PLASMA NEUTRALIZAR FOR H\textsuperscript{*} BEAMS

M. V. Grossman
Brookhaven National Laboratory
Upton, New York

Abstract
Neutralization of \( \text{H}^* \) beams by a hydrogen plasma is discussed. Optimum target thickness and maximum neutralization efficiency as a function of the fraction of the hydrogen target gas ionized is calculated for different \( \text{H}^* \) beam energies. Also, the variation of neutralization efficiency with respect to target thickness for different \( \text{H}^* \) beam energies is computed. The dispersion of the neutralized beam by a magnetic field for different energies and different values of \( B^z \) is found. Finally, a type of plasma jet is proposed, which the author feels will be suitable for a compact \( \text{H}^* \) neutralizer.

I. Introduction
An integral component of proposed neutral beam injectors based on \( \text{H}^* \) ions is the neutralizer which converts the accelerated \( \text{H}^* \) ions into neutral particles. The neutralizer should have a high neutralization efficiency, a low gas input and impurity input to the beam line, minimum power requirement, long lifetime, and high reliability. It should also be insensitive to the hydrogen and alkali metal present in the beam line, compatible with the beam transport system, and have little effect on the neutral beam dispersion. Several types of \( \text{H}^* \) neutralizers have been proposed, including a magnetic field neutralizer,\textsuperscript{1} photo-detachment neutralizer,\textsuperscript{2} gas neutralizer,\textsuperscript{3} ionized metal vapor neutralizer,\textsuperscript{4} and hydrogen plasma neutralizer.\textsuperscript{5} In this paper some aspects of hydrogen plasma neutralizers will be discussed.

II. Neutralizer Parameters
The parameters of the plasma target are determined by the \( \text{H}^* \) beam energy, the beam cross-sectional dimensions, the beam pulse duration and how compact a neutral beam injector is desired. The optimum target thickness of the neutralizer, that is, the target thickness resulting in the highest fraction of \( \text{H}^* \) converted to \( \text{H}^0 \), depends on the \( \text{H}^* \) beam energy.\textsuperscript{6,9,10} For a single target species, e.g., a fully ionized hydrogen plasma, the variation of neutral particle intensity, \( I^\text{m}(\tau) \) as a function of target thickness, \( \tau \), is given as:

\[
\frac{dI^\text{m}(\tau)}{d\tau} = \tau_0 I^\text{m}(\tau),
\]

(1)

where \( I^\text{m}(\tau) \), the \( \text{H}^* \) ion intensity is given as:

\[
I^\text{m}(\tau) = \exp\left[\tau \cdot \frac{\tau_0 \cdot \tau_1 \cdot \tau_2}{\tau_3 \cdot \tau_4 \cdot \tau_5} \right],
\]

(2)

The incoming \( \text{H}^* \) intensity is normalized to 1, that is:

\[
I^\text{m}(0) = 1.
\]

(3)

The cross sections, \( \tau_0 \) and \( \tau_1 \), are the sum of the cross sections shown in Table I for a plasma neutralizer. The values of the cross sections used are taken from the references indicated in Table I. As in Refs. 4 and 9, it is assumed that \( \tau_a = \tau_b \).

<table>
<thead>
<tr>
<th>Reaction</th>
<th>Reaction</th>
<th>References Used</th>
</tr>
</thead>
<tbody>
<tr>
<td>a ( \text{H}^+ + e^- \rightarrow \text{H}^0 + 2e^- )</td>
<td>11,12</td>
<td></td>
</tr>
<tr>
<td>b ( \text{H}^+ + \text{H}^+ \rightarrow \text{H}^+ + \text{H}^+ )</td>
<td>11,12</td>
<td></td>
</tr>
<tr>
<td>c ( \text{H}^+ + e^- \rightarrow \text{H}^+ + e^- )</td>
<td>13</td>
<td></td>
</tr>
<tr>
<td>d ( \text{H}^+ + e^- \rightarrow \text{H}^+ + 2e^- )</td>
<td>9</td>
<td></td>
</tr>
<tr>
<td>e ( \text{H}^+ + \text{H}^+ \rightarrow \text{H}^+ + \text{H}^+ )</td>
<td>9</td>
<td></td>
</tr>
</tbody>
</table>

\[
\tau_0 = \tau_a + \tau_b + \tau_c
\]

\[
\tau_1 = \tau_d + \tau_e + \tau_f
\]

Equation (1) can be integrated in order to determine \( I^\text{m}(\tau) \). This results in:

\[
I^\text{m}(\tau) = \exp\left[\tau_0 \cdot \tau_1 \cdot \tau_2 \cdot \tau_3 \cdot \tau_4 \cdot \tau_5 \right] - \exp\left[\tau_1 \cdot \tau_1 \cdot \tau_2 \cdot \tau_3 \cdot \tau_4 \cdot \tau_5 \right]
\]

(4)

where, it is assumed that \( \tau_1 \ll \tau_0 \).

