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UCRL- 89844
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UCRL--89844

DE84 002727

CONF-831180--1

PHOTODETACHMENT TECHNOLOGY

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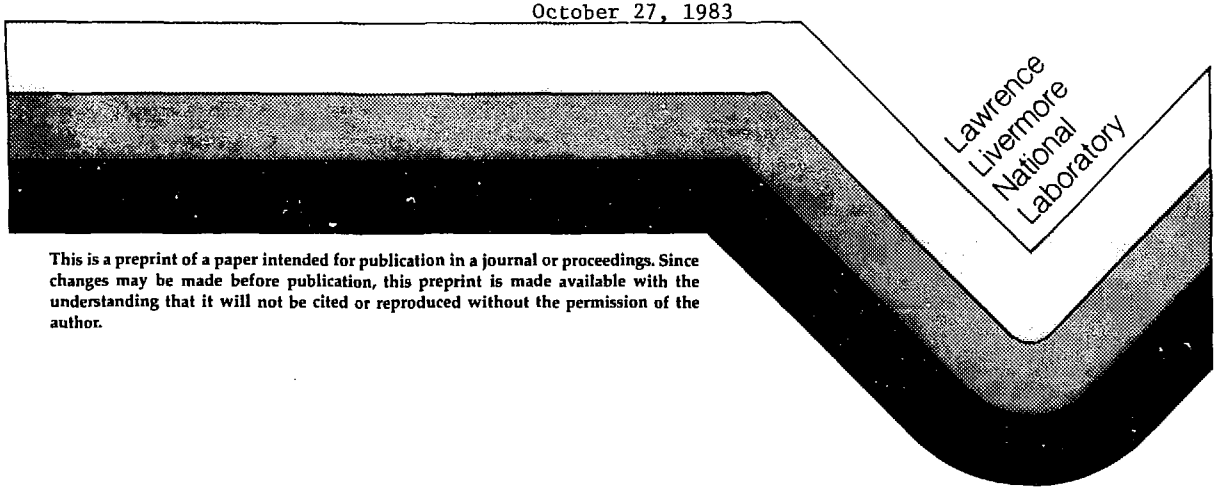
This paper was prepared for submittal to the 3rd International Symposium on the Production and Neutralization of Negative Ions and Beams, Brookhaven National Laboratory, Associated Universities, Inc., Upton, NY, November 14-18, 1983.

October 27, 1983



PHOTODETACHMENT TECHNOLOGY*

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ABSTRACT

This report gives an analysis of a neutral beam line formed of negative ions and stripped in a photoneutralizer. Estimates are made of its performance when neutralized by an atomic-iodine laser.

INTRODUCTION

Photodetachment, in a high-power neutral beam injector, is an effective method of neutralizing high-energy negative ions. It can neutralize a large fraction of a negative ion beam, while leaving many of the negative impurity ions unneutralized. A well-designed system requires the addition of neither gas, vapor, nor plasma.

Although the physics of photodetachment is well-known,[1] some technological advances must be made before we can design and build a large photoneutralizer. As presently conceived, we need an efficient, high-power laser of suitable wavelength, along with an optical resonator of high gain in which the negative ion beam is neutralized. Suitable mirrors with high reflectivity and low scattering have been developed;[2] they are capable of handling high-power irradiances. In addition, however, a highly transparent window is needed to separate the laser gain medium from the evacuated resonator through which the ion beam passes.

Preliminary studies of laser windows and resonator designs are in process.[2] Currently under development is a continuously operating laser that can be used to neutralize negative hydrogen, deuterium, and tritium beams,[3] i.e., the supersonic chemical oxygen-iodine laser.[4] Meanwhile, a study contract to evaluate the efficiency and cost of a chemical recycling plant is in process.[5]

In the following I derive a series of equations to determine the operating efficiency and fraction of neutrals obtainable with a photoneutralized negative ion beam line, and discuss the significance of these results with respect to the design of various neutral beams.

