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ELECTRON COLLISIONAL DETACHMENT PROCESSES FOR A 250 keV D ION BEAM IN A PARTIALLY IONIZED HYDROGEN TARGET

Stephen Edward Savas Ph.D. thesis

September 1980



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Electron Collisional Detachment Processes for a 250 keV D⁻ Ion Beam in a Partially Ionized Hydrogen Target^{*}

Stephen Edward Savas

(Ph.D. Thesis)

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September 1980

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Electron Collisional Detachment Processes for a 250 keV D⁻ Ion Beam in a Partially Ionized Hydrogen Target

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ABSTRACT

Neutral atom beams with energies above 200 keV may be required for various purposes in magnetic fusion devices following TFTR, JET and MFTF-B. These beams can be produced much more efficiently by electron detachment from negative ion beams than by electron capture by positive ions. We have investigated the efficiency with which such neutral atoms can be produced by electron detachment in partially ionized hydrogen plasma neutralizers.

We have calculated neutralization efficiencies for partially ionized hydrogen targets making use of cross sections from the literature. Previously calculated only for a pure electron gas neutralizer, this result has been extended to conditions of arbitrary mixture of hydrogen gas and plasma using an averaging technique on the cross sections for the different target species. We have also studied the effect of a mixtures with contaminating gases and O_2 and N_2 on the neutralizer efficiency. The purpose of these studies was to learn what might be expected of a laboratory plasma neutralizer including the effect of atmospheric gases desorbed from walls. In order to check the previously measured cross sections and the neutralizer efficiencies calculated from them, we have constructed a target plasma for neutralization efficiency measurements. The target is a pulsed, high voltage hot cathode discharge (~ 1 msec, 1.5 kV,~ 100 A) from a large emitting area cathode (10.75 x 2.2 cm) made of La B₆. The discharge takes place in an evacuated stainless steel chamber in a solenoidal magnetic field. (.7 kG \leq B \leq 1.8 kG). Both anode and cathode were gas baffled to reduce the ambient gas density. The maximum electron target thickness, measured by a laser interferometer, exceeded 3.10¹⁴ cm⁻² along the horizontal center line. The target thickness of gas was measured in the absence of plasma to be of the order of 10¹⁵ cm⁻² under typical conditions.

We have measured the efficiency of neutralization for target thicknesses up to .3 of the optimal thickness. The measurement was done by detecting the different charge state components of the beam after they emerged from the plasma. The counting was done using a seven channel amplifier -- discriminator - scaler chain, processing pulses from an array of diffuse - junction Silicon detectors. Each detector was aligned so as to intercept ions of a given charge state after having been electrostatically analyzed. The detectors were protected from visible light and U.V. from the plasma by aluminum coated polypropylene films (~ 70-80 μ gm/cm² Al.) The count totals for each detector were read and stored by a computerized data handling system.

The result of our measurements is in good agreement with that calculated from cross sections from the literature we have made estimates of the gas target thickness for different assumptions about the effect of the plasma. We believe the major effect to be dissociation of the molecular H_2 by the plasma electrons. Subtracting out the effect of this gas numerically we find that the plasma is in fact a superior neutralizer for negative deuterium ion beams at 250 keV. If we extrapolate to optimal target thickness (we have achieved ~ 90% of this, though not while able to count for a target composed of ~ 40% charged particles, electrons and ions, we expect 76-78 neutralization efficiency of ~ 38% ionized plasma that we achieved.

R. V. Pyle

Committee Chairman

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CHAPTER I. INTRODUCTION

A. Uses and Importance of Negative Hydrogen Ions

In this work we study collisional electron detachment processes for negative hydroger ions by charged particles and gases in laboratory plasmas. The importance of these negative ions in the physics of the solar atmosphere.¹ the ionosphere² and electric discharges³ in gases has long been appreciated. They have also proved to be useful in accelerator applications for attaining higher particle energies in "Tandem" accelerators and direct beam extraction from cyclotrons. Recently, a use has been found for negative ions in controlled fusion research. The easiest and most common method of fusion plasma heating, using induced currents can not produce sufficient plasma temperatures for fusion to take place. However, a new technique, neutral beam injection (see Fig. 1), has shown recently at Princeton's PLT⁴ and Livermore's 2XIIB⁵ that it can raise the plasma temperature well past the point of "breakeven," where as much energy is produced by fusion as is used to heat the plasma. In future experiments neutral beams of higher energy might be needed to penetrate to the center of larger fusion plasmas⁶ or drive plasma currents in D.C. tokamaks⁷ or control end plug potential in tandem mirrors.⁸ These higher energy beams (> 200 keV) can be produced most efficiently by stripping an accelerated negative ion beam.

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Figure 1

B. Neutral Beams for Plasma Heating

Early sources of these beams were able to achieve fluxes of about ten ampores of neutral deuterium at energies of 20 keV per atom. More recent sources, for instance those being tested for use in Princeton's TFTR experiment, can produce more than 40 amperes of neutrals at a peak energy of 120 keV per atom. The "neutral beam" sources currently used in controlled fusion research convert the extracted positive ions into neutral atoms by electron capture in hydrogen gas. For a thick gas neutralizer the efficiency of conversion to neutrals is a function only of the ratio of the electron capture cross section of the ion to the stripping cross-section for the atom (See Fig. 2). (Realistically, the target is not thick enough for the above to be strictly true, but the simple model shows the dependence of the neutralization efficiency on energy of the ion beam.) Since the stripping cross section falls above 50 keV, asymptotically as ln(E)/E, while the capture cross section falls off much more rapidly, the efficiency of neutralization falls off faster than linearly in the beam energy. Thus, for instance, this efficiency for a proton beam in $\rm H_2$ gas is 91 percent at 20 keV but only 15 percent at 100 keV (Fig. 3). For molecular ion beams dissociation processes allow higher efficiency of neutralization for optimized gas targets.⁹

C. Neutral Beams from Negative Ion Beams

For a negative ion beam the neutralizer efficiency does not suffer from the same unfortunate energy dependence as for a positive ion

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beam. This is essentially because the excess electron in the ion being much less tightly bound (.7544 eV) than the first electron (13.6 eV) causes that weakly bound electron to have a much larger collisional detachment cross section in regions of higher energy. Since the neutralization efficiency involves only the competition between the different collisional electron detachment processes, this makes possible highly efficient production of neutral atom beams.

- 13 -Figure 2





This efficiency can be expressed as a function of two ratios of electron stripping cross sections: 10

$$F_{0} \max = f\left(\frac{\sigma_{01}}{\sigma_{-10}}, \frac{\sigma_{-11}}{\sigma_{-10}}\right)$$
(1)

where σ_{01} is the cross section for electron loss by the atom, σ_{-10} for single electron loss by the negative ion and σ_{-11} for double electron loss by the negative ion. These ratios remain nearly constant as beam energy increases, and for a hydrogen gas target yield an efficiency in excess of 50 percent. This is quite adequate for experimental reactors but not for commercial reactor where there might be hundreds of megawatts of neutral beam power required. Calculations by Riviere and Sweetman ¹¹ and an experiment by Dimov et al.¹² have shown that plasma used as a neutralizer for negative hydrogen beams can produce at least 80 percent efficient conversion to neutrals and possibly as much as 87 percent conversion. This can make a significant improvement in the overall reactor efficiency.

D. Experimental Purpose

Our purpose in this work has been to make calculations based on most recent cross section measurements and to test measuring this by the maximum fraction of a 200 keV to 300 keV D^- ion beam which can be converted to neutrals in a hydrogen plasma target. We pass a 250 keV D^- ion beam through a highly ionized, dense, pulsed hydrogen discharge. The different charge components of the emergent beam are then analyzed electrostatically and counted separately using a solid state detector array and fast electronic pulse counting equipment. From the dependence on the density of plasma and gas of the final charge state fractions we can infer the maximum efficiency with which such a beam can be converted to neutral atoms. As we will discuss later (Ch. V), our target is highly, but not fully, ionized hydrogen plasma. Based on measured cross sections we expect the contaminating H₂ gas not to have a significant degrading effect on the neutralization efficiency.¹³ It also is a check that other processes of possible importance to neutralization efficiency do not cause a significant reduction of it. A detailed assessment of the various atomic processes relevant to neutralization efficiency is done in Chapter II.

E. Practical Neutralizer Problems

A second major purpose in this experiment has been to confront practical problems involved in building such a plasma neutralizer. Among these are: achieving sufficient plasma target thickness; reducing to tolerable level the gas which precedes and follows the plasma along the beam path; handling problems of beam transport due to the magnetic field used to confine the plasma; We believe that our plasma successfully meets these requirements and we have made measurements to verify this.

There are other requirements for a practical plasma neutralizer which we have not addressed in this experiment, but which are as equally important. Our plasma target only lasts for a few milliseconds, whereas useful neutralizers should function continuously for at least several seconds. The type of electric discharge we make is not capable of being extended by more than three orders of magnitude in duration. Another type of discharge must be made which is more suitable for continuous operation. When the neutral atoms emerge from our plasma target they have increased their divergence in one direction to eight degrees or more. This is due to the bending of the negative ion beam in the magnetic field used to confine the plasma. Unfortunately, we have made our discharge so that the ion beam must trave? perpendicular to that field in order to cross the plasma. A more suitable plasma target should either have a magnetic field only at the surface of the plasma or a field parallel to the beam's motion.

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Chapter II. ATOMIC PHYSICS PROCESSES

A. H Ions

The negative hydrogen ion has recently been the object of renewed theoretical and experimental interest due to controlled fusion applications. Early calculations by Hylleraas¹⁴ and later Pekeris¹⁵ established precise values for binding energy (.7544 eV) and size $(\langle r \rangle = 2.71 a_{o})$ before 1960. The first experimental work dealt with photodetachment 16 and collisional detachment of electrons from fast H⁻ ions in gas targets.¹⁷ Astrophysical interest stimulated early theoretical work on photodetachment 18 . but it was not until much later that experiment and theory sucessfully addressed the problem of electron collisional detachment by fast electrons or ions. Some very difficult experiments^{19,20} utilized the crossed beam techniques and overcame problems due to gas collisions and uncertainty in target thickness measurements. Theoretical work²¹ using the Bethe Sum rule at high impact energies was later augmented by a Born approximation result²², valid at intermediate energy (> 1 Rvdberg). Problems remaining with the theory involve appropriate wavefunctions for the final state and the use of an estimate of the oscillator strength distribution in the former case and a difficulty with needed higher partial wave terms in the latter. Also the theory has not adequately addressed the problems of the atom in the final state being excited or ionized.²³ However, recent work²⁴ provides

upper limits to these cross sections which we will make use of below. We also make use of semi-empirical estimates²⁵ of cross sections which have not been measured or calculated by more rigorous theoretical techniques. It seems to us that the opportunity exists for more accurate and specific calculation of many of the above cross sections using the Glauber^{26,17} approximation which has proved accurate in a number of applications.

According to the current understanding, there are no bound excited states of this negative ion. the excited states are all so-called "auto detaching" unstable states: $2S^2$ singlet S, 2S2P triplet P and the $2p^2$ singlet D and a few others, all of which have energies about 10 eV above the free electron - hydrogen atom ground state. The second electron, being so weakly bound, would be expected to have a large cross section for detachment, both by electron collision and photons. The photodetachment cross section has been measured²⁸ to be greater than 10^{-17} cm² throughout the visible region of the spectrum. The electron collisional detachment cross section is very large, having a maximum value of almost one hundred times πa_2^2 .

B. Plan for Data Evaluation

In our experimental work we have observed the final charge state composition of our initially negative deuterium ion beam after it has traversed a highly ionized hydrogen plasma target. Our first aim in this chapter is to understand how collisions with the different constituents of the plasma and the gas contribute to the final beam composition. To do this we will make use of known and estimated charge changing cross sections from the literature (see Fig. 4) and measured target thicknesses. Using our charge fraction measurements of the emergent beam for a range of target thicknesses we can deduce the cross sections for specific collision processes of interest. We also give a parameter study of neutralization efficiency for a range of contamination conditions for a negative hydrogen ion beam incident on a hydrogen plasma-gas mixture. Our target consists of electrons, H^+ , H_2^+ , and a small number of H_3^+ ions, as well as H_2 , N_2 , and O_2 , gases. We assess the effect of each of the many possible charge-changing collision processes which can contribute to the final beam fractions.





C. Previous Cross Section Measurements

The earliest collisional electron detachment measurements for negative hydrogen ions were made for gas targets.²⁹ An early review article³⁰ gives measured detachment cross sections for H_2 , N_2 , 0₂, CO, CO₂, He, Ne, and Ar targets, but for many of these the coverage of the range of projectile energies was very spotty. some of these gaps were later filled in by a number of experimenters. 31 but many still remain, and unfortunately, include beam energies relevant to this work. This is not, we believe, due to any intrinsic difficulty for hydorgen ion energies of the order of 100 to 300 keV but rather because of a lack of interest in the experimental community. For the most part, interpolations from cross sections at greater and lesser energies seem to be good, as well as consistent with theoretical estimates of energy dependences.³² Very recently the electron detachment cross sections for atomic and molecular $\operatorname{hvdroden}\ \operatorname{targets}^{33}$ were measured in the energy range of interest and found to be quite close to interpolated estimates. ³⁴ Estimated cross sections for N_2 and O_2 targets, which are relevant to this work, seem adequate for the single detachment processes (σ_{-10} and $\sigma_{0,1}$), but are much more questionable for the double detachment process (o_11).

D. Electron Detachment by Charged Particle Collisions

In contrast to experiments with gas targets those for electron detachment of negative hydrogen ions by charged particle targets are quite difficult. The first²⁰, done in 1966 for electrons, got too large a result for σ_{-10} at electron energies above 150 eV. Later measurements $^{19, 35}$ agreed with one another and with calculations 21 felt to be reliable at electron energies of several Rydbergs and higher. (See Fig.5). The only experimental measurement for double detachment by a charged particle target³⁶ seems quite suspicious to us. Based on a comparison with data for H_2 target and a Born approximation calculation 24 , we would expect a somewhat smaller value than was found. A difficulty in this experiment is the very small ratio of positive to negative ions in the post-collision beam. The only measurement of a cross section for an ion ${\tt target}^{37}$ confirms the expectation that the single detachment cross section, σ_{-10} , is essentially the same for protons as for electron targets at $H^$ energies ~ 100 keV. Unmeasured cross sections which are relevant to this work include: σ_{-10} for such ion targets as 0^{+n} , \aleph^{+n} for n = 1,2,3,4; σ_{-11} for all ion targets and σ_{01} for all ion targets except protons. Notable among the ionic targets in the latter two case are H_2^+ , N_2^+ , O_2^+ and N^{+n} and O^{+n} for n = 1, 2, 3, 4. Other unmeasured cross sections of possible interest include those (σ_{-1*}) for electron detachment processes which leaves the H atom in an excited state for N_2 , and O_2 targets. Also those for many targets species mentioned above.

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É.

We feel the importance of knowing many of these cross sections is not great in our work. Our measurements have shown that N₂, the most abundant contaminent, comprises only a few percent of background gas. We further believe that nitrogen ions in the discharge serve mostly to increase the electron density, and do not themselves have a great effect on the ratios (σ_{-10}/σ_{01} , and $\sigma_{-10}/\sigma_{-11}$) of the averaged cross sections.

