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ARC RESEARCH. Some Considerations on the Application of the A-48 Accelerator to the Sherwood Program

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The large beam currents anticipated from the A-48 Accelerator suggest its possible application to the Sherwood program. One possible application considered here is a proposal to accelerate molecular ions to high energies for injection peripherally[1] into a mirror machine, and to exploit the fact that at the high energies available the various cross sections for the loss mechanisms are falling off much more rapidly with energy than are the cross sections for the gain processes. Taking as an example a 250 ma H_2^+ molecular ion beam current it is shown that it may be possible to achieve values for $\beta = (8\pi nkT)/H^2$ ranging from 1% to 100% in times ranging from milliseconds to tens of seconds. The β's are achieved by injecting the beam into a mirror machine containing a neutral gas density corresponding to a pressure of 10^{-3} mm Hg to 5×10^{-8} mm Hg. The possibility of accelerating D_2^+ ions in the A-48 Accelerator is also discussed.

It is well known that the charge exchange cross section for protons in H_2 gas falls off very rapidly with proton energy above 50 kev. At 100 kev it has a value of 10^{-17} cm^2, at 500 kev 10^{-20} cm^2, and falling off inversely as the sixth power of energy at high energies.[2] The cross section for various processes involving optically allowed electronic transitions on the other hand should vary as $\ell nE/E$ in the energy range for which the Born approximation is valid.[3] A summary of cross sections versus energy for several processes of this sort together with the charge exchange cross section is shown graphically in Fig. 1. The cross sections for the reactions of interest here

(a) $H_2^+ \rightarrow H + H^+$

(b) $H_2^+ \rightarrow H^+ + H^+$

against collisions in both H_2 gas and ionized gases are not as readily available; however, the similarity of these processes with those shown in Fig. 1 strongly suggests they are of the same magnitude. For the purpose of this discussion the cross section for each of the two processes above will be taken as equal and of the same magnitude as processes (2) and (3) in Fig. 1.

The proposal considered here is essentially an extension of the neutral beam proposal of E. Lauer,[4] with the H_2^+ ion taking the place of Lauer's neutral H atom. The reason for considering the H_2^+ ion at these higher energies rather than neutral beams is simply that large H_2^+ ion beams are anticipated from the A-48 Accelerator, whereas the production of large neutral beams at high energies is limited by the very small charge exchange cross section. The H^- ion would be equally applicable, but it does not appear to be as readily available from the A-48 ion source as is the H_2^+ ion.[5] Also, reaction (a) may be of interest in providing a high energy neutral beam.

It should be noted that Luce has proposed the use of the molecular ion at more modest energies, hoping to achieve the breakup and trapping by passing the molecular ion beam through an arc or electron beam maintained along the axis of the mirror machine.

Consider first the most elementary process: the incoming H_2^+ molecular ion beam colliding with the neutral gas to give trapped protons, which in turn interact with the neutral gas by charge exchange. If n_{01} is the density of trapped high energy protons, we have (see glossary for definition of terms)

$$\frac{dn_{01}}{dt} = \frac{3L}{V} N_{\ell} n\sigma_{01} v - n_{01} n\sigma_{10} v \qquad (1)$$

the factor 3 arising from the fact that two H_2^+ ions will give three trapped protons by (a) and (b). The solution of (1) is

$$n_{01} = \frac{3L}{V} N_{\ell} \frac{\sigma_{01}}{\sigma_{10}} \left[1 - e^{-n\sigma_{10} vt} \right] \qquad (2)$$

Equation (2) indicates an equilibrium density independent of the neutral gas density and proportional to the ratio of gain to loss cross sections. For the sake of an example, assume the H_2^+ is directed into a mirror machine composed of two Mark I drift tube magnets. To estimate the volume in which the ions are contained during the buildup assume the ions are contained in a cylinder of radius equal to the radius of curvature of the H_2^+ ion, and a length equal to one radius. Take the path length L of the molecular ion in the machine as three quarters of a circumference. In principle this path length could be considerably longer but the angular tolerances on the injected beam would probably be prohibitive. Sine in general it is desirable to achieve equilibrium in as short a time as possible the neutral gas density is increased until the mean free path of the incoming ion is comparable to the path length in the machine. For a volume of 2×10^5 cm^3 and a 250 ma ion beam the shortest time to reach equilibrium is much less than one second. Table I summarizes the equilibrium densities and β's in terms of the H_2^+ ion energies available from the A-48 accelerator for 5000 and 7500 gauss fields in the mirror machine.

