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THE EFFECT OF COMPONENT PERFORMANCE PERTURBATIONS ON NEUTRAL BEAM INJECTION SYSTEM PERFORMANCE IN THERMONUCLEAR REACTORS

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ABSTRACT

The effect of component performance perturbations on the efficiency of injection of neutral beams into thermonuclear reactors is discussed for a specific type of a neutral beam injector. Based on the model chosen, which includes using direct conversion of the unneutralized portions of the ion beam and recovery of the losses from each element of the injector system, quantitative effects of component performance perturbations are presented as a function of the injected deuterium atom energy, using positive and negative deuterium ions. The component performances having the largest leverage on the system efficiency are, in decreasing order, the accelerator efficiency, the trapping fraction, the neutralizer loss direct conversion and the neutralizer power efficiency.

INTRODUCTION

Fusion power reactors based on the mirror machine principle require the continuous injection of high energy particle beams to maintain the plasma against end losses. The injector system efficiency strongly affects the overall efficiency of a mirror reactor system, as is evident from the the power flow diagram in Fig. 1. Reference 1 considers the "in principle" injection system efficiency for injecting high energy neutral beams into a plasma. This report considers the effect of component performance perturbations on the injection system efficiency.

INJECTION SYSTEM EFFICIENCY

The injection system is shown in Fig. 2, and Fig. 3 is its power flow diagram. Positive ions are produced in a source and accelerated to an energy of E^+. These ions are passed through an alkali metal vapor cell that converts them to negative ions. The negative ions are accelerated

$$\eta_{sys} = \frac{[0.8Qm + (1 + 0.2Q)(1 - \eta_{DC})]\,\eta_T + (1 + 0.2Q)\,\eta_{DC} - \frac{1}{\eta_I}}{[0.8m + 0.2]\,Q} = 0.32$$

$$\frac{\delta\eta_{sys}}{\eta_{sys}} = \frac{\frac{\delta\eta_I}{\eta_I}}{\{[0.8Qm + (1 + 0.2Q)\,(1 - \eta_{DC})]\eta_T + (1 + 0.2Q)\,\eta_{DC}\}\,\eta_I - 1} = 2.51\,\frac{\delta\eta_I}{\eta_I}$$

