A TANDEM ACCELERATION HIGH INTENSITY H^- ION SOURCE*

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ABSTRACT

A source capable of providing at least 10 mA of H^- ions for injection into the linac, after acceleration to 750 keV, is required for the Zero Gradient Synchrotron (ZGS) booster injector program. A tandem acceleration ion source is being developed to satisfy this requirement. The source is theoretically capable of producing a measured current of 20 mA but has not yet done so. The largest currents obtained to date have been limited to about 10 mA for reasons which appear to be related primarily to H^- beam attenuation due to stripping in the beam analysis chamber, which separates the H^- source from the ion pump chamber in the geometry under consideration. Gas flow into the plasma source is continuous; outflow may be continuous or pulsed. Reduction of the average flow to 1 cm^3/min (760 Torr, 20° C) or less is a prerequisite for operation in the 750-keV terminal of the preinjector, where space and power for a conventional high speed, large capacity pump are not available.

Introduction

A source capable of providing at least 10 mA of H^- ions for injection into the linac, after acceleration to 750 keV, is required for the ZGS booster injector program at Argonne. A tandem acceleration ion source is being developed to satisfy this requirement.

A schematic representation of the present source geometry is shown in Fig. 1. Positive ions (H^+, H_2^+, H_3^+) are extracted from a hydrogen plasma and accelerated across a 2.5-mm gap. Those which are not intercepted by the extractor grid (of transparency $\tau_1 = 77.4\%$), enter directly into a 16.3-cm long charge exchange tube tapered to transmit a beam with an initial diameter $d_o = 1.19$ cm and a half-angle divergence of 15 mrad. The tube is filled with a target gas consisting of the hydrogen outflow from the plasma source.

In the tube, charge exchange and dissociation result in a beam with H^+, H^o, and H^- components having all, one-half, and one-third of full energy. For the

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purpose of this discussion, the full energy will be assumed to be 15 keV. Protons emerging from the charge exchange cell are stopped by a retarding field which adds 15 keV of energy to those fractions of the 5-, 7.5-, and 15-keV H^- beam components which are not intercepted by the suppressor grid (of transparency τ_2 = 77.4%).

Further details of the H^- source are shown in the schematic of Fig. 2. The positive ion source is a modification of the Pierce extraction extended stationary arc duoplasmatron described at the last linac conference.[1] The Pierce extraction geometry, with a 14.3-mm accelerating gap, has been replaced by a planar geometry with a 2.5-mm gap.

Gas flow into the source is continuous through the inlet shown in Fig. 2. Outflow into the charge exchange tube may be continuous, or it may be pulsed by means of a gate valve in the anode.

Bias voltages of 500 V on the extractor and suppressor grids prevent loss of electrons from the charge exchange tube. The electrons, produced by ionization of the target gas, are required to neutralize the space charge of the entering positive ion beam.

The method of injecting a high intensity, essentially parallel, ion beam directly (without an intervening drift space) into a charge exchange cell filled with the hydrogen outflow from a plasma source has been used previously by Dimov et al.[2] An improved version of the source of reference has produced a 15-mA, 13.5-keV H^- ion beam.[3]

Source Performance

The source under consideration here is theoretically capable of producing measured H^- currents of 15-20 mA, but has not yet done so for reasons which appear to be related primarily to attenuation of the H^- beam in the beam analysis chamber. The chamber followed the H^- source and preceded a 2400-liter/sec ion pump in the experimental arrangement used until early July of this year.

In early July the 2400-liter/sec ion pump, which had been used for almost six years in ion source testing and development, failed completely after several months of operation at reduced efficiency due to intermittent short circuiting of various pumping elements because of cathode warpage.

Our effort since the pump failure has been directed toward the construction of a new vacuum system which will use a titanium bulk sublimator and a

400-liter/sec ion pump in place of the 2400-liter/sec pump. The new system, with a number of needed improvements in the ion source and beam diagnostic equipment, has been completed and is being debugged. The new pump chamber has been placed between the source and the beam analysis chamber to reduce H^- beam attenuation in the magnetic field region of the analyzer.