Table I

	H_2^+ Energy	Equilibrium Density	Equilibrium $\beta = \frac{8\pi nkT}{H^2}$	Equilibrium Time	Neutral Gas Pressure
D.C. Injector (5000 Gauss)	120 kev	6×10^8/cc	2×10^{-5}	10^{-5} sec	5×10^{-3} mm Hg
λ/4 Accelerator (5000 Gauss)	1.2 Mev	1.4×10^{10}	1%	2×10^{-3} sec	5×10^{-3} mm Hg
A Tank (7500 Gauss)	3.7 Mev	3×10^{11}	30%	1/10 sec	5×10^{-3} mm Hg

The advantage of higher energies is obvious from Table I. The values for β listed in Table I are interesting, however a $\beta = 1$ at the $\lambda/4$ accelerator energy would be desirable if possible. To achieve these ion densities several mechanisms suggest themselves, many of which have already been considered by Lauer. If, for example, we assume that as the hot ion density builds up other cold ions or electrons are available to serve as collision centers for the H_2^+ ion beam an exponential buildup of ion density is possible. If we assume that for each proton trapped there is one new ionized collision center we can add an additional term to equation (1),

$$\frac{dn_{01}}{dt} = \frac{3L}{V} N_\ell n\sigma_{01}v - n_{01}n\sigma_{10}v + \frac{3L}{V} N_\ell n_{01}\sigma_{01(+)}v \tag{3}$$

which has the solution,

$$n_{01} = \frac{\frac{3L}{V} N_\ell n\sigma_{01}}{\frac{3L}{V} N_\ell\sigma_{01(+)} - n\sigma_{10}} \left[e^{\left(\frac{3L}{V} N_\ell\sigma_{01(+)} - n\sigma_{10}\right) vt} - 1 \right] \tag{4}$$

If $(3L/V)N_\ell\sigma_{01(+)} > n\sigma_{10}$ an exponential buildup is possible. If we ask that $n\sigma_{10}$ be no greater than a tenth $(3L/V)N_\ell\sigma_{01(+)}$ and again consider the 250 ma case at the $\lambda/4$ accelerator energy a neutral gas pressure of 5×10^{-8} mm Hg will allow a buildup to a $\beta = 1$ approximately in 80 seconds. This time is very short compared to the coulomb scattering through the mirrors which at these energies and densities is on the order of 10^3 seconds.

One might also consider the charge exchange of trapped protons with the incoming H_2^+ beam. Such a process would result in the loss of the original proton but the gain of two new protons, with a net gain of one; if the cross section for such a process were as large as 10^{-16} cm^2 it would lead to results similar to those of the previous paragraph.

As the high energy trapped protons churn through the neutral gas they leave behind a wake of cold H_2^+ ions which in turn are broken up into protons by processes (a) and (b). If we neglect for the moment the fact that these cold ions are scattered out of the mirrors by coulomb scattering, and write $n_{cH_2^+}$ for the density of cold H_2^+ ions and n_{cH^+} for the density of cold protons, we have

$$\frac{dn_{cH_2^+}}{dt} = n_{01}n\sigma_{a01}v - n_{cH_2^+}n\sigma_{a10}v_c \tag{5}$$

$$\frac{dn_{cH^+}}{dt} = 3n_{01}n_{cH_2^+}\sigma_{b01}v - n_{cH}\, n\sigma_{b10}v_c \tag{6}$$

Taking n_{01} as constant we can integrate (5); because of the large σ_{a10} cross section (on the order of 10^{-15} cm^2)[3] $n_{cH_2^+}$ will rapidly come into equilibrium. Inserting this equilibrium value for $n_{cH_2^+}$ into (6) and integrating, we have, again in equilibrium,

$$n_{cH+} = \frac{3n_{01}^2}{n}\left(\frac{v}{v_c}\right)^2 \frac{\sigma_{a01}}{\sigma_{a10}} \frac{\sigma_{b01}}{\sigma_{b10}} \tag{7}$$

Taking values $\sigma_{b01}/\sigma_{b10} \simeq 1$, $\sigma_{a01}/\sigma_{a10} \simeq 5 \times 10^{-2}$, $v/v_c \simeq 2.5 \times 10^2$, (7) reduces to

$$\frac{n_{cH+}}{n_{01}} \simeq 10^4 \frac{n_{01}}{n} \tag{8}$$

If we consider again the case of the $\lambda/4$ accelerator beam coming into equilibrium with the neutral gas at a neutral gas pressure of 3×10^{-5} mm Hg ($n = 10^{12}$), then, from (8) n_{cH+}/n_{01} 10^2; with such a density of cold ions interacting with the H_2^+ beam a $\beta = 1$ would be achieved in another 1/10 second. But this result is unreasonable of course because of the neglect of the coulomb scattering.

Garran[6] has suggested that the stability of these cold ions against coulomb collision may be enhanced by the simultaneous application of the rf heating method currently under consideration. It would be hoped that this would allow a buildup to a $\beta = 1$ in times on the order of seconds.

