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A PROTOTYPE HIGH CURRENT, HIGH DUTY FACTOR NEGATIVE HYDROGEN LON SOURCE FOR LAMPF*

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Introduction

Present plans for the high current proton storage ring at LAMPF incorporate charge changing (stripping) injection of H⁻⁻ ions in all modes of operation.¹ Achievable stored current levels in this device will be strongly dependent on the maximum H⁻⁻ beam intensity which can be accelerated by the linac, consistent with acceptable beam spill. This requirement has stimulated a program to develop an H⁻⁻ ion source capable of providing a suitably high peak current (up to 25 mA) at high duty factor (up to 12%), with a normalized x,x' or y,y' emittance acceptable to the accelerating system. The value of this last parameter is not completely defined for high current operation, but appears to be restricted to less than 0.15 π cm-mrad.

There are presently two main approaches which could lead to H- ion sources providing this kind of performance. These are a) the charge exchange method. in which an intense proton beam is fractionally converted to HT beam in a suitable charge adding medium, and b) the direct extraction method, in which HT ions are obtained by a surface emission process associated with a gas discharge plasma. The first method has been used (with H₂ as the exchange medium) for a number of years at several accelerator installations (including LAMPF) to produce moderate pulsed H⁻ ion currents.² More recently, a high current multiple-aperture H+ source has been used with cesium as the charge exchange medium to produce DT currents of 30-50 mA in DC operation.³ The direct extraction technique has lately been developed to yield very large H⁻ currents by the Novosibisk group in the USSR,⁴ and these results have now been thoroughly reproduced in the US by the group at BNL.⁵ Most of the direct extraction work has been at very low duty factor pulsed operation, and it is not clear how such sources will scale to high duty utilization. Furthermore, it appears that the emittance of the beams extracted from such H⁻ sources is not small $(0.2\pi$ - $0:3\pi$ for 25 mA). The charge exchange method, on the other hand, has been shown to be capable of high duty or even DC operation, and as far as can be determined. should yield beam emittances comparable with or smaller than these values.

While both approaches may eventually find optimum application in different situations, it is not obvious, at present, which scheme will turn out to be the most satisfactory for LAMPF. A prototype charge exchange H⁻⁻ ion source has been constructed as a first step in the development program and is presently being evaluated. Work on surface emission direct extraction techniques is in the planning stages.

Charge-Exchange Scheme and Choice of Exchange Gas

The charge-exchange approach to H⁻ beam production can be outlined as follows. A high current H⁺ ion beam is generated at a suitable energy by a discharge plasma and extraction system. In order to obtain large beams in the low energy (keV) range it has been found necessary to employ devices having large extraction areas and closely spaced multiple aperture (accel-decel) extraction electrodes. This is a consequence of the Child-Langmuir-Schottky law, governing the relation between the space charge limited extracted ion current and the parameters of the extraction geometry:

$$I = \frac{4A\varepsilon_0}{9} \left(\frac{2e}{m}\right)^{1/2} \frac{V_0^{3/2}}{d^2} \text{ amperes/m}^2 \tag{1}$$

where I is total extracted ion current, A is the area of the extraction electrodes, d the electrode spacing, V_0 their potential difference, and e/m and ε_0 have their usual meanings. The H⁺ beam is projected through a windowless thin gas or vapor target, where a fraction is converted to H⁻ beam by one of the following processes.

(1)
$$H^{+} + X \rightarrow H^{\circ}(1S) + X^{+}$$

 $H^{\circ}(1S) + X \rightarrow H^{-} + X^{+}$
(2) $H^{+} + X \rightarrow H^{\circ}(2P) + X^{+}$
 $H^{\circ}(2P) \rightarrow H^{\circ}(1S) + v(1.6 \times 10^{-9} \text{sec})$
 $H^{\circ}(1S) + X \rightarrow H^{-} + X^{+}$

where X represents the target atom. Whether the process goes through the H° ground state or its first excited state depends on the difference $|\Delta E|$ between the internal energies of initial and final configurations, the reaction having the smaller $|\Delta E|$ being favored. After emerging from the charge exchange cell, the H⁻ beam is accelerated and focused by an electrostatic lens system. For LAMPF accelerator application, it would then be suitably matched to the accelerating column of the Cockroft-Walton injector, accelerated to 750 keV, and transported to the linac.