E. Neutralization Efficiency

In the production of neutral atom beams from positive ions the efficiency is strongly dependent upon the beam energy. This efficiency can be expressed for a thick gas neutralizer as a function of the ratio of electron capture to loss cross sections:

$$F_{0} = \frac{1}{1 + \frac{\sigma_{01}}{\sigma_{10}}}$$

where σ_{10} is the capture cross section, σ_{10} , is the stripping cross section and F_{o} is the neutral fraction in the limit of an infinitely thick target.

For a negative deuterium ion beam with a pure electron gas neutralizer (if deuterium atoms had no excited states) we can calculate the neutralization efficiency exactly using the cross sections for only three charge-changing processes.²⁹

$$\eta_{0} = \frac{\sigma_{-10}}{\sigma_{-10} + \sigma_{-11}} \cdot \left(\frac{\sigma_{01}}{\sigma_{-10} + \sigma_{-11}}\right)^{\frac{\sigma_{01}}{\sigma_{-10} + g_{11} - \theta_{1}}}$$
(1)

Is the fraction of the negative ions made neutral traversing such an optimized target with a line density of:

$$(n)_{opt} = \frac{1}{\sigma_{-10} + \sigma_{-11} - \sigma_{01}} \ln \frac{\sigma_{-10} + \sigma_{-11}}{\sigma_{01}}$$
(2)

where σ 's represent the cross sections for the following collision processes:

(a) $H^- + e \rightarrow H^\circ + 2e$ for which we denote the cross section^{19,20,35}: $\sigma_{-10}(e)$

(b) $H^- + e \rightarrow H^+ + 3e$ with the cross section³⁶: $\sigma_{-11}(e)$

(c) $H^{\circ} + e \rightarrow H^{+} + 2e$ which has for its cross section³⁸: $\sigma_{n1}(e)$

F. Plasma Target Constituents and their Effects

Even for a fully ionized hydrogen target there are several collision processes beside (a), (b), (c), which have an important effect on its neutralization efficiency. These processes are stripping collisions with atomic and molecular hydrogen ions as the target. We believe that there is a negligible amount of H_3^+ and a small but unknown amount of H_2^+ in our target plasma. The stripping cross sections for H_2^+ are not known so we will consider only atomic ions as targets.

There is experimental evidence³⁷ that (d) $H^- + H^+ \rightarrow H^+ + H^+ + e$ or $+ 2H^+$

has a cross section σ_{-10} (H⁺) very nearly equal to that of process (a) in the energy region of interest. However, one of the other two processes involving proton targets is known to have a larger cross section than that for an electron target. The one that has been measured³⁹ is σ_{01} (H⁺):

while the other,
$$\sigma_{-11}$$
 (H⁺):
(f) H⁻ + H⁺ \rightarrow 2H⁺ + 2e
or \rightarrow H⁺ + H + e

has not been measured. Because the cross section for collision (e) is 62 percent greater than for (c) at a hydrogen energy 150 keV the neutralization efficiency for a pure hydrogen plasma target is several percent less than for a pure electron target. The exact amount depends on the cross section for (f), which has not been measured or calculated.

Actually, if we have a uniform mixture of species and electron capture and excitation cross sections are negligible, we can use Eq. 1 to compute efficiency if the cross sections are appropriately averaged:

- 27 -

- 28 -Figure 6


Figure 7



$$\overline{\sigma}_{1j} \stackrel{\simeq}{=} \frac{1}{n_{\text{TOT}}} \sum_{\alpha} n_{\alpha} \sigma_{1j}(\alpha)$$
(3)

where the sum a is over all species in the target.

Our plasma target is also contaminated by gas, primarily hydrogen, which further reduces its efficiency as a neutralizer. We find that the stripping cross sections for H_2 molecule targets, ³³ $\sigma_{-10}(H_2)$, $\sigma_{01}(H_2)$ are small compared with (b), (e) and probably (f). As a result when we calculate the efficiency using equations (1) and (3) for varying mixtures of hydrogen gas and plasma we find (see Fig. 6) only a slight loss of efficiency, even when the gas has comparable density.

The stripping cross sections for N₂ and O₂ gases⁴⁰⁻⁴⁵ are somewhat larger than for H₂. We have measured the increase in N₂ and H₂O pressure following discharges and find negligible amounts of H₂C and small amounts of N₂. The N₂ pressure rises above ambient level for a few tens of milliseconds to the order of several times 10⁻⁵ Torr. This amount would be enough to cause a measurable diminution in the neutralization efficiency for an optimally thick target (see Fig. 7).

The gases present are also capable of being targets for electron capture collisions of the beam particles. The cross section $^{40, 45, 46}$ σ_{10} at energies of interest are < 10^{-16} cm² for N₂, O₂, and H₂O and ~ 3.10^{-17} for H₂. When we combine these with known gas pressures in the plasma chamber, we estimate there to be negligible effect on the neutral fraction in the emergent beam. (See Appendix A-1).

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G. Excited State Effects

We have assumed above that the hydrogen atom is a single state system, and have ignored the effects of excited states on neutralizer processes. In fact, collisions with target species will excite a fraction of the atoms in the beam.⁴⁷ These excited atoms, whether metastable or not, have a non-negligible probability of making a further collision before returning radiatively to the ground state. They also have a much larger cross section for being electron-stripped than ground state atoms.^{25,48} This causes a lowering of the neutral fraction and efficiency. In order to evaluate this loss we must consider the following processes:

- i) excitation of H⁻ or H^{\circ} in the beam to n > 2 states of H⁰
- ii) de-excitation, by collisions, of above states

iii) electron stripping from atoms in excited states.

We need not consider the n = 2 metastable as distinct from the 2P state since the 2S and 2P are strongly mixed by the electric field due to the beam's motion across the magnetic field.⁴⁹ We find that we can model the excited state effects as a sum of increases in the cross sections σ_{01} and σ_{-11} from n = 2 and n = 3 excitation collisions. (see Appendix A-2)

$$\delta \sigma_{01} = \left(\frac{\sigma \star 1 \sigma 0 \star}{\sigma \star 1 + \sigma \star 0} \right) n=2 + \left(\frac{\sigma \star 1 \sigma 0 \star}{\sigma \star 1 + \sigma \star 0} \right) n=3$$
$$\delta \sigma_{-11} = \left(\frac{\sigma_{-1} \star \sigma \star 1}{\sigma \star 0 + \sigma \star 1} \right) n=2 + \left(\frac{\sigma_{-1} \star \sigma \star 1}{\sigma \star 0 + \sigma \star 1} \right) n=3$$

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where $\sigma_{\star 1}$ is the cross section for stripping from an excited atom, $\sigma_{\star 0}$ is for collisional de-excitation and $\sigma_{-1\star}$ and $\sigma_{0\star}$ for collision production of excited atoms from negative ions and atoms, respectively. We could compute neutralization efficiency loss directly from these, except that some of the cross sections needed are not known. If we make use of estimates based on known cross sections,²⁵ and assuming a target density of 10^{14} cm⁻³ we find a reduction of the order of 1 percent in n. Thus we do not expect to see a significant loss of neutralization efficiency due to excitation effects in beam atoms.

III. Experimental Approach and Equipment

A. Experimental Approach

In this experiment we measur, the final charge state fractions of a negative hydrogen ion beam after it traverses a highly ionized, magnetically confined hydrogen plasma. The beam is extracted as positive ions from an R.F. ion source, and is allowed to drift in dilute gas where a fraction of these ions capture two electrons to become negative jons. The negative jons are then accelerated to between 100 to 300 keV per nucleon by a TNC model 9500 accelerator. The beam is then focused and steered electrostatically and the momentum selected using a large bending magnet. The selected beam is collimated to about a milliradian using a pair of collimators ~ 1.5 meters apart. The collimated beam is then bent upward electrostatically so that it will be travelling horizontally after bending down in the confining magnetic field around the discharge. The ions make collisions in the plasma and some change their charge state causing them to deviate from the path of the negative ions. The resulting mixed beam is "fanned out" across the field. This beam passes through an exit slot in the scattering chamber and then passes between a pair of plates which electrostatically analyse the beam into its different charge state components. These different beam components are then stopped in solid state detectors, and the current pulses for each particle are amplified, discriminated and counted. The totals for each charge state beam component can then be

combined with line density information to yield cross sections for the various processes. When the line density exceeds 10^{15} (particles/cm²), we can determine the neutralization efficiency directly by varying the target thickness.

See Figure 8 for a plan view of the beamline and plasma target chambers.

B. Arc Requirements

The most novel and difficult part of this experiment is the hot cathode hydrogen discharge. Use as a plasma target requires that the surrounding pressure be $\sim 1 \text{ m}$ Torr; that the degree of ionization in the plasma be > 10; and that the maximum integrated charged particle density be of the order of 10^{15} cm⁻². We have achieved these by using a pulsed hydrogen discharge along a nearly solenoidal magnetic field. See Table 1 for the electrode and arc parameters. We made the cathode large in area (2.2 cm x 10.75 cm) in order to get a uniform plasma density over a large cross-sectional area. This was necessary to insure that the integrated density over the path of the negative ion beam was measurable and insensitive to small changes (~ 1mm) in the ion beam trajectory. In order to limit the density of surrounding gas it was necessary to make the discharge pulsed in a fast pumpable chamber evacuated to $< 5.10^{-6}$ Torr, and to inject gas for the discharge with a very fast value 50 into a baffled anode (See Fig. 9). In order to achieve long cathode life we have used a rectangular piece of sintered La B_6^{-51} which we heat by radiation from a

tungsten filament placed behind it. (See Figs. 10,11). In order to achieve electron densities of the necessary order of magnitude > $10^{13}/\text{cm}^3$ we have found it necessary to use arc voltages > 1500 V and magnetic field strengths > 1 k Gauss. It was also necessary to shape the B field so as to have a radial minimum on the magnetic axis. This means the field has an axial maximum which is at the symmetry plane of the coils halfway between the anode and cathode (see Fig. 12).

Parameter	Value
Anode-Cathode Separation	18 cm
Cathode Dimensions	10.75 cm x 2.2 cm x .2 cm
Cathode Material	Sintered La B6
Discharge Voltage	>500 Volts, < 2k Volts
Discharge Current	< 250 Amperes
Magnetic Field	720 Gauss < B < 1700 Gauss
Duration of Discharge	<pre>< 1 millisecond</pre>
Background gas pressure	<u><</u> 5. 10 ⁻⁶ Torr
H2 Pressure During discharge	$.6 \cdot 10^{-3}$ Torr < P < Torr

Table I. A list of physical characterietics of discharges.

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ANODE AND SUPPORT FLANGE







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CATHODE







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CATHODE





- 41 -Figure 12

C. Arc Operation

Because of its unusually high voltage and low gas pressure this electric discharge has been difficult to start and maintain in the proper mode of operation. We have used a guartz-shielded tungsten wire with an exposed tip placed just in front of the anode to start the discharge. We pulse this starter with -40 kV about 600 usec after injecting the hydrogen gas into the anode. The resulting local arc draws a few thousand amps for a few microseconds and provides plasma to set up a sheath at the cathode thereby making an electric field to extract electrons. Once the arc has been struck it can operate in two distinct modes (See Fig. 13). The preferred mode of operation involves uniform thermionic emission by the cathode resulting in an arc current between 20 and 250 Amps with the arc voltage only slightly less than the supply voltage of 1000 to 2000 volts. When we inject too much gas or the background pressure is too high the arc makes a transition to a second mode in which the arc current is of the order of 1000 Amps and the arc voltage falls to less than 100 volts. In this mode the arc seems non-uniform spatially and is no longer the pink color characteristic of the other mode (seems bluish to the eye). We have seen evidence of "tracking" on the cathode surface possibly due to "hot" spots which may occur during the second mode of operation.⁵² These spots have been observed in cold cathode discharges to provide large currents and move on the cathode surface causing irregular "tracks".

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- 43 -Figure 13



A) Mode Transition DURING DISCHARGE



B) HIGH VOLTAGE MODE DISCHARGE



C) MODE TRANSITION PRECEEDED BY OSCILLATION IN BOTH VOLTAGE AND CURRENT



D) HIGH VOLTAGE MODE WITH OSCILLATIONS D. Ion Source

Our negative ion beam is of extremely low current (< 10^{-12} amperes), as is necessary if we are to be able to count each particle which traverses the plasma target. The beam is first extracted from a pyrex R.F. ion source bottle at between 2 and 10 keV per positive ion. This varies since we frequently vary the extraction voltage in order to change the beam current. The extracted current may be of the order of 10^{-6} amperes of positive ions, though we believe it to be of the order of 10^{-8} A during data taking. Immediately after it is extracted the beam is allowed to drift in a passage at constant energy to produce the negative D ions. We designed the diameter of the passage by considering its conductance to gas flowing from the source and its effect on the gap lens which follows it. The conductance determines the fraction of positive ions converted to negative ions by electron capture since the average gas density varies inversely with the conductance. The maximum fraction of a 10 keV proton beam which can be made negative is about 2 percent. This would require that the integrated gas density in the drift region be $< 2 \times 10^{15}$ molecules/cm². Since we only need 0.1 percent negative yield we need a line density of 10^{14} cm⁻². Thus, we designed the passage to be 3 cm long and 0.34 cm in diameter. This diameter must also be greater than that of the aperture in the gap lens so that its focusing properties are not adversely affected. What we have done is to have most of the length of the passage be the proper diameter but the last 0.5 cm is of a diameter slightly larger than the aperture in the gap lens.

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It is also important to prevent electrons created in the drift region and on the walls from being accelerated down the column. These cause a burden on the power supply and are a source of possibly dangerous high energy x-rays when they hit collimators or the beampipe. These are stopped by a > 100 gauss magnetic field supplied by small permanent magnets and 3/16" diameter iron pole pieces which cause the field to be localized in the drift region.

See Figure 14 for a drawing of our negative ion source.

E. Beamline

After the negative ions are accelerated down the column they are allowed to drift for approximately a meter, and are then focused in an electric quadrupole lens and steered electrostatically. Both the quadrupole and the steering plates are of standard design using long pole pieces and low voltages (500 volts for the steering plates and 3000 volts for the quadrupole).

The beam then is steered into our target beamline by a large bending magnet. The magnet has pole faces ~ 15 cm diameter and separated by ~ 10 cm. There are shaped pole pieces which provide some degree of focusing. The field in this magnet, which has water-cooled copper windings, can be maintained above 10^4 gauss. This is easily sufficient to bend 300 keV D⁻ ions through the 13.5° angle between the initial accelerator beamline and the target and analysis chamber beamline. The beam duct is trident-shaped at the magnet allowing $\pm 13.5^\circ$ and 0° bending angles.

