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ANOTHER LOOK AT PHOTODETACHMENT OF
NEGATIVE DEUTERIUM IONS IN NEUTRAL BEAM INJECTORS

J. H. Fink
G. W. Hamilton

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Lawrence
Livermore
Laboratory

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ABSTRACT

Photodetachment is more desirable than other types of neutralizers of negative deuterium ions because it is cleaner, produces no gas or vapor, selectively detaches D^- and not heavy impurities, and may be more efficient. However, good overall efficiency in comparison with the alternatives is attainable only under the appropriate conditions of ion beam current density and thickness and with sufficient efficiencies of the laser and of the mirrors of the optical cavity. Analysis of these conditions indicate that the overall efficiency of an 11 A beam of 200 keV D^0 using photodetachment is competitive with that for a beam neutralized in a gas cell, using the expected values of laser and mirror efficiencies.

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J. H. Fink,* G. W. Hamilton

1. Introduction

When considering the advantages of forming neutral beams out of negative ions by means of photodetachment, the additional power required to operate the photon source must not be neglected. In general photodetachment is more desirable than gas, metal vapor or plasma strippers. It is cleaner, requiring no additional gas or vapor to be introduced into the beam line. It provides a neutral beam of higher purity than the other stripping cells because the photon process is highly selective, neutralizing D^- without neutralizing OD^- and other negative ion impurities. In addition it offers the prospect of a higher stripping efficiency. Whereas gas or vapor cells of suitable thickness will neutralize about 60% of a negative ion beam, and a plasma of proper thickness will neutralize 80%, photodetachment is capable of stripping in excess of 90% of the exposed ion beam. This high stripping efficiency results in a greater neutral current density and a less critical problem with disposal of the remaining un-neutralized fraction of the ion beam. As a consequence, it provides more effective use of the ion sources and ion source power supplies, etc. However, when considering the impact of

*On Assignment from Westinghouse Electric Corporation.

photodetachment upon the operating efficiency and capital cost of a neutral beam injector, its advantages can be offset by the power requirements of the photodetachment cell itself.

Because the bulk of the optical energy loss occurs at the mirrored walls of the stripping cell, and very little energy is spent in stripping electrons from the negative ions, the power requirements are of less significance in neutral beam injectors of very large currents. In fact, efficient photodetachment in an injector of several hundreds of amperes seems possible with today's technology. But for use on a small injector of 10 A or so, additional development is required to make an efficient unit.

2. Evaluating Photodetachment in a Beam Line

In the following we consider the effect of replacing a metal vapor stripping cell, along with its associated un-neutralized ion-energy recovery circuit, by an advanced, laser-excited, photodetachment cell.

The original beam line, as first described in a field-reversed mirror pilot reactor study¹, was designed to deliver 11 A of 200 keV neutral deuterium atoms. Fig. 1 shows the beam line schematic.

The study shows the injector operating efficiency to be 54%. Taking the reciprocal of this, we find that an input power of 1.85 watts is needed per watt of neutral beam output. If the energy recovery unit were removed, the input would have to increase by the amount that had been saved. The study shows this to be 0.18 watts recovered per watt output. Thus the beam line operating without

energy recovery has an efficiency whose reciprocal is 2.03 watts per watt.

To operate the vapor stripping cell, the study shows an input of .03 watts per watt of output was needed. Removing this from the power needs of the neutral beam injector leaves the input power required to form the negative ion beam per watt of neutral beam output at 2.00 watts power watt. Thus if the total power required to form the negative ion beam is designated P_n , and the neutral beam power output is designated P_o , then $P_n/P_o = 2.00$.