For the present source geometry, the source is theoretically capable of producing approximately 13 mA of 30-keV H^- ions with an extraction voltage of 15 kV; but it fell far short of doing so with the configuration of source followed by the beam analysis chamber and then the ion pump chamber. As the voltage was raised above 15 kV, the obtainable beam current increased up to the highest voltages which could be held, i.e., about 20 kV. It will be shown below that this behavior is consistent with attenuation of the H^- beam in the beam analysis chamber.

With the gas shutter absent and a continuous gas flow of 9.5 cm^3/min (760 Torr, 20° C), an H^- beam of 8 mA was obtained. A positive ion current of about 2.5 mA was obtained at the same analyzing magnet setting. The extraction voltage was about 17 kV.

When the shutter was installed and the average gas flow was reduced to 1 or 2 cm^3/min, an H^- current of about 10 mA was obtained. The corresponding H^+ current was about 2 mA.

These results will be discussed after a consideration of the events occurring in the region between the source and the collectors of negative and positive ions.

Charge Exchange in a Deflection Field

The beam emerging from the negative ion accelerating gap consists of 5-, 7.5-, and 15-keV neutrals and 20-, 22.5-, and 30-keV H^- ions. The gas density in the source exit cylinder is still rather high; charge changing collisions add 15-keV H^- ions and protons covering the full range of possible energies to the list of particles emerging from the source.

In the geometry under consideration, the multicomponent beam emerging from the source enters a beam analysis chamber where the charged components are separated from each other and from the neutral beams which continue on through this chamber and into the ion pump chamber. A transverse magnetic field is used to separate the charged component beams.

A cross section of the beam analysis chamber is shown in schematic form in Fig. 3. Also shown are the trajectories of some of the charged beam components (some of the lesser components have been omitted) in the ideal case where charge exchange occurs at a negligible rate in the magnetic field region. The trajectories are for an initially parallel beam.

The assumption, used in drawing the trajectories, that the gas density in the beam analysis chamber is negligibly small is not even approximately correct; and, therefore, the actual situation is more complicated than that shown in Fig. 3 since particles which acquire or lose charge in the deflection field do not follow the trajectories as drawn.

A simple calculation shows that for the densities prevailing in the beam analysis chamber the 30-keV H^+ component, derived from 30 keV H^- by a double electron stripping process, is entirely negligible and could just as well have been omitted from Fig. 3. At the prevailing densities, the 20-, 22.5-, and 30-keV H^- beams will be attenuated by charge exchange losses in the magnetic field; however, the beam trajectories will remain well defined since the rates of production of new H^- ions of these energies, by cyclic charge exchange, are negligible.

On the other hand, the rates of production of 15-keV H^- and H^+ ions from neutrals are not negligible in the magnetic field region. In fact, the H^- and H^+ beams derived from 15-keV neutrals are both large compared to the 30-keV H^- beam. When the magnetic field is adjusted to collect 30-keV ions, 15-keV H^- and H^+ ions produced at various points along the H^o beam path will also be collected.

Symmetry of the collector geometry requires that 15-keV H^- and H^+ ions be collected at rates in the same ratio as their rates of production. If collisions between energetic particles having different velocities are ignored, a neutral beam of N_o particles/sec entering the magnetic field will be attenuated by the formation of n_- negative ions/sec and n_+ positive ions/sec in the gas target of π atoms/cm^2. In the present instance,

$$n_-/N_o \simeq 1 - e^{-\pi\sigma_-} \approx \pi\sigma_- ,$$

$$n_+/N_o \simeq 1 - e^{-\pi\sigma_+} \approx \pi\sigma_+ ,$$

and

$$n_-/n_+ = \sigma_-/\sigma_+ \simeq 0.20$$

where σ_- is the cross section for the production of H^- from H^o in H_2, and σ_+ is the corresponding cross section for the production of H^+. Thus in the case where a continuous flow of 9.5 cm^3/min of hydrogen gave an H^- beam of 8 mA and an H^+ beam of 2.5 mA at the same magnet setting, we may assume that the negative ion collector was receiving about 0.5 mA of 17-keV H^- ions. (Here we use the actual rather than the nominal value of the energy.)