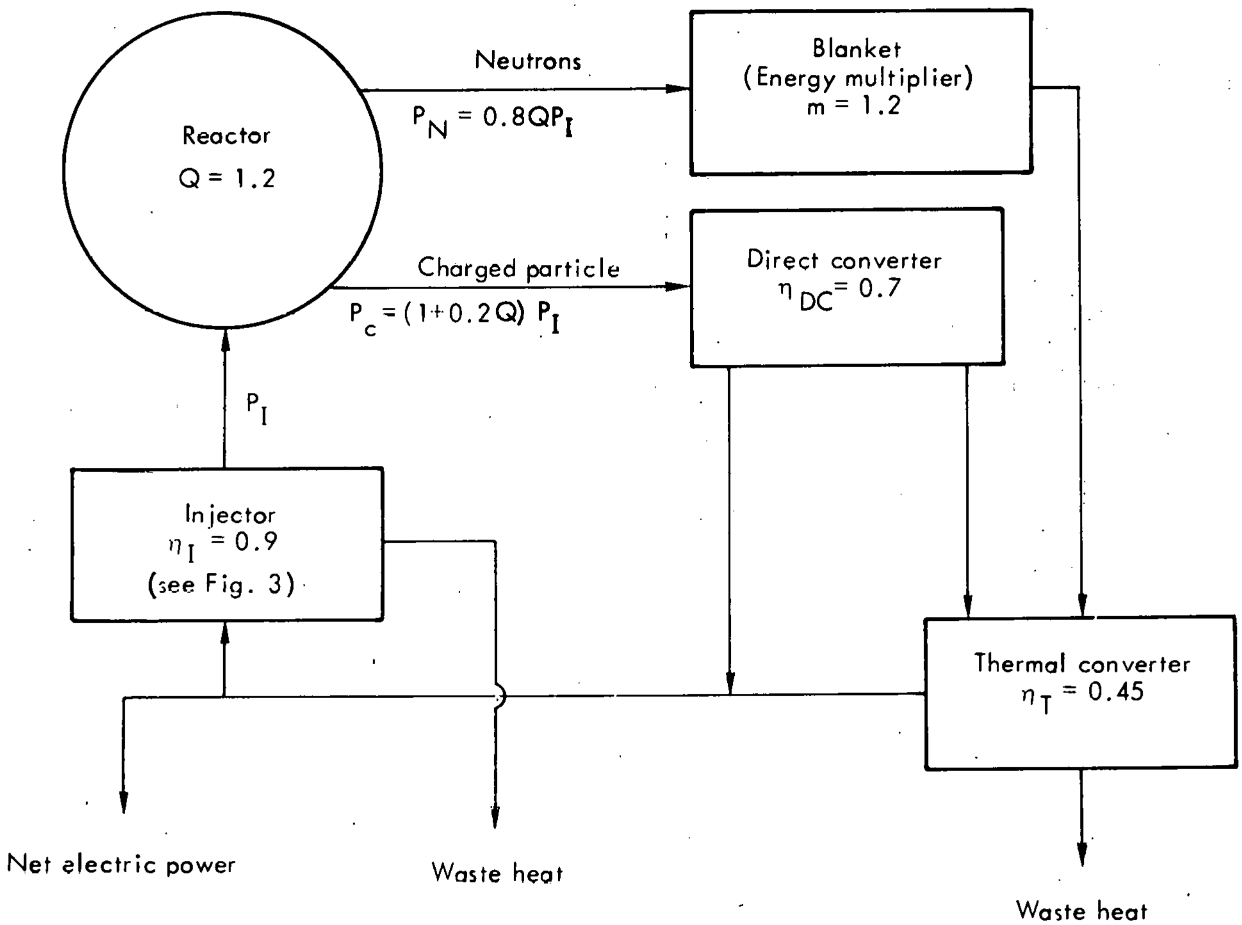

Fig. 1. Power flow diagram for D-T mirror reactor with direct conversion.