The reciprocal of the efficiency of another injector delivering the same neutral output but using a different stripping cell can be determined by modifying the ratio P_n/P_o to reflect the new stripping efficiency and adding the input power per output watt needed to operate the new stripping cell, using a photodetachment cell whose stripping efficiency is η_p instead of a metal vapor cell with a stripping efficiency of $\eta_v = 62\%$. The negative ion current needed to provide the same neutral current changes by a factor, η_v/η_p . Furthermore, the ratio of power needed to form the negative ion beam per output watt changes by about the same amount. Therefore, if the power required to operate a photodetachment cell in this beam line is P_p , the reciprocal of the efficiency of the new beam line is:

$$\frac{1}{\xi_{photo}} = \left(\frac{\eta_v}{\eta_p} \right) \left(\frac{P_n}{P_o} \right) + \left(\frac{P_p}{P_o} \right) \quad (1)$$

Let us consider a minimum acceptable photodetachment operating condition at an efficiency equal to that of before, i.e. $\xi_{\text{photo}} \approx 54\%$ and with a photodetachment efficiency, η_p , somewhat better than the previous stripping efficiency, $\eta_v = 62\%$. When introduced into Eq 1, these criteria result in:

$$P_p/P_0 \leq \left(1.85 - \frac{1.24}{\eta_p} \right) \quad (2)$$

3. Analyzing the Photodetachment Cell

The neutralization efficiency of a photodetachment cell² (see Fig. 2), can be evaluated from the expression³:

$$\eta_p = (1 - e^{-\alpha_s}) , \quad (3)$$

in which

$$\alpha_s = \left(\frac{\sigma}{h\nu} \right) \phi \left(\frac{L_s}{v_D} \right) , \quad (4)$$

and

σ is the photodetachment cross-section

h Planck's constant

ν the light frequency

ϕ the light intensity (W/cm^2)

L_s the length of the stripping cell

v_D the velocity of the deuterium ions.

At a wavelength approximating the optimum stripping cross-section for negative deuterium ions:

$$\frac{\sigma}{h\nu} = 170 \text{ cm}^2/\text{Joule} , \quad (5)$$

while the ion velocity at a potential V_0 is roughly:

$$v_D = 10^6 V_0^{-1/2} \text{ cm s}^{-1} \quad (6)$$

Hence:

$$\alpha_s = (1.7 \times 10^{-4}) \phi L_s V_0^{-1/2} \quad (7)$$

From Eq 3

$$\alpha_s = \ln \left[\frac{1}{1 - \eta_p} \right] \quad (8)$$

Therefore:

$$L_s = (5.9 \times 10^3) \frac{V_0^{1/2}}{\phi} \left[\ln \frac{1}{1 - \eta_p} \right] \quad (9)$$

If there are N mirrors within the optical cavity, each photon is reflected 2N times for each transit of the laser. The area of each mirror is $2TL_s/N$. The energy density ϕ includes four light beams propagating both forward and backward in the transverse direction and forward and backward in the longitudinal direction. Therefore, the power loss for each reflection is $(\phi/4)(2TL_s/N)(1-R)$. If it is assumed that the predominant loss of optical power is to the mirrors the stimulated power produced by the laser must be

$$W_L = (TL_s) \phi (1-R) \quad (10)$$

in which T is the mirror height per Fig. 2 and
 R is the mirror reflectivity.

Assuming a laser efficiency of ϵ_L , the power required to
operate the photo detachment cell becomes:

$$P_p = TL_S (1-R) / \epsilon_L \quad (11)$$

If a beam of negative ions of uniform current density J_- filled
90% of the area between the mirrors, shown in Fig. 2, the neutral
current flowing out of the stripping cell would be:

$$I_o = 0.9 \eta_p J_- TS, \quad (12)$$

where S is the mirror separation distance. The power in the neutral
beam would be:

$$P_o = 0.9 V_o \eta_p J_- TS, \quad (13)$$

Thus the power need of the photo detachment cell, the ratio of
the input watts to operate the laser (Eq 11) to the output watts in
the beam (Eq 13) is:

$$\frac{P_p}{P_o} = 6500 \frac{(1-R) V_o}{\epsilon_L J_- S}^{-\frac{1}{2}} \frac{1}{\eta_p} \ln \left[\frac{1}{1-\eta_p} \right] \quad (14)$$