Discussion of Results

The results obtained to date with a pulsed gas outflow are rather disappointing since they fall far short of expectations. Some insights into the difference between expected and actual results may be obtained from a detailed analysis of the results obtained with a continuous gas flow of 9.5 cm^3/min in the absence of the gas shutter. The analysis is based on the assumption that during the arc pulse of 350-μsec duration, steady state conditions similar to those obtained in continuous operation prevail.

For a given geometry, an approximate expression for the expected H^- current is

$$I_{H^-} \simeq \tau_1 \tau_2 \eta \Gamma_1 I_{total} \qquad (1)$$

where τ_1 and τ_2 are the grid transparencies, η is the proton to H^- conversion efficiency, and Γ_1 is the H^+ fraction of I_{total}, the total positive ion beam extracted from the plasma. η is a function of target thickness and H^+ beam energy and has a maximum value of 0.02 for a beam energy of 15 keV and a target thickness of 6.4×10^{15} atoms/cm^2, or about 100 μcm in terms of the product of the average pressure of the target gas and the length of the charge exchange cell.[4]

For arc currents of the order of 100 A, a reasonable estimate for Γ_1 is about 0.85. Using this value, along with $\eta = 0.02$ and $\tau_1 = \tau_2 = 0.77$, we find

$$I_{H^-} \simeq 0.011\, I_{total} .$$

A hydrogen gas flow of 1 cm^3/min (760 Torr, 20° C) is equivalent to 67 mA of H_2^+ or 134 mA of H^+ at 100% conversion efficiency. Given a flow of 9.5 cm^3/min, if 8 cm^3/min (about 84%) of the flow is converted into ion beam, with 75% of this (6 cm^3/min) going into H^+ and the remainder into H_2^+, we have

$$I_{H^+} = 6 \times 134 = 804 \text{ mA}$$

$$I_{H_2^+} = 2 \times 67 = 134 \text{ mA}$$

$$I_{total} = 938 \text{ mA}$$

$$I_{H^-} = 10.4 \text{ mA} \quad \text{(at the source)}$$

$$I_{H^-} = 10.4\lambda \text{ mA} \quad \text{(at the collector)}$$

where λ is an attenuation coefficient which can be calculated if the pressure distribution is known.

For molecular flow, the conductance of each portion of the vacuum chamber along the beam path can be calculated from the equation for the conductance of a short tube of circular or rectangular cross section:

$$F = 3638 \, KA(T/M)^{1/2} \, cm^3/sec \tag{2}$$

where K is Clausing's factor, A the cross sectional area, T the absolute temperature, and M the molecular weight in g/mole.[5] The steady state pressure distribution for a given gas flow can then be calculated. Such a calculation shows that a hydrogen flow of 9.5 cm^3/min constitutes a target whose thickness is about 9.7 μcm or 6.4×10^{14} atoms/cm^2. The 34-keV H^- beam is attenuated by approximately 20% in traversing this target. With $\lambda \doteq 0.20$, the previous expression for I_{H^-} at the collector gives $I_{H^-} \simeq 8.3$ mA. To this we should add 0.5 mA for the 17-keV H^- contribution to the collector current. This gives $I_{H^-} \simeq 8.8$ mA for the calculated collector current. Agreement with the measured current of 8 mA is fair, perhaps fortuitously so in view of the estimates and simplifying assumptions used in the calculation. We note in passing that for a given target thickness the H^- beam attenuation rate decreases with increasing energy, while H^- production increases.

Attenuation of the H^- beam is expected to be negligible with the new sublimation pump chamber placed between the source and the beam analysis chamber. An improved gas shutter, discussed below, is presently undergoing mechanical tests. It is expected to reduce the average flow rate to less than 1 cm^3/min. Successful reduction of the average flow rate is a major objective of the H^- source development program and a prerequisite for installation of the source in the 750-keV terminal of the Cockroft-Walton preinjector for the ZGS, where sufficient space and power for a conventional high speed, large capacity pump are not available.

The Pulsed Gas Shutter

Earlier models of the gas shutter used a thin, flat stainless steel blade as a gate in sliding contact with one end of an alumina cylinder having an inside diameter of 9.1 mm and a 1.6-mm thick wall. These shutters could be made to work freely or give a good seal, but not both simultaneously without reducing their lifetimes to several days or hours of operation.