The optimum target thickness, \( \tau_0 \) and maximum value of \( I^\text{m}(\tau) \) are found by setting \( \frac{dI^\text{m}(\tau)}{d\tau} \) equal to zero in Eq. (1). The result is:

\[
\tau_0 = \tau_a + \tau_b + \tau_c
\]

\[
\tau_1 = \tau_d + \tau_e + \tau_f
\]

(5)

(6)

The optimum target thickness, \( \tau_0 \) and maximum value of \( I^\text{m}(\tau) \) are found by setting \( \frac{dI^\text{m}(\tau)}{d\tau} \) equal to zero in Eq. (1). The result is:
TABLE II

<table>
<thead>
<tr>
<th>H⁻ Energy kV</th>
<th>σ₀ [10⁻¹⁶ cm⁻²]</th>
<th>σ₁ [10⁻¹⁶ cm⁻²]</th>
<th>σ₂ [10⁻¹⁶ cm⁻²]</th>
<th>σ₃ [10⁻¹⁶ cm⁻²]</th>
<th>σ₄ [10⁻¹⁶ cm⁻²]</th>
<th>σ₅ [10⁻¹⁶ cm⁻²]</th>
<th>σ₆ [10⁻¹⁶ cm⁻²]</th>
<th>σ₇ [10⁻¹⁶ cm⁻²]</th>
<th>σ₈ [10⁻¹⁶ cm⁻²]</th>
<th>σ₉ [10⁻¹⁶ cm⁻²]</th>
<th>σ₁₀ [10⁻¹⁶ cm⁻²]</th>
<th>σ₁₁ [10⁻¹⁶ cm⁻²]</th>
</tr>
</thead>
<tbody>
<tr>
<td>10</td>
<td>8</td>
<td>8</td>
<td>24</td>
<td>0</td>
<td>.71</td>
<td>9.8</td>
<td>.62</td>
<td>4.5</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>15</td>
<td>20</td>
<td>20</td>
<td>16</td>
<td>0</td>
<td>1.1</td>
<td>8.1</td>
<td>.70</td>
<td>3.8</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>20</td>
<td>30</td>
<td>30</td>
<td>12</td>
<td>0</td>
<td>1.3</td>
<td>6.6</td>
<td>.76</td>
<td>3.4</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>75</td>
<td>31</td>
<td>31</td>
<td>3.2</td>
<td>.68</td>
<td>1.6</td>
<td>.28</td>
<td>.87</td>
<td>5.2</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>150</td>
<td>20</td>
<td>20</td>
<td>1.6</td>
<td>.69</td>
<td>1.1</td>
<td>.02</td>
<td>.87</td>
<td>7.3</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>1000</td>
<td>4.8</td>
<td>4.8</td>
<td>.24</td>
<td>.20</td>
<td>.19</td>
<td>.5 x 10⁻⁷</td>
<td>.88</td>
<td>34</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

\[ \eta^o = \left( \frac{\sigma_{10}}{\sigma_{701}} \right)^{-\frac{2}{1}} \] (5)

\[ \eta_m = \frac{1}{\sigma_{701}} \ln \frac{\sigma_{10}}{\sigma_{01}} \] (6)

Table II indicates the values of the different cross sections used for the calculation of \( \eta^o \) and \( \eta_m \) and the calculated values \( \eta^o \) and \( \eta_m \). These are computed for several values of the beam energy. This table shows the importance of using a fully ionized neutralized target rather than a neutral target. In the case of a fully ionized plasma a neutralization efficiency of 98% is possible while for a hydrogen gas target a neutralization efficiency of only 64% is possible for a beam energy of 1000 keV.

It is also of interest to know how rapidly the neutralization efficiency varies with target thickness in the region of \( \eta_m \). Figure 1 shows this for several beam energies. The broad peaks indicate an insensitivity to \( \eta_m \) near the optimum target thickness.

One notes that all of the above calculations are based on cross section measurements having an error associated with them of about ±10 to ±20%. This, of course, introduces an uncertainty in the calculated value of \( \eta^o \) and \( \eta_m \). As an example, for a beam energy of 150 keV:

\[ \eta^o = 97 ± 3\% \]

\[ \eta_m = 7.9 ± 0.6 \times 10^{14} \text{ cm}^{-2} \]

assuming cross section uncertainties of ±20%. 

