STATUS OF THE LAMPF H^- INJECTOR*

by

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ABSTRACT

Simultaneous acceleration of H^+ and H^- beams at LAMPF is planned, with the H^- beam to be used as an independently controlled source of 800-MeV protons for use in nucleon physics investigations. As such the H^- design intensity is low, variable up to 1.67-mA peak (100-μA average). Initial operation of the H^- injector, expected in January, will be at about 10% of this level. Research on H^- sources yielding up to 2.5 mA is presented, along with details of the injector installation.

I. INTRODUCTION

The development of an H^- ion source at LAMPF has centered around charge exchange of protons in hydrogen. Although a maximum of only 2% of the proton beam can be converted to H^- ions by this method, it has the advantage of not requiring additional substances in the vacuum system and the hydrogen outflow from the proton source can be channeled into a charge exchange canal so that no increase in hydrogen flow is required. The H^- beam intensity is then determined by exchange efficiency, target thickness, and the amount of proton current extracted and transmitted through the charge exchange canal. The maximum H^- yield, assuming sufficient target thickness to reach charge exchange equilibrium, is proportional to $\eta V^{3/2}$ for a given extraction geometry, $\eta(V)$ being the equilibrium H^- fraction and V being the beam extraction voltage. Although η is a maximum of 0.02 at 15 keV, $\eta V^{3/2}$ is still increasing at 50 keV, as shown in Fig. 1. Operation near 15 keV is desirable to minimize source and power supply requirements.

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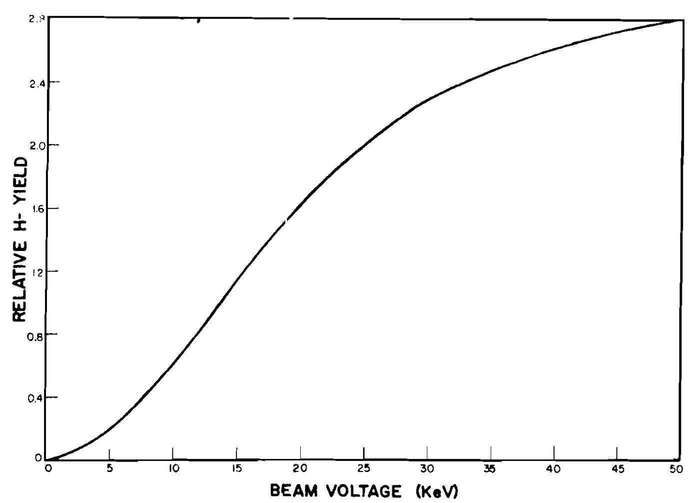

Fig. 1. Relative expected H^- yield vs beam voltage (V) where yield is $\eta V^{3/2}$, η being the equilibrium fraction of H^- in hydrogen gas.

II. EXPERIMENTAL DEVELOPMENT

A. General Remarks About Source Development

Both single aperture source (SAS) and multiaperture aperture source (MAS) types have been investigated for LAMPF, and there are certain features common to both.

Most interesting of these is the predominance of H_2^+ ions in our extracted beam. Whereas the duoplasmatron source output is known to be 75/25 H^+/H_2^+, the measured H^- yields show that the ratio is about 50/50 when the source is used with the charge exchange canal. It is believed that the reaction

$$p + H_2 \rightarrow H^0 + H_2^+ - 1.8 \text{ eV}$$

occurs in the expansion cup region with a cross section of about 10^{-15} cm^2, as evidence by an experiment in which a pressure of 5 μ of D_2 was introduced into the expansion cup region. The resultant negative ion beam contained comparable components of H^- and D^- originating from H_2^+ and D_2^+, respectively, but very little D^- from D^+ extraction.

The main disadvantage of using an H_2^+ beam is that its dissociation leads to an energy spread[2]

$$\Delta\phi = \pm 2\sqrt{\phi_0 \phi_d}$$

(where ϕ_0 is the beam energy and ϕ_d is the dissociation energy) or ± 600 eV at 20-kV extraction. This energy spread and the associated emittance increase do not appear to be a problem for use with LAMPF; however, the resulting H^- beam will consist of one component at twice the extraction potential for $H^+ \rightarrow H^-$ and another at 3/2 this potential for $H_2^+ \rightarrow H^-$, giving two beams at the linac separated in energy by half the extraction voltage, unless steps are taken to suppress one component. In addition there will be some H^- beam deficient in energy by as much as the extraction voltage due to charge exchange of protons in the accelerating gap.