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*Work performed under the auspices of the U.S. Department of Energy by the Lawrence Livermore National Laboratory under contract number W-7405-ENG-48.

†On assignment from Negion, Inc., Hayward, CA.

OXYGEN-IODINE LASER CHEMISTRY

Figure 1 is a block diagram of a deuterium neutral beam injector. Negative ions are extracted from their source, accelerated to the desired energy, and injected into the laser resonator. A large fraction of the negative ions is neutralized as they travel through the resonator toward their target. Subsequently, the small fraction of the beam that remains ionized is deflected out of the neutral beam path, to be collected at the ion dump.

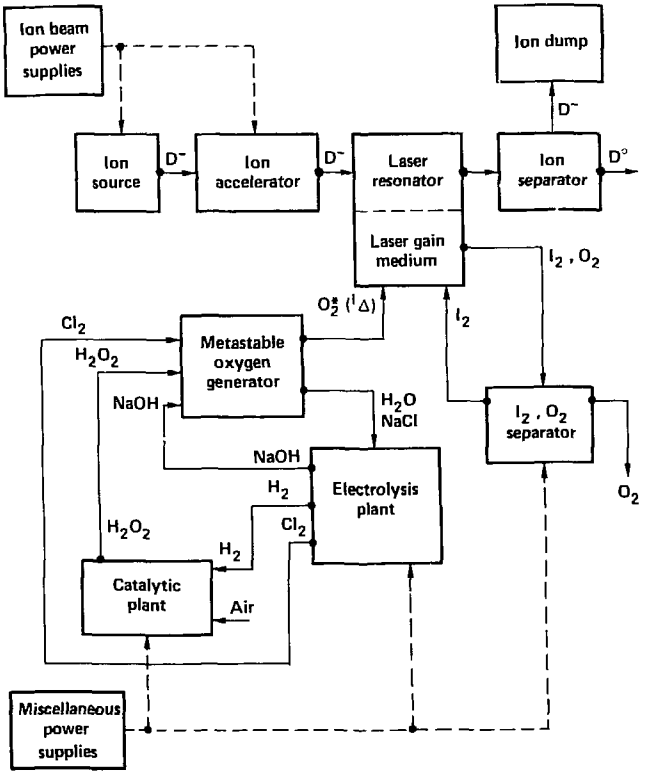

Fig. 1. Block diagram of a deuterium neutral beam injector that uses photoneutralization.

The laser is fueled by metastable oxygen molecules $O_2^*(^1\Delta)$ and iodine vapor. Through a series of involved reactions, the metastable oxygen dissociates the iodine molecules and raises the newly liberated iodine atoms to an excited spin-orbit $I^*(^2P_{1/2})$ state. The concentration of excited iodine soon becomes sufficient for lasing, and stimulated emission occurs at a wavelength of 1.315 μm, with the transition from the excited state $I^*(^2P_{1/2})$ to the ground

state $I(^2P_{3/2})$. Metastable oxygen molecules re-excite the ground state iodine atoms, and the cycle repeats many times as the gases flow through the laser at supersonic velocities. Lasing stops at the far side of the laser where the supply of metastable oxygen is insufficient to maintain the necessary population inversion of excited iodine.

Metastable oxygen molecules are generated by bubbling chlorine gas through a solution of hydrogen peroxide and sodium hydroxide whereby

$$Cl_2 + H_2O_2 + 2NaOH \rightarrow O_2^*(^1\Delta) + 2NaCl + 2H_2 \ . \qquad (1)$$

For an experimental installation chlorine, peroxide, and sodium hydroxide could be purchased and supplied in large tanks, but in an actual reactor they would most probably be continuously recycled at less cost. The sodium chloride and water that remain after the production of metastable oxygen can be reconverted into sodium hydroxide and chlorine.