![Neutralization Efficiency as a Function of Target Thickness](image)
In utilizing the neutralizer one would like to be certain that the entire accelerated beam can pass through it. Thus, the transverse dimensions of the accelerated H beam imply the minimum cross-sectional dimensions of the neutralizer target. For a 150 keV beam of several amperes a plasma target 10 by 10 cm in cross section would be a suitable size for the type of beam systems being developed at BNL. Ideally, the neutralizer target would be narrow, about 5 cm so that it would allow for a very compact neutral beam injector. These dimensions imply a mean plasma density of $1.6 \times 10^{14}$ cm$^{-3}$ throughout the 500 cm$^3$ volume or about $8 \times 10^{14}$ ions. A schematic of an injector system utilizing such a neutralizer is shown in Fig. 2.

The duration of the H beam pulse also has an important effect on the neutralizer design since the plasma ions and electrons have a finite confinement time within the neutralizer volume. This loss is enhanced if the target has a large cross section and a small width. However, using a highly directed plasma jet or an external magnetic field would reduce these losses.

In the case of a plasma jet the directed velocity of the target particles affects the rate at which plasma must be generated by the neutralizer. Consider the number of particles per second that would be required for a neutralization of a 150 keV beam. Assume the directed energy of each particle is 2 eV (as may be obtained from a stack washer gun). The proton velocity $v$ is $2 \times 10^6$ cm/s. If $r$ is the neutralizer target dimension perpendicular to the plasma velocity and to the beam direction, then the minimum particle flow from the neutralizer to achieve a target thickness of $\tau_m$ is:

$$I = \tau_m v r,$$

$$I = 2 \times 10^{22} \text{ particles/s},$$

III. Effect of a Magnetic Field on the Neutralized Beam

The use of a magnetic field to confine a plasma may be helpful in reducing the required plasma current supplied by the neutralizer. However, when the magnetic field is transverse to the beam direction additional dispersion of the H beam occurs resulting in a spreading of the neutralized beam. Equation (1) can be rewritten as:

$$\frac{d\phi}{d\phi} = \left[ (1-j) \exp(-5g) + j \exp(-5h) \right]$$

where:

$$j = \frac{r}{2 \pi r_0^2}; \quad h = \frac{r}{b \tau_0^2}; \quad g = \frac{r}{b} \tau_1^4,$$

$$z = \text{the target width}, \quad \text{and} \quad q = \text{the magnitude of an electron charge}.$$

Figure 2 shows, quantitatively, the effect of the magnetic field on the beam envelope. It is noted that spreading of the beam occurs only in one plane and only in a positive $\zeta$ direction. Thus, by proper positioning of the beam system the effect of the dispersion can be minimized. Figures 3 and 4 are plots of Eq. (8) for 150 and 1000 keV energy beams assuming optimum target thickness. Different values of $B-z$ are shown. The values of $B-z$ at which the beam dispersion is considered large will depend, in part, on the distance between the neutralizer and injection port.
IV. Effect of Degree of Ionization on Neutralization

Most plasma sources produce only a partially ionized plasma. It is of interest, therefore, to see the effect of partial ionization on maximum neutralization efficiency and optimum target thickness. Equations (1 and 2) can be written in a more general form to include any number of types of target particles as follows:

\[
d\frac{d\tau^2(\tau)}{d\tau} = I^-(\tau) \sum_{j} n_j \tau_{j-10}^j - I^+(\tau) \sum_{j} n_j \tau_{01}^j
d\]

where:

\[
d\frac{dI^-(\tau)}{d\tau} = -I^-(\tau) \sum_{j} n_j (\tau_{j-11}^j + \tau_{j-10}^j)
d\]

or

\[
I^-(\tau) = I^-(\tau_0) \exp(-\sum_{j} n_j (\tau_{j-11}^j + \tau_{j-10}^j) \tau)
\]

As before: \( I^+(\tau_0) = 1 \).

Also, \( n_j = n_j h_j \)

where: \( n_j \) is the density of the \( j \)th type of particle. Defining three coefficients as:

\[
A = \sum_{j} n_j (\tau_{j-11}^j + \tau_{j-10}^j),
\]

\[
B = \sum_{j} n_j \tau_{j-10}^j,
\]

and

\[
C = \sum_{j} n_j \tau_{01}^j.
\]

Equation (9) can be written as:

\[
d\frac{d\tau^2(\tau)}{d\tau} = B \exp(-\tau A) - C I^+(\tau).
\]

Equation (16) can be solved to give:

\[
I^+(\tau) = \frac{B}{C} \left( \exp(-\tau A) - \exp(-\tau B) \right)
\]

and the maximum neutralization efficiency is:

\[
I_m^+ = \frac{A}{B} (1-N/C).
\]