For a single gap extractor of radius r and gap d the space-charge limited current is found to be approximately[3]

$$i = I_0 (V/V_0)^{3/2} (r^2)/(d + r)^2 \quad . \qquad (1)$$

Satisfactory focusing of the beam requires[4] $r/d \leqslant 0.5$, which should give $I_0 \sim 200$ mA at $V_0 = 15$ kV. If more current is required, a multiaperture source will in principle allow the production of arbitrarily large currents.

Gas contaminants in the arc can be a serious problem,[5] since they will reduce the space charge limited current sharply if they produce ions with a low value of e/m. In an experiment to examine the magnitude of this effect either oxygen or air was introduced into the arc chamber along with the normal amount of hydrogen, and the negative ions produced were analyzed with a magnet capable of deflecting 30-keV mass 20 ions into a Faraday cup. The negative ion yields were measured as a function of contaminant percentage (Fig. 2), calculated from the measured gas flows and the relative conductance of the source aperture for different gases. Introduction of either gas is seen to reduce the H^- yield dramatically, and introduction of oxygen greatly increases the X^- yield, thus identified as oxygen. Magnetic analysis indicates mass 18 ± 4. When no external gas is added there is a 10% heavy ion yield, dropping to 5% after pumping several hours after opening the system. This would be accounted for by the observed system partial pressure of 2 x 10^{-8} mm of water if all the contaminant ions originated in the source. This result points out the need for good vacuum practice, although about a dozen unbaked Vitor O-rings were used in the test source.

After extraction the beam enters the charge-exchange canal, which is biased so as to prevent electrons produced in the charge-changing collisions from being accelerated into the duoplasmatron and to retain them in the canal for charge neutralization of the positive ion beam. In practice it has been found that the optimum H^- yield occurs at a bias voltage just below the trapping voltage, so that a relatively large current is drawn from the canal power supply. The reason for this is not known although it may be the result of partial space charge neu-

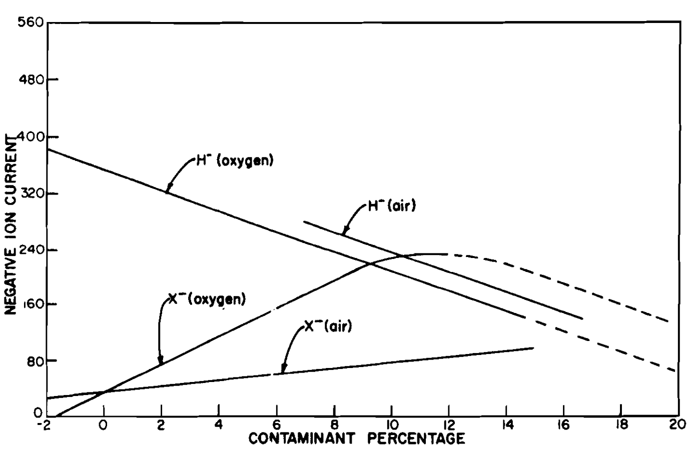

Fig. 2. H^- and heavy negative ion yield vs percentage air or oxygen in the duoplasmatron arc chamber at 15-kV extraction voltage. Data points have been eliminated for clarity, and the heavy ion yield has been extrapolated to zero, indicating about 2% contamination of the arc under normal operating conditions.

tralization in the accelerating gap. Experiments with an extractor grid, which caused a large increase in supply current, lend support to this supposition.