The chemical recycling method indicated in Fig. 1 is a commercial process using an electrolyic diaphragm cell[6] in which

$$2NaCl + 2H_2O \rightarrow 2NaOH + Cl_2 + H_2 \ . \qquad (2)$$

Hydrogen produced by this reaction is subsequently used to make hydrogen peroxide by means of the Quinone catalytic process,[6] another commercial procedure. The power required to operate the laser is the sum of the power needed to operate the catalytic and electrolysis plants, various gas compressers, filters, etc., plus the power needed for the boiler that separates the spent iodine from the oxygen.

MAXIMUM BEAM-LINE EFFICIENCY

Neglecting any loss of neutrals betwen the neutralizer and the neutral beam target, we define the efficiency of a beam line that uses a gas neutralizer as ϵ_B, the efficiency with which the high-energy negative ion beam was formed, multiplied by η, the fraction of negative ions that is neutralized. This assumes that (a) the power needed to operate the gas cell and to pump away the gas introduced by the gas cell is negligible; (b) the background gas pressure in the accelerator and beyond the neutralizer is low; and (c) the beam path from the neutralizer to the beam target is of reasonable length.

In contrast to a gas cell, which requires negligible power, the power P_N needed to operate a photoneutralizer is significant. Hence, the efficiency of such a neutral beam line is

$$\epsilon_P = \eta/(\epsilon_B^{-1} + P_N/P_B) \ , \qquad (3)$$

in which P_B is the power of the negative ion beam as it enters the neutralizer.

The maximum fraction of neutrals obtainable from a negative ion beam passing through a gas cell is determined by the cross sections of the various interactions between the beam and the background gas.[7] On the other hand, the neutral fraction obtainable with a photoneutralizer is a function of its design and of the power used to operate it. A more powerful photoneutralizer can always be used to make the neutral fraction larger than that produced by a gas (or vapor) cell.

The efficiency of a photoneutralized beam line can exceed that of a gas cell if the power saved (by forming a smaller negative ion beam with a larger neutral fraction) is greater than the power spent to operate the photoneutralizer. For this reason, a photoneutralizer can be designed to produce an optimum neutral fraction that corresponds to a maximum beam-line efficiency. The condition for the maximum is established by setting the derivative of the beam-line efficiency with respect to the neutral fraction, equal to zero. The result is

$$\varepsilon_B^{-1} = \eta_o \, d(P_N/P_B)/d\eta - P_N/P_B \ , \tag{4}$$

in which η_o is the optimum neutral fraction at which the neutral beam-line efficiency is maximum. When we introduce Eq. (4) into Eq. (3), we get an expression for the maximum beam-line efficiency:

$$\varepsilon_p = [d(P_N/P_B)/d\eta]^{-1} \ . \tag{5}$$

NEUTRALIZER THICKNESS

Assume that a negative ion current of I_o enters the photoneutralizer and a current I_z leaves there unneutralized as shown in Fig. 2. With the beam uniformly exposed to light of an average irradiance of ϕ_w (W/m^2), electrons are stripped from the negative ions at a rate of

$$dI/dt = -\rho \, I \ , \tag{6}$$

where

$$\rho = \sigma \, \phi_w/(h\nu) \ , \tag{7}$$

and σ is the photodetachment cross section, while $(h\nu)$ is the energy of the photons irradiating the beam.

When we introduce the ion velocity $v = dz/dt$ into Eq. (6) and integrate over the length of the neutralizer Z, we get the neutral fraction of the output beam as

$$\eta = 1 - \exp\left[-\sigma/(h\nu) \, v^{-1} \int_0^Z \phi_w dz\right] \tag{8}$$