The basic choices in development of a practical charge exchange H⁻ source lie in what kind of H⁺ generator to use, and what charge exchange material to select. Due to the variation in optimum H⁺ energy and H⁺ \rightarrow H⁻ conversion efficiency for possible charge exchange media, these are closely coupled matters. We have chosen to concentrate on the alkali metal vapors (particularly cesium and sodium), which have maximum conversion efficiencies at beam energies of 0.5-5 keV. This choice has dictated selection of an H⁺ injection system optimized for low energy operation, which at present is a multiple aperture reflex-arc duoplasmatron of the LLL MATS II type.⁶ It may be advantageous eventually to replace it with a device designed along the lines of the LBL H⁺ source, which appears to have at least a 5 times higher output brightness.

Table I compares the relative suitability of the common aikali vapors and the more conventional H₂ as charge exchange media for H⁻ ion production. Row 1 lists the maximum equilibrium H⁻ fraction (F^{on}) after traversal of the medium, row 2 the H⁺ beam energy (E_m) corresponding to the maximum, row 3 the H⁺ current required I(H⁺) at E_m for 25 mA of H⁻ ions, and row 4 the minimum power P(H⁺) required by the extraction system to generate this beam. The data for F^{on} and E_m were obtained from Ref. 7 for Li, Na, K, and Cs. The bracketed F^{on} and E_m data for cesium are those of Ref. 8, which are not inconsistent with those of Ref. 7, since they represent an extension to lower H⁺ energy.

As can be readily seen, the use of any of the alkali vapors as the charge exchange medium represents an enormous savings in the power needed to produce the

TABLE I

Target	F°	Em(eV)	I (H+) (mA)	P(H+)(watts)
Li	.06	3,500	416	1,456
Na	.12	2,500	208	520
к	. 14	1,300	178	231
Cs	.21 (.26)	750 (400)	119 (96)	89 (38)
H ₂	.02	15,000	1,250	18,750

initial H⁺ beam, in comparison with the use of H₂. Actually this is a very conservative estimate, since the additional power in the discharge (much greater for the large H⁺ currents needed in the H₂ case than for the alkalis) has been neglected. Cesium is by far the most efficient H⁺ + H⁻ converter. However, it suffers from the fact that very low beam energy is required to achieve this efficiency, and the V^{3/2} factor in Eq. (1) makes it difficult for the H⁺ source to supply sufficiently large currents. Sodium vapor, whose efficiency (H⁺ → H⁻) is .12 at a much higher beam energy (2.5 keV) is probably a more satisfactory charge exchange medium. Furthermore, the maximum in the energy dependence curve of F[∞] for sodium is broad compared with that for cesium; the conversion efficiency does not fall below .10 for H⁺ beam energies up to 5 keV.

A number of other factors enter the picture, in addition to those implied or explicit in Table I. The most important is the brightness or 4-dimensional phase space density $B = 2I/\epsilon_X \epsilon_Y$ of the H⁻ beam produced in the charge exchange process, where ϵ_X , ϵ_Y are the normalized areas in (x,x') and (y,y') space occupied by a beam of current level I. The output current of the MATS II source (for a given extraction and collection geometry) has been shown to depend on extraction voltage roughly as $V^{3/2}$. Since the geometry of the apparatus is fixed, the un-normalized "acceptance" areas $\epsilon_X/\beta\gamma$ and $\epsilon_Y/\beta\gamma$ are independent of beam energy, and the normalized 4-dimensional emittance is then proportional to $(\beta\gamma)^2$. The H⁺ beam brightness then varies approximately as

$$B(H^{+}) \sim \frac{V^{3/2}}{(\beta\gamma)^2} \sim \frac{V^{3/2}}{V} = V^{1/2}.$$
 (2)

Neglecting the scattering which occurs in the H⁺ \rightarrow H⁻ conversion process, the resulting H⁻ beam brightness varies as B(H⁻) ~ (F^{\infty})B(H⁺) = F^{\infty}V^{1/2}. From Table 1, the values of this relative brightness factor (arbitrary units) are: Li(3.5), Na(6.0), K(5.0), Cs(5.8), and H₂(2.4). If we consider the value for sodium at E = 5 keV, where F^{\infty} = 0.10, this parameter rises to 7.0.

Given the goal of maximizing both H⁻ intensity and beam brightness, without excessive power consumption, the previous considerations suggest that sodium is the optimum charge exchange medium. However, for experimental reasons, the first measurements on the prototype charge exchange source are being conducted using cesium.

Description of the Test Stand

The essential components of the charge exchange ion source test stand are schematically indicated in Fig. 1. More detail is shown in Fig. 2, a photograph of the test stand, with the first vacuum chamber open.



