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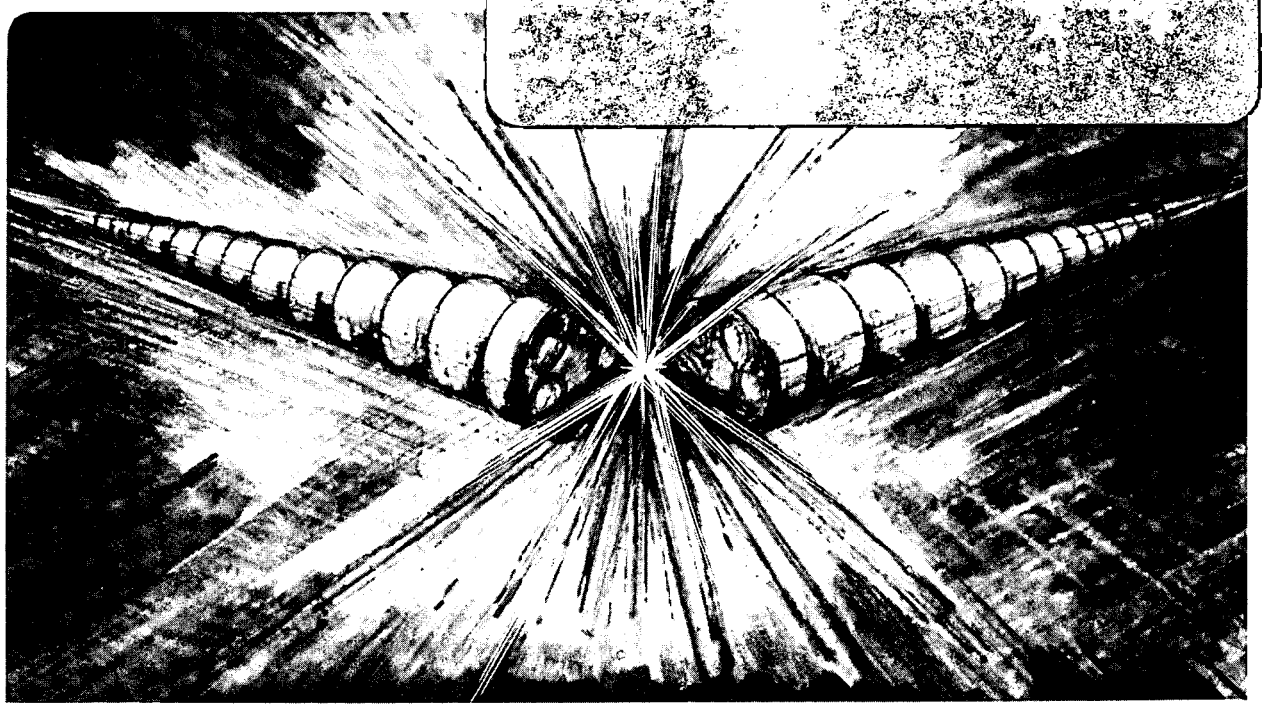

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NEUTRALIZER OPTIONS FOR HIGH ENERGY H^- BEAMS*

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ABSTRACT

An energy spectrum of neutral beams is presented and the ranges over which various neutralizers give the most satisfactory performance is discussed.

INTRODUCTION

A neutralizer converts a negative ion beam into a neutral beam, but it also increases the beamline cost, weight and size while reducing its output power, efficiency and possibly the reliability of the entire system. In addition it scatters the newly formed neutrals, altering the beam current density distribution, causing the beam divergence to get larger and the brightness to go down.

In the following, the role of neutralizers for hydrogen ion beams is reviewed, and the problems encountered over a range of beam energies are discussed. Consideration is given to enhancing the goals of the neutral beam application, be they the highest neutral fraction, optimum overall efficiency or maximum beam brightness, etc.

Efficiency is undoubtedly the most critical parameter. No matter what beamline characteristics are considered important, a good design will provide them efficiently. Thus the maximum neutral fraction that can be obtained from a passive neutralizer, one which requires negligible additional power, is very important. The efficiency of a neutral beamline using such a neutralizer is proportional to the fraction of the incident ion beam that becomes neutral F^o i.e.;

$$n_o = n_{NEG} \cdot F^o \qquad [1]$$

where n_{NEG} is the efficiency of the ion beam from which the neutrals were formed.

For a driven neutralizer, in which the neutral fraction is a function of the power P_n needed to operate the neutralizer, the efficiency of a neutral beamline is more complex:

$$n_o = n_{NEG} \frac{F^o}{1 + (P_N - P_{ER})/P_{IN}} \qquad [2]$$

where P_{IN} is the power needed to form the the negative ion beam,

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and P_{ER} is the energy recovered from the ions in the un-neutralized fraction of the beam.