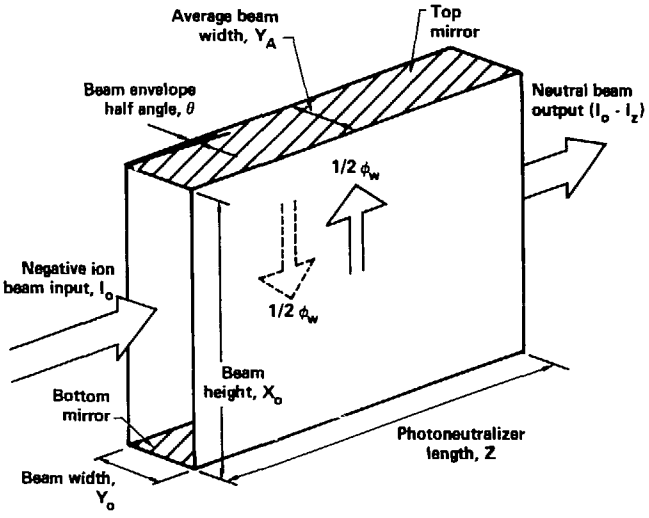

Fig. 2. Geometry of a photoneutralizer.

where

$$\eta = 1 - I_z/I_o \ . \tag{9}$$

If S (W/m) is defined as

$$S = \int_o^Z \phi_w \, dz \ , \tag{10}$$

i.e., the thickness of the radiant flux in the photoneutralizer, then the length of the neutralizer must be approximately

$$Z = S/\phi_w \ , \tag{11}$$

and from Eq. (8),

$$S = (2eV/M)^{1/2} \ (h\nu/\sigma) \ \ln \ [1/(1 - \eta)]. \tag{12}$$

In Fig. 2, the irradiance of the top and bottom mirrors, ϕ_M, is half of ϕ_w, i.e., $S/(2Z)$ (W/m^2), because ϕ_w equals the radiant flux going up toward the top mirror plus that going down toward the bottom mirror. Meanwhile, the ion beam passing through the neutralizer has an average width Y_A so that it is exposed to a total irradiance of

$$P_o = S \ Y_A \ . \tag{13}$$

Figure 3 shows the fraction of neutrals obtainable from a neutralizer of thickness S.

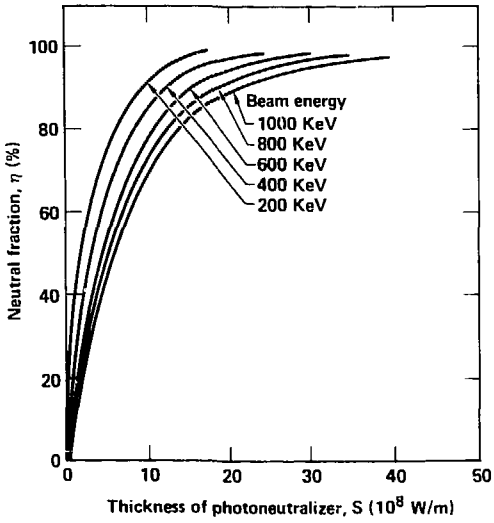

Fig. 3. Neutral fractions obtainable from negative deuterium ion beams as a function of irradiance thickness in a photoneutralizer.

EVALUATION OF P_N/P_B

The gain of the resonator G can be defined as the ratio of the radiant power in the resonator P_o to the power needed to excite it P_L. If ε_L is the efficiency with which the laser produces the light that excites the resonator, the total power required to operate the photoneutralizer must be

$$P_N = P_L/\varepsilon_L \ , \tag{14}$$

whereby

$$P_N = P_o/(G\ \varepsilon_L) \ . \tag{15}$$

As the power in the negative ion beam is

$$P_B = I_o\ V \ , \tag{16}$$

the ratio P_N/P_B becomes

$$P_N/P_B = \Gamma^{-1}\ \ln[1/(1 - \eta)] \ , \tag{17}$$

in which

$$\Gamma = (M/2e)^{1/2}\ V^{1/2}\ (I_o/Y_A)\ \sigma/(h\nu)\ G\ \varepsilon_L \ . \tag{18}$$