- 46 -Figure 14



Negative los Source

XBL 514-9265

Once past the magnet the beam is allowed to drift to a collimator placed in the front of a gas-cell chamber on the target beam line. This collimator is made of .063" thick copper with a .050" diameter hole in the center. Even when well focused, most of the beam is stopped at this collimator. The remaining beam, which is on the order of 0.1 to 1 percent of that before the collimator, passes first through an evacuated chamber. (used in previous experiments as a gas target cell), then through a 1-1/2 to 2 foot length of 1-1/2" diameter evacuated duct. an electric gate valve and a second collimator. The pressure throughout this region is kept at or below 10^{-6} torr by a liquid nitrogen trapped 4" diffusion pump under the chamber. At this pressure less than 1 percent of the negative ions are stripped by collisions with gas molecules. Furthermore, the divergence of the negative ions which do pass through the second collimator will have (according to our estimates) been increased less than 1 percent by elastic collisions. The evacuated chamber is 8" in diameter and has ports for an ion gauge and a Faraday cup to monitor beam current. The beam duct is stainless steel with "conflat" flances 2-3/4" outer diameter. The electric gate valve allows us to isolate the vacuum of our scattering and analysis chambers from that of the beamline. Finally, the second collimator is made from a 1-3/4" diameter .063" thick copper disc with a beveled 0.020" hole which also acts as a copper gasket for two 3/4" conflat flanges. The beam which emerges from this collimator has a maximum divergence of about a milliradian

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and has \sim 1 percent of the current of the beam before the collimator. During counting the current entering the scattering will be of the order of 10^{-13} amperes.

F. Steering the Ion Beam through the Plasma Target

After the beam emerges from the second collimator it passes through a region where its current can be monitored and the beam steered (see fig. 15). Immediately following the second collimator the beam traverses a "T" section where a small, magnetically suppressed Faraday cup can be moved into the beamline to measure the total current. The cup was designed so that both electrical leads and mechanical support are incorporated into a single tube which slides in a "Wilson" seal. Following the Faraday cup is a section of duct containing flat parallel 3/4" diameter plates aligned to allow steering of the beam in a horizontal plane. We need only use these to correct for misalignments of our magnetic field and vertical steering and have allowed for up to 10 milliradians horizontal correction. Immediately down beam from the horizontal steering section are the vertical steering plates. These are rectangular 1-3/4" x 3/4" and curved to allow for large bending angles. The purpose of these is to put the beam into a sufficiently upward trajectory that they will, after being bent downward in the magnetic field in the scattering chamber, be traveling horizontally when it arrives at the plasma. The angle of bending required for this depends

Scattering Chamber Injection Assembly



Figure 15

on the energy of the beam ions, their mass and the magnetic field. We have designed the plates to allow a bending angle of between 2^0 and 12^0 .

Following the vertical steering plates is a flexible beamline section which connects to the scattering chamber. This section consists of a 2-3/4" diameter, 3" long "conflat" bellows; an adapter from 2-3/4" 0.D. flange to 1-1/3" 0.D. flange; a 1-1/3" diameter, 2-3/4" long mini-conflat bellows; and a pair of stainless steel "braces" which attach to all three of the above pieces. The result is a flexible duct which allows the beam to follow its curving trajectory from the vertical steering plates to the entrance flange of the scattering chamber. The braces are pinned to the ends of the bellows section and to the adapter between. As the scattering chamber is raised the braces assure that the bellows are positioned so as to allow the beam to pass unimpeded.

G. Target and Analysis Chambers

The vacuum system is made up of several interconnected chambers which serve various purposes in our experiment. The first chamber which the beam enters is the scattering chamber; it is 12" in length and 8" in diameter. Connected to it on one end is the duct (8" diameter) which leads to both the titanium getter pump and the smaller (4") duct which leads to the analysis chamber. Along the 4" duct is a bellows, which was necessary to allow the system to fit together, and a manual gate valve. This duct connects with the

- 50 -

analysis chamber which sits atop a pumping "stack". The scattering chamber also connects to the analysis chamber directly via a 1" wide trapezoidal duct which allows the team to pass from the scattering chamber to the analysis chamber.

See Figures 16 and 17 for views of the target and analysis chambers.

The beam enters the scattering chamber and passes into the plasma target and then through a vertical slot into the trapezoidal duct leading to the analysis chamber. The entrance for the scattering chamber is a 3/4" diameter, 1-3/4" long tube ending in a mini-conflat flange. It allows enough room for the full range of beam trajectories of interest as well as leaving space above for a port for a movable Langmuir probe. Once the beam has passed the entrance tube it enters the scattering chamber. The beam, once in this chamber can be monitored by a movable Faraday cup which can be positioned where the midpoint of the plasma would be during a discharge (this cup must be retracted during an actual firing of the arc). During a discharge, the D° and D^{\dagger} made from the D° beam while passing through the discharge are spread out in a direction perpendicular to the field and the beam's direction of motion ($e_e = v \times B$) (see Fig. 18). The resulting fan-shaped beam passes through the slot in the tack of the scattering chamber and moves in the centerplane of the trapezoidal duct toward the analysis chamber.

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Vacuum System (TOP VIEW)

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XBL 7910-12494

H. Beam Analysis and Detection

At the end of the duct the beam passes between a pair of electrostatic deflection plates which separate the "fan" of neutrals from the fan of positive ions in the direction perpendicular to their spread. The remaining negative ions are deflected, too, opposite to the positive ions. These different charge state components then pass into the analysis chamber where they are counted separately. The analysis chamber is cylindrical, 12" long and 10" in diameter with its axis parallel to the original beam line. The solid state detector arrays are mounted inside about 4" from the front of the analysis chamber on adjustable brackets. The analysis chamber also has a pyrex window at the rear to allow diagnostics to "see" through the plasma target. This is mounted into a 10" 0.D. conflat flange which, when removed, allows access to all components in the chamber.

The positive and neutral beam components enter this chamber as vertically diverging fans which are separated horizontally due to the actions of the electric field applied in the end of the duct. The negative component is below the neutral and is separated solely by the action of the confining field. These pass into a set of eleven solid state detectors 30 mm x 15 mm x 3 mm mounted vertically in arrays with 12 mm sides adjacent (see Fig. 19). This array is held in place and electrically connected with a three gold plated detector holders. Mounted on the front of these detector holders are aluminum coatings on $25 \ \mu g/cm^2$ polypropylene foils which stop both light and electrons from the plasma and surfaces in the analysis chamber from entering the detectors.

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XBC 800-14882

Figure 18

See Figure 20 for a drawing of the detector support and holder assembly.

I. Diagnostics

The diagnostics in our experiment have been used to measure plasma properties, gas pressure and composition, and beam properties. The plasma diagnostics used include Langmuir probes and a He-Ne laser interferometer to measure electron density and electron temperature. We have mea ured gas composition with a quadrupole mass analyzer and pressure on sub-millisecond time scale using a Penning ionization gauge. Beam current has been measured with Faraday cups and charge state composition with solid state detectors in an electrostatic analyzer.

1. The Langmuir Probe

The Langmuir probes used were double probes movable through the long and short dimensions of the plasma through "Wilson" seals and having ~ I μ sec response time. The body of the probe was pyrex glass while the sleeves, which limited the probed area, were made of quartz so as to minimize the evaporation into the discharge. The probe itself was made of two 0.020" diameter tungsten wires which passed through uranium glass seals. The two tungsten wires protrude 0.060" (horizontal moving probe) and .100" (vertical moving probe) beyond the quartz sleeves and are separated from one another by ~.19". The probe was moved by hand, in steps of 1/4" or 1/8" through the 4-1/4" width and 7/8" thickness of the discharge to arrive at the density profile (shown in chapter 4). See Fig. 30 for an illustration of probe positions.

The voltage across the probe was swept by amplifying the output of a sawtooth generator. The circuit which provided the probe voltage was kept at "floating" potential by using a transformer with a 0.COI" permalloy tape core to isolate the probe circuit from the supply circuit which had one side grounded. The probe current was read by use of an LED telemeter unit which eliminated the need for the oscilloscope to float with the probes. Effort was made to reduce the capacitance to ground of the floating part of the probe driver circuit so as to reduce the time needed for the plasma to charge this circuit up to floating potential. We were able to reduce the capacitance by using a hand wound transformer to less than 10^{-9} farads. This gives us a charge-up time of < 100 nanoseconds. (See Appendix B).

In order to understand the data we have used the analysis of $Chen^{53}$ and the detailed curves of Brown and Kunkel⁵⁴. Our situation is essentially that the sheath width is small compared with mean free paths and gyroradii, and the probe diameter is much larger than the sheath but smaller than the ion gyroradius.

- 58 -Figure 19



Solid State Detector Array

XBL 814-9290

- 59 -Figure 20



SIDE VIEW

Solid State Detector Assembly

XBL 814-9289

2. Laser Interferometer

The laser interferometer we have used was designed and built by Booth Myers and Ben Feinberg for use on the TORMAC experiment⁵⁵. This apparatus uses a Michaelson geometry with all optical components mounted in a single rigid framework. This has two legs which fit around the chamber containing the plasma when the interferometer is suspended on springs from a support scaffold. It achieves a sensitivity of about .001 radian by using a feedback stabilized reference-leg pathlength kept 90° out of phase with the plasma-piercing-leg path. The feedback stabilization has a response time greater than 100 usec so that the -50 usec rise time for the plasma does not allow the signal due to the plasma to be compensated and thereby lost. In order to prevent electrical noise effects on the photodiode circuit, which is used to read the light intensity, the light signal is conveyed by a light-pipe to a shielded chassis located several feet from the plasma chamber.

The relation which gives average density from phase shift is:

$$\delta \mathbf{p} = \pi \cdot \frac{n!}{\lambda n} \mathbf{c}$$

where n is average density, 1 is plasma thickness, $\lambda = 6.328 \times 10^{-7}$ m, n_c is the critical density at which ω_p = the frequency of the laser light.

See Appendix B for a drawing of the interferometer.

3. Penning Gauge

We have designed and built our own fast PIG gauge in order to assure that it had the required characteristics. It was necessary that the

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filling time of the gauge be approximately 100 usec or less in order to get a sufficiently small response time to measure the gas density variation during a 1 millisecond discharge. Further, it was necessary to have stable, quick starting operation at pressures approaching 10^{-6} torr. Lastly, it was desired that there be no mode changes in the Penning discharge between 10^{-6} torr and 5 \cdot 10^{-3} torr, and, if possible, linearity of the discharge current in the pressure throughout this pressure region. We were fortunate to locate a reference to studies of the effects of anode and cathode geometry on discharge characteristics⁵⁶. It was also found to be necessary to shield the gauge from the light from our arc discharge.

See Figure 21 for a drawing of the gauge.

4. Faraday Cups

We have used several movable Faraday cups in order to assure ourselves that the intensity and path of our ion beam are as required. These cups are movable out of the beam line in order to allow the beam to pass once its properties are measured. The cups are of standard design except that the physical support and electrical lead have been integrated into a single 3/4" diameter tube which slides in the "Wilson" seal allowing movement. The suppression of secondary electrons is accomplished by small permanent magnets placed inside the outer box which produce a ~100 gauss magnetic field inside the inner cup. The body of each cup that is the outer cup, is made of 0.031" cold rolled steel. This serves as a flux return as well, increasing the magnetic field inside while reducing the field outside. This is needed in order not to deflect the ion beam when the cup is moved out of its path. The front cover on the cups is removable and we have ones with several different size holes for different purposes. The cups are located (see Figs. 15 and 30):



Penning Ionization Gauge Figure 21

XBL 814-9278

- a) Immediately after collimator 2 between the final beam-line valve and the horizontal injector steering plates.
- b) In the scattering chamber approximately at the midpoint of the target plasma region.
- c) In the analysis chamber just in front of the solid state detector array.

See Figure 22 for a drawing of a cup.

5. Solid State Detectors

The solid state detector array and its associated electronics allow us to count the ions and atoms of each charge state separately after the beam has passed through the plasma target. There are three arrays of detector chips, where each chip is 3.0 cm x 1.2 cm. The positive ion detector has four chips, the neutral and beam monitoring detector has six chips, and the negative ion detector has one chip. Each of these chips has its own connector and vacuum feed-through to allow separate testing to assure correct operation. Each array of chips comprising a detector is held in a gold-plated aluminum housing which has side mounted panels holding the electrical connectors and an 80 to 100 μ gm/cm² aluminum foil mounted to the front. The side panels are made of copper- and gold-plated NEMA-G which has holes for the connectors and contacts for both holding and making electrical connection to each of the chips. The foil in front of each array is
in the form of a coating on polypropylene film which is supported by a rectangular aluminum frame. See Figure 23 picture of the detector arrays.

More detailed drawings of the various system components can be found in Appendix C.



Faraday Cup

XBL 814-9279



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Figure 23

Chapter IV. Plasma Target Properties

We describe in this chapter what we have learned about the behavior of our electric discharge and the properties of the plasma target it provides. First, we describe past experiments on which our work is based and what we have done differently. We then give a description of the electrical chara:teristics of its operation under a range of conditions. Among the parameters varied are gas input, voltage, magnetic field strength and cathode heater power. Finally, we discuss the properties of the plasma and what we have used to measure them. We present electron density and temperature dependences on arc parameters and position in the plane of ion beam motion. We also give a simple model for the ion and electron motion in the discharge and the energy transfer between electrons from the cathode and the thermal electron population in the discharge column.

A. Previous Experiments

The first experiments to achieve a D.C. highly ionized hydrogen plasma, were done at Oak Ridge in the late 1950's and early 1960's. The DCX experiment ⁵⁷ used a differentially pumped long chamber with a constant, axi-symmetric field of several kilogauss. The cathode was made of a tungsten tule, heated by ion bombardment from the discharge. Gas

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was introduced at both anode and cathode. Densities approaching $10^{14}/\text{cm}^3$ and electron temperatures exceeding 15 e.V. were achieved. This served as the model for the plasma target experiment built at Lawrence Livermore Lab in 1973.⁵⁸ This discharge used the minimum B mirror coil from the "Baseball I" experiment. The electrodes were placed in the mirror throats so as to be aligned with one another along the magnetic field. A high degree of ionization was achieved by pulsing the discharge in a well evacuated chamber. The cathode \therefore s a tungsten rod heated resistively while the copper anode was also used for the gas inlet. The 2.5 k V arc voltage was applied for approximately a millisecond producing an arc current of up to 300 Amperes. Electron density approaching 10^{14}cm^{-3} and an electron temperature of 16 e.V. were achieved.

Our experiment was designed making use of the experience gained in the Livermore work. We needed a slightly thicker plasma target with greater uniformity. To achieve this we used electrodes with a rectangular shape (10.75 cm x 2.2 cm) and heated our LaB_6 cathode radiatively. We do not need absolute MHD stability and therefore found an axi-symmetric anti-mirror to be a suitable magnetic field configuration. We can tolerate a somewhat higher degree of gas contamination and therefore do not need the efficiency of gas utilization or chamber volume of the Livermore experiment. Our discharge is like that of Ref. 58, a pulsed beam-plasma discharge with electrical characteristics similar, but slightly modified to suit our different experimental needs. See Table II for a list of arc plasma parameters.

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Table II. The characteristics of the arc discharge plasma.