Measurements on source performance have included extracted current, neutral current equivalent at the charge exchange canal exit, H^- current, energy, momentum, and emittance. All currents were measured calorimetrically except for the negative ion beam, for which the Faraday cup was found to be reliable. The Bate[6] code was used to calculate extracted current, and it was found that the predictions were 10-20% high, which is reasonable agreement in view of measurement uncertainties. In a study of the duoplasmatron, a calorimeter was used as as an extractor. Extracted current was found to be independent of extraction voltage, as expected, and was 5 mA/A arc current for an anode aperture of 1.0 mm (Fig. 3), with little dependence on gas flow or magnetic field. In subsequent experiments extracted proton currents for a given extraction geometry were often inferred from this fact rather than measured. The resulting H^0 and H^- conversions were always substantially lower than the expected values of 88% and 2% respectively. The reason for this may be lack of proper neutralization in the canal; the H^- yield was only 10-50% of the expected value for all sources investigated. A 30° bending magnet before the Faraday cup is sufficient to eliminate electrons and heavy ions, and energy analysis has been made with a Faraday cup capable of holding a retarding potential of up to 50 kV for the purpose of definitely identifying H^- ions produced from H^+ or H_2^+ beams.

Emittance measurements were made by observing the beam pattern after it had passed through a 9 x 9 grid of 0.05 mm holes and drifted 1 cm to a quartz scintillator.

B. Single Aperture Source

Following the experimental work of Harrison,[4] a set of electrodes with various hole sizes and spacing was fabricated (Fig. 4), and H^- current was measured as a function of pertinent parameters. The measured perveances when optimized for H^- yield (with proton current inferred from arc current) compared favorably with the Harrison predictions, but the H^- yield was a maximum of 20% of the expected value. As shown in Fig. 5, H^- yield rises steeply with canal voltage in a manner expected if the extracted beam were mostly H_2^+, as believed. Variation of H^- current with source gas flow, or equivalently, target thickness, was anomalous. As shown in Fig. 6, the measured cross sections[1] predict a leveling off at approximately 100 μcm thickness. The increased power supply current that accompanies increased gas flow may help focus the beam in the extractor gap, since optimum performance requires canal bias voltage set to give large canal current. When a grid was used over the extractor, the H^- yield varied as predicted with gas flow. The power supply current was then high, presumably due to acceleration of secondaries produced by beam impingement on the grid. Although grids are not likely to survive at the LAMPF

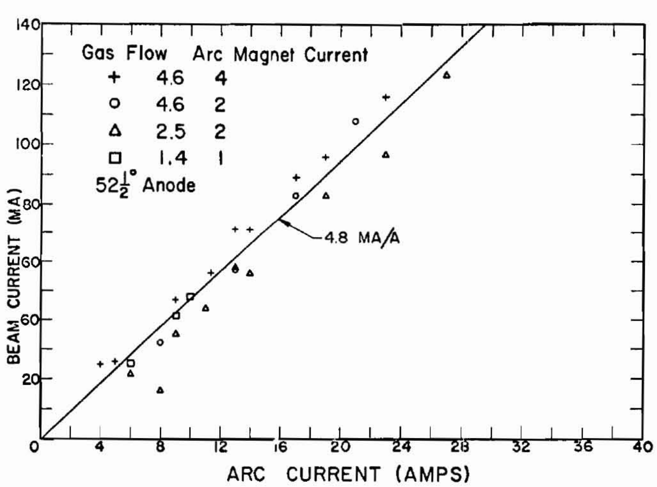

Fig. 3. Variation of extracted positive ion current with arc current for various gas flow and arc magnet current settings.

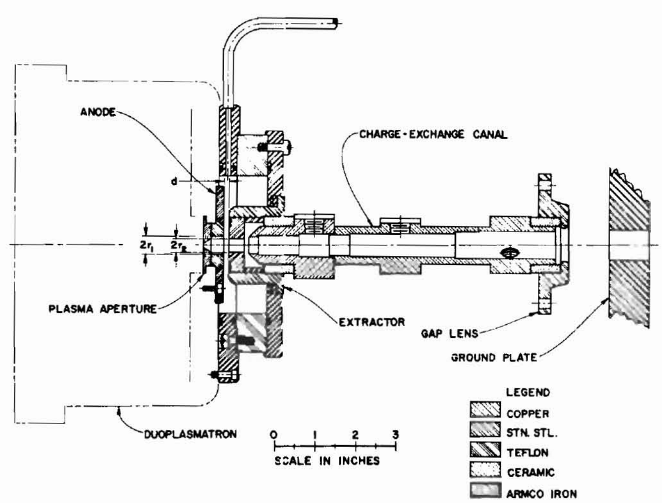

Fig. 4. Single aperture extraction H^- ion source employing flat plate electrodes.