In this case, there is an optimum beam line efficiency with respect to line density which is a function of the relationship between the neutral fraction and P_N. In general, this relationship is difficult to estimate because it depends upon features of the design of the neutralizer rather than fumdamentals of physics. It is evident that the preferred neutral fraction will be less than the maximum.

There are applications where the divergence of the neutral beam θ_o must be below a given maximum. As an approximation, for a neutral beam formed from an ion beam of divergence θ_{NEG}:

$$\theta_o^2 = \theta_{NEG}^2 + \theta_N^2 \qquad [3]$$

in which θ_N is the neutralizer's contribution to the divergence of the neutral beam. With non-relativistic beams, θ_N is roughly inversely proportional to the square root of the beam energy. Because θ_N is a function of the line density, or wavelength with photodetachment, of the neutralizer, it is related to the neutral fraction and the efficiency with which the neutral beamline operates. The upper limit to θ_o might be attained at less than maximum efficiency and optimum neutral fraction.

A similar situation exists for beam brightness. On the assumption that the beam is gaussian and a peak brightness B_o at a focus is of importance, it can be shown that:

$$B_o = B_{NEG} \frac{F^o}{1 + (\theta_N/\theta_{NEG})^2} \qquad [4]$$

where B_{NEG} is the peak brightness of the ion beam. Once again a compromise is required to attain the highest beam brightness at the most favorable beamline efficiency.

Whereas the previous discussion was concerned with neutralizer options as they relate to the application of neutral beams, in the following options are considered in relation to the beam energy.

AT LESS THAN 50 keV

If one were to examine the energy spectrum of neutral hydrogen beams, he would find positive ions to be the preferred source of neutrals at low beam energies. Such neutral beamlines are more desirable because they are more efficient, support higher current densities and operate with higher gas efficiencies than negative ion sources. In addition the loss of positive ions at fractions of the beam line energy, resulting from charge exchange with the background gas in the accelerator, is considerably less than the corresponding loss of negative ions would be.

With respect to divergence and brightness, a comparison of the two types of neutral beamlines reflects the relative divergence and brightness of the ion beams. However, it is known that the increase in divergence caused by neutralizing negative ions is significantly less than that of positive ions.[2]

FROM 50 keV to ABOUT 80 keV

At higher energies than 50 keV, the choice of a positive ion beam as a source of neutrals is not as evident. With increasing beam energy, the efficiency of the beamline goes down. As shown in Fig. 1, the cross sections for electron attachment in a gas cell fall off, causing the optimum neutral fraction, equivalent to that of a positive ion beam passsing through a hydrogen neutralizer of infinite line density, to become less and less. See Fig. 2.

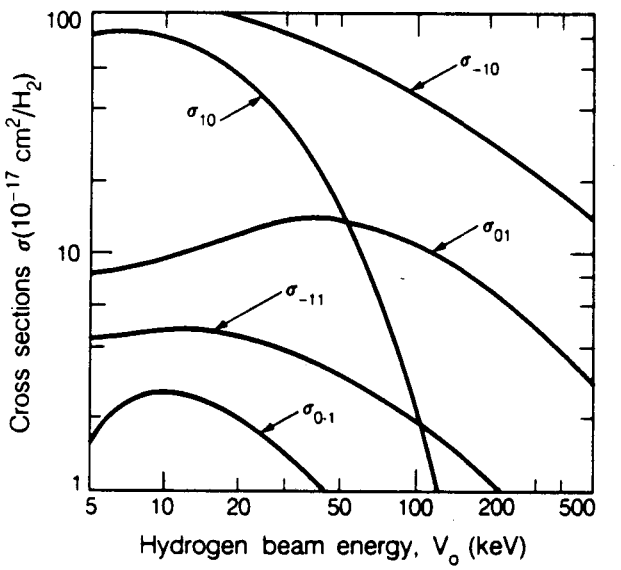

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Fig. 1. Hydrogen cross sections in H_2.

As the power consumed by the accelerator increases, the efficiency of the positive ion source becomes a smaller factor in the overall beamline performance. In addition, the decreasing neutral fraction cuts into the advantages of a higher emitted current density and the better gas efficiency a positive ion source provides. Problems arise if the application requires a mono-energetic beam of neutrals because molecular ions break up when neutralized, into neutrals of fractional beam energy.

