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PHOTODETACHMENT OF NEGATIVE ION BEAMS
IN THE PRESENCE OF A BACKGROUND GAS^{*}

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ABSTRACT

To suppress space charge blow-up in an ion beam passing through a photo-neutralizer, it is necessary to introduce some background gas. An analysis is presented of the neutralization of a high energy, > 200 keV negative deuterium ion beam, exposed to photo-detachment while in the presence of deuterium. With a gas thickness of less than 0.01 torr-cm, the neutral fraction in the output beam is found to be about the same as that gotten from the photo-neutralizer operating in vacuum.

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I. INTRODUCTION

Photodetachment is an attractive means of neutralizing high energy negative ion beams. In contrast to a maximum neutral fraction of roughly 80% from a plasma cell and about 60% from a gas cell, it can be made to neutralize almost 100% of an incident negative ion beam.

This is advantageous because the higher neutral fraction will form the desired neutral current from a smaller current of negative ions. For the beamline to be more efficient however, the power saved by accelerating the smaller current of high energy negative ions must be greater than the power used to operate the photodetachment cell.

Although photodetachment is usually considered as a process to be done in a vacuum, some background gas may be desirable. In many applications, beam divergence is critical and a low pressure of gas, of the order of 10^{-4} torr, is needed to suppress the space charge of the negative ions and stripped electrons in the neutralizer. Low energy positive ions, created along the beam path by collisions with the gas molecules, 'neutralize' the space charge and thereby minimize the beam divergence.

The object of this work is to analyse the effect of a deuterium gas background on photodetachment of high energy, negative deuterium ions. In the following, I present the usual equations for neutralizing a negative ion beam in a gas, simplified by the use of only two cross sections, i.e. for stripping negative ions, σ_{-10} and for ionizing neutrals, σ_{01} . As can be seen in Fig. 1, these are the only cross sections of significance for a deuterium beam of 200 keV or more in a deuterium gas target.

II. DISCUSSION

A. Gas Neutralizers

A beam of high energy negative ions passing through a gas cell of line density Π will be changed into a fraction F^+ of positive ions, F^- negative ions and F^0 neutrals. This process is described by the following equations:

$$\frac{dF^-}{d\Pi} = -\sigma_{-10} F^- \quad (1)$$

$$\frac{dF^0}{d\Pi} = \sigma_{-10} F^- - \sigma_{01} F^0 \quad (2)$$

$$F^- + F^+ + F^0 = 1 \quad (3)$$

From the above, the neutral fraction of the beam is found to be:

$$F^- = \left(\frac{\sigma_{-10}}{\sigma_{-10} - \sigma_{01}} \right) (\exp \{-\sigma_{01}\Pi\} - \exp\{-\sigma_{-10}\Pi\}) \quad (4)$$

B. Photo-neutralizers

In contrast to gas neutralizers, a photodetachment cell illuminated by light of an intensity Φ ($\text{W}\cdot\text{cm}^{-2}$) neutralizes negative ions at a rate:

$$\frac{dF^-}{dt} = - (h\nu)^{-1} \sigma \Phi F^- \quad (5)$$

where σ is the photodetachment cross section at the wavelength ν ; see Fig. 2.

Introducing the beam velocity, $v = dz/dt$, into the previous equation results in:

$$\frac{dF^-}{dz} = - (v \cdot h\nu)^{-1} \sigma \Phi F^- \quad (6)$$

From which the neutral fraction resulting from photo-detachment is found:

$$F_{p0} = 1 - \exp\{-(v \cdot h\nu)^{-1} \sigma \Phi Z\} \quad (7)$$

C. Combined Gas and Photo-neutralizers

Because the gas density, n is relatively uniform throughout the neutralizer, Eq. 6 can be modified such that:

$$\frac{dF^-}{d\Pi} = - (nv \cdot hv)^{-1} \sigma_{\Phi} F^- , \quad (8)$$

where Π , the line density of the gas, equals nZ .