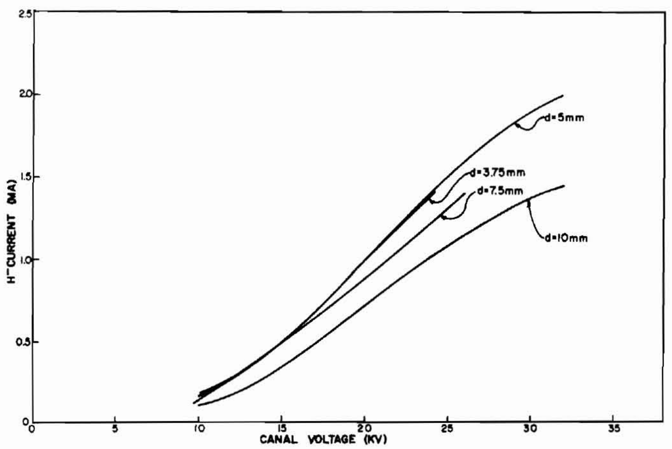

Fig. 5. H^- current vs canal voltage for a flat plate SAS, $r_1 = 7$ mm, $r_1/r_2 = 1.5$, for various values of extractor gap d.

duty factor of 6%, the experiment showed that the conversion efficiency is still only a third of the expected value and that a copious supply of electrons in the accel-gap is beneficial.

Since a single electrode extractor will cause field perturbations due to its finite aperture, an experiment was tried using an extra accel electrode to correct the field shape. The extractor electrode was operated at 15 kV, the accel electrode was varied up to 60 kV, and the charge exchange canal was kept at 15 kV. With 45 kV accel potential, the field bulge at the 15-kV electrode should have been removed and the field at the plasma should then have

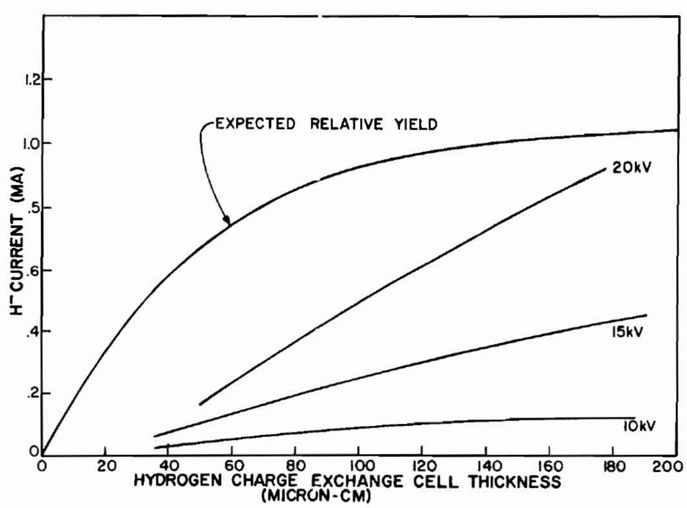

Fig. 6. H^- yield vs target thickness for three canal voltages. The expected yield curve is calculated from the known charge transfer cross section (Ref. 1). A single aperture source with flat plate electrodes was used where $r_1 = 7$ mm, $r_2/r_1 = 1.5$, and d = 5 mm.

been unaffected by the extractor aperture size. Two experiments were carried out, one using a separate charge exchange canal gas feed with Pierce extractor and anode electrode shapes and the other (Fig. 7) using gas flow from the source for the canal with a tapered cone extractor geometry. Both geometries yielded about 75% of the predicted proton current but only 10-20% of the expected H^-. Increased accel voltage improved H^- yield, but the beam divergence in the canal still appeared to be the main loss factor. Since the two-electrode extractor appeared to offer no advantage, this approach was dropped.

