved to date are not good enough for use in a spallation-neutron-source driver without auxiliary chopping. In an attempt to improve these parameters, we placed a 100-lpi, 80%-transparent tungsten mesh [10] across the collar opening, 1 mm

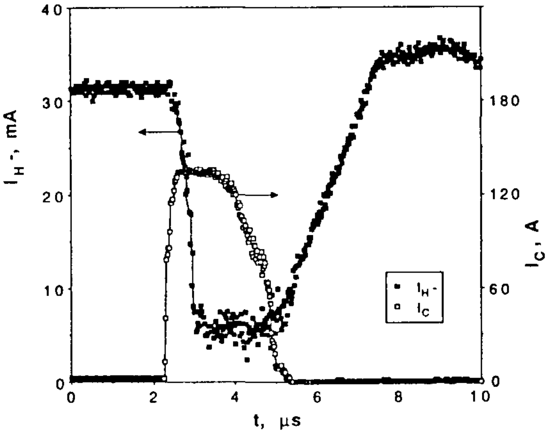

Figure 4. A 10-µs-wide slice of a 400-µs-wide H^- beam pulse. The 5.5-µs-wide chopped hole has 450-ns fall and 2.6-µs rise times.

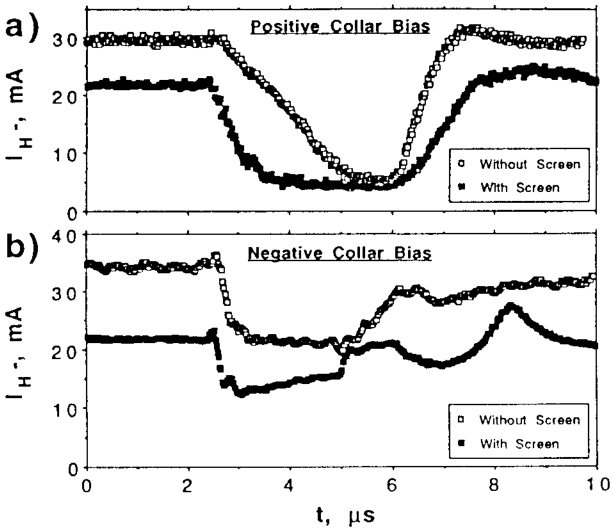

Figure 5. H^- current waveform for the L = 6.0 mm, R = 4.6 mm collar with (filled squares) and without (open squares) the 100 lpi tungsten mesh for a) a 0-V (10 V above the -10 V floating voltage), 108-A, 3.5-μs-long collar pulse and b) a - 370-V, 35-A, 2.5-μs-long collar pulse.

from the end of the L = 6.0 mm and R = 4.6 mm collar that is closest to the emission aperture. The H^- current waveforms, with and without the 100 lpi screen, are shown in Fig. 5. The positive-voltage-pulser current rise time is 300 ns (Fig. 5a); the negative-voltage-pulser current rise time is 40 ns (Fig. 5b). The design details of the positive and negative pulsers [9] cause the difference in the current rise times. The H^- beam modulation is only slightly affected by the tungsten screen (after correcting for the 80% screen transparency), as is the rise time at the end of the positive pulse (Fig. 5a) and the fall time at the start of the negative pulse (Fig. 5b). However, the presence of the screen shortens the H^- beam fall time from 2.5 μs to 1.0 μs for the positive pulse. The H^- beam rise time at the end of the negative pulse also appears to be affected by the presence of the screen. The dominant effect of the screen mesh is to shorten the H^- current fall time for positive collar bias.

For a 200-mA extracted electron current and a 4-cm total length of wire in the mesh, we estimate [11] that the screen bias needed to block the plasma from the emission aperture is ≈200V. We have not observed shut off of I_e or I_{H^-} for V_c as low as -460 V. Perhaps using another pulser (with increased output voltage) to lower V_c below -460 V will shut off the I_e and I_{H^-} emission. We have not yet reached a limit for increasing the positive collar voltage. If $V_c < -300$ V, for some collars I_e increases to the point where the extraction gap breaks down. For the collar in Fig. 5, the 100 lpi screen lowered I_e.

On the premise that some H^- are produced by charge-changing collisions of H^o from the discharge on the cesiated molybdenum emission-aperture surface [12] exposed by the 3.0-mm-id collar (L = 2.4 mm], we reduced R to 1.25 mm to shield the emission aperture from the discharge. This did lower the H^- current extracted before and after the collar pulse, but it had no effect on the H^- current extracted during the collar pulse. It also had no effect on the H^- beam fall and rise times. Decreasing the collar length L from 2.4 to 1.2 mm for the R = 1.5 mm collar increased the extracted H^- current before and after the collar pulse, but left the H^- current extracted during the collar pulse unchanged. The H^- current rise time was also unchanged, but the H^- current fall time was shortened to 400 ns.

We estimate an upper limit to the achievable response times by calculating the sound speed v_s in the H^- source. Assuming kT_e and kT_i = 1 eV, $v_s = [kT_e + \gamma kT_i]^{1/2}/M = 1.96 \times 10^6$ cm/s ($\gamma = 3$). A typical collar radius is 0.15 cm, so the average distance a plasma particle has to travel to the collar wall is ≈R/3 = 0.05 cm. The time to clear the plasma from the collar region is ≈0.05 cm / 1.96 x 10^6 cm/s = 26 ns. This estimate shows that the Penning source should meet the required 20 ns beam fall time. The limit to the H^- beam rise time is not understood — we observe that the shorter the collar pulse width, the faster the H^- beam rise time. Perhaps for ≈200-ns-long pulses, the rise time will be much shorter than presently observed. The H^- beam fall and rise times must be considerably shortened, and the beam modulation fraction increased from 90% to 99.99%, before H^- beam chopping in the 8X source only (no auxiliary chopper) will be useful in advanced spallation-neutron-source drivers. Stevens [13] used the transport code SCHAR [14] to calculate the space-charge-induced time spreading of a 40-mA, 100-keV, 2-cm diam H^- beam in a 1-m long LEBT. For an H^- beam neutralization of 95% he finds the time spread is ≤0.4 ns. Thus, if ≤20-ns fall and rise times can be provided by chopping in the ion source, it is likely that they will be preserved in transport. Provided the fall and rise times can be shortened, the achieved 90% H^- beam modulation fraction may have application in a driver that has a second chopper placed between two RFQs [1,4].

Future Work

Further development is needed to decrease the H^- beam current fall and rise times and to increase the efficiency of the H^- beam modulation. The H^- beam fall time has been limited by the voltage-pulser rise time; replacing the 300-500 ns voltage pulser with a 20 ns pulser may shorten the H^- beam fall time. Placing 100 lpi mesh on the L = 1.2 mm, R = 1.5 mm collar may further shorten the 400-ns H^- fall time achieved without the mesh. The H^- beam fall time and the modulation efficiency may also be limited by the pulsed positive voltage applied to the collar. A voltage pulser that significantly increases V_c may also improve these parameters.

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