DESIGN AND PERFORMANCE CHARACTERISTICS OF THE ZERO GRADIENT SYNCHROTRON (ZGS) H- ION SOURCE AND RELATED SYSTEMS

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Summary

An expression for the maximum H- current obtainable from an H+ beam by charge exchange in hydrogen has served as a guide in the design and development of a source of H- ions for booster injection into the ZGS. Here it is used as a criterion in the evaluation of test-bench results obtained with the present test source. Space and power limitations in the 750-keV terminal of the preinjector have led to the use of titanium sublimation pumping to handle large instantaneous gas loads. Power limitations and the need for high pumping conductance have led to the substitution of electrostatic deflection for magnetic deflection in the beam separator.

Introduction

During initial development of a 500-MeV rapid-cycling booster injector for the ZGS, 50-MeV H- ions will be injected into the booster and the ZGS on alternate pulses. Stripper foils will convert the H- ions to protons for acceleration to the full energy of whichever machine they enter. A 5-mA, 500-μs pulse of 50-MeV H+ ions will be required once every 1-1/4 s. If beam losses are limited to those occurring in the linac, 10 mA of H+ from the source will yield the required 50-MeV beam. Additional current will be required to offset any losses occurring between the source and the 750-keV high gradient accelerating column or in the beam line from the column to the linac.

At present, H- ions are produced in a charge exchange cell receiving the positive ion output of an extended stationary arc duoplasmatron source. The hydrogen target gas in the cell is supplied by the pulsed outflow from the duoplasmatron. A shutter valve in the source anode limits the duration of pulsed flow to about 20 ms/pulse and the average flow to about 0.2 cm³/min (760 Torr, 20°C). In the cell, charge exchange and dissociation result in a beam with H+, H0, and H- components having all, one-half, and one-third of full energy. Positive ions emerging from the cell are stopped by the retarding field of a tandem acceleration arrangement which increases the energy of emergent H+ ions by an amount equal to the full energy of the positive ions from the duoplasmatron.

Source Design Characteristics

The H- source configuration is shown in Fig. 1. Negative high voltage (15-20 kV) is applied to the charge exchange cell. The extractor and suppressor grids are biased approximately 500 V negative with respect to the cell to prevent the loss of free electrons required to neutralize the space charge of the positive ion beam entering the cell. The electrons are supplied by secondary emission from the grids and the cell wall, as well as by ionization of the target gas. Some secondary electrons from the suppressor grid are accelerated to ground potential with the H+ ions. They acquire an energy corresponding to the cell potential plus the bias potential.

An expression for the maximum H- beam current derivable from a proton beam by charge exchange in hydrogen is easily derived from the Child-Langmuir 3/2 power law. If the multicomponent beam just fills the charge exchange cell and grazes the wall with negligible loss, the magnitude in milliamperes of the H- beam emerging from the source is given by

\[ I \approx \frac{1.35 \tau_1 \tau_2 \tau_3 \eta M_{1/2}^{3/2}}{d^2}, \]

where \( \tau_1 \) is the H- fraction of the positive ion beam, \( M \) is the effective mass number of the beam, \( \eta \) is the fraction of the H+ beam converted into H-, and \( V_{ex} \) is the extraction voltage. The other symbols are defined in Fig. 1. If beam loss to the charge exchange cell wall is not negligible, \( d \) must be replaced in Eq. (1) by \( d_w \), the effective beam diameter at the plasma boundary. Using the notation of Fig. 1, \( d_w = D_2 - 2a \) (Fig. 1), where \( a \) is the half-angle divergence (assumed constant) of the beam which just grazes the cell at its exit.

For the present source, \( \tau_1 = 0.77, \tau_2 = \tau_3 = 0.90, d = 119 \text{ mm}, d_1 = 2.5 \text{ mm}, d_2 = 1 = 165 \text{ mm}, D_2 = 169 \text{ mm}, \eta = 0.75, M_{1/2}^{3/2} = 1.2, \) and \( \eta = 0.02. \) (The last three values are estimates.)

If the above values are used in Eq. (1), we find that an extraction voltage of 15 keV gives 13 mA of H- while 20 keV gives 20 mA in the ideal case of a beam just filling the charge exchange cell and grazing the wall with negligible loss. In the actual source, wall losses are not negligible, and the effective beam diameter is less than 119 mm.
Titanium Sublimation Pumping and Electrostatic Deflection to Minimize Stripping Losses

The shutter valve reduces average gas flow to values of the order of 0.2 cm³/min (760 Torr, 20°C) when the arc and the gas are pulsed once every 2-1/2 s. However, instantaneous gas flows are of the order of 20 cm³/min; the vacuum system must, therefore, have adequate capacity and sufficiently high conductance to insure that loss of H⁻ due to charge exchange over the path from the source to the accelerating column is negligible.

Stripping losses were not negligible in the system described in reference 3. That system, in which a beam separation chamber intervened between the source and a 2400 l/s ion pump (~5800 l/s for H₂) has been replaced with a new one in which a pair of electrostatic deflection plates are mounted above a Model 214-5000 titanium bulk sublimator, manufactured by the Ultek Division of Perkin-Elmer Corporation. A baffle is used to shield the deflection plates from titanium and prevent charge-changing collisions between H⁻ and titanium. A 400 l/s ion pump is used to pump noble gases and reduce pump-down times.