Parameters	Values
Measured Electron Temperature	δ eV <u><</u> Te < 10 eV
Electron Density	$2.10^{12} < n_e \le 6.10^{13} \text{ cm}^{-3}$
Target Thickness (charged particles)	$3.10^{13} < 2 \overline{n}_e \times \ell < 9.10^{14} \text{ cm}^{-2}$
Debye Length	3 . 10 ⁻⁴ cm \leq $_{\lambda D}$ \leq 2.10 ⁻³ cm
Electron Gyroradius	.005 < a _e < .015 cm
Plasma Parameter	$10 < 1n (\Lambda) < 13$
Electron-Ion Mean Free Path	.6 < < 50 cm
Plasma Frequency	7.10 ¹⁰ < ω _e < 4.10 ¹¹ sec1
Ion Cyclotron Frequency	$7.10^6 < \Omega_i < 1.7 . 10^7 \text{ sec}^{-1}$
Electron Cyclotron Frequency	1.3 . $10^{10} < \Omega_{e} < 3.10^{10} \text{ sec}^{-1}$
Cross Field Diffusion Time (Bohm Diff'n)	1.6 . $10^{-5} < \tau_{B} < 5.10^{-5}$ sec.

B. Electrical Characteristics

We have operated the discharge under a range of values of arc voltage, magnetic field, cathode temperature and gas injected and observed the dependence on these of the arc current as well as the general behavior of the discharge (see Fig. 24). The ease of starting and stability of the arc are not affected by the variation of the voltage. The arc current is a monotone increasing, but not linear, function of the arc voltage. We have observed that the arc is more easily started and, less likely to change to the second mode of operation at lower values of the magnetic field. However, the higher field strengths are needed to obtain arc current above 100 amperes. For a cathode temperature of approximately 1500°C the arc current is of the order of 10 Amperes. As the temperature is increased the current rises approximately linearly with the rate dependent on the voltage and magnetic field. It is clear from this dependence on voltage and B that the arc current is not solely due to thermionic electrons from the cathode. This will be discussed in more detail in a later section. When we inject amounts of gas less than 20 micron liters we have been unable to start the discharge reliably and for more than 100 micron liters we observe hashy current and voltage and sometimes a rapid transition to the high-current, low voltage mode of operation within these limits, the arc current is a monotonic function of the amount of gas injected.

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C. Plasma Measurements

We have measured electron density and temperature in the arc using a Langmuir probe and electron line density with a laser interferometer under a range of conditions to assure its sufficiency as a target plasma. The measured dependences include spatial in vertical and horizcatal (parallel to the beam's plane of motion) directions (see Fig. 25; dependence on magnetic field starth, arc voltage and gas injected (see Fig. 26). The Langmuir probe measured density was integrated along a horizontal path (show in Fig. 30) was used for relative electron density values in the horizontal profile and was compared with the laser interferometer measurement of the integrated electron density (see Fig. 27). We found excellent agreement under most arc conditions at high B field strength and when the arc was run at maximum gas feed. The agreemer was not as good for low gas feed and lower magnetic fields. The probe data were interpreted using the model of Brown. Kunkel and Compher 54 for a drifting plasma in a magnetic field. The electron temperature deduced from probe data is felt to be reliable only for arge amounts of injected gas since implausibly large values an found when the arc is gas "starved". The electron temperature is between 5 and 9 e.V. for arc conditions of interest. The temperatur increases slightly with increasing magnetic field or decreasing gas injection and is approximately independent of arc voltage. The density rises rapidly with increasing magnetic field and voltage but rises with gas input only for small amounts injected after which it "plateaus".

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HORIZONTAL POSITION (CM)

Ťε Ne oNe ∙Te 2 3 9 1.5 ¢ ď 0 ٥ 2 8] o . 7 .5 1 1600 1550 5 5 CATHODE CEMPERATURE (*C) Ast intraj: ۰. ۰ 2.5 Ľ; 0 11 è 3 2 ٥ o 10 8 2 1.5 ŝ ø 1 1 9 1.5 ē นก 80 120 1 INJECTED GAS (4-1) MAGNETIC FIELD (KILODAUSS) NBL 6010-13646

- 75 -Figure 26



- 76 -Figure 27

D. Discharge Physics

In this section we try to understand the particle motion and power balance in the discharge. Ion and thermal electron motion are treated using one-dimensional fluid equations. The interaction between thermal electrons and primary electrons from the cathode is treated with the 3-D fluid approximation (see Appendix C-4). For the above approximations to be appropriate we have assumed the following: that there is a single species of ion which has zero temperature; that the electrons and ions are lost predominantly along the magnetic field; the interaction between the electrons and ions only maintains quasi-neutrality; and that there are two species of electrons, thermal and primary. The thermal electrons which may have densities approaching 10^{14} per cm³; and primary electrons from the cathode which the evidence leads us to believe have energies approximately equal to their charge times the cathode voltage, which energy is mostly in directed motion toward the anode. The latter group may have a density approaching 10^{10} per cm³ and possible energy spread of order 10% their total energy.

We believe that the fast primary electrons heat the plasma electrons by a two-stream instability and these plasma (5-9 eV) electrons are primarily responsible for the ionization of the gas (Appendix C-1). We have evidence that this ionization takes place mostly in the anode (Appendix C-2) and that a large fraction of the ions created there flow along field lines to the cathode. Where their speed of flow is given by:

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$$v(x) = \frac{c_{s}}{F(x)} \left(\frac{n_{o} c_{s}}{2} + \frac{1}{2} \sqrt{n_{o}^{2} c_{s}^{2} - 4F(x)^{2}} \right)$$

Where c_s is the ion sound speed and n_o is the peak density. And their density given by the equation:

$$n(x) = \frac{F(x)}{v(x)}$$

where F(x) is defined as the total ion flux through a plane at a distance x from the anode. We also know that the potential is approximately given by:

$$\phi(x) = \ln\left(\frac{n(x)}{n_0}\right)$$

which comes directly from the quasineutrality of the arc column. We can see from a plot of this (see Figure 28) that there are sheaths at both anode and cathode which serve to confine the thermal electrons electrostatically in the arc column. See Appendix C-2 for the derivation of the above in which ions and thermal electrons have been treated as a 1-D fluid. We have treated this interaction in the cold fluid model and refer to other experiments⁵⁹ for estimates of heating rates which we use in the attempt to account for the power flow in the discharge column.





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Power Balance

Most of the power flowing into the discharge goes promptly into the surfaces of the anode and cathode. The large potential drop at the cathode caused the ion current flowing to it, I_i , to put there an amount of power ~ $I_i \times V_{arc}$. The primary electrons emitted from the cathode strike the anode with most of their original energy. The fraction of these which are backscattered by the anode are reflected by the cathode potential barrier and returned to be absorbed in the anode surface. Thus, power deposited in the anode is given by $I_{p} \times (V_{arr} - \delta V) + (power deposited by thermal electrons and ions)$ flowing into the anode). This oV is the average energy lost by a primary electron due to instability effects in the discharge plasma. (See Appendix C-4). This energy, lost by the primary electrons, heats the plasma electrons. The plama electrons lose energy through collision with the gas molecules and atoms and through thermal electron and ion flow into the anode. The existence of the discharge is sustained by this 6V, ~ 10% of V $_{\rm arr}$. If we use the estimate (Appendix C-3) for the relative magnitude of I_i and I_p , we find that $\sim 96\%$ of the arc power is lost directly to the electrodes while only about 4% sustains the plasma. See Figure 29 for an estimate of the power necessary to maintain the plasma in the column.

There have been some complicating factors which have severely limited the scope of our calculations. The source function of ions includes contributions due to gas in the cathode region as well as between the anode and cathode. This affects the ion flow speed and secondary electron emission from the cathode. Since we are unable to make measurements or trustworthy calculations of gas pressure in the anode we have made a simple model of the pressure distribution there. We know that primary electrons from the cathode hit the anode and produce secondary electrons but the number of secondary electrons depends on the energy of the primaries which have an unknown distribution. The ions which bombard the cathode product relandary electrons, but we do not know the secondary emission coefficient of LaB₆. This secondary emission causes the electron emission density from the cathode to be dependent on ion bombardment current as well as on cathode temperature, and thus make the emission current a complicated function of the perpendicular loss rate, the gas input and the arc voltage.



Chapter V

Ion Beam Detection and Data Reduction

This chapter deals with measurements assuring appropriate ion beam transport and detection as well as the reduction of neutralization efficiency data. From Fig. 18 we see that the trajectory of the D⁻ beams is curving as it passes through the scattering chamber. We have made measurements assuring that this trajectory passes through the plasma of the electrical discharge as indicated in Fig. 18. The "fans" of neutral deuterium atoms and positive ions from stripping of the D⁻ ions (~ 8° and 16° in width, respectively) must be aligned in three ways each in order to be fully counted. Furthermore, the "spot" size of the beam on the detectors must be assured to be less than the width of the detector. We must also verify that false counts due to electrical noise and radiation from the plasma are far fewer than counts from beam particles. Lastly, we must know how many counts are lost due to the "dead" time of the detectors and the counting electronics. The counting data are in the form of total counts for each charge state emergent from the plasma plottod as a function of the thickness of the plasma target. From these we deduce the stripping cross section σ_{-10} and σ_{-11} for a plasma target neutralizer, and can estimate efficiencies for optimally thick laboratory plasma.

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A. Target Penetration

To assure that the D⁻ beam passes through a known and maximum thickness of plasma the position and angle of entry of the beam must be within limits set according to the density profile of the target. As we can see from Fig. 25 of Chapter IV, the beam must enter and leave the discharge region less than .6 cm from its horizontal midplane in order to pass through the densest plasma. To assure this we first centered the beam in a Faraday cup located, as shown in Fig. 30, 3/16" above the discharge midplane. We then inserted a 5 μ qm/cm² carbon foil at the front boundary of the discharge region, removed the Faraday cup, and observed the "neutral" spot on a phosphor coated plate just in front of the detectors. By iteratively adjusting magnetic field and vertical deflector voltage we were able to center the trajectory in the Faraday cup while making the neutrals emergent from the foil move in a "cone" with axis in a horizontal direction. Thus, we assured that the D⁻ beam enters the discharge region moving horizontally about .6 cm above the plasma midplane. By calculation using the measured magnetic field and beam energy we then assured ourselves that the D⁻ beam exits the plasma region within the required distance of the horizontal midplane. This calculation was checked by comparing the predictions with the measured location of the detected D⁻ beam.

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B. Positioning Charged and Neutral Beams on Detectors

In order to assure that each charge-state component of the beam is almost fully counted we must make several tests in which the different beam components are deflected across the various detector chips. The first test assures that the "cone" of ions emergent from the aluminum coated foil which covers each detector holder can be almost fully counted. As shown in Fig. 20 the foil is ~ 1 cm from the detector and by calculation 95% of the ions emerge within a cone with a $\sim 7^{\circ}$ half-angle. We know from measured current into Faraday cups versus deflector voltages that the beam is < 1 mm when it arrives at the foil, so we expect the "spot" size to be > 3-1/2 mm on the detector chip. The result of the "sweep" of the beam across a detector is shown in Fig. 31 from which we infer a beam "spot" slightly greater than 1/2 the chip width of ~ 5 mm. Thus, we find with the spot centered on a chip that we detect > 98% of the ions incident on the foil. We have also swept the beam in like manner across the negative ion detector and verified similar "spot" size. See Fig. 31.

The next test is to assure that the "fan" of neutrals will be centered in the three appropriate detector chips simultaneously. to do this we raise the pressure in the scattering chamber to ~ .1 m-Torr (by opening a needle valve to the air) and vary the horizontal steering voltage in the injector section. What we find is the count rates on the neutral detectors as a function of the horizontal steering voltage. See Fig. 32. Since the sweep using the analysis

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- 87 -Figure 31

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Figure 32



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plates shown in Fig. 31 is done at a horizontal deflector voltage of -750 V we see that in the range between -500 V and -1.2 kV the neutrals are almost all detected on chips 2, 3 and 4.

The final horizontal alignment of the beams involves increasing the potential between the analysis plates to find the range of voltages for which the negative and positive ions are simultaneously fully detected in their respective detectors. Since the neutrals from the plasma are not deflected we must first set the horizontal steering voltage in the range 500 V to -1200 V. Then we measure the count rates on the negative and positive ion detectors relative to the count rate on a neutral detector as a function of the analyzing voltage. The results can be seen in Figs. 31 and 33. We thus maintained an anal- ysis voltage of 12 kV through-out the remaining measurements.

It is also necessary to assure that the neutrals, and positive ions created by collisions in the plasma region are collected on the desired detector chips. What we have done is again to use the 5 ugm/cm^2 carbon foil as a target for the D⁻ beam while varying the vertical deflector voltage. The foil is placed at the front of the plasma region and the neutrals and positive ions emerge in narrow cones which then separate in the magnetic field and the scattering chamber. The count rate on the relevant chips is measured and plotted as functions of the vertical deflector voltage. See Fig. 34. To assure that the neutrals made at the back of the plasma region are collected in the desired detectors we moved the foil to the horizontal midpoint of the discharge region and swept the vertical deflector voltage, observing the count rate of the emergent neutrals on the appropriate chips.

Figure 33



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- 91 -Figure 34



C. Counts Lost due to Pileup and Discriminator Action

Because the counting rate for positive ions is so much less than for negative ions (due to the small target thickness), and neutral atoms, we must have a high rate of negative ion counting to get acceptable statistics on the positive ion count. This high rate into the minus counter and to a lesser degree the neutral counters causes a loss of counts due to accidental coincidence of particle impact within the minimum resolving time of the counting system. Since the resolving time is ~ 1/2 µsec for the negative counter and ~ 1 µsec for the neutral, and since we run at a maximum rate of ~ 200 kHz into the negative and ~ 100 kHz into the neutral, we expect to lose < 10% of the pulses which should have been counted. We have measured the count loss rate by varying the beam rate while keeping a constant gas target and measuring the relative count rates of two different charge state components of the beam on different counting channels. The result, shown in Fig. 35, allows us to correct the apparent count total by making an easily computed correction

```
Corrected Count = <u>Actual Count</u>
1 - vt
```

where

 $\tau = minimum resolving time of counting system$

and

```
v = Actual Count
Time of counting
See Table III for the value of used in different conditions.
```

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We must take great care in setting the lower level of the discriminators used in counting the pulses from particle impact in order to lose a minimum number of counts. Because the detector chips have variable thicknesses of "dead" layers, the amplifiers for different channels have different noise spectra we must set the level for each discriminator separately. We have used two procedures to do this: First, we take a pulse height spectrum using a multi channel analyzer and set the pulse amplitude on a "tail" pulser so as to give the same spectrum as the ion impacts. We then set the threshold on the discriminator so as to count 99% or more of the pulses from the pulser. Unfortunately, the width of the peak from the pulses becomes increased when the pulses are analyzed during an intense discharge. It is therefore necessary to lower the threshold, in some cases into the "noise peak," so as to count a sufficient fraction of the pulses. The second technique used to set thresholds is to have ions and atoms impact on several detectors at once by leaking gas into the scattering chamber at a fixed rate. Then we adjust the threshold downward from a high value until we find a "plateau" in the count rate ratio. The latter technique does not work very well when there is little separation between signal and noise peaks. See Fig. 36 for graphs and count ratios versus threshold value.

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Table III. Counting chanel speeds and grouping.