We introduce Eq. (17) into Eq. (4) to get the condition for maximum beam-line efficiency:

$$\Gamma = \epsilon_B \left[\eta_o/(1 - \eta_o) + \ln(1 - \eta_o)\right] , \tag{19}$$

while from Eq. (5) the maximum efficiency is found to be

$$\epsilon_p = \Gamma (1 - \eta_o) . \tag{20}$$

Figures 4 and 5 show the optimum neutral fraction and the maximum beam-line efficiency, respectively, as functions of parameter Γ. Note that the larger the Γ, the higher the neutral beam-line efficiency and the greater the neutral fraction. As Γ gets even larger, the optimum neutral fraction nears 100%, while the maximum beam-line efficiency approaches the efficiency with which the negative ion beam was formed. Figure 6 shows the maximum beam-line efficiency as a function of the associated optimum neutral fraction.

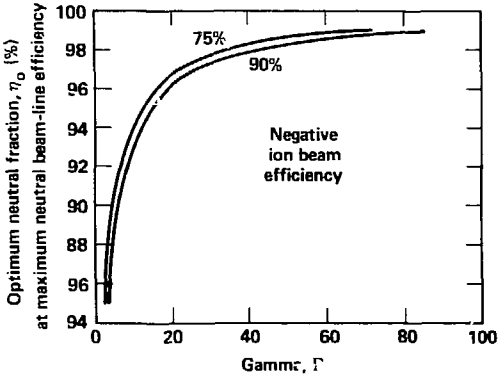

Fig. 4. Optimum neutral fraction as a function of Γ.

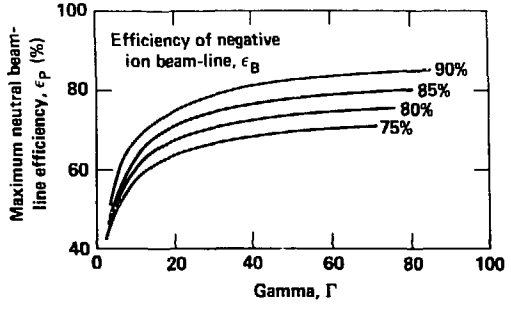

Fig. 5. Maximum neutral beam-line efficiency as a function of Γ.

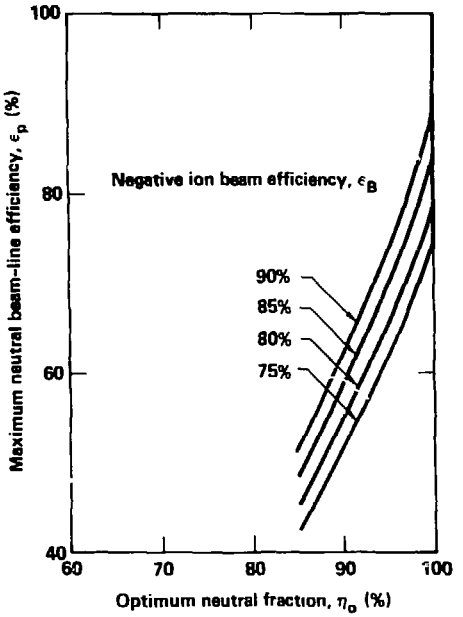

Fig. 6. Maximum neutral beam-line efficiency as a function of the optimum neutral fraction.

EVALUATION OF Γ

The development, at this time, of a photoneutralizer for a deuterium beam is not sufficiently advanced to evaluate Γ with any assurance. Specifically, we can only estimate the gain that might be attained in a suitable laser resonator, while the ultimate efficiency of the laser is uncertain. Nevertheless, it is evident that an efficient negative ion beam and a large Γ are essential to form a neutral beam injector of optimum performance.

As defined by Eq. (18), Γ is composed of six factors. The first, $[M/(2e)]^{1/2}$, is a function of beam composition; for a deuterium beam, it is approximately equal to 10^{-4} ($V^{1/2}s/m$). The second, $V^{1/2}$, relates to beam energy, and the third, I_o/Y_A, is a function of beam geometry.