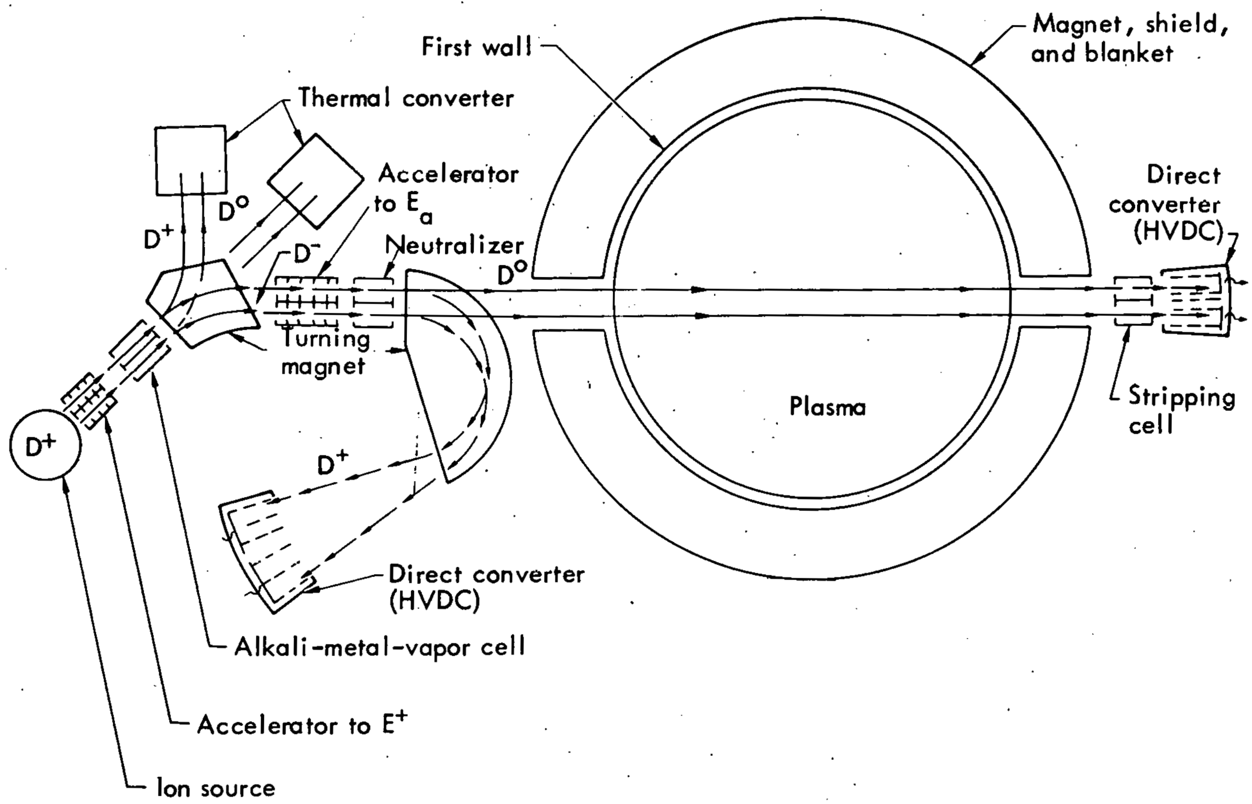

Fig. 2. Schematic of neutral beam injection system using negative ions formed in an alkali metal vapor cell.

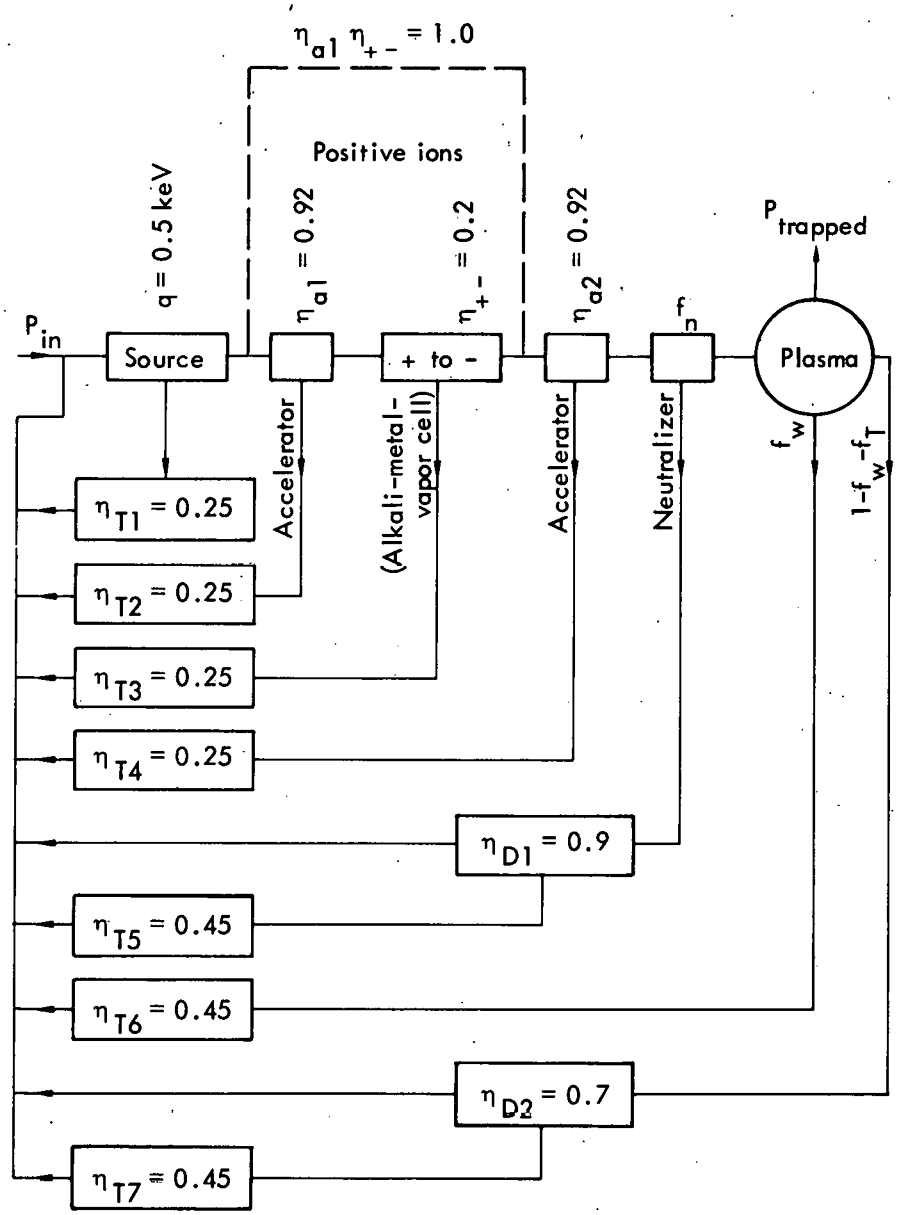

Fig. 3. Power flow diagram for injector system.

to the desired injection energy and neutralized, and the neutral atoms are injected into the plasma. The ions not neutralized are magnetically separated from the neutrals and guided into a direct converter, where a fraction of the energy of the charged particles is recovered.