Pulse Resolution for Counting Channels

Channel	1,2 3	-	.5μs 1.2μs
	4	-	2.0µs
	5-8	-	5.0µs

Charge State for Each Channel

Negative Ions	-	Channels 1 and 4
Neutral Atoms	-	Channels 2 and 3
Positive Ions	-	Channels 5,6,7 and 8

D. Counts Lost due to Angular Scattering and Post Plasma Region Charge Exchange

In order to estimate the fraction of ions lost due to angular scattering in the volume, we estimate the maximum angle for detection and the angular scattering cross section for deuterons on protons, deuterons and electrons. If the beam ion is deflected by 6 mrad in the scattering chamber it stands $\approx 25\%$ chance of not being counted. The maximum scattering angle for scattering on electrons for a deuterium ion is:

The cross section for this process is:

$$\sigma = 10^{-17} \text{ cm}^2 = \pi \cdot \frac{e^4}{\left(\frac{m_e}{m_i} \cdot E_i\right)^2}$$

where E_i beam ion energy. The cross section for scattering of deuterons of f a massive point particle with unit charge is:

$$\sigma(\underline{e}) \approx \pi[b(\underline{e})]^2 \approx \pi \cdot \left(\frac{\underline{e}^2}{\underline{e} \cdot \underline{E}_i}\right)^2$$





which for $E_i = 250 \text{ keV}$, e = .006 rad gives

 $c \approx 3 \cdot 10^{-20} \text{ cm}^2$.

These estimates are such that beam losses are expected to be less than .01: due to binary collisions.

The losses of ions due to post-plasma charge charging collisions is calculated using known cross sections and measured gas densities. The first process we need to consider is the fraction of neutral atoms stripped to positive ions. The cross section, c_{01} , for this process is $= 10^{-16}$ cm² while the target thickness is $< 5.10^{14}$ cm⁻² of H₂ gas. Thus, we expect less than 5 of the neutrals to be lost. Actually, by looking at the ratio of counts on channel 4 to those on [channel 1 and known cross sections we would expect 1.5 to 2: of the neutrals are lost by late stripping collisions.

The other processes of possible importance are electron capture collisions. The most important of these involves capture by neutrals to become negative ions. The cross section is $\sim 10^{-18}$ cm² and for a target thickness $< 10^{15}$ cm⁻² we find less than .1 of the neutrals to be affected. The other involves electron capture by positive ions. The cross section times target thickness for this process gives a loss of about 1% of these ions.

E. Counter Data Analysis

The pulses of charge produced when beam particles stop in the detector chips are amplified and counted separately in 8 channels. Totals are taken for each shot for each of the channels. Typically, 20 to 50 shots are taken under the same target conditions to provide adequate statistical accuracy in count totals for each channel. After each shot the count in each channel is corrected for pulses lost due to "pileup" and then added to the running total for that channel. At the end of a run the sum is corrected for the "gaps" between the active regions of the detectors and for the noise due to radiation from the arc discharge. Typically, the beam is turned off once in every 2 to 4 shots to monitor the count rate due to noise from the plasma. A typical shot has lasted 1 millisecond and given > 100 counts in channel 1, tens of counts in each of channels 2 and 3, ten or fewer in channel 4 and a few counts in each of channels 5 through 8. Thus, a run might produce thousands of counts in channel 1 but only a few tens of counts in channels 5 through 8.

In Table IV we show the total neutral counts for each of the plasma runs we have made. During many of these runs we monitored the counting accuracy by displaying the amplifier output for each channel on a storage oscilloscope. In this way we could estimate the fraction of counts lost for each channel due to various causes (error in "pileup" estimate and setting of discriminator lower level) and correct problems. These were added as corrections to count totals. The statistical error is assumed to be Gaussian with standard deviation $\sigma = N$ where N is the total count in any channel.

	Errors_ (1)					Errors _o (1)				Errors, (%)						
RUN	н_	Ρ	7 777	51	N	T	Cx TOT	st	N	T	Cx TOT	st.	τοτ	f	f.	"o
1(4)	2100	.5	5.5	2	916	10	1 10.5	3.5	113	10	26 43	32	3129	.29	.04	.033
2(5)	1960	1	5 5,5	2	1455	5	1 6	2.5	34	100	100 185	120	3449	. 42	.01	.030
3(5)	1148	. 5	8 9	3	1080	10	1 10,5	3	114	20	16 30	15	2342	.46	.05	.052
4(6)	1150	2	7 8	3 '	946	3	.5 4.5	3.5	67	25	25 56	43	2158	. 44	.03	.028
5(6)	994	1	7 8	3	1045	5	.5 6	3	57	100	16 116	56	2096	. 50	.03	.035
6(7)	4360	2	3 4	1.5	2315	3	1 4	2	269	12	77 21	15	6944	. 33	.04	.016
7(15)	5724	1	3 3.5	1.5	2457	5	.5 5.5	2	744	50	6 112	100	8425	.2ª	دن.	510.
8/16)	460 3	1	3 3.5	1.5	2582	5	.5 5.5	2	•	Bad due	statisti to noise	cs	7368	. 35	(.025)	.021
9(17)	2855	Z	3 4	2	1908	3	.2 4	2.5	-	Bad Gue	<tatisti to noise</tatisti 	c s :	4898	. 39	(.0275)	.022
10(18)	2855	2 40	3	2	734	5	1 6.5	3.7	-	Bad đue	statist' to noise	cs .	3650	. 20	(.0160)	.015
1:(19)	3184	2	3 4	2	1362	5	.5 6	2.7	-	Bad due	statisti to noise	cs :	4639	.29	(.02)	.022
12(20)	4799	2.5	3 4.5	1.5	2793	5	.3 5.5	1.9	30.9	10	13 18.5	8	7901	. 35	.04	. 022
13(21)	2386	1.5	3 5	2	1548	7	7.5	2.5	168	7	20 35	8	41.50	. 38	.04	.031
14(22)	1646	.8	3	2.5	1188	5	4	з	90	50	11	35	2924	. 4]	.03	.026

Table IV. Count totals for different charge state and random errors for each account.

Where:

 P^{μ} pileup error. We have checked the ratic h_0/N_s for runs with large numbers of counts against those with small numbers. Also, have looked at data used to estimate pileup as function rate.

T = Counts lost or gained due to action of discriminator at lower threshold level.

 $C_g = -$ Counts gained or lost due to charge changing collisions after the plasma.

Sy = Statistical error due to finite number of particles counted. Gaussian statistics assumed.
Typically, this is a few percent or less for negative and neutral channels and as much as a few percent for the positive channels. The column headed "error" is the square root of the sum of the squares of the statistical error and the uncertainty in the correction.

F. Plasma Target Thickness

As discussed in chapter IV we used a laser interferometer to measure the target thickness of electrons in the discharge. We have assumed that the ion density is equal to the electron density and that the density profile is accurately measured by a Langmuir probe. (See Fig. 25 in Chapter IV) making use of a graphical representation of the beam trajectory through the plasma profile we estimate the target thickness to be $\stackrel{<}{=}$ 90% of the peak target thickness measured by the laser interferometer. We have estimated the random error in the interferometer measurement of density to be ~ 10% based on the scatter of the data and the repeatability of the results. It is difficult to estimate the systematic error, but comparisons with probe data and variation with laser line of sight suggest it to be less than 15%. See Fig. 37 for interferometer data used to get plasma target thickness under conditions where beam runs were made (results seen in Table V).

Unfortunately, all attempts to operate the counter at high plasma densities failed, due to x-rays from the plasma. These x-rays caused by electron excitation of impurities in the plasma, gave noise

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counting rates far in excess of beam ion rates. This prevented us from beam counting for plasma densities above 2.10^{13} cm⁻³ (a factor of 3 below the maximum obtained). For the maximum plasma target thickness achieved we found approximately 50 neutral fraction-a result several times higher than chat for the gas after the discharge was crowbarred.

- 103 -Figure 37a



- 104 -Figure 37b



Ag. 1.

- 105 -Figure 37c



- 105 -Figure 37d



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G. Gas Thickness

It is necessary to have an estimate of the target thickness of gas and its composition in order to draw useful results from the plasma target data. It was not feasible to measure the gas target thickness in the presence of the plasma. What we did measure was gas target thickness immediately after discharge. We also have measured gas density during the discharge with a Penning ionization gauge at the wall of the scattering chamber. We have estimated the gas density in the presence of the plasma from data taken without plasma using a succession of approximate models. We do know from a comparison of Penning gauge and beam through gas data (See Table V) that there is "streaming" component to the gas density in front of the anode. This is not detected by the Penning gauge. It is not possible from our data to determine whether streaming or ambient gas is preponderant as a contaminent in the discharge. However, we did make an estimate of their relative importance in the absence of plasma from our data. We then estimated the amount of gas lost due to ionization and dissociation to get our estimate of contaminant gas. (See Appendix D).

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Table V. Gas target thickness measured during and after discharges.

-

	Backgro	ound Gas
No Plasma	Ion Beam	PIG Gauge < > _t
V _G = 280 V V _G = 300 V	8.3 · 10 ¹⁴ 1.27 · 10 ¹⁵	$3 \cdot 10^{14}$ 6.6 $\cdot 10^{14}$
After Short Plasma (600 µs)		
$v_{G} = 260 V$ $v_{G} = 280 V$ $v_{G} = 300 V$	6 · 10 ¹⁴ 8 · 10 ¹⁴ 1.2 · 10 ¹⁵	$\begin{array}{rrrrrrrrrrrrrrrrrrrrrrrrrrrrrrrrrrrr$
After Long Plasma (1000 µ s))	
$v_G \approx 280 \text{ V}$ $v_G \approx 300 \text{ V}$	7.6 · 10 ¹⁴ 2 1.2 · 10 ¹⁵	3.5 · 1014 8 · 1014

If we were to assume that streaming gas from the anode was the predominant contaminant of the plasma, we would estimate that an upper limit to the target thickness of gas in the plasma was given by the value we have measured after the discharge. If we use this value for the gas target thickness, we get the results in Fig. 38 for the neutral fraction as a function of plasma target thickness. If on the other hand we assume that ambient gas is the main contaminant, we would estimate the average gas target thickness to be approximately 1/2 the value measured after the discharge. We then get the result in Fig. 39 for neutral fraction versus plasma target thickness.

Our best estimate based on the data we have is that the streaming gas density is about twice the magnitude of the ambient. This can be seen by comparing the target thickness measured by the Penning Gauge with that measured by using the D^- beam in the absence of plasma. The data also suggests a 10%-20% increase in ambient gas due to the desorption of gas from surfaces due to plasma electrons and light emission.

If we make a gas target thickness estimate based on the estimated proportions of the streaming and ambient gas components then allowing for the minimum reduction due to ionization or dissociation effects by the plasma, we find the results shown in Fig. 40. We have calculated the reduction in gas density due to plasma using a simple molecular flow model (see Appendix D) which deals with streaming and ambient components separately and we find a somewhat greater reduction in the streaming component which is due mostly to dissociation of H_2 molecules into fast atomic hydrogen. The result is not very sensitive to electron temperature or density but is sensitive to assumptions made about path length of molecules and atoms in the anode. Surprisingly, too, the model is not very sensitive to the ratio of ambient to streaming gas target thickness.





- 112 -Figure 39







CHAPTER VI

Summary and Conclusions

The purpose of this experiment has been to assure that a hydrogen plasma neutralizer is capable of the high efficiencies predicted on the basis of previously measured cross sections. The neutral yields expected based on these cross sections are shown in Fig. 6. All previous experiments for D^{-} stripping by charge particles have been done in extremely thin targets (i.e., crossed beam experiments), and thus would not have detected any thick target effect due to multiple collision events. Furthermore, the practical questions such as gas contamination and providing adequate target thickness to achieve optimal neutral yields have not been previously addressed experimentally. These are crucial to the utility of plasma neutralizers.

A. Summary of Results

The result of our measurement is summarized in Table VI in which we give the values of No, fo, (n]) gas and (n]) plasma which we have used in deriving the data seen in Figs. 38 through 40 of the previous chapter, along with their error bars. If we compute from each of these sets of points the cross section c_{-10} , which gives the best fit to neutral yield (see Appendix D-1), we find the result shown in Table VII.

RUN	f _{u,p}	f _{o,in}	۸f 0	σ 0	ſ _{+,p}	f +,m	^ለ ք ₊	°+	(N _{H2}) _b	(N _{H2} °) _b	2(ne ⁿ)	dne.
1(4)	. 37	.29	.08	.033	.038	.04	.00	.017	6.60 ¹⁴	8.4 . 10 ¹ ′	10 ¹⁴ cm ²	 17%
2(5)	.43	.42	.01	.03	.041	.01	.03	.019	6.10 ¹⁴	8.10 ¹⁴	1.4 . 10 ¹⁴	1 3%
3(5)	.47	.46	.01	.052	.043	.05	.01	.015	6.10 ¹⁴	7.6.10 ¹⁴	1.9 . 10 ¹⁴	12%
4(6)	.46	. 44	.02	.028	.042	.03	.01	.017	6.10 ¹⁴	8.10 ^{1.}	1.8.10 ¹⁵	12%
5(6)	.47	. 50	.03	.035	.027	.03	.00	.018	4.10 ¹⁴	3.6 . 10 ¹⁴	1.8.10 ¹⁴	12%
6(7)	. 37	.33	.04	.016	.038	.04	.00	.008	6.10 ¹⁴	8.4 . 10 ¹⁴	10 ¹⁴	13%
7(15)	.30	.29	10,	.018	,026	.03	.00	.018	4.10 ¹⁴	6.10 ¹⁴	8.10 ¹³	14%
8(16)	.35	. 35	.00	.021	.026	-	-	-	4.10 ¹⁴	5.10 ¹⁴	1.3.10 ¹⁴	10%
9(17)	. 39	. 39	.00	.022	.025	-	-	-	4.10 ¹⁴	4.4 . 10 ³⁴	1.7.10 ¹⁴	10%
10(18)	.225	. 20	.025	.015	.015	-	-	-	3.10 ¹⁴	4.10	6.10 ¹³	16%
11(19)	.29	. 29	.00	.022	.017	-	-	-	3.10 ¹⁴	3.5 . 10 ¹⁴	1.7.10 ¹⁴	13%
12(20)	.37	. 35	.02	.022	.037	.04	.00	.007	6.10 ¹⁴	8.2 . 10 ¹²	10 ¹⁴	132
13(21	.415	. 38	.035	.031	.039	.04	.00	.013	6.10 ¹⁴	7.8 . 10 ¹⁴	1.4 . 10 ¹⁴	10%
14(22)	.47	. 41	.06	.026	.061	.03	.03	.02	7.5 . 10 ¹⁴	1.2 . 1075	1.3 . 10 ¹⁵	10%

Table. VI. Neutral and positive ion fractions measured and predicted ion base on gas model (see Appendix D). Gas and plasma target thickness for each measurement.

Table VII. The value of sigma computed from neutral fraction due to the plasma. (deduct from measure neutral fraction and gas model).