The new valve is shown in Fig. 4. The stainless steel blade of the earlier models has been replaced by an alumina cylinder (with a diameter of 11.8 mm and a length of 28.6 mm), which slides inside of another alumina cylinder with two 9.5-mm diameter holes on the source axis. The sealing surfaces of the two cylinders are finished to about 10 μin., and the clearance between them is about 2×10^{-4} in. or 5 μ. The stroke is about 19.5 mm. Iron is kept far from the source axis to minimize the disturbance to the magnetic field in the plasma region. Viton rings are used as shock absorbers.

The opening and closing characteristics, in test bench operation with the valve uncapped to avoid compression of trapped air, are shown in Fig. 5. The upper trace is the output of a photodiode looking at a light source on the far side of the valve. The lower trace shows the current flowing through the valve solenoid. The sweep speed is 10 msec/cm. Capping of the valve will reduce the time during which the valve is open, since the cap functions as a spring in stopping and reversing the motion of the shutter.

Acknowledgements

A complete list of everyone who has contributed to the H^- source work would include every present and a number of former members of the Injector Group, most members of the Accelerator Division, and a very large number of Central Shops personnel. Pulsing of the gas outflow, rather than the inflow, was suggested by R. Perry. The present design of the gas shutter is the culmination of an effort to which A. Gorka, R. Wehrle, R. Batch, A. Suzuki, G. del Castillo, and R. Mogil have made important contributions.

References

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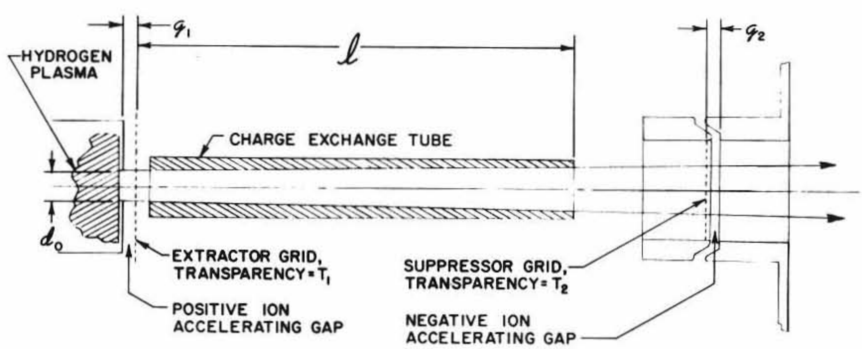

Fig. 1. A schematic representation of the tandem acceleration H^- ion source.

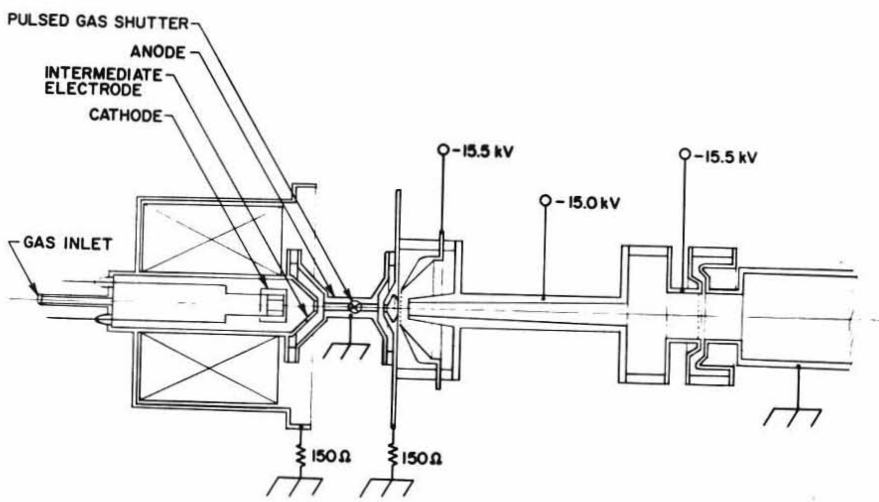

Fig. 2. A more detailed schematic of the source.