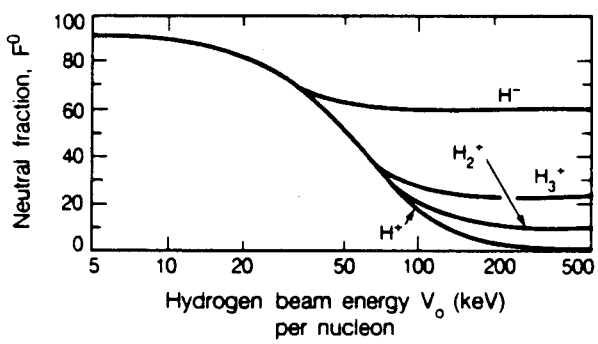

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Fig. 2. Maximum neutral fractions for hydrogen beams in hydrogen.

Of course the fraction of positive molecular ions extracted from the source can be minimized and those that remain can be removed before they are accelerated to any appreciable energy. In addition, the neutral beamline efficiency can be enhanced by means of energy recovery.[3] Nevertheless, there is an energy, of the order of 80 keV, above which the reduced neutral fraction makes even such measures ineffective.

On the other hand, the maximum neutral fraction of a negative hydrogen ion beam traveling through a hydrogen gas cell levels off at about 60%, and becomes relatively independent of additional increases in the beam energy. Whereas the efficiency of a negative ion beam, including the ion source, accelerator and miscellaneous services, is about 80% over a broad range of energies, the overall efficiency of a neutral beamline based on negative ions will not vary much with the beam energy and will be about 48%. Furthermore, there are no negative molecular ions to worry about.

It is also possible to take advantage of energy recovery with negative ion beams. Whereas the components of positive and negative ions are of the same order of magnitude in a beam of optimum neutral fraction, the positive ion component is considerably smaller in a neutralizer that is under dense, i.e., at less than optimum line density. Under these circumstances at maximum efficiency, the neutral fraction will be less than maximum. If the energy of both the positive and negative ions could be recovered the maximum beamline efficiency would be increased by almost 10%, while the neutral fraction remained at just about maximum.

As a result, neutral hydrogen beams formed out of negative ions of this energy range can be made competitive with beams formed of positive ions. Above 80 keV, the poor efficiency of neutral beams based upon positive ions make them impractical.

FROM 80 keV TO ABOUT 1 MeV

In this range of energy, the simple hydrogen gas cell becomes marginal and consideration must be given to alternative neutralizer designs. Problems arise from the increasing line density of the neutralizer needed to form a maximum fraction of neutrals. As the energy goes up, the neutralizer must either become longer or operate at a higher average pressure.

In practice there are limits to the neutralizer length. Depending upon the application, these could relate to its weight, but most likely to its cost. This includes not just the weight or cost of the neutralizer, but also its housing, containment structure, and magnetic shielding.

Problems originating from excessive neutralizer pressure result from the extra gas it introduces into the beamline. Because the beam losses are proportional to the background gas pressure, it is essential that the gas flow be minimal and whatever gas does get into the beamline is pumped away at an acceptable pressure. This is difficult to accomplish with a neutralizer of large diameter.

It should be recognized that the loss of a small fraction of the neutral beam, due to ionizing collisions with the background gas, is not as serious as the damage high energy ions can cause if they are neutralized before they have been properly aimed and focussed. To mitigate this, consideration must be given to more extensive pumping or, possibly, other types of neutralizers. Different gases, vapors, plasmas, gas or plasma jets or even photodetachment might be made to form acceptable neutralizers. A brief discussion of some of the choices follows.

Because the cross sections for electron attachment σ_{10}, σ_{0-1} and σ_{1-1}) drop off rapidly[4] with increasing beam energy V_o, the characteristics of neutralizers of high energy negative ion beams are functions of the electron detachment cross sections. At energies in excess of 100 keV, these cross sections (σ_{-10}, σ_{01} and σ_{-11}) are proportional to each other and they decrease, for non-relativistic beams, in accordance with the Born approximation[5] at a rate proportional to $v_o^{-1} \ln\{A\ V_o\}$ in which A is a function of the material of which the neutralizer is formed.