SH0T	2Ne1	°-10 Gas Model A	°-10 Gas Model B	°-10 Gas Model C
1	1.10 ¹⁴ cm ⁻²	.62.10 ⁻¹⁵ cm ²	1.70.10 ⁻¹⁵ cm ²	1.23.10 ⁻¹⁵ cm ²
2	1.44	1.82	2.59	2.21
3	1.88	1.91	2.51	2.16
4	1.7ć	1.77	2.37	2.08
5	2.5	2.16	2.75	2.82
6	1.0	1.06	2.21	1.70
8	1.47	1.98	1.98	2.23
Ģ	1.7	1.71	2.35	2.30
:0	. 58	. 8 <u>9</u>	2.22	1.73
1	1.1	1.55	2.31	2.19
2	1.0	1.23	2.47	1.95
3	1.4	1.40	2.17	:.87
4	1.5	1.39	2.13	1.65
14	$\frac{(2n_e^{1})_i}{\frac{(2n_e^{1})$	$\frac{0^{(i)}}{2.44} = \begin{cases} 1.59 \\ 2.44 \\ 2.1! \end{cases}$	10 ⁻¹⁵ cm ² for m 10 ⁻¹⁵ cm ² for m 10 ⁻¹⁵ cm ² for m	odel A odel B odel C
42 1=	$\frac{(2n_e)_i}{(2n_e)_i}$	<u>10'1)</u> : -10	2.05 . 10 ⁻¹⁵ cm ²	
itanda	ard Deviation - :	42 <u>t</u> <u>i=1</u> <u>(</u>	$\frac{2n_{e}^{(i)}}{\frac{42}{z}} \frac{1}{(2n_{e}^{(i)})_{i}}$	-10 ²
		= .51 . 10	- ¹⁵ cm ² = 25% 5 ₋₁₀	

B. Conclusions

From the results of Table VII and Figs. 39 and 40, we conclude that hydrogen plasma promises improved efficiency over gas targets as a neutralizer for D⁻ beams. This confirms expectations based on neutralization efficiencies computed using previously measured cross sections. In this experiment we have achieved - 90% (though only - 25% while able to count) of the optimal target thickness for neutralization. Estimating the gas contamination for these conditions (90%), we find that the target is - 40% charged particles. We believe these results show that the thickness and purity of plasma for a useful neutralizer are obtainable. The neutralization efficiency extrapolated to plasma conditions achieved is - 75., - 20% better than expected for a hydrogen gas target. This shows that hydrogen plasma target merits further effort and deserves the attention of reactor designers.

While the maximum thickness of plasma achieved was - 9 x 10^{14} cm⁻² (which is - 90% of optimal) the upper limit useable, while able to count, was 2.5 x 10^{14} cm⁻². At this useable maximum thickness, we found a gas contaminant thickness of about 4 x 10^{14} cm⁻². This is a composition of about 40% charged particles. The maximum neutral fraction of the initial D⁻ beam achieved was 50%. Based on an average over gas models, we estimate c_{-10} for the charged particles in the plasma to be $(2.05 \pm 0.5) \times 10^{-15}$ cm² $\pm 5 \times 10^{-16}$ cm². Using only the more plausible gas model (BC) we get $c = (2.3 \pm 0.5) \times 10^{-15}$ cm² $\pm 5 \times 10^{-16}$ cm². Using models BC

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and assuming the previously measured value for σ_{01} to be correct, we estimate σ_{-11} to be 6.7 x 10^{-17} cm² \pm 7.1 x 10^{-17} cm². If we use only model C, we get a lower limit for $c_{-11} = 3.7 \times 10^{-17}$ cm². If we use the above cross values to calculate a projected neutralization efficiency for an optimally thick target with a 40. degree of ionization, we find that:

ro = 76.2 (pessimistic

= 78.4 (optimistic)

The practical problems with this technique for neutral beam production are many and difficult. In our pulsed plasma we observed N_2 contamination that would possibly have been serious had the discharge lasted tens of milliseconds. We observed the divergence predicted in neutrals and positive ions. The cathode durability and reliability of the discharge might be improved but great care will be required to achieve consistent long term arc performance. A particular problem was arc spotting in refractory metal (Ta, W) surfaces near the discharge. The heavy impurities caused by this would have a clear path into a fusion reactor device.

C. Future Experiments

It seems to us that the primary problems with our plasma as a realistic neutralizer are its shot duration and the divergence (~ 8°) it produces due to magnetic field in the emergent neutral beam. We believe a parallel or surface-field plasma can have adequate

degree of ionization and duration while giving much reduced divergence. One such possibility is an ECRH plasma, noted for its high gas efficiency and durability, with a modest magnetic field parallel to the beam direction. The field could be as little as a few hundred gauss with electron densities of the order of 10^{12} cm⁻³. (It has been reported that radiation at ~ ω_c or a small harmonic is absorbed although $\omega_e > \omega_c$). Another possibility is to use the magnetic bucket approach for confinement with plasma provided by RF discharge or hot cathode discharge. We believe the plasma neutralizers so produced can give worthwhile improvement in efficiency over gas neutralizers at small extra cost.

GLOSSARY OF TERMS AND USAGE

- A + B > C + D, indicates a collision process in which the particle B is assumed at rest and A is "Fast"; C is also assumed to be fast. Often we will omit specific mention of the slow reaction fragments.
- onm(A) is in general the total cross section for a
 hydrogen or deuterium atom or ion with initial
 charge n to collide with some atom, ion or
 molecule, A, resulting in a final charge state m of
 the hydrogen. This number is a function of the
 relative speed of the reactants.
- n₀ is the maximum fraction of a negative hydrogen beam which can be converted to neutral in a given target substance. In our work this will be either gas or plasma or a mixture of these.
- A^s is an atom, ion or molecule of element A with charge state s, and number of atoms per particle = n.

 n_{α} density of species α in units of particles per cm^3 .

Τ _α	Temperature of particles of type a (usually
	electrons or molecular gas)
٧ _a	Thermal speed of species α
f _a (v)	Yelocity space distribution function of species $\boldsymbol{\alpha}$
ja	current density of species a
k ^a	thermal conductivity paralle: to the magnetic field
	of species a
S(x)	plasma source function.
x	distance along magnetic field from anode to cathode.

I, ion current to the cathode.

- ^Ie . Electron current emitted from cathode.
- 80 change in the phase of a light wave, due to the plasma dielectric action.

ø electrical potential.

ⁿ c	critical density.
Darc	arc voltage.
F _{0,+,-}	the fraction of the original beam with electrical charge o,+ or
R _p	ionization rate due to primary electrons.
R _s	ionization rate due to secondary electrons.

References

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- 1. R. Wildt, Astrophysical Journal 89, 295 (1939).
- D. F. Martyn and O. O. Pulley, <u>Proceedings Royal Soc. Vol A 154</u>, 445 (1963).
- J. L. Spencer-Smith, Philosophy Magazine 19, 866 (1936).
- H. Eubank, et al., Phys. Rev. Lett. 43, 270, (1979).
- 5. F. Coensgen, et al., Phys. Rev. Lett. 35, 1501, (1975).
- 6. A. C. Riviere, Nucl. Fus. 11, 363, (1971).
- K. B. Axon et. al. <u>8th International Conference on Plasma Physics</u> and Controlled Nuclear Fusion Research (IAEA).
- 8. R. Moir; private communication.
- 9. K. Berkner, et al., Nuclear Fusion 15, 249, (1975).
- 10. S. K. Allison, Rev. Mod. Phys. 30, 1137, (1958).
- D. R. Sweetman, A. C. Riviere, et al., "Fast Neutralization Injection for Plasma Heating and Reactor Start-up", <u>4th International Conference on Plasma Physics and Controlled Nuclear</u> Fusion Research (IAEA), Vol. III, p. 393 (1971).
- 12. Dimov, et al., Sov. Phys. Tech. Phys. 47, 1881, (1977).

- M. Grossman, BNL <u>Symp. on Prod. and Neutralization of Neg. Ions and</u> Beams, BNL 1977.
- 14. E. A. Hylleraas Zeitschrift fur Physik 60, 624 (1930).
- 15. C. L. Pekeris, Phys. Rev. 121, 1649 (1958).
- 16. L. Branscomb and W. Fite, Phys. Rev. 93, 651 (1954).
- 17. P. M. Stier and C. F. Barnett, Phys. Rev. 103, 896 (1956).
- H. S. W. Massey and D. R. Bates; Astrophysical Journal <u>91</u>, 202 (1940).
- 19. D. F. Dance et al.; Proc. Roy. Soc. A299, 525 (1967)
- 20 G. Tisone and L. Branscomb; Phys. Rev. 170, 169 (1968).
- 21. M. Inokuti and Y. Kim; Phys. Rev. 173, 154 (1968).
- 22. O. Bely and S. B. Schwartz; Journal of Physics B2, 159 (1969).
- 23. F. Faisal and A. Bhatia; Phys. Rev. B6, 270 (1973).
- 24. R. J. Tweed; J. Phys B11, 2547 (1978).
- 25. L. C. Johnson; Ap. J. 174, 227 (1972).
- R. J. Glauber; <u>Lectures in Theoretical Physics</u>, editor: W. E. Brittin et al., Interscience, N.Y. 1959 Vol 1, p. 315
- 27 H. Tai, et al; Phys. Rev. A1, 1819 (1970)
- 28. L. Branscomb and S. Smith, Phys. Rev. 98, 1028 (1955).
- 29. S. K. Allison, Rev. Mod. Phys. 30, 1137 (1958).
- S. K. Allison and M. Garcia-Munoz in <u>Atomic and Molecular Processes</u>;
 D. R. Bates, Ed. Academic Press, 1962.
- 31. H. Tawara and A. Russek, Rev. Mod. Phys. 45, 178 (1973).
- 32. D. R. Bates and J. C. G. Walker, Proc. Phys. Soc. 90, 333 (1967).

- 33. J. Geddes et al; J. Phys. B13, 319 (1980).
- 34. C. F. Barnett et al., ORNL-5206 (1977).
- 35. B. Peart, P. S. Walton and K. T. Dolder, J. Phys B3, 1346 (1970).
- 36. Peart and Dolder, J. Phys. B4, 88 (1971).
- 37. B. Peart et al., J. Phys. <u>B9</u>, 304 (1976).
- 38. W. Fite et al., Phys. Rev. 112, 1411 (1958).
 - A. Boksenberg, Ph.D. Thesis, Univ. of London (1961).
- 39. H. B. Gilbody, Proc. Royal Soc. A277, 137 (1964).
- 40. P, M. Stier et al., Phys. Rev. 103, 896 (1956).
- 41. G. W. McClure, Phys. Rev. 134, A1226 (1964).
- 42. T. Jorgenson et al, Phys. Rev. 140, A1481 (1965).
- 43. W. L. Fite et al. Proc. Royal Soc. A268, 527 (1962).
- 44. Ya. M. Fogel et al, Soviet Phys. JETP 7, 400 (1958).
- 45. L. H. Toburen et al., Phys. Rev. 171, 114 (1968).
- 46. U. Schryber, Helv. Phys. Acta 40, 1023 (1967).
- 47. W. E. Kauppila et al., Phys. Rev. A1, 1099 (1970).
- 48. A. J. Dixon et al, Proc Royal Soc. A343, 333 (1975).
- 49. Bethe and Satlpeter, Handbuch der Physik Vol 35 page 373.
- D. H. Birdsall, and D. E. Ping, Review of Scientific Instruments <u>36</u>, 1777 (1965).
- 51. J. N. Lafferty, Journal of Applied Physics 22, 229 (1951).
- J. M. Meek and J. D. Craggs, <u>Electrical Breakdown of Gases</u>, Oxford University Press, p. 433 (1953).

- Francis F. Chen, <u>Langmuir Probes</u> in "Plasma Diagnostic Techniques" Huddlestone AND Leonard Eds. Academic Press, 1965.
- 54. I. G. Brown et al., Physics of Fluids 14, 1377 (1971).
- 55. M. Levine et al., Lawrence Berkeley Laboratory Report 4491 (1976).
- 56. G. Conn and H. Daglish, Vacuum 3, 24 (1953) and 4, 136 (1954).
- R. A. Gibbons and R. J. Mackin in <u>Proceedings of the 5th Conference</u> on <u>Phenomena in Ionized Gases</u>, (Munich, 1961).
- 58. E. B. Hooper and O. Anderson UCRL-76703 (1976).
- 59. M. Seidl et. al., Phys. Fl. 19, 78 (1976).
- 60. A. G. Englehardt and A. V. Phelps, Phys. Rev. 131, 2115 (1963).

Appendix A-1

Electron Capture Effects

$$\frac{dF}{d\pi} = F_{+}(-\sigma_{10} - \sigma_{1-1}) + F_{0}(\sigma_{01}) + F_{-}(\sigma_{-11})$$
(1)

$$\frac{dF_{0}}{d\pi} = F_{+}(\sigma_{10}) + F_{0}(-\sigma_{01} - \sigma_{0-1}) + F_{-}(\sigma_{-10})$$

$$\frac{dF_{-}}{d\pi} = F_{+}(\sigma_{1-1}) + F_{0}(\sigma_{0-1}) + F_{-}(\sigma_{-10} - \sigma_{-11})$$
So we seek eigenvalues through the determinant:

$$\begin{bmatrix} (-\lambda - \sigma_{10} - \sigma_{-1-1}) & \sigma_{01} & \sigma_{11} \\ \sigma_{10} & (-\lambda - \sigma_{01} - \sigma_{0-1}) & c_{-10} \\ \sigma_{1-1} & \sigma_{0-1} & (-\lambda - \sigma_{-10} - \sigma_{-11}) \end{bmatrix}$$
which gives the characteristic equation:
(2) $0 = -\lambda^{3} - \lambda^{2}(\sigma_{-10} + \sigma_{-11} + \sigma_{01} + \sigma_{0-1} + \sigma_{10} + \sigma_{1-1})$

$$-\lambda \{\sigma_{-10} \circ_{01} + \sigma_{-10} \circ_{10} + \sigma_{01} \circ_{-11} + \sigma_{10} \circ_{-11}$$

which gives the reduced equations

(3)
$$\lambda^2 + \lambda (\Sigma \sigma_{ij}) + C = 0 \text{ and } \lambda = 0$$

 $i \neq j$

and thus,

$$\lambda = \frac{1}{2} \sigma_{ij} + \frac{1}{2} \left(\sum_{i \neq j} c_{ij} \right)^2 - 4C$$

if we expand the expression for the square root, we find

(4)
$$\lambda_{+} - \frac{1}{2} \sum_{\sigma_{ij} \pm \frac{1}{2}} \sum_{\substack{\sigma_{ij} \pm \frac{1}{2} \\ i \neq j \in K}} \sum_{\substack{\sigma_{ij} \pm \frac{1}{2} \\$$

Following Geller et al* we know the solution for F_i is:

$$F_{i}(\pi) = \sum_{j} a_{ij} e^{+\lambda j\pi}$$

where we find the a_{ij} by matching to the boundary conditions that $F_{-}(0) = 1$, $F_{+}(0) = F_{0}(0) = 0$ and Eq. (1). Expanding the expression (4) using the fact that

(5)
$$c_{-10} \gg c_{01} \gg c_{-11} \gg c_{10} \gg c_{0-1} \gg c_{1-1}$$

at the energy of interest, we have for an entering D beam:

(6)
$$F_{-}(\pi) \cong A e^{-\pi\lambda} + (1-A)e^{-\pi\lambda^{+}}$$

 $F_0(\pi) \cong (C-K) e^{-\pi \lambda^-} - C e^{-\pi \lambda^+} + K$

 $F_{\perp}(\pi) \cong (D+K-1) e^{-\pi \lambda^{-}} - D e^{-\pi \lambda^{+}} + 1-X$

```
where \lambda_{-} = c_{01} + c_{10} + s
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 $\lambda_{+} = -10 + \sigma_{-11} + \sigma_{0-1} - S$

 A new approach for Neutral Power Injectors based on negative deuterons. R. Geller, B. Jacquot, C. Jacqupt, P. Sermet. Nuclear Instruments and Methods <u>175</u>, 261 (1980).

and
$$s = \frac{3}{4} \frac{\sigma_{01}^2}{\sigma_{-10}^2} (\sigma_{-11} - \frac{1}{3} \sigma_{01}) - \frac{3}{4} \frac{\sigma_{-11}^2}{\sigma_{-10}^2} (\sigma_{01})$$

 $K = \frac{\sigma_{10}}{\sigma_{01} + \sigma_{10}}$
 $C = \frac{\sigma_{-10} - \sigma_{01}}{\sigma_{-10} - \sigma_{01} + \sigma_{-11} + \sigma_{0-1} - \sigma_{10} - 2S}$
 $A = \frac{\sigma_{0-1} - S}{\sigma_{-10} - \sigma_{01} + \sigma_{11} + \sigma_{0-1} - \sigma_{10} - 2S}$
 $D = -(A + C)$

Now we can easily calcualate the effect on $F_0(\pi)$ due to electron capture collisions with gas molecules.

(7)
$$\delta F_0(\pi) \cong \pi \left(\frac{\sigma_{10} - \sigma_{0-1}}{\sigma_{-10} - \sigma_{01} + \sigma_{-11}} \right) (\sigma_{10} - \sigma_{0-1})$$

where m is the target thickness.

which for optimal target thickness
$$\cong \frac{\ln\left(\frac{\sigma-10^+ \sigma-11}{\sigma_{01}}\right)}{\sigma_{-10}^{\sigma-\sigma_{01}^{\sigma-\sigma_{01}^{\sigma-11}}}$$

gives a change in neutralization efficiency:

$$\delta F_{0}(\pi) \approx \frac{\sigma_{10}^{2}}{(\sigma_{-10} - \sigma_{01} + \sigma_{-11})^{2}} \ln \frac{\sigma_{-10} + \sigma_{-11}}{\sigma_{01}}$$

 \sim 10⁻⁴ for 250 keV D⁻ beam in an \sim 10% ionized hydrogen target





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Appendix A-2

Excited State Effects

- (1) $\frac{dF}{d\pi} = -F_{-}(\sigma_{-10} + \sigma_{-11} + \sigma_{-1*}) + F_{0}\sigma_{0-1}$
- (2) $\frac{dF_0}{d\pi} = F_{-\sigma_{-10}} + F_{\star \sigma_{\star 0}} + F_{+\sigma_{10}} F_0 (\sigma_{01} + \sigma_{0\star} + \sigma_{0-1})$
- (3) $\frac{dF_{\star}}{d\pi} = F_{-}\sigma_{-1}\star + F_{0}\sigma_{0}\star + F_{+}\sigma_{1}\star F_{\star}(\sigma_{\star 0} + \sigma_{\star 1})$
- (4) $\frac{dF_{+}}{d\pi} = F_{-} c_{-11} + F_{0} c_{01} + F_{\star} c_{\star 1} F_{+} c_{10}$

where $\pi = n$. x for any homogeneous target substance, "Target thickness". σ_{I-1} the double electron capture process is neglected, since it has a negligibly small cross section in the energy range of interest. F_{\star} is the total population of excited states. If we examine the terms in Eq. (3) we find that both terms which increase the excited state population have comparable size cross sections which are much smaller than the cross sections for the processes which decrease its population. For our beam where the fraction $F_{\pm} + F_{0}$ is nearly 1 and only changes very slowly we can conclude that F_{\star} reaches essentially a steady population soon after entering the target and so the left side of Eq. (3), is approximately zero. If we solve for F_{\star} from (3) and substitute into Eq. (4), we find:

(5)
$$\frac{dF_{+}}{d\pi} = F_{-} \circ_{-11} + F_{0} \circ_{01} + \left(\frac{F_{-} \circ_{-1} \star + F_{0} \circ_{0*}}{\circ_{\star 0} + \circ_{\star 1}}\right) \circ_{\star 1}$$

- $F_{+} \circ_{10}$

where we have ignored the term $F_+ \sigma_{+*}$ since F_+ and σ_{+*} are small compared with F_- and σ_{-*} or F_0 and σ_{0*} . If we regroup these terms, we can write:

(6)
$$\frac{dF_{+}}{d\pi} = F_{-} \left(\sigma_{-11+} \frac{\sigma_{-1} \star \sigma_{\star 1}}{\sigma_{\star 0} + \sigma_{\star 1}} + F_{0} \left(\sigma_{01} + \frac{\sigma_{0} \star \sigma_{\star 1}}{\sigma_{\star 0} + \sigma_{\star 1}} \right) - F_{+} \sigma_{10}$$

and thus we can reduce the original four equations to three with increased values for σ_{-11} and $\sigma_{01}.$

Appendix B

Apparatus

1. Coils

The coils which make the confining field for the discharge were designed by us for this experiment. They are 48 turns of $1/2" \times 1/2"$ hollow core copper conductor with an inner diameter of 11", an outer diameter of 16-5/8" and a height of 5-1/4". The conductor is water cooled using a single water circuit for each coil. Adjacent turns are electrically insulated from one another by double lapped mylar and cloth tape. The structural integrity is provided by "potting" the coils in epoxy resin.

2. Flux Return and Magnetic Shield

In order that the return flux from the confining field not perturb the beam before or after the scattering chamber we have built a cylindrical "can" of cold rolled steel which fits around the coils. This has a 3/8" wall thickness and an outer diameter of 17-1/2" and is cut into two sections by a plane which contains the cylindrical axis. There are two beam duct ports, five diagnostic access ports and an opening for magnet water and coil connection cut out of the iron. The access ports are 2-1/2" diameter and the front and rear ports for the beam are 4" diameter and 2" x 6", respectively. The lower half of the flux shield also serves as the physical support for the coils and scattering chamber.

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Cathode

The target in the scattering chamber is a plasma created by a high voltage discharge along a magnetic field between a thermionic cathode and an anode. The cathode itself is a slab of sintered lanthanum hexaboride 4-1/4" x 7/8" x 0.1". This is held in a "picture-frame" type holder which allows the back to be heated by the radiation from tungsten filament while the front side acts as a thermionic electron emitter for the plasma. This holder frame is supported by three molybdenum tubes which are clamped at the other end onto a water cooled copper slab. This in turn is mounted on a slightly larger piece of machinable ceramic which serves also to insulate the cathode from, while attaching it to, the support structure (which is at anode potential = ground). This ceramic piece also supports the LaB₆ and the tungsten heater filament assembly. In order to minimize the required power we have surrounded the cathode piece and tungsten filament with four to six layers of heat shielding. These shields are made of dimpled molybderum and tantalum sheet 0.033" to 0.005" thick. These shields extend almost 2" in front of the cathode and form an elongated box which has a rectangular hole in the front just large enough for the discharge to pass.

Among the considerations which weighed heavily in the design were durability, power efficiency and uniformity of cathode temperature. We decided on radiative heating because of the great problems anticipated in holding the necessary voltage for electron bombardment heating in such a small, closed structure where many surfaces are not allowed to get hot and thereby de-gas. Durability required that we not let many components get so but that they experienced grain growth and its consequent embrittlement. It also required us to allow for differential expansion of components made of different materials or with unequal temperatures. It was also important to increase the length and diameter of the heater filament in order to reduce its needed operating temperature while providing adequate radiated power.

It was necessary to make several modifications of the support structure for the cathode and the heat shields in order to attain the required efficiency. The support rods have had heat shields put on them and holes cut in them to reduce heat conduction to the copper support block. We have added double heat shields between the region behind the cathode and that in front to reduce the radiation leaking out around the cathode. In order to achieve the desired uniformity of temperature it was necessary to try several different designs for the filament. The essential factor in attaining the needed uniformity was reducing the filament area behind the center of the cathode. Since radiation is the dominant mechanism of heat transfer one must uniformize the radiation incident on the back side of the cathode. Geometric arguments show that for best uniformity of a radiating rectangular heater behind a rectangular cathode the radiance of the heater must increase monotonically as one moves away from the center.

4. Anode

The anode itself is made of three parts. There is a copper box 4-5/8" x 2-1/4" x 1-1/4" with 3/16" thick walls, a tantalum rectangle

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 $4-1/4" \times 2" \times 0.060"$, and a duct having rectangular cross section 7/8" x 4-1/4" made of 0.010" molybdenum. These three fit together so as to provide both the electrical positive contact for the discharge and its gas supply. The gas enters in the middle of the closed side of the copper box to a reservoir whose front side is the 0.060" thick rectangle. From there it flows through eight holes, .060" diameter, into long, narrow rectangular chambers above and below the discharge and open to it. The gas then flows out through the duct where much of it becomes ionized by passage through the discharge. The positive electrode for the arc is provided by the tantalum plate; specifically, that part of the piece which is exposed through the rectangular duct.

The discharge is started by a -40 kV pulse to a 0.040" diameter tungsten rod which has been placed in the back region of the duct through a hole in its wall. This rod is shielded from spurious breakdown by a 5 mm quartz sleeve which covers it all the way from the support flange where it is clamped into the high voltage feed-through to the anode.

The gas is supplied using a very fast designed and built at Lawrence Livermore Lab by Dale Birdsall.⁵⁰ We have modified it so that the base bolts directly behind the anode. Essentially this is a needle valve which is driven open by current pulse of tens of kilo amperes passing through a fifty turn coil which drives an aluminum plate to which the needle valve is attached.

- 135 -
- 136 -Figure B-1



Copper Coils

15. 514-9275





Magnet Flux Return Shield

KBL 814-9286

- 138 -Figure B-3





XBL 814-9287

- 139 -Figure B-4





XBL 814-9287

Figure B-5





e. -----

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Appendix C-1

Electron Ionization and Thermal Conductivity

it is necessary to calculate the relative importance of the different populations of electrons in producing ionization in the discharge volume. We also demonstrate that the electron temperature deep in the anode due to the finite heat conductivity of the electron population is not significant.

The ionization rate of the H₂ molecules due to the primary electrons from the cathode is:

$$R_{p} = \left(\frac{j_{p}}{e}\right) \left(\sigma_{H_{2}}^{i}(E_{e} = 1500)\right) n_{H_{2}}$$

whill that of the secondary thermal electrons is:

$$R_{s} = n_{e} n_{H_{2}} \int f_{m}(v) \sigma_{H_{2}}^{i}(v) d^{3}v$$

wher we use the values appropriate, that is,

$$j_{p} \sim 2A/cm^{2}$$
, $\sigma_{H_{2}}^{\dagger}(E_{e} = 1500 \text{ eV}) \sim 1.3 \cdot 10^{-17}$

and

$$n_e = 10^{13} \text{ cm}^{-3} \text{ and } \int f_m(v) \sigma_{H_2}^i(v) d_v^3 \approx 2.10^{-9}$$

For a Maxwellian population of electrons at 7 eV

thus $\frac{R_s}{R_p} > 100$ and the ionization by primary electrons can be neglected.

The temperature drop in the anode can now be estimated by using:

$$(\Delta T_{e})(K^{e} = (R_{s})(50 \text{ eV})(5 \text{ cm})$$

where we have used 50 eV energy loss per electron-ion pair created.

$$K^e = 3.2 \frac{(nkT_e)\tau_e}{me}$$
 for τ_e the electron ion

collision time and where, (from NRL formulary)

$$\tau_e = 3.44 \cdot 10^5 \frac{\tau_e^{3/2}}{n} \approx \frac{3\sqrt{m_e} (k\tau_e)^{3/2}}{4\sqrt{2\pi} ne^4}$$

The resulting value for ΔTe for $N_{H_2} = .5 \cdot 10^{14} \text{ cm}^{-3}$ is $\Delta T_e \approx 1/6 \text{ eV}$, which is a negligible temperature drop.

Appendix C-2 Fluid Model of Arc Behavior

If we assume that gradients (T_e and n) and electric fields perpendicular t- the magnetic field are small and that the ion temperature is much less than the electron temperature we may use a two fluid model to understand our electric discharge.

(1)
$$\frac{\partial}{\partial x} (r_j(x) v_j(x)) = S(x)$$
 Ion Continuity

(2)
$$\frac{\partial}{\partial x} (M n_j(x) v_j^2(x)) = -en_j(x) \frac{\partial \phi(x)}{\partial x}$$
 Momentum flow

and for electrons

(3)
$$en_e \frac{\partial \phi(x)}{\partial x} = kT_e \frac{\partial n_e(x)}{\partial x}$$
 Electron pressure
Balance

where $n_e(x)$, $n_i(x)$ are electron and ion densities, $v_i(x)$ is the flow speed of the ion fluid, $\phi(x)$ is the electric potential and T_e is the electron temperature.

Then, if we integrate equations (2) and (3) we find

(4)
$$F(x) = n(x) v(x) = \frac{n_0 v(x)}{\left(1 + \frac{v(x)^2}{C_s^2}\right)} = \int_s^x S(x') dx'$$

where $C_s^2 = \frac{k^T e}{M}$ (ion sound speed)²

 $n_{\mbox{\scriptsize O}}$ = the ion density where the ion flow speed is zero. and

S = stagnation point where n = n(s).

We know that the anode potential is negative with respect to the plasma potential (from measurement of the floating potential of a probe in the plasma and from the fact that the thermal electrons in the discharge column must be repelled electrostatically at the anode to give electron densities of the order measured). It is thus clear that there will be a maximum of the electric potential somewhere between anode and cathode and that ions formed between this and the anode will flow to the anode, whereas those formed between stagnation point and cathode will flow to the cathode. To determine where this point is we use the assertion of Hooper that the flux to cathode and anode are equal in magnitude. Thus, the stagnation point is at x, such that the value of the integral

$$\int_{A}^{x} S(x') dx' = \frac{1}{2} \int_{A}^{C} S(x') dx$$

where A ard c denote anode and cathode respectively, and

$$F(A) = -\frac{1}{2}n_0c_s = -F(C) = \int_x^C S(x') dx$$

If we assume gas pressure is much higher in the anode than elsewhere, we find that the ion flow speed outside the anode is at the sound speed. If on the other hand the cathode region is a source of ions equal to the anode, then the stagnation point is midway between them where the density is also a maximum. If R is defined as the ratio of ions produced in the cathode region to the total for anode and cathode we find that the speed and density in the intermediate region are given by

(6)