C. Multi Aperture Source

The multiaperture source (MAS) has a grid of plasma-extractor apertures, each aligned and designed to produce parallel beamlets. Thus, the current limit of (Eq. 1) for a single aperture source can be overcome; this approach has been used successfully by several experimenters.[7,8] A LAMPF version of a MAS is shown in Fig. 8. Some experiments have been carried out with a 7- and 19-hole MAS, and the results of H^- yield with the latter vs canal voltage are shown in Fig. 9. At high extraction voltage, the H^- yield was estimated to be about 1% of the extracted current (where 2% is expected); however, the extracted current was only about a third of the expected value. This loss is attributed to the fall-off of the plasma density at the outer holes of the plasma-extractor aperture plate, as was evident from visual observation of the H^- beamlet pattern at the Faraday cup viewing screen. Emittance of

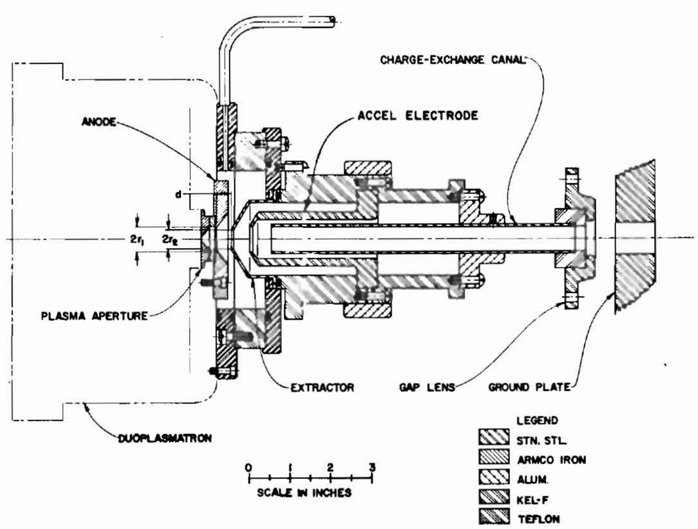

Fig. 7. Layout of an experimental dual extractor ion source.

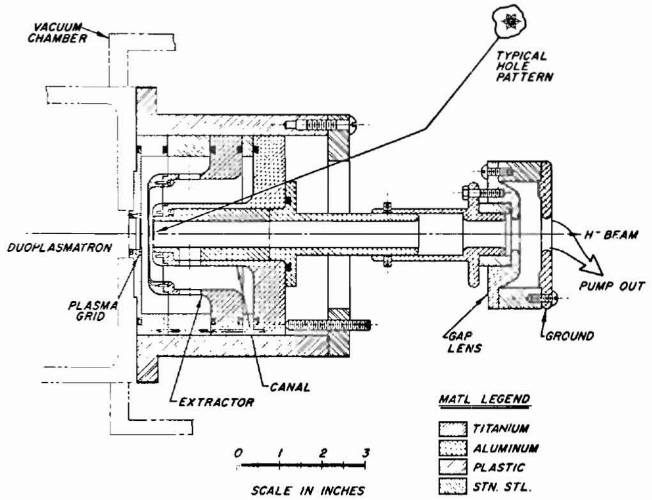

Fig. 8. Layout of multiaperture ion source.

the 19-hole MAS beam was about 2.5 cm-mrad (750 keV equivalent). Further experiments on MAS will include a 37 aperture model, and more extensive calorimetric measurements.

III. H^- INJECTOR SYSTEMS

The H^- ion source will be housed in the equipment dome of a 750-kV injector: the Cockcroft-Walton high-voltage generator and controls will be similar to those now in operation in the H^+ injector.[9] The ion source will be mounted on a rail structure that is to be housed on the entrance cone of the accelerating column. The design is modular in concept so that different plasma generators or extractor electrodes can be installed. A gate valve has been inserted following the change exchange canal so that modifications can be made to the ion source end of this system without having to let the accelerating column up to air.

The accelerating column and dome vacuum system, together with the H^- ion source, are shown in Fig. 10. The design is almost identical to that employed in the H^+ injector[9] except for the ion source and the electrode configuration in the column. Since the design current requirements for the H^- beam are an order of magnitude less than those for the H^+ beam, a uniform gradient accelerating tube can be used rather than the Pierce design. Therefore, thin planar electrodes with large apertures have been employed. Provision has been made to bias the last electrode of this column to prevent positive ions from backstreaming up the accelerating tube.