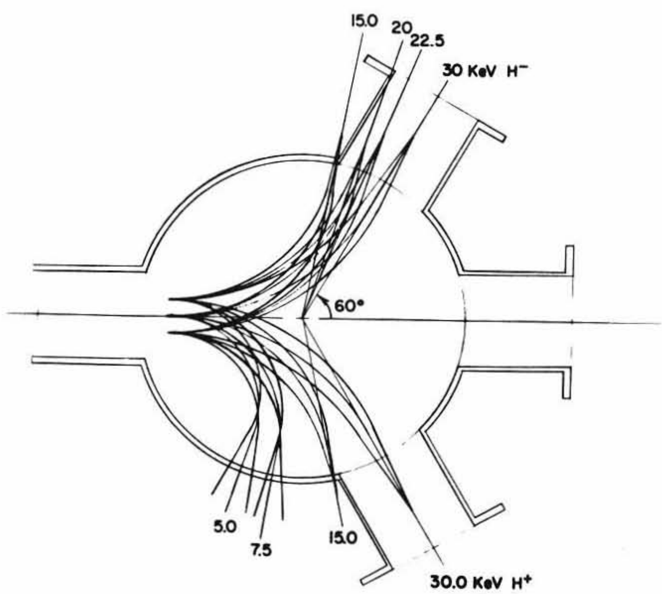

Fig. 3. Geometry of the beam-analysis chamber.

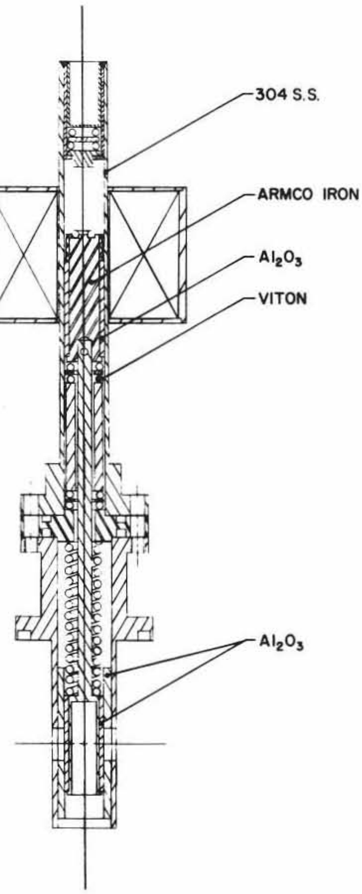

Fig. 4. Design of the new pulsed-gas shutter.

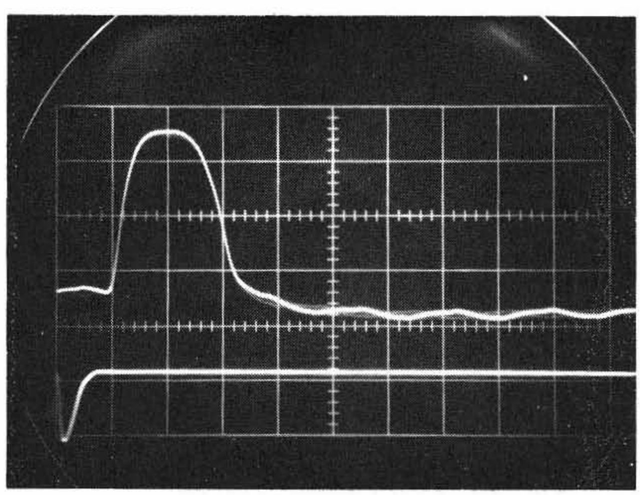

Fig. 5. Top trace: photodiode response to a light pulse transmitted by the gas shutter. Lower trace: valve solenoid current. Sweep speed is 10 msec/cm.

DISCUSSION

J. Claus (BNL): Could you tell us what the stroke of the valve is and its dynamical weight?

J. A. Fasolo (ANL): The stroke is 3/4 of an inch, and the mass for the last one was about 21 g. This one is heavier.

J. Claus (BNL): What is the back pressure?

J. A. Fasolo: This seals against the flow from the ion source. What we want to do is reduce the average gas load to something less than 1 cc per minute, and, hopefully, less than 1/10 cc per minute, if we can.