$$\mathbf{v}_{int} = c_s \left(\frac{1 - 2\sqrt{R(1-R)}}{1-2R} \right)$$

and

(7)
$$n_{int} \approx \frac{n_0}{2} (1 - 2R) \cdot \left(\frac{s}{v_{int}}\right)$$

If we define R as the ratio of electron-ion pairs produced between the cathode surface and any point x to the total production between anode and cathode, then the above v_{int} and n_{int} are the speed and density at that point x.

We can then easily find the potential by integrating eq. (3) to obtain:

$$\phi(x) - \phi(s) = \frac{kT_e}{e} \ln\left(\frac{n_e(x)}{n_e(s)}\right)$$

Appendix C-3

Power Use by Thermal Electrons

We have estimated the power required by the thermal electrons in the discharge as a function of the electron temperature for a constant gas flow through the anode. The two mechanisms for thermal electron power loss which we consider are ionization and particle flux to walls, notably the anode. We assume that the anode potential is about $3kT_e/e$ below the plasma potential, that the secondary electron emission from the anode (made of Tantalum) is 1.5 at an energy of 1.3 kV, and that primary electron current comprises a fraction a of the total discharge current. We have then for ion power flow into anode and cathode assuming each ion carries $3kT_e$ to the wall while electrons kT_e :

$$P_i = 2(1-2) I_{ARC} + 3kT_e = 6(1-2)nA (kT_e)^{3/2} m_i^{-1/2}$$

where I_{ARC} is total arc current and T_{e} is electron temperature. A is the cathode area and a is the fraction of the current carried by electron emission from the cathode. For electrons we get:

$$P_e = 2(1-2) I_{ARC} + kT_e + 2 I_{ARC} + kT_e$$

where the second term is for secondary electrons from the anode. For ionization loss we have:

$$P_{H} = 2(1-a) I_{ARC} + 50 eV.$$

where the 50 eV is the geometric mean of the upper and lower limits for ionization losses estimated by Hooper et al.⁵¹ We need to estimate the density for a given temperature so we use the experimental result shown below. To obtain these data we varied the thermionic current from the cathode while keeping the gas input, magnetic field and arc voltage the same. (The points can be fitted to a quadratic function in the temperature $n_e \approx 1.5 \cdot 10^{12} (T_e - 5.7)^2 + 4.8 \cdot 10^{12})$. From this we estimate the dependence of thermal electron power required on the electron temperature for other parameters held fixed. We have used a value of 3/8 for α which we got by subtracting the calculated ion current to the cathode from the total current. This is about 50 larger than the value found by Hooper et al. for their experiment, which can easily be due to the difference in geometry and cathode material. Also, the errors in our measurements are such that the probable error in α is

1/8 (i.e. 3/8 1/8).

The power needed by thermal electrons is about 4 of the total discharge power. Since the primary electrons comprise about 3/8 of the total current, this means that if the power for the thermal electrons comes from the primary electron stream, that ~ 11 of the primary electrons energy must be transferred to the plasma. This figure should vary with magnetic field and gas pressure, though it is beyond the scope of this work for us to make estimates of this variation.

Appendix C-4

Instability Effects

We have the plasma dielectric functions:

(1)
$$e_{p} = \frac{2\omega_{p}^{2}}{k^{2}v_{e}^{2}} \left(1 + \frac{\omega}{k_{z}v_{e}} \cdot \Sigma \cdot Z \cdot \frac{\omega - n \cdot \omega_{c}}{k_{z}\cdot v_{e}} \cdot e^{-\lambda} I_{n}(\lambda)\right)$$

where $\lambda = k_{\perp}^2 v_e^2 / 2\omega_c^2$, for the plasma electrons, and I_n in the vessel function

(2)
$$\epsilon_{\rm b} = \frac{\omega_{\rm b}^2}{\omega_{\rm c}^2} - \frac{\omega_{\rm c}^2}{(\omega - k_z V)^2} - \frac{k_z^2}{k^2} + \frac{\omega_{\rm c}^2}{(-K_z V)^2 - \omega_{\rm c}^2} - \frac{k^2}{k^2}$$

for a cold beam injected parallel to the field into a plasma. The solutions for a cold plasma are: for $\underline{m=0}$

(3)
$$\frac{\omega_{i}}{\omega_{o}} = \frac{3}{2} \left(\frac{\omega_{b}^{2}}{2\omega_{c}^{2}} \right)^{1/3} \left(\frac{x^{2} - 1}{(x^{2} - 1)^{2} + g^{2} x^{2}} \cdot \frac{x^{2} - 1 + g^{2}}{x^{2} + g^{2}} \right)^{1/3}$$

where $x = \frac{k}{c} / \frac{1}{c}$ and $g = \frac{k}{c} \frac{V}{c}$, and for $\underline{m=1}$

(4)
$$\frac{x^2}{x^{-1}} = \frac{1}{2} \frac{x^{-1}}{c} g\left(\frac{1}{x} \frac{x^2 - 1}{(x^2 - 1)^2 (x + 1)^2 + g^2 x^4}\right)$$

$$\frac{(x+1)^2 (x^2-1) + g^2 x^2}{(x+1)^2 + g^2} \right)^{1/2}$$

We now estimate g.
Since
$$2\pi \text{ cm}^{-1} \leq k_{\perp} \leq k_{D}$$
, and
 $V/\omega_{c} = \frac{V}{\omega_{e}} \cdot \frac{\omega_{e}}{\omega_{e}} \approx \frac{V}{\omega v_{e}} \cdot \frac{1}{k_{D}} \cdot 5 \approx 70 \text{ k}_{D}^{-1}$
Therefore $70 \frac{\lambda_{O}}{L_{\perp}} \leq g \leq 70$.
Since $\lambda_{D}/L_{\perp} \approx 7.10^{-4}$ thus $5 \cdot 10^{-2} < g < 70$.

Now we must determine for which k is the mode fastest growing.

For m=0 the mode which grows the fastest is the mode with $g = g_{min}$, for m-1 the $g = g_{max}$ is fastest growing. If we put in the value of x = 6, g = .05, m = 0. For g << 1, x >> 1.

(6)
$$\frac{\omega_{i}}{\omega_{o}} \approx \frac{\omega_{i}}{\omega_{p}} \approx \frac{3}{2} \left(\frac{\omega_{b}^{2}}{2\omega_{c}^{2}}\right)^{1/3} \left(\frac{1}{x^{2}}\right)^{1/3} \approx \sqrt{\frac{3}{2}}$$

where here $\frac{a}{b}^2 = \frac{n_o}{n_e} \quad \frac{a}{e}^2 \approx 5.10^{-4} \quad \frac{3}{e}$

and
$$\frac{\omega_c}{\omega_e} \approx \frac{1}{x^2} \approx .028$$
, so,

$$\frac{\omega_i}{\omega_o} \cong .055$$

If x=6, g=70, m=1 we find

$$\frac{\omega_{i}}{\omega_{-1}} \approx \frac{\omega_{i}}{\omega_{e}} \approx \frac{1}{2} \frac{\omega_{b}}{\omega_{c}} \cdot \frac{1}{9x} \approx 2 \cdot 10^{-4}$$

so we expect the m=0 mode to be the most important. The effect of finite plasma temperature on the m=0 mode is negligible for the situation where the arc voltage is more than 100 times the plasma electron temperature. This is not true for the m=1 mode where the growth rate is reduced to 1/3 of its cold plasma value when the plasma electron temperature becomes 1% of the electron stream energy. As a result of the dominance of the m=0 mode, we can compute the growth rate as a function only of the densities of the different components. Because the value of $g = k_V/c$ can be so small for a discharge as large in cross section as ours, we can ignore the dependence of the growth rate on the cyclotron frequency.

Although the instability we have described should ideally be convective, we believe it likely that it is absolute due to feedback caused by wave reflections at the electrodes. We assume that once the beam is more than a few growth lengths into the plasma the energy loss rate is constant. If we now estimate the growth rate for a cold-beam plasma m=0 instability to be:

$$\omega_{e} \cong 1.8 \cdot 10^{11} \text{ sec}^{-1}$$

 $n_{b} \cong 5.10^{-4-n} \text{ e}$
 $\gamma_{m=0} \cong .05 \omega_{e} \cong 9.10^{9} \text{ sec}^{-1}$

so the growth length
$$\approx \frac{V_{beam}}{Y_{m=0}} \approx .25 \text{ cm}.$$

This means that we would expect the beam to complete its evolution to the "quasilinear" distribution if the cold-beam-plasma growth rate were correct. However, as soon as the distribution function for the beam electrons broadens due to instability effect, the energy transfer from the beam to the plasma requires the growth of modes with lower phase velocity. If the saturation of the original unstable mode is by "trapping", then the continuation of the energy transfer is via the growth of "sidebands". The growth rate of the sidebands is slower than that of the original mode. In order for the distribution to evolve to the quasilinear (see Fig. C-2) result it then requires a somewhat longer time. In the work by Briggs dealing with the interaction of a warm beam in plasma it was found that:

$$\gamma_{W} = \gamma_{WARM BEAM} \cong \frac{\sqrt{3}}{2} \alpha \left(\frac{N_{b}}{N_{e}} \right) \left(\frac{E_{b}}{E_{th}} \right) \omega_{e}$$

If we assume a=1, meaning the whole beam population participates, then we can solve for the warmest beam (i.e., the maximum value of E_{th}) which has sufficiently large γ_w for the growing waves to reach saturation. For this we use the result from simulations that about 7 growth periods (i.e. $7\gamma_{WARM BEAM}^{-1}$) are required for saturation of a growing mode. The time for growth we assume to be the length of the arc divided by the beam speed. Thus,

$$\frac{E_{th}}{E_{beam}} \approx \frac{.43 (15 \text{cm}) \left(\frac{N_b}{N_e}\right)_{\omega_e}}{7 \text{ V}_{beam}} \approx .036$$

for a typical condition of arc current and voltage. We expect, based on the experimentally observed evolution of beam distributions, that the spread in beam energies, E_{+h} , is approximately equal to the net energy loss of the beam due to instability effects. See Fig. C-2. Furthermore, when a mode characteristic of a given beam temperature saturates, it is because the beam distribution has been modified. We therefore would expect the final beam temperature and net energy loss to be greater than the above result. This result is not inconsistent with our finding from electron power balance that each primary electron needs to contribute to ~ 100 eV to the thermal population to sustain the plasma. Unfortunately, we cannot produce from the preceeding treatment, the dependence of the heating rate on the magnetic field strength. We can see from the above result that the power transfer to thermal electrons should be quadratic in the emission current of the cathode but we cannot easily relate this to our measurements (i.e. the density of beam electrons). It has been observed however, in other experiments that the discharge will operate at approximately a constant ratio of plasma to cyclotron frequencies this means that we expect the plasma electron power dissipation to be quadratic in the magnetic field strength. This is approximately the observed dependence.

- 152a -Figure C-4



APPENDIX D-1

Small Target Thickness Approximation

In the following, we will neglect the cross sections σ_{0-} , σ_{10} since, at the energies of interest they are much smaller than the other cross sections which affect each beam species.

$$\frac{dF_{+}}{dx} = n_{T0T} \quad \overline{o}_{01} \quad F_{0} + \quad \overline{o}_{11} \quad F_{-}$$
(1)

$$\frac{dF_{0}}{dx} = n_{TOT} - \bar{\sigma}_{01} F_{0} + \bar{\sigma}_{-10} F_{-}$$
(2)

$$\frac{dF}{dx} = n_{TOT} \quad \overline{\sigma}_{-10} + \overline{\sigma}_{-11} F_{-11}$$
(3)

where σ are cross-sections averaged over species weighted by density. Integrating (3) for $F_0(0) = F_+(0) = 0$ and $F_-(0) = 1$

$$\mathbf{F}_{(\mathbf{x})} = \mathbf{e}^{\mathbf{\alpha}\mathbf{X}} \tag{4}$$

$$a = \sum_{s} n_{s}(\sigma_{-10}(s) + \sigma_{-11}(s)) = n_{T0T}(\bar{\sigma}_{-10} + \bar{\sigma}_{-11})$$

where s = species in Target.

Now, using this on (2) and noting that $\sigma_{-10} >> \sigma_{01}$ we get

$$F_{0}(x) \tilde{\beta} | \sigma(1 - e^{-\alpha X}) \quad \text{for} \qquad (5)$$

$$\beta = \sum_{s} n_{s}(\sigma_{-10}s) = n_{TOT} \cdot \tilde{\sigma}_{-10}.$$

This is not a very good approximation and will be improved below. First, we look at (1) integrating using (4) and (5) we get:

$$F_{+}(x) = \frac{\gamma}{\alpha} \left(1 - e^{-\alpha X} \right) + \frac{\beta \delta}{\alpha} \left[x - \frac{1}{\alpha} \left(1 - e^{-\alpha X} \right) \right]$$
(6)

where

$$Y = \sum_{s} n_{s} \sigma_{-11}(s) = n_{TOT} \cdot \overline{\sigma}_{-11}$$

$$\delta = \sum_{s} n_{s} \sigma_{-11}(s) = n_{TOT} \cdot \overline{\sigma}_{-01}$$

since $\gamma + \beta = \alpha$ and $F_{+} + F_{0} + F_{-} = 1$ we get that

$$F_{0} = \beta/\alpha \left(1 - e^{-\alpha X}\right) - \frac{\beta\delta}{\alpha} \left(x - \frac{1}{\alpha} \left(1 - e^{-\alpha X}\right)\right]$$

$$\equiv \beta\left(x - \frac{1}{2} x^{2} \left(\alpha + \delta\right)\right)$$
(5)

APPENDIX D-2

Gas Target Thickness Estimates

We need to make an estimate of an upper limit to the line density of gas mixed in with the plasma during the counting of beam ions. We have two types of data to rely on, Penning gauge results during the discharges and charge state fraction counting after the discharge is crowbarred. The Penning gauge indicates that the gas density in the arc chamber rises linearly during a discharge and remains constant for a few hundred microseconds after it is crowbarred. Based on this we would expect the average density of gas to be half that measured after the discharge, if the plasma had no effect on the gas density ion in the same volume. However, when the ion beam was used to measure the gas density after discharges of shorter duration it was found to be almost equal to that after longer discharges. In order to understand how to reconcile the seeming contradiction, we must note that there is a jet of gas emergent from the anode which contributes to ion beam measurements but not to that of the Penning gauge. This jet density decreases in time due to exhaustion of gas in the anode, while the ambient gas pressure in the chamber increases approximately linearly in time. We don't know the relative magnitude of these gas densities precisely, but based on the constancy of their sum and the \sim 3 m.s emptying time of the anode the stream density is two of three times the average magnitude of the ambient density for a 1 millisecond discharge

In order to set the total density we first estimate the reduction in each of these due to the presence of the plasma. For the streaming component we estimate an upperbound on its density in the plasma by assuming a 15 cm path length in plasma, including bounces in the anode. We then use our calculated values for dissociation and ionization rates (Fig. D-3) as functions of electron temperature to estimate the emergent flows of H₂ and H. (The H atoms are assumed to have 1 eV energy due to Franck-Condon effect). The result is shown in Fig. D-1. We estimate the ambient gas density by assuming that all emergent gas remains in the arc chamber as H₂ but can be ionized or dissociated in the 2 cm of plasma it needs transverse to reach the beam. The result is shown in Fig. D-1. We then take the sum with the stream component weighted double to get the result of Fig. D-2 for the upper limit to the fraction of the gas which endures in the presence of the plasma. The result of this was used as gas model C in tables VI and VII and Fig. 40.

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- 159 -Figure D-3