Compared to the other electron detachment cross sections, σ_{-11} is small. Thus only σ_{-10} and σ_{01} are needed to approximate the neutral fraction that corresponds to a gas cell of any line density.[6] The following approximation is acceptable because the cross-sections are only known to no better than ±15% and the neutral fractions to ±5%. Given the ratio of the cross sections:

$$r_{-10} = \sigma_{-10}/\sigma_{01} \ , \qquad [5]$$

the neutral fraction, as a function of the neutralizer line density, π is:

$$F^o = \left(\frac{r_{-10}}{r_{-10} - 1}\right) \left(e^{-\sigma_{01}\pi} - e^{-r_{-10}\sigma_{01}\pi}\right) \qquad [6]$$

from which the <u>maximum</u> neutral fraction:

$$\text{MAX } F^o = (r_{-10})^{(1/[1 - r_{-10}])} \qquad [7]$$

is found at the <u>optimum</u> line density:

$$\pi_o = \left(\frac{1}{\sigma_{01}}\right) \frac{\ln\{r_{-10}\}}{[r_{-10} - 1]} \qquad [8]$$

Values of Max F^o and the product ($\sigma_{01} \cdot \pi_o$) are shown in Fig. 3 as functions of the ratio r_{-10}. It is evident that the larger r_{-10}, the higher the maximum neutral fraction and the smaller the product ($\sigma_{01} \cdot \pi_o$) will be.

Because r_{-10} equals the ratio of two terms with the same energy dependence, it is independent of the beam energy. Therefore, neither Max F^o or the product ($\sigma_{01} \cdot \pi_o$) are functions of the energy. On the other hand, the optimum line density π_o, being inversy proportional to σ_{01}, increases with the beam energy.

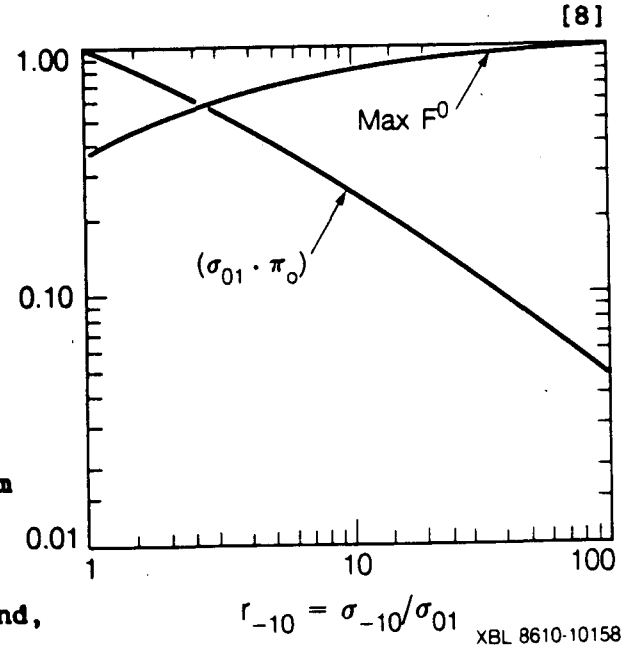

Fig. 3. F^o and ($\sigma_{01} \cdot \pi_o$) as functions of r_{-10}.

To reduce the length of an optimum neutralizer, other gases with electron detachment cross sections greater than those of hydrogen could be used. For instance, an optimum argon neutralizer for a 200 keV hydrogen beam has a line density that is about 30% that of hydrogen.[7] Unfortunately however, the maximum neutral fraction obtained with other gases may not be as high as that of hydrogen. Indeed, the optimun neutral fraction obtained with argon is about 48% in contrast to 58% for hydrogen. Clearly, there is the possibility of a trade off between neutralizer length and beamline efficiency.

In general maximum neutral fractions observed with most elements range from below 50% to something over 60%. Furthermore[8], it appears that large molecules have lower optimum neutral fractions than might be expected from the sum of their atomic components. The few experimental studies that have been carried out on large molecules confirm this, frequently yielding maximum neutral fractions of less than 50%.

Measurements of the additional beam divergence obtained with different gas neutralizers[2] indicate a very weak dependence on Z. It is largely the result of inelastic collisions corresponding to electron detachment. With increasing beam energy it varies, in the non-relativistic range, inversely with the square root of the energy, V_o.

It is also possible to reduce the neutralizer length and minimize the gas flow by means of gas or plasma jets. This is discussed with regard to gases other than hydrogen in the 1977 proceedings of these symposiyms.[9] A cesium metal vapor jet, using a plug nozzle of the type first proposed for the formation of negative ions by double charge exchange[10] could be advantageous for these applications. The optimum line density of cesium is only 17% of that of hydrogen, while its maximum neutral fraction is about the same.[7] As for plasma jets, they have been tried[11] and found to be effective but not efficient in that all of the power used to ionize the plasma is lost in one pass of the jet across the beamline.