Introducing this into Eq 2, the condition for advantageous use of photodetachment is found to be:

$$f(\eta_p) = \frac{1}{1.85 \eta_p - 1.24} \ln \left[\frac{1}{1 - \eta_p} \right] \leq 1.5 \times 10^{-4} \left[\frac{\xi_L J_{SV_0}}{(1-R)} \right]^{\frac{1}{2}} \quad (15)$$

This condition is the easiest to satisfy when $f(\eta_p)$ is a minimum. $f(\eta_p)$ is shown plotted in Fig. 3, from which it can be seen that $f(\eta_p)$ is a minimum with $\eta_p = 90\%$. At higher neutralization efficiencies it takes so much power to activate the lasers that the beam line becomes impractical. At lower neutralizing efficiencies the power required to form the negative ion beam increases, leaving very little power to operate the laser at the desired beam line power efficiency.

From Fig. 3 and Eq 15, the minimum condition for satisfactory performance at 200 KeV is:

$$J_{SV} \geq \frac{80 (1-R)}{\xi_L} \quad (16)$$

4. Laser and Mirror Development Needed for this Application

The beam line under consideration delivers 11A of neutrals, with

$$\eta_p = 0.9.$$

Thus from Eq 12:

$$J_{TS} = 13.6 \quad (17)$$

and from Eq 16:

$$T = 0.172 \frac{\xi_L}{(1-R)} \quad (18)$$

To allow the ion beam with a 0.5° half angle divergence to be fully exposed to the light it is assumed that the mirror height must be at least 3 cm. Thus:

$$\left(\frac{\epsilon_L}{1-R}\right) \geq 17.5 \quad (19)$$

Values of ϵ_L as a function of R for this condition are shown plotted in Fig. 4. This establishes difficult conditions for the laser and mirror designer to meet. The laser efficiency must be better than 1% and the mirror reflectivity greater than .999.

If $\epsilon_L/(1-R) = 17.5$, then from Eq 16:

$$J_- S = 2.3 \quad (20)$$

and J_- , the negative ion current density will have to be $.023 \text{ A cm}^{-2}$ if $S=100 \text{ cm}$.

With reference to the length of the stripping cell, Eq 9, it is assumed that the maximum total incident energy density of light on the mirror surfaces is $\phi_{\text{Max}} = 20 \text{ kW/cm}^2$. Thus for $V_0 = 200 \text{ kV}$ and $\eta_p = 0.9$, it follows that $L_s = 150 \text{ cm}$.

5. Conclusion

From this analysis it is evident that the present laser and optical mirror technology is close to making photodetachment of negative ions a competitive process. As this brief study shows, the laser and mirror performance can be relaxed somewhat for beams of higher energy (see the $v_0^{1/2}$ dependance in Eq. 15) and of higher current (as related to the J_S product in Eq. 15).

The most conservative goals of our D^- beam development laboratories are for ribbon-shaped beams of $J_- = .02 \text{ A/cm}^2$, which is the right order of magnitude for the requirement of equation 20. Therefore, if the other assumptions are correct, photodetachment will be competitive with a gas cell in overall efficiency for production of 11 A beams at 200 keV. Under these marginal conditions the other advantages of photodetachment will be more important than the small difference in overall efficiency. At higher values of J_S the overall efficiency for the photodetachment system will be improved.

References

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Beamline schematic of an 11-A, 200-keV D injector (ion source chamber dimensions: roughly 1 by 1 by 2 m).

FIGURE 1

Laser activated photodetachment cell.

FIGURE 2

The critical condition for advantageous use of photoattachment,
 $f(\eta_p)$ as a function of the neutralization efficiency.

FIGURE 3

The relationship between laser efficiency, ξ_L and mirror reflectivity, R that must be met to operate an 11A, and 22A 200 keV deuterium neutral beam injector at a power efficiency of 45%. The photodetachment cell under consideration has a stripping efficiency of 90%.

FIGURE 4