IV. COLUMN AND GAP LENS OPTICS

The beam extracted from the H^- ion source will be focused to a crossover in front of the accelerating column by means of the tandem gap lens. This lens system consists of a series of three ungridded, electrostatic aperture plates with ~ 2-cm apertures. The lens is capable of focusing the H^- beam in the charge exchange canal to a 2-mm diam at the object point of the column. In order to eliminate loading the accelerating column with energetic H^0 and electrons, a plate with a 2-mm aperture has been placed at the object point of the column. This 2-mm aperture then acts as an effective source for the accel-

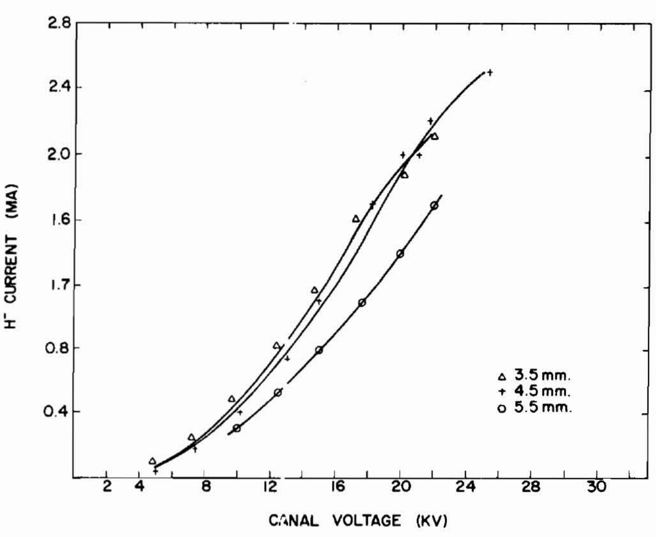

Fig. 9. H^- yield vs canal voltage for a 19-hole MAS with r_1 = 1.5 mm, r_2 = 1.0 mm and various values of d.

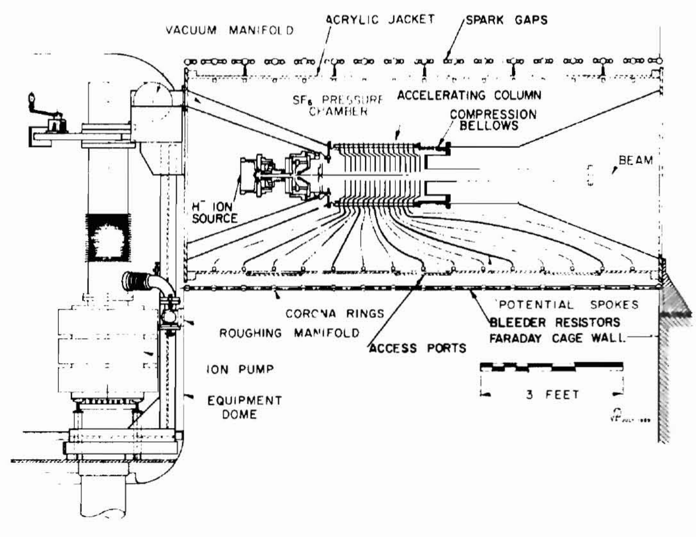

Fig. 10. Layout of the H^- accelerating column showing the dome vacuum manifolds and the H^- ion source.

erating tube. The initial ion source layout is shown in Fig. 11 and is similar to a test stand version which yielded up to 2.2 mA (Figs. 4 and 5).

The object distance has been chosen somewhat larger than the entrance focal length of the accelerating tube so that the size of the beam leaving the accelerating tube will be nearly equal to the size of the beam at the object aperture plate. This choice results in an image distance of 129 cm and a tube magnification of -3.45. The focusing and magnification trajectories are shown in Fig. 12.