A high Q, multiply ionized plasma provides another approach.[12] With a plasma consisting of ions of density n_Q, primarily of charge state Q, and of neutral gas density n_o, the ionization fraction is:

$$f = \frac{n_Q}{[n_Q + n_o]} \qquad [9]$$

The effective electron detachment cross sections of the plasma, being the sum of the weighted contributions of the ions, electrons and neutrals, are:

$$\sigma(Q,f)_{-1o} = f\sigma(Q)_{-1o} + Qf\sigma(e)_{-1o} + (1 - f)\sigma_{-1o} \qquad [10]$$

$$\sigma(Q,f)_{o1} = f\sigma(Q)_{o1} + Qf\sigma(e)_{o1} + (1 - f)\sigma_{o1} \qquad [11]$$

with the following approximations:

$$\sigma(Q)_{-1o} = Q^2\sigma(i)_{-1o} = Q^2\sigma(e)_{-1o} \qquad [12]$$

$$\sigma(Q)_{o1} = Q^2\sigma(i)_{o1} = Q^2\sigma(e)_{o1} = Q^2\sigma_{o1} \qquad [13]$$

in which $\sigma(i)$ is the cross section of a singly ionized $Q = 1$, ion, the ratio of the plasma cross sections becomes:

$$r(Q,f)_{-1o} = \frac{(Q^2 + Q)f[\sigma(i)_{-1o}/\sigma_{-1o}] + (1 - f)r_{-1o}}{(Q^2 + Q - 1)f + 1} \qquad [14]$$

The maximum neutral fraction along with the product of the ionizing cross section, per Eq. 11, and the optimum line density of the ions in the plasma are the same as shown in Fig. 3, when $r(Q,f)_{-1o}$ is substituted for r_{-1o}, and $[\sigma(Q,f)_{o1} \cdot \pi(Q,f)_o]$ for $\sigma_{o1} \cdot \pi_o$. The optimum line density of the plasma in the neutralizer, i.e. the sum of the ion and neutral line densities, is then:

$$\pi(Q,f)_o = \frac{\ln\{r(Q,f)_{-1o}\}}{\sigma_{o1}[Q^2f + Qf - f + 1] \cdot [r(Q,f)_{-1o} - 1]} \qquad [15]$$

while that of the ions is:

$$\pi(Q)_o = f \cdot \pi(Q,f)_o \qquad [16]$$

and that of the neutrals is:

$$\pi(0)_o = [1 - f] \cdot \pi(Q,f)_o \qquad [17]$$

Figure 4 shows curves of the maximum neutral fraction, for $Q = 1$ and 5, versus the ionization fraction of the plasma, with the assumption that $\sigma(i)_{o1}/\sigma_{o1} = 25$ and $r_{-1o} = 3.5$. Figure 5 shows how the product of the ionizing cross section $\sigma(Q,f)_{o1}$ and 1) the optimum plasma line density $\pi(Q,f)_o$, 2) the corresponding ion line density in the plasma $\pi(Q)_o$ and 3) the corresponding neutral line density $\pi(0)_o$ vary with the plasma ionization fraction for ion charge states $Q = 1$ and 5.

When $Q = 1$, the above equations are applicable to plasma neutralizers with

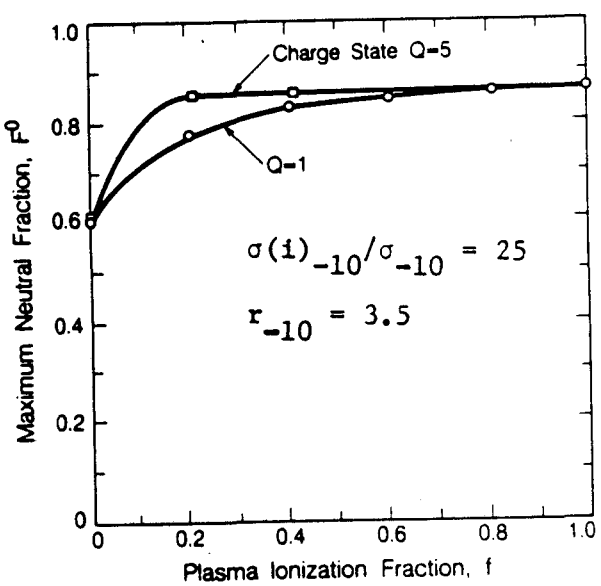

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Fig. 4. The maximum neutral fraction as a function of the ionization fraction for plasmas with charge states of Q=1 and 5.