The titanium, a 1-1/4-in diam rod with 5-1/2 in of usable length, can furnish 500 g of titanium over its lifetime. The rod is heated to sublimation temperatures by 6-keV electrons from a concentric tungsten ring filament. The sublimation rate is governed by control of the emission current from the filament. There are ~950 in² of surface available for deposition of titanium in this system. With a continuous hydrogen flow of 3 cm³/min (38 ml/s), a pumping speed of 18300 l/s is obtained at 2.2 x 10⁻⁶ Torr. This pressure is read on a gauge near the sublimator, but not on a direct line of sight. A gauge at the top of the vessel, above the deflection plates, reads ~6 x 10⁻⁶ Torr.

The sublimator is operated in a vertical position. Filament sag results in shorting and failure after ~75 h. Flaking of titanium film from nearby surfaces occasionally results in intermittent shorting and has contributed to pump failure.

The stainless steel sublimation chamber in use in the 750-keV terminal has a cooled (11°C) gettering surface of ~3000 in². For a 3-h run with a continuous hydrogen flow of 3.1 cm³/min (39.5 ml/s), measurements now in progress give a steady-state pumping speed of 73000 l/s at a pressure of 5.4 x 10⁻⁷ Torr. (This is for a sublimator emission current of 180 mA, which may or may not be optimum.) Short excursions to flows of 4.05 and 4.9 cm³/min have given speeds of 89000 and 82000 l/s respectively. Horizontal mounting in the new chamber is expected to eliminate failures due to filament sag and flaking or at least greatly reduce the frequency of failure.

The 35° deflection plates are curved to give maximum deflection sensitivity. In contrast to the bending magnet they replace, they require negligible power. While the vacuum chamber construction in the 2-1/4-in gap between the pole pieces of the magnet imposed a conductance limit on pumping speed to a small fraction of the pump capability, the test stand chamber which houses the deflection plates has only a small limiting effect; the new chamber will have virtually none. Deflection voltage breakdowns are infrequent in spite of low energy beam bombardment of the plates when they are set for full energy H⁻. When breakdowns occur, they are usually triggered by high-voltage breakdowns in the source.

Source Performance

A number of problems have been encountered in efforts to determine beam magnitude and quality. Not all of them have been solved. The problems stem in part from the large number of beam components which have to be separated and measured against a background of stray energetic electrons from the suppressor grid and the electrostatic deflection regions. Efforts to obtain emittance measurements with a single slit followed by an array of strip collectors whose amplified signals are processed by an on-line computer, as at NAL, have thus far failed because of poor signal-to-noise ratios for the small currents we are trying to measure. A two-wire probe with signals developed across 10³Ω resistors has given us beam width information we were unable to obtain with the emittance gear. (Modifications now in progress are expected to eliminate the problems we have had with the emittance gear.)

A spectrum obtained with a Faraday cup having a 3-in diam aperture is shown in Fig. 3. The cup was located at the exit from the main chamber, 14.5 in from the source exit plane. Four peaks are discernible. The first, and largest, is due to 15.5-keV electrons from the suppressor grid. The second is due to 20 keV H⁻, the third to 22.5 keV H⁻, and the last to 30 keV H++. Subtraction of a 4-mA background gives 14 mA for the 30-keV peak. The components are not fully resolved; stray electrons, as well as 22.5 keV H⁻, may be contributing to this 14-mA peak. When the Faraday cup aperture was reduced to a 1.25 in x 2.5 in vertical slit, the maximum beam obtained at this position was about 10 mA.
The spectrum of Fig. 4 was obtained with the vertical aperture and the cup mounted at the exit of the box which holds the probe drive for profile and emittance measurements. The peaks are due to 18-keV H\textsuperscript{+}, 18.5-keV electrons, and 24-, 27-, and 36-keV H\textsuperscript{+}.

A horizontal scan with wires 21.5 and 26.5 in from the source was obtained with the source operating under the same conditions. The profiles are shown in Fig. 5. Most of the beam (more than 99\%) is retained if beam widths are defined as shown in Fig. 5. We then obtain 2.26 in and 2.63 in for the beam widths in planes 21.5 and 26.5 in from the source. The apparent beam divergence is thus 37 mrad at the 21.5-in plane. A vertical scan under similar conditions gives widths of 2.25 and 2.69 in at the 21.5- and 26.5-in planes and an apparent divergence of 44 mrad at the first plane.

The results obtained to date indicate that the maximum effective beam diameter at the plasma boundary is \(\sim 70\%\) of the exit aperture diameter. Using this value, the beam divergence at the exit of the charge exchange cell is calculated to be about 25 mrad. The energy gain in the H\textsuperscript{+} accelerating gap reduces this to about 18 mrad. The difference between these values and the measured vertical divergence of \(\sim 44\) mrad at the 21.5-in plane must be due to space charge spreading of the beam. A feel for the effect of space charge in the current and energy regimes of interest here is obtained by noting that a 10-mA, 36-keV H\textsuperscript{+} beam which is initially parallel will double in size over a drift space equal to 23.5 beam diameters and acquire a half angle divergence of 38 mrad.

The beam divergence and size in at least one plane (the vertical) can be reduced by relocating the suppressor grid to the vicinity of the charge exchange cell and eliminating the ground grid, thus converting the H\textsuperscript{+} accelerating gap into an electrostatic lens. This will not be attempted until we have some good emittance measurements to guide the lens design effort.

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References