Having originated from a slit in an ion source similar to the Lawrence Berkeley Laboratory (LBL) self-extracting negative ion source,[8] the ion beam is very narrow (see Fig. 2). It enters the neutralizer with a cross section of Y_o by X_o (m^2), where $Y_o << X_o$.

For the neutralizer to function efficiently, its width must closely match that of the ion beam. Thus, the average width of the neutralizer is the same as the average width of the ion beam traveling through it. If the neutralizer length is Z, then

$$Y_A = Y_o + \theta Z , \qquad (21)$$

in which θ (rad) is the half angle of the beam envelope (Fig. 7). To irradiate the most ions with the least light, the ion beam cross section should be rectangular (Fig. 2), and is approximately such when the neutralizer is located close to the ion source where the initial beam width Y_o is sharply defined.

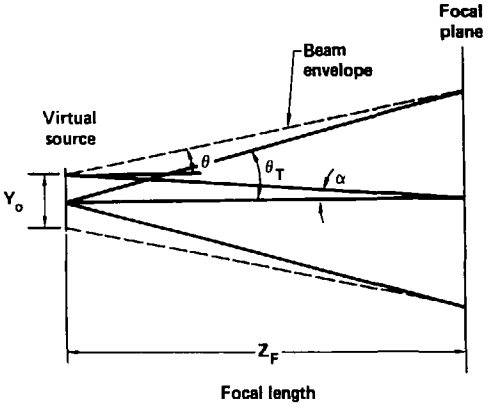

Fig. 7. Schematic of the high-energy beam from the virtual source to the focal plane.

As the negative ion beam passes through the neutralizer, it must be space-charge neutralized to prevent the half angle of the beam envelope from becoming unnecessarily large. This is accomplished by adjusting the background pressure. However, the pressure must not be so high as to strip an excessive fraction of the negative ion beam in front of the neutralizer, or to ionize a significant fraction of the high-energy neutrals beyond the neutralizer.

If we assume the space-charge forces are neutralized, the average width of the neutralizer can be minimized by means of suitable beam optics. Let θ_T represent the divergence angle corresponding to that of an ion emitted anywhere over the surface of the source with a transverse velocity equal to the most probable transverse velocity, and a longitudinal velocity equal to $(2eV/M)^{1/2}$. Then

$$\theta = \theta_T - \alpha \ , \tag{22}$$

in which α is the angle formed by the beam geometry as shown in Fig. 7. Because the emittance is an invariant of a beam of given energy,

$$\theta_T = C/Y_o \ , \tag{23}$$

in which C is a constant related to the beam emittance.

From Eq. (21), then,

$$Y_A = Y_o + CZ/Y_o - \alpha Z \tag{24}$$

and minimum Y_A is obtained when

$$Y_o = (CZ)^{1/2} . \tag{25}$$

Neglecting α,

$$\text{minimum } Y_A \leq 2(CZ)^{1/2} . \tag{26}$$

From the dimensions of a negative ion source currently under development at LBL,[9] we estimate C at 0.034 mm-rads. Thus, for a neutralizer 2.0 m long, minimum Y_A is about 0.05 m, and

$$I_o/Y_A = 20\ I_N/\eta , \tag{27}$$

in which the negative ion beam current I_o is taken to be equal to the neutral beam current I_N, divided by the neutral fraction η.

The fourth term of gamma equals the photodetachment cross section σ at the wavelength of the laser, divided by the corresponding photon energy $h\nu$. With an atomic iodine laser, $\sigma/(h\nu) = 0.012\ m^2/\text{Joule}$, as shown in Fig. 8. Photons from an atomic iodine laser do not have sufficient energy to strip C^-, O^- or OH^- ions.[10] On the other hand, we can see from Eq. (12) that the mass and photodetachment cross section of O_2^- are such that a photoneutralizer capable of neutralizing 95% of a 200-keV D^- beam will strip 75% of the O_2^- impurity in the beam. Obviously, O_2^- is undesirable.