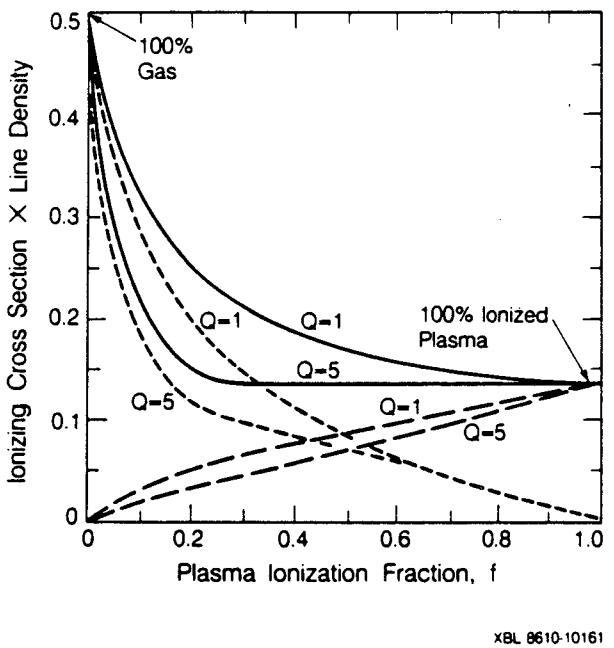

Fig. 5. The product of the ionizing cross section $\sigma(Q,f)_{01}$ and:
_____ The optimum plasma line density.
_ _ _ The ionline density.
----- The neutral line density.

singly charged ions. When f = 0, they describe a gas neutralizer and when f = 1, a fully ionized plasma. Both Figs. 4 and 5 show the advantages of a high Q plasma at relatively low ionization fractions. But the most significant advantage results from the cross section $\sigma(Q,f)_{01}$ which increases, and thereby reduces the optimum line densities by a factor of approximately Q^2.

The maximum neutral fraction obtained with any plasma neutralizer depends upon the gas of which it is formed. A fully ionized hydrogen plasma, for instance, will provide a maximum neutral fraction of approximately 85%.

Plasma neutralizers have been investigated in the past[13] and the high neutral fraction found at relatively low ionization fractions make them more efficient than they otherwise might be. However, it is important to keep the magnetic field that confines the plasma from interacting with the ion and increasing the beam divergence to an unacceptable level.[14]

It should be noted that there is some uncertainty about the effect of the plasma on the beam optics. Depending on whether it is slightly positive or negative, the plasma can act as a divergent or convergent lens to the un-neutralized ions traveling through the neutralizer. In addition, any plasma oscillations can cause a significant increase in the beam divergence.

To establish the efficiency of a neutral beamline equipped with a plasma neutralizer, it is necessary, per Eq. 2, to determine the ratio of the power needed to sustain the plasma in the neutralizer with respect to the power needed to form the negative ion beam. The intricacies of the various proposed neutralizer designs, make it difficult to estimate this ratio with any confidence. Obviously, the beam diameter, as well as the effectiveness of the radial confinement of the plasma are critical.

Photodetachment[15] has the potential of being the basis of a very desirable neutralizer. Without the introduction of additional gas, it could provide a high neutral fraction with a neutralizer of reasonable length and help form a neutral beamline of high efficiency. Most concepts call for an intense laser beam to be reflected back and forth across the path of the negative ions to be neutralized. The performance of such neutralizers depend upon the laser, its wavelength and efficiency, the mirrors, their reflectivity and ability to withstand high levels of radiation, and the design of the optical cavity.

Because the neutral fraction obtained from photodetachment is a function of power used to drive the optical system, the efficiency of a photoneutralized beamline is described by Eq. 2. While the neutral fraction can be made to approach 100%, it will probably be considerably less in a beamline of reasonable efficiency. As with plasma neutralizers, it is impossible to determine the power needed to operate a photo-neutralizer in a general way. It depends upon such things as the beam energy, the wavelength of the photons, the efficiency of the light source and the gain of the optical resonator which, in the final analysis, must be determined experimentally.

As for the increase in beam divergence caused by photodetachment, it is a consequence of the difference between the energy of the photon and the binding energy of the extra electron which forms the negative ion. Upon neutralization, this energy is shared between the newly released electron and the newly formed neutral. Because the photodetachment cross section and the beam divergence are functions of the wavelength, that wavelength which establishes the minimum divergence, the maximum neutral beamline efficiency and the maximum brightness are not the same. In fact, tunable lasers of wavelengths suitable to maximize the beamline efficiency are probably not available today.

Some of the lasers under consideration include a huge array of small cw Gallium Arsenide lasers with a wavelength of 0.84 μm, a vast chemical Iodine laser of 1.31 μm and a high power Neodymium-YAG laser of 1.06 μm.