These suggestions are intended to be considered primarily as a possible starting mechanism, that having achieved a high β at these high energies one would return to a low energy neutral injection in order to sustain the reaction.

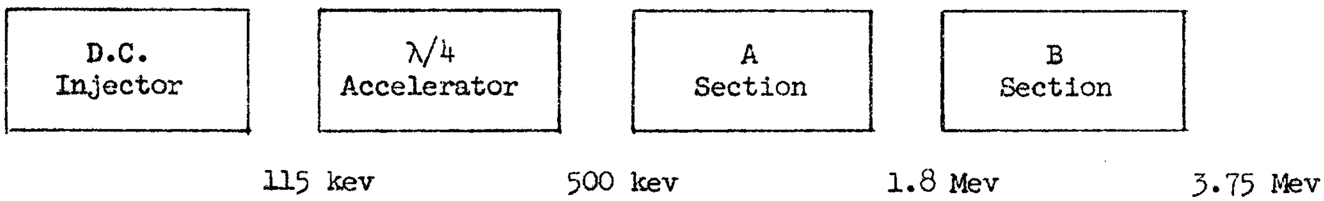
These order of magnitude considerations seem to be sufficiently promising to warrant a more detailed study, in particular the effect of exchange of energy between the hot and cold components of the plasma and its effect on the buildup times.

Possibility of Accelerating D_2^+ Ions in A-48

The discussion so far has been limited to the H_2^+ ion which could be accelerated in A-48 in the same fashion as is the deuteron, the ion for which the accelerator was designed. But since the D_2^+ ion is of primary interest it is interesting to speculate on the possibility of accelerating this ion in the A-48 accelerator.

The most straightforward approach would be to double the injection energy and accelerating gradients throughout; however, the possibility of maintaining such gradients is extremely remote. The accelerator is intended to provide a 7.5 Mev deuteron, but if a deuteron were to come through as a 2 $\beta\lambda$ rather than a 1 $\beta\lambda$ particle, it would have half the velocity or one-fourth the energy, i.e. 1.85 Mev. Requiring only one-fourth energy would allow, in principle at least, for acceleration at one-fourth the design deuteron gradient. This would suggest accelerating D_2^+ ions at half deuteron gradient. A more detailed analysis taking into account the reduced efficiencies of the accelerating gaps at these lower velocities indicates D_2^+ ions could be accelerated in a phase stable fashion as 2 $\beta\lambda$ particles through A and B sections, providing the gradient in the A section were twenty to thirty per cent over the design deuteron gradient, and were about ten per cent less than the design deuteron gradient in the B section.

To accelerate D_2^+ ions through the A and B sections as 2 $\beta\lambda$ particles requires the proper ion velocity from the $\lambda/4$ accelerator. The nature of the $\lambda/4$ accelerator is such that the gaps be spaced odd multiples of $\beta\lambda/2$; the problem is then to find a combination $(2n + 1)\beta\lambda/2$ which will provide the proper velocity consistent with reasonable requirements on the d.c. injector. A suitable phase stable configuration throughout, pending a more detailed study with the differential analyzer, is one in which the first paddle is operated as $5/2\ \beta\lambda$, the second as $7/2\ \beta\lambda$, with 115 kev D_2^+ injection. The block diagram below summarizes the various D_2^+ energies that would be available.



The focusing requirements for D_2^+ ions are somewhat less encouraging though not impossible. Solenoidal focusing fields of 12 kg up to the A section and tapering upward to 14 kg at the entrance of the B section, then tapering downward through the B section, seem to be indicated. The magnetization curves for these drift tube magnets together with previous experience with high fields of this sort indicate they could be achieved if sufficient magnet power were available. An exception must be made for the first six magnets in the A section which apparently will saturate near 11,000 gauss. Two or three of these magnets would need to be replaced to achieve adequate focusing in this region. If a new accelerator were to be built to exploit this method a strong focusing system would seem to be indicated.