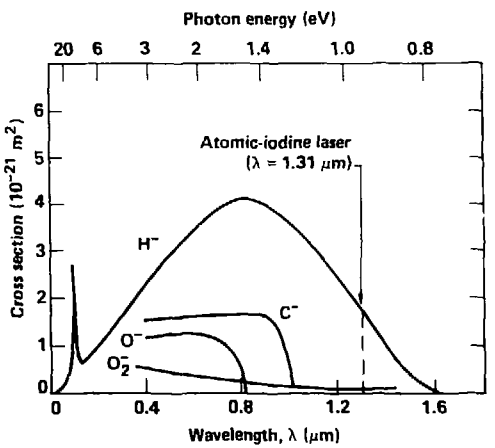

Fig. 8. Photodetachment cross section of negative hydrogen, carbon, oxygen, and oxygen molecules. (Adapted from Ref. 11.)

The fifth term G is the gain of the laser resonator. It is inversely proportional to the optical losses resulting from scattering and absorption in the laser window, mirrors, and gain medium, plus the losses resulting from optical diffraction within the resonator itself. I will not pursue this subject here because it is discussed elsewhere in these proceedings.[2] However, I believe that

the development of low-loss mirrors of very high reflectivity makes a resonator with a G of 500 possible.

The sixth and last term is laser efficiency ε_L. If ε_C is the efficiency with which the metastable oxygen is recycled; $(\varepsilon_{in} - \varepsilon_{out})$, the fraction of the metastable oxygen that is consumed in the laser; and ε_U, the fraction of metastable oxygen that excites the iodine atoms; then

$$\varepsilon_L = 0.96\ \varepsilon_C(\varepsilon_{in} - \varepsilon_{out})\ \varepsilon_U\ , \tag{28}$$

in which 0.96 is the ratio of the energy of metastable iodine to metastable oxygen molecules. Although it is impossible to know at this time what the efficiency of a fully developed supersonic atomic iodine laser will be, my estimates fall within 3 to 12%.

NEUTRAL BEAM CURRENT

We can determine the neutral beam current needed to obtain a maximum beam-line efficiency by introducing the six factors of Γ, previously discussed, into Eqs. (18) and (20). The result is

$$I_N = 83.3\ (\varepsilon P/\varepsilon L)\ V^{-1/2}\ \eta_o/(1 - \eta_o)\ . \tag{29}$$

This equation can be solved for any maximum beam-line efficiency ε_P by using the corresponding optimum neutral fraction η_o shown in Fig. 6. Figure 9 shows the result for a neutral beam line based upon a negative ion beam whose efficiency ε_B is 85%.

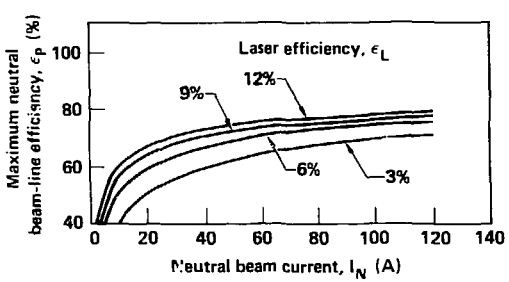

Fig. 9. Maximum efficiency of a 200-keV neutral beam line obtainable with a neutral beam current, I_N. The negative ion beam was formed at an efficiency of ε_B = 85%, while the average width of the resonator was 0.05 m, and its length, 2.0 m.

Because so much energy is lost to the resonator mirrors, in contrast to the energy used for photodetachment, the larger the beam current neutralized in a resonator of given mirror area, the more efficient the beam line. However, there is a limit to the neutral current that can be carried in a beam of reasonable size. Ion sources deliver only so many amperes of negative ions per meter of beam height (X_o per Fig. 2). The present LBL surface conversion source is expected to deliver 6 A/m, but this may be larger in other sources now under development. With a 10% loss of negative ions during acceleration, the present source will provide about 5.4 A/m of neutrals.