Some of the injected neutrals charge-exchange with the trapped reactor plasma ions such that the neutrals formed escape from the plasma before ionization occurs. These neutrals deposit their energy over the reactor first wall. The portion of the injected beam that is not trapped in the reactor plasma and is not deposited on the first wall can be stripped of an electron and the energy partially recovered in a second direct converter.

The overall injection efficiency is defined as

$$\eta_I = \frac{P_T}{P_{ex} - P_{rec}} ,$$

where P_T is the trapped power, P_{ex} is the power expended in producing the ions and accelerating them to the energy required for a given injection energy, and P_{rec} is the amount of power lost in the injection system components that is recovered in direct converters or thermal converters. For the injection system shown in Fig. 3, the overall injection system efficiency is

$$\eta_I = \eta_{a2}\, f_n\, f_T \Bigg[1 + \frac{q}{M\eta_{+-}\,\eta_{a1}\, E}\,(1 - \eta_{T1}) + \frac{E^+}{ME}\Bigg[\left(\frac{1 - \eta_{+-}\,\eta_{a1}}{\eta_{+-}\eta_{a1}}\right) + (1 - \eta_{a2})\,\eta_{T4} - \left(\frac{1 - \eta_{a1}}{\eta_{a1}}\right)\frac{\eta_{T2}}{\eta_{+-}} - \left(\frac{1 - \eta_{+-}}{\eta_{+-}}\right)\eta_{T3}\Bigg] - (1 - \eta_{a2})\,\eta_{T4} - \eta_{a2}\Big((1 - f_n)\,[\eta_{D1} + (1 - \eta_{D1})\,\eta_{T5}] + f_n\Big\{(1 - f_T - f_w)\,[\eta_{D2} + (1 - \eta_{D2})\,\eta_{T7}] + f_w\,\eta_{T6}\Big\}\Big)\Bigg]^{-1} , \quad (1)$$

where M is the ratio of the mass of the ion to the mass of the injected atom, E is the energy of the injected atom, f_n is the fraction of the ions entering the neutralizer that are neutralized, f_T is the fraction of the neutral beam that is trapped in the reactor plasma, f_w is the fraction of the neutral beam that charge-exchanges with the reactor plasma ions without undergoing a reionizing collision, and the remaining symbols are defined in Fig. 3.

For positive ion injection, Eq. (1) reduces to

$$\eta_I = \eta_{a2} f_n f_T \Big[1 + \frac{q}{ME} (1 - \eta_{T1}) - (1 - \eta_{a2}) \eta_{T4} - \eta_{a2} \Big((1 - f_n) \times [\eta_{D1} + (1 - \eta_{D1}) \eta_{T5}] + f_n \Big\{(1 - f_T - f_w) \times [\eta_{D2} + (1 - \eta_{D2})\eta_{T7}] + f_w \eta_{T6}\Big\}\Big)\Big]^{-1}, \qquad (2)$$

with $\eta_{+-} = \eta_{a1} = 1$ and $E^+ = 0$. Note that if negative ions are produced directly from the source, Eq. (2) also gives the overall injection system efficiency.

CIRCULATING POWER AND CURRENT OF A NEUTRAL BEAM INJECTOR SYSTEM

There are other considerations of neutral beam injector systems besides the injector efficiency. The first is the circulating power within the injector system, which is defined as the ratio of the accelerator power, P_{acc}, to the trapped power, P_T. The circulating power should be minimized to reduce the operating cost of the injector system. For the injector system shown in Fig. 3,

$$\frac{P_{acc}}{P_T} = \frac{1 + \frac{E^+}{ME}\left(\frac{1 - \eta_{+-} \eta_{a1}}{\eta_{+-} \eta_{a1}}\right)}{\eta_{a2} f_n f_T} . \qquad (3)$$

For the injection system using ions directly from the source,

$$\frac{P_{acc}}{P_T} = \frac{1}{\eta_{a2} f_n f_T} . \qquad (4)$$

Another consideration is the circulating current which is defined as the ratio of the beam current from the source, I_{source}, to the beam current trapped in the plasma, $I_{trapped}$. The circulating current should be also minimized to reduce the cost of the injection components. For the injection system shown in Fig. 3,

$$\frac{I_{source}}{I_{trapped}} = \frac{1}{\eta_{a1}\ \eta_{+-}\ \eta_{a2}\ f_n\ f_T\ M}, \tag{5}$$

which reduces to

$$\frac{I_{source}}{I_{trapped}} = \frac{1}{\eta_{a2}\ f_n\ f_T\ M} = \frac{P_{acc}}{M\ P_T} \tag{6}$$

for an injection system using ions directly from the source.