A comparison of Eq. 8 with Eq. 1 shows that in the presence of a background gas, photodetachment contributes an additional factor to the negative ion stripping cross section:

$$\sigma_{pD} = (nv \cdot hv)^{-1} \sigma_{\Phi} \quad (9)$$

which can be evaluated in terms of the neutral fraction F_{pD} that would be obtained with the photo-neutralizer operating in vacuum. By introducing Eq. 9 into Eq. 7:

$$\sigma_{pD} \Pi = \ln(1 - F_{pD})^{-1} . \quad (10)$$

To determine the neutral fraction F_c in a combined gas and photo-neutralizer, the cross section σ_{-10} in Eq. 4 should be replaced by $(\sigma_{-10} + \sigma_{pD})$, resulting in:

$$F_c = \left(\frac{\sigma_{-10} \Pi + \ln(1 - F_{pD})^{-1}}{(\sigma_{-10} + \sigma_{o1}) \Pi + \ln(1 - F_{pD})^{-1}} \right) \times \\ (\exp\{-\sigma_{o1} \Pi\} - (1 - F_{pD}) \exp\{\sigma_{-o1} \Pi\}) . \quad (11)$$

In the above, no allowance was made for the presence of background gas at either end of the neutralizer. If this is an important factor, consideration will have to be given to the charge changing collisions that alter the beam

composition along the beam path from the negative ion accelerator to the entrance of the neutralizer. As a consequence, the neutralizer will have to be modified to take the altered beam composition into account, as well as optimise the neutral fraction at some location beyond the neutralizer where the background gas density is negligible.

III. RESULTS

Cross sections, taken from reference 1, were used in Eq. 11 to determine F_c at photodetachment intensities needed to obtain neutral fractions of 20, 40, 60, 80, 90, and 95% in vacuum. Figs. 3, 4 and 5 show the results for three beam energies (200, 500 and 1000 keV respectively) as functions of the thickness of the background gas. The line density Π (molecules/cm²) in Eq. 11, was converted to gas thickness (torr-cm) as shown in the figures, on the assumption that the background gas temperature is 300 K.

With a gas thickness of less than 0.01 torr-cm, corresponding to a 1 meter long neutralizer with a background gas pressure smaller than 10^{-4} torr, the curves show the neutral fractions of the three beams of different energies to be about the same as what would be obtained with photodetachment in vacuum. At greater gas thicknesses, the beam penetration varies with beam energy while the neutral fractions are a function of the intensity of the photodetachment.

A photo-neutralizer capable of neutralizing 80% or more of a negative ion beam in vacuum, establishes a neutral fraction that does not change much with gas thickness until some critical thickness is reached. It then decreases rapidly as the gas thickness increases. This is a consequence of the high fraction of neutrals in the beam subject to ionizing collisions with the background gas, in contrast to the low fraction of negative ions available to form additional neutrals.

With a photo-neutralizer that neutralizes less than 80% of a negative ion beam in vacuum, the neutral fraction increases with gas thickness to a maximum where the rate at which neutrals are formed, out of negative ions by photodetachment and collisions with the background gas, equals the rate at which neutrals are lost to ionizing collisions. Under these conditions, the maximum neutral fraction is greater and the thickness of gas at the maximum is less than that of an optimized gas cell by itself.

As the gas thickness is increased even more, the negative ions in the beam become depleted and, because the rate of neutral formation falls off, the neutral fraction drops sharply.

III. CONCLUSIONS

This work leads to four general conclusions.

1. Photo-neutralization of a negative deuterium ion beam is not greatly affected by a background deuterium gas thickness less than 0.01 torr-cm.
2. While the neutral fraction of all beams drops off rapidly in over dense gas targets, high energy beams penetrate the farthest.
3. At lower photodetachment intensities, corresponding to less than 80% neutralization in vacuum, the addition of photodetachment enhances a gas neutralizer, increasing the neutral fraction and reducing the thickness of the optimum gas target.
4. For some applications, gas neutralizers enhanced by photodetachment might be practical. The comparatively little power needed to operate a photoneutralizer that would neutralize 50 or 60% of a negative ion beam in vacuum might be off set by the power saved by the increased neutral fraction the photoneutralizer provides.

REFERENCES

1. K.H. Berkner, R.V. Pyle, J.W. Stearns, Nuclear Fusion, Vol. 15, p. 249, 1975.
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FIGURE CAPTIONS

- Fig. 1: Cross sections for charge changing collisions of deuterium ions and atoms with deuterium gas. Note that the cross section σ_{1-1} is too small to show on the graph. (Data taken from Ref. 1).
- Fig. 2: The photodetachment cross section for stripping electrons from negative deuterium ions. (Taken from Ref. 2).
- Fig. 3: Calculated neutral fractions for combined gas and photo-neutralizers of 0.2, 0.5 and 1.0 MeV negative deuterium ion beams.

Fig. 1

XBL 8510-4351

Fig. 2

XBL 8510-4352

Fig. 3

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