Fig. 1. Schematic representation of the charge exchange H⁻ ion source test stand.



Fig. 2. View of ion source test stand showing H⁺ generator, change exchange cell, and beam calorimeter.

The positive ion generator is a LLL MATS II type multiple aperture ion source, whose construction and performance characteristics have been adequately described in the literature.⁶ The plasma and accel-decel machined copper grids incorporate 279 holes in a hexagonal array, with 0.27 cm between centers. Hole diameters are: plasma grid (0.16 cm), accel grid (0.20 cm), and decel grid (0.16 cm). The plasma forming region is operated at extraction potential relative to ground, and is supplied by electronics located in an insulated rack powered by a 20 KVA isolation transformer. A UV window in the vacuum wall between the anode and plasma boundary grid permits spectroscopic observation of the plasma in this region.

The vacuum system to which the MATS II source is coupled is modular, consisting of a set of rectangular steel frames covered by demountable aluminum plates on four sides. All experimental hardware is mounted on these plates, which permits considerable flexibility in altering the configurations of diagnostics, etc. Each vacuum box is pumped by a single 2400 %/sec diffusion pump through a water cooled chevron baffle.

The alkali vapor charge exchange cell is designed for use with either cesium or sodium. Construction details are shown in Fig. 3, a photograph of the unit mounted on its supporting plate. The system consists pasically of a heated and valved stainless steel reservoir (25 g capacity for cesium) and a recirculating charge transfer cell. The cell is a 3.2 cm (1.D.) stainless steel tube, 36 cm long, containing three layers of #160 stainless steel mesh pressed into its interior surface. The central 15 cm is clamped in a copper block heated by coaxial heater wire; this region can be elevated to 250°C. The ends of the steel tube are clamped in independently heated (or cooled) copper blocks which are used to maintain these regions at a temperature slightly above the solidification point (29°C for cesium, 98° for sodium). The central region is run with liquid alkali metal in the mesh in equilibrium with its vapor at a temperature high enough to provide adequate target thickness for optimum $H^+ \rightarrow H^$ conversion. As the vapor proceeds towards the ends of the cell it condenses on the cooled walls and is returned by capillary action in the mesh to the central region. This recirculating technique reduces the loss of alkali vapor from the cell by a very large factor (up to 1000), minimizing contamination of the vacuum system, electrical breakdown of the extraction system, and consumption of the alkali metal.⁹

Instrumentation

The total beam current and its charge state composition are measured by two independent systems. The first is a combined calorimeter and guarded Faraday cup, located 20 cm downstream from the charge exchange cell. A set of apertures can be selectively interposed between the beam detector and the cell, and the entire system can be scanned across the beam diameter permitting both beam profile and total beam measurements. This instrument is used for measurement of the beam current and power distribution transmitted through the charge exchange cell, and provides no information on charge state composition.



Fig. 3. Alkali vapor charge exchange cell and supply reservoir mounted on vacuum box lid.

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The latter is provided by a magnetic differential analyzing system located in the second vacuum chamber. In this arrangement, a 1 mm aperture is scanned horizontally across the beam from the charge exchange cell.

The beam pencil defined by this collimator is passed through a uniform field electromagnet which splits it into the various positive, negative, and neutral components present. In addition to the H⁻, H⁺, and H^o fractions, there are also the H_2^+ , H_3^+ , and positive, negative, and neutral beams arising from charge exchange and dissociation of these ions in the alkali cell. The negative and positive beam components are deflected by 30° into two electrostatically guarded Faraday cups. The neutral component is incident on a negatively biased clean copper surface, and measured by secondary electron emission.

Program Status

The charge exchange H⁻ source test stand is now sufficiently complete for a program of measurements to be initiated. The H+ source has been run, briefly, at I keV beam energy, producing up to 25 mA of positive ions transmitted through the charge exchange cell, with no alkali vapor present. Given the ratio of the beam diameter for our starting geometry and that of Ref. 6, this is about what should be expected. The charge exchange cell has been tested with cesium in a separate vacuum chamber, and satisfactory wetting and loading of the stainless steel 'Wick" has been observed. As can be seen in Fig. 3, the cell is provided with a flap closure system for sealing off the open ends, so that the entire tube can be heated to a high temperature during startup; this is necessary to induce proper wetting of the mesh by the alkali metal. A preliminary experiment with the H+ source running and the charge exchange cell loaded with cesium has indicated difficulties in holding voltage across the accel-decel electrodes. However, testing is at a much too early stage for any substantial conclusions to be drawn at present.

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