Calculations[10] have been carried out to determine the transfer matrix for this accelerating tube design. The transfer matrix from the object plane to the exit of the accelerating tube is given by:

$$R = \begin{pmatrix} R_{11} & R_{12} \\ R_{21} & R_{22} \end{pmatrix} = \begin{pmatrix} -1.000 & -0.166 \\ -0.032 & -0.204 \end{pmatrix}$$

where

$$\begin{pmatrix} x \\ x' \end{pmatrix} = R \begin{pmatrix} x_0 \\ x'_0 \end{pmatrix} \quad \text{and} \quad \begin{pmatrix} y \\ y' \end{pmatrix} = R \begin{pmatrix} y_0 \\ y'_0 \end{pmatrix}$$

and where the pertinent dimensions are in cm and mrad. Using this transfer matrix, the phase space distributions expected at the exit of the accelerating tube have been calculated for a series of en-

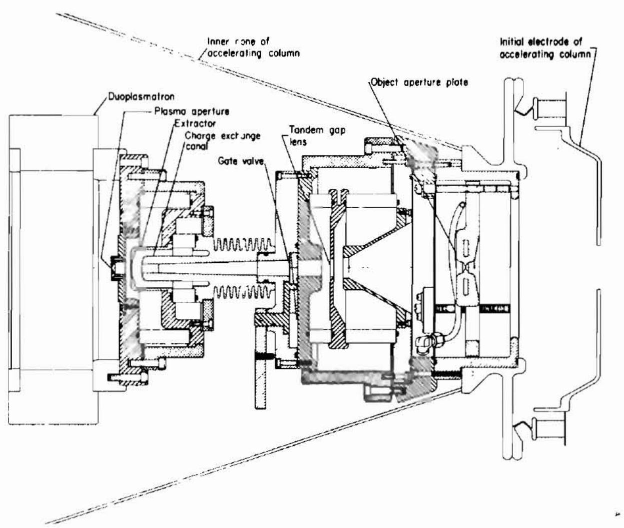

Fig. 11. Layout of H^- ion source (SAS with flat plate electrodes) showing the tandem gap lens and object aperture plate.

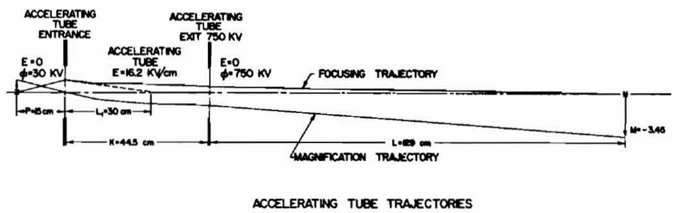

Fig. 12. Magnification and focusing trajectories for the H^- accelerating column.

trance aperture size and are presented in Fig. 13.

V. BEAM TRANSPORT SYSTEM

The beam transport system for the H^- injector will be patterned very closely to the system now in operation for the high intensity H^+ injector. The transport magnets will be identical so that replacement by substitution can be made in the future if necessary. The transport optics will be similar to that for the H^+ beams except that the beam size in the H^- transport line will be smaller because of the lower beam current. No prebuncher is planned initially in this beam line since the expected reduction of H^- beam loss in the linac afforded by the operation of a prebuncher is not significant for the low current H^- beams now envisioned. Beam diagnostic systems similar to those now in use on the H^+ beam line will be incorporated on the H^- beam line and will include emittance scanners, beam current transformers, viewing screens, and beam position monitors.

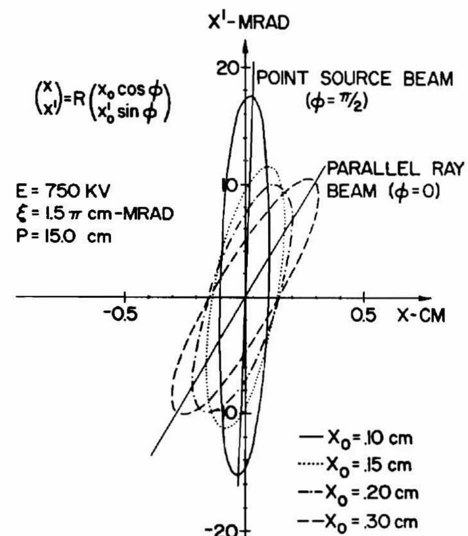

Fig. 13. Calculated phase space orientations expected for the H^- beam at the exit of the accellerating column.

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