The optimum target thicknesses are:

\[
\frac{n_j}{n_j h_j} = \frac{1}{C-A} \ln \frac{C}{A}.
\]

Consider the case of a hydrogen plasma in a molecular hydrogen gas. Let:

\[
n_o = \text{plasma density, and}
\]

\[
n_2 = \text{hydrogen density}.
\]

A parameter \( f \) is defined so that

\[
n_2 = f n_o.
\]

Then Eqs. (13 to 15) become:

\[
A = n_o \left( \tau_{-11}^2 + \tau_{-10}^2 + f \tau_{-11}^2 + f \tau_{-10}^2 \right)
\]

\[
B = n_o (\tau_{-10}^2 + f \tau_{-10}^2)
\]

\[
C = n_o (\tau_{01}^2 + f \tau_{01}^2).
\]

The hydrogen molecule target cross sections are shown in Table III. Figure 5 shows the variation of \( I_m^+ \), Eq. (18), with respect to the fraction of the \( H_2 \) target ionized. Figure 6 shows the variation of \( \tau_m \), Eq. (19), with respect to the fraction of the \( H_2 \) target ionized. These calculations were carried out for two values of the beam energy, 150 and 1000 keV. The most interesting point is that only a small change occurs in the neutralization efficiency for large decreases in the ionization fraction. For example, at 1000 keV the neutralization efficiency is 81% for an ionization fraction of 0.10. The optimum target thicknesses
of the plasma has decreased to \( 25 \times 10^{-4} \text{ cm}^{-3} \) while the hydrogen molecule target thickness is \( 1.1 \times 10^{-8} \text{ cm}^{-3} \).

### Table III

Cross Sections for \( \text{H}_2 \) Target

<table>
<thead>
<tr>
<th>Energy (keV)</th>
<th>( \sigma_{-01}^{2} ) (x10(^{-16}) cm(^{-2}))</th>
<th>( \sigma_{-11}^{2} ) (x10(^{-16}) cm(^{-2}))</th>
<th>( \sigma_{-10}^{2} ) (x10(^{-16}) cm(^{-2}))</th>
</tr>
</thead>
<tbody>
<tr>
<td>150</td>
<td>0.67</td>
<td>0.011</td>
<td>1.5</td>
</tr>
<tr>
<td>1000</td>
<td>0.10</td>
<td>0.0015</td>
<td>0.35</td>
</tr>
</tbody>
</table>

### Fig. 5

**MAXIMUM NEUTRALIZATION EFFICIENCY FOR \( \text{H}^- \) IONS IN A HYDROGEN PLASMA AS A FUNCTION OF FRACTION OF TARGET IONIZED**

---

V. A Proposal for Further Study

In order to produce the required hydrogen plasma target it is proposed that a coaxial plasma jet (or a number of smaller jets) operating in a deflagration mode be utilized to form the plasma target. Such devices have been developed as rocket thrusters\(^{17,18,19}\) and plasma injectors.\(^{20}\) Densities in the \( 10^{-4} \text{ cm}^{-3} \) range can be achieved along the jet plume which extends considerably beyond the jet nozzle. Arc currents of \( 10^3 \text{ A} \) and arc voltages of about 100 volts are typical discharge parameters obtained for the steady state mode of operation of some of these devices.\(^{17}\) Because of electromagnetic forces generated by the discharge, the plasma jet is well collimated.\(^{19}\) By using a series of small jets it is the author's feeling that a thin plasma target could be formed which would be suitable for several amperes of \( \text{H}^+ \) at 150 keV in a compact neutral beam injector having an neutralization efficiency of between 80 and 87%. For the higher target thickness needed for 1 MeV \( \text{H}^+ \), it may be necessary to use a larger target thickness (larger \( z \)) or to use a transverse magnetic field to compress the plasma into a smaller \( z \).

### VI. Conclusion

Various aspects of a hydrogen plasma neutralizer have been discussed and it was noted that neutralization efficiencies of 150 keV \( \text{H}^- \) ions as high as 87% can be obtained in a fully ionized hydrogen target and 80% in a 10% ionized hydrogen gas target. The presence of a transverse magnetic field increases the dispersion of the neutral particles formed in the neutralizer, though the effect is of practical importance only at high values of \( B^2 \). In addition, a method of forming the plasma target has been discussed which will be well-suited for a compact neutral beam injector.
References


3. C. Lam, Neutralization of an H Beam with Gas Jets, Proc. this Symposium.


8. Figure 2 taken from Th. Sluyters and K. Prelac, High Energy Neutral Injectors Based Upon Negative Ion SP Sources, Session VIII of this Symposium.