GLOSSARY

Equation (1)

n_{01} = density of trapped hot protons

L = path length of the H_2^+ beam in the reacting section

V = volume of the reacting section

N_ℓ = number of ions per unit length in the H_2^+ ion beam

n = neutral gas density

σ_{01} = cross section for H_2^+ breakup in H_2 gas

v = velocity of hot ions

σ_{10} = cross section for charge exchange of protons in H_2 gas

Equation (3)

$\sigma_{01(+)}$ = cross section for H_2^+ breakup in ionized gas

Equations (5) and (6)

σ_{a01} = cross section for ionization of H_2 gas by fast protons

σ_{a10} = cross section for charge exchange of cold H_2^+ ions in H_2 gas

σ_{b01} = cross section for breakup of H_2^+ by fast protons

σ_{b10} = cross section for charge exchange of cold protons in H_2 gas

v_c = velocity of cold ions

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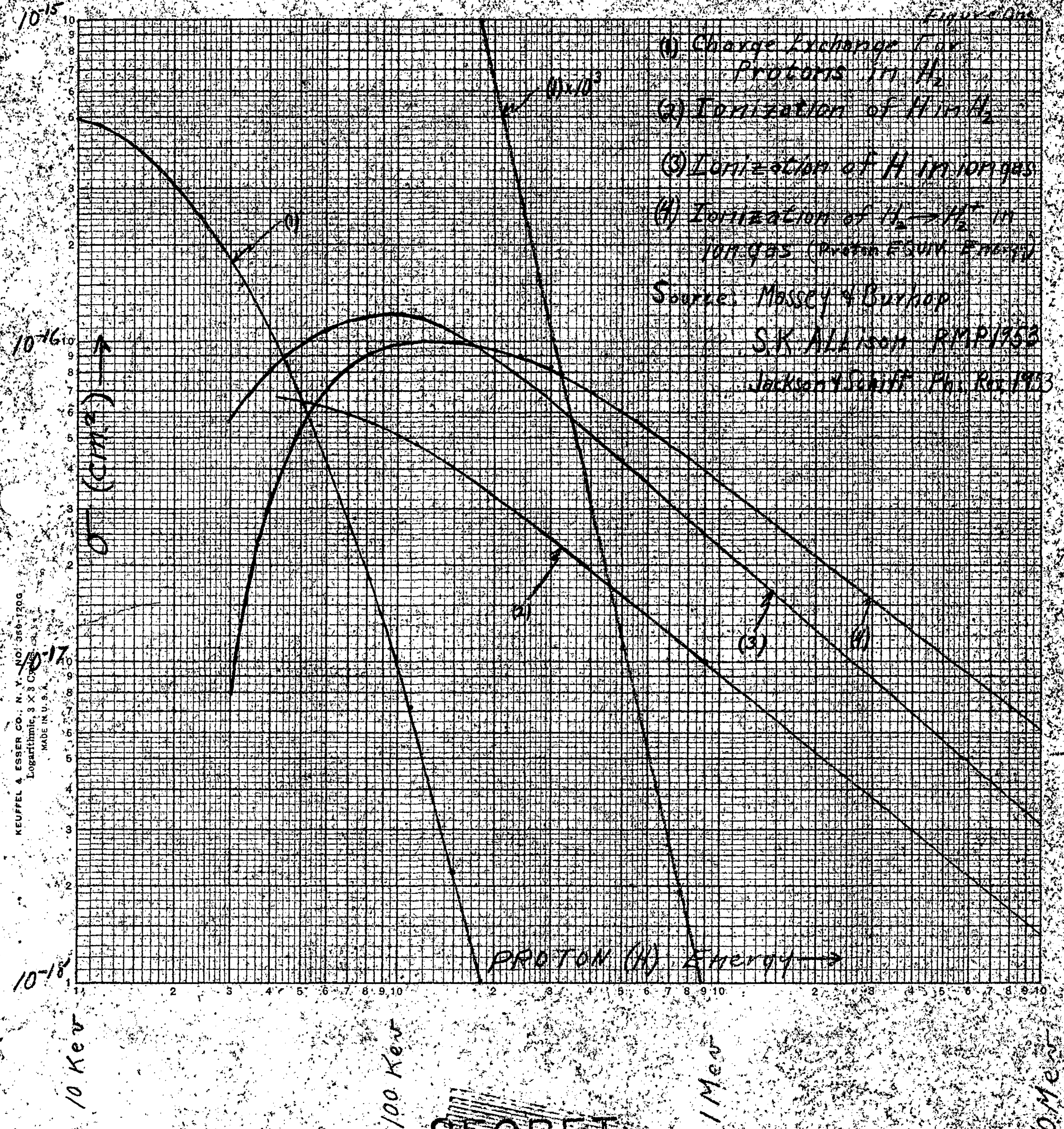
(1) Charge Exchange For Protons In H_2
(2) Ionization of H in H_2
(3) Ionization of H in ion gas
(4) Ionization of $H_2 \rightarrow H_2^+$ in ion gas (Proton Equiv. Energy)
Source: Massey & Burhop
S.K. Allison RMP 1953
Jackson & Schiff Ph. Rev 1953
(1)x10^3
(1)
(2)
(3)
(4)
10^{-15}
10^{-16}
10^{-17}
10^{-18}
σ (cm²) →
PROTON (H) Energy →
10 Kev
100 Kev
1 Mev
10 Mev
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