LITHIUM BEAMS

Of interest is a comparison of the photodetachment of a Li^- beam with a D^- beam, when both use the chemical iodine laser previously discussed.[11,12] Assume both beams operate with the same neutral fraction, whereby the ratio of the thickness of their respective neutralizers, per Eq. (12), is

$$S_{Li}/S_D = (M_D/M_{Li})^{1/2}(V_{Li}/V_D)^{1/2}\ (\sigma_D/\sigma_{Li}) \ . \qquad (30)$$

If the two beams are of identical height and width,

$$\Gamma_{Li}/\Gamma_D = (M_{Li}/M_D)^{1/2}(V_{Li}/V_D)^{1/2}(J_{Li}/J_D)(\sigma_{Li}/\sigma_D) \ , \qquad (31)$$

in which J_{Li} and J_D are the current densities of the lithium (Li) and deuterium (D) ion beams, respectively.

At the laser wavelength 1.315 μm, the photodetachment cross section of D^- is about 1.8×10^{-21} m^2, while that of Li^- is roughly 1.4×10^{-20} m^2 (Figs. 8 and 10).[13] For beams of the same energy, $S_{Li}/S_D = 0.069$, and $\Gamma_{Li}/\Gamma_D = 14.5\ (J_{Li}/J_D)$. For beams of the same velocity (where $V_{Li}/V_D = M_{Li}/M_D$), $S_{Li}/S_D = 0.129$, and $\Gamma_{Li}/\Gamma_D = 27.0\ (J_{Li}/J_D)$. In both cases, the thickness of the Li neutralizer is of the order of 10% of that of D. Furthermore, if the current density of the Li^- negative lithium ion beam could be made to approach that of today's D sources, Γ_{Li} would be quite large, whereby the efficiency of the neutral Li beam line would be about that with which the Li^- ion beam was formed. Consequently, an efficient negative ion source and accelerator are essential to form an efficient Li neutral beam.

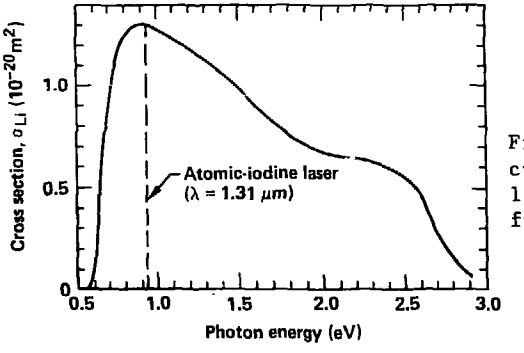

Fig. 10. Photodetachment cross section of negative lithium ions. (Adapted from Ref. 13.)

CONCLUSION

This analysis shows that the maximum efficiency of a neutral beam requires the optimization of both the negative ion beam and the photoneutralizer. The efficiency of the neutral beam line can not be greater than that of the negative ion beam from which it was formed; therefore, the performance of the ion source, accelerator, and ion transport must be optimized.

To effectively use a photoresonator, the negative ions must be formed into a thin ribbon beam. In addition, the beam current density should be high, while the negative ion beam is space-charge neutralized.

Although the chemical iodine laser is the preferred choice for photoneutralizing hydrogen, deuterium, tritium, and lithium beams, experimental verification of the laser performance at full power is required. While some performance data of the supersonic laser are available, its ultimate overall efficiency is obviously not known. To help estimate this, a study of the efficiency of the laser chemical recycling system has been initiated. In addition, computer studies are planned to design the laser resonator and to optimize the resonator gain, while advanced concepts of the window are verified. I believe that components of a full-scale, multi-ampere demonstration of photoneutralized negative ion beams could be available in about 4 years.

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