The choice of cw lasers of wavelengths suitable for stripping H^- is limited but by means of Raman shifters, a range of wavelengths can be obtained. However, to tailor a photo-neutralizer to optimize the maximum the beamline efficiency, neutral beam brightness, etc. will require the development of efficient free-electron-lasers.[16]

FROM 1.0 TO 25 MeV

Until now, it has been assumed that the negative ion beams were accelerated in a simple gridded structure. But intense electric fields are required to form high energy beams in this manner. At high voltages, the electrodes are subject to occasional breakdown, making the accelerator unreliable. Furthermore, high voltage terminals exposed to the atmosphere must be constructed with very large radii to inhibit corona, while the stray

capacitance about the system has to be limited to prevent the stored energy from sustaining a catastrophic arc at breakdown. While it is possible to contain the electrodes in oil or a pressurized gas such as SF_6, the container increases the capacitance of the system, possibly making matters worse. Thus at some energy ranging from 0.75 to roughly 2 MeV, depending upon the skill of the designer, rf accelerators will have to be used to form the negative ion beams from which neutrals are formed.

With rf accelerators, the efficiency of the negative ion beamline is decreased by a factor related to the efficiency with which the wall plug is converted to rf power, roughly 60%. As a consequence, at energies in excess of 2 MeV, the neutral beamline efficiency is expected to be less than 30%.

With regards to neutralizers, the optimum line densities continue to increase as the beam energy goes up, making this a particularly difficult region. Unless constraints on the neutralizer length are greatly relaxed, gas neutralizers are most probably unacceptable. Gas and vapor jets remain a possibility if they can be well confined and, depending upon the beam diameter and the beamline efficiency requirements, either a high Q plasma or a photo-neutralizer might be considered.

ABOVE 25 MeV

At 25 MeV, the optimum line density is so large that the neutralizers can be formed out of solid foils or possibly liquid films of several mg/cm^2. Because the optimum line density of any neutralizer is of the order of 1 to 2 mean-free-paths, irrespective of the beam energy, and the collisions per mg/cm^2 is nearly the same for all elements at any given energy[17], the mg/cm^2 for all optimized gas, vapor, liquid and foil neutralizers is about the same. Thus, the higher the beam energy, the greater the optimum line density and the more weight there is in an optimum foil or film to provide strength.

Preliminary experiments were conducted on a thin liquid sheet, produced by spraying high-purity Fomblin oil on a rapidly rotating disk, to determine its effectiveness as a neutralizer.[18] The concept of a liquid sheet or film is attractive because it is self replenishing and self healing while under bombardment. The results were encouraging and it is likely that the maximum neutral fraction will be of the order of gas or foil neutralizers.

As for foils, in particular carbon foils, present technology[19] is such that large diameter assemblies of great strength can be formed at line densities of more than 1 to 2 mg/cm^2. The assemblies consist of thin foils mounted on a strong, fine meshed grid of about 90% transparency, made of carbon fibers of up to 100 microns in diameter. The maximum neutral fraction, averaged over the grids obtained with such foils is expected to be about 55%. Because the required structural strength of the grid, i.e., the diameter of the carbon fibers, is independent of the beam energy, the grid is heated more at lower beam energies at which their stopping power is greater. Calculations indicate

that the carbon fibers should be able to withstand the resulting thermal stress. It is expected that hydrogen beams of 25 MeV will have little affect on the foil, but the useful life of a carbon foil could be reduced by atomic oxygen erosion. In some environments special precautions may be required.

To operate at higher efficiencies, it will be necessary to use a driven neutralizer based upon either a high Q plasma or photodetachment. To be efficient, the power needed to operate either of these neutralizers must be considerably less than that of the negative ion beam. However, as can be seen from Eq. 2, the beamline efficiency cannot be better than that with which the negative ion beam was formed.

At 50 to 100 MeV, the beam velocity becomes an appreciable fraction of that of light and relativistic effects start to become important. Figure 6 shows the ratio of velocities, $\beta = v/c$ as a function of the kinetic energy of the beam. Specific proton accelerators are noted in the figure as items of general interest. Although I do not intend to discuss relativity in any detail, there are three effects which should be mentioned here. At relativistic energies: 1. The electron detachment cross sections increase with the beam energy at a slower rate, making the optimum neutralizer line densities somewhat larger than they otherwise might be.

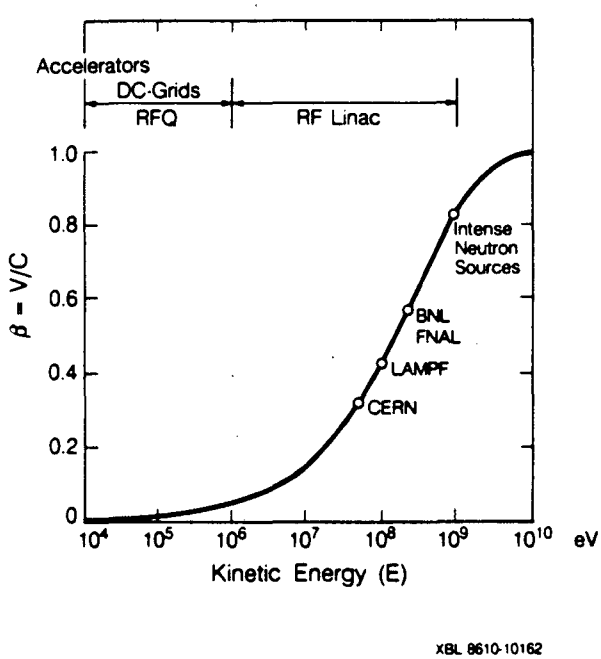

Fig. 6. β as a function of the kinitic energy of a hydrogen beam.

2. The added beam divergence resulting from neutralization decreases at a slower rate with increasing beam energy.
3. The wavelength of the photons seen by the moving ions is less than that in the rest frame of the laser, while the photon line density appears to be greater. Figure 7 shows the laser wave length as seen in the laboratory in contrast to the nonrelativistic photodetachment cross section as seen in the frame of the moving ions.

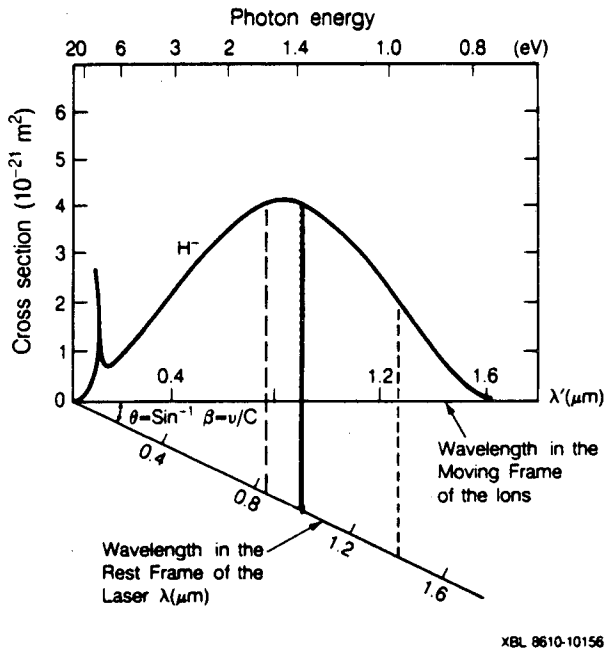

Fig. 7. Photo detachment cross section in the frame of the moving ions.
_____ Galium Aresnide Laser.
_ _ _ Neodymium-YAG Laser.
----- Atomic Iodine Laser.

CONCLUSIONS

Figure 8 shows a spectrum of beam energies, indicating the approximate range over which the various types of neutralizers might be useful.

Obviously there are many options for neutralizers of high energy negative hydrogen beams. Future delopment should make photodetachment a more viable prospect and there probably are a few concepts that have not been thought of yet. But before the most desirable neutralizer can be selected, the critical items of the neutral beam specification, such as the efficiency, divergence, or brightness, etc. must be identified.

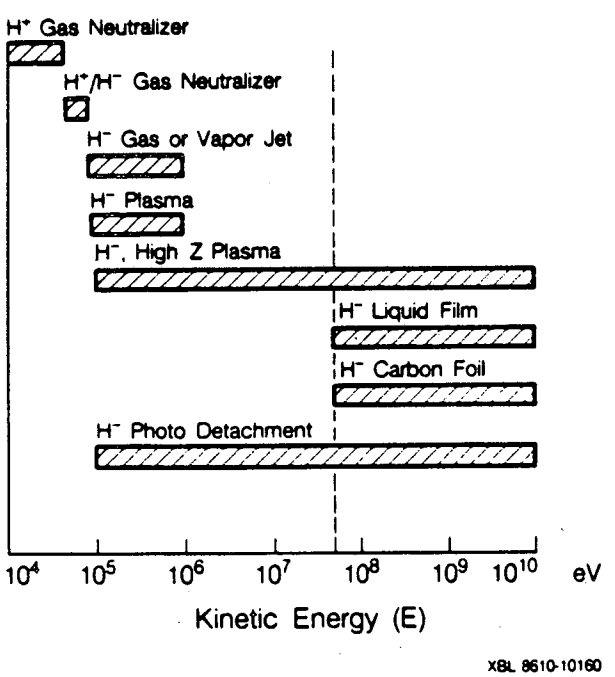

Fig. 8. Approx. energy range of various neutralizers.

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