COMPONENT PERFORMANCE

Table 1 summarizes the injection system component performances for a neutral beam injection system using deuterium ions. These component performances are probably an upper limit, since they do not account for some real effects (e.g., beam divergence in the system and removal of neutral gases from the system). The efficiencies of the energy recovery components are assumed to be invariant with the energy of the injected atoms.

Table 1. Component performances for neutral beam injection system (from Ref. 1).

Component	Performance
Source	$q = 0.5$ keV/ion
Accelerators	$\eta_a = 0.92$
Alkali vapor cell	$\eta_{+-} = \begin{cases} 1.0 \\ 0.2 \end{cases}$
Neutralizer (f_n)	See Fig. 4
Plasma (f_w, f_T)	See Fig. 5
Energy recovery system	$\eta_{T1} = \eta_{T2} = \eta_{T3} = \eta_{T4} = 0.25$ $\eta_{T5} = \eta_{T6} = \eta_{T7} = 0.45$ $\eta_{D1} = 0.9$ $\eta_{D2} = 0.7$

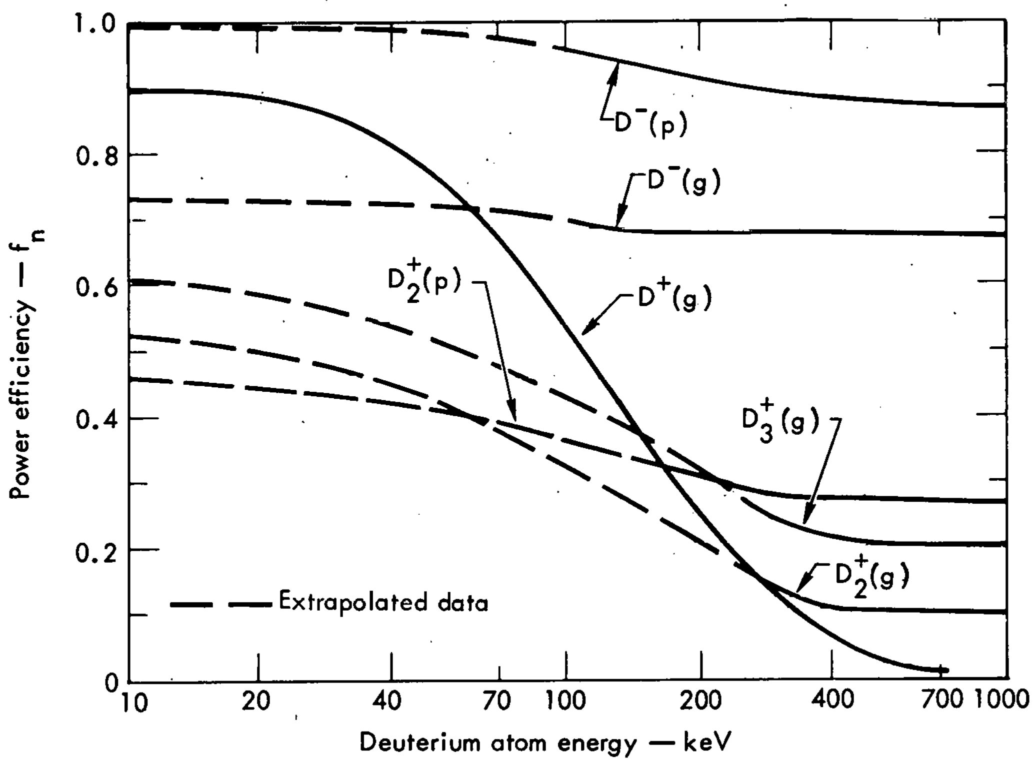

Fig. 4. Neutralizer power efficiency as a function of deuterium atom energy From Refs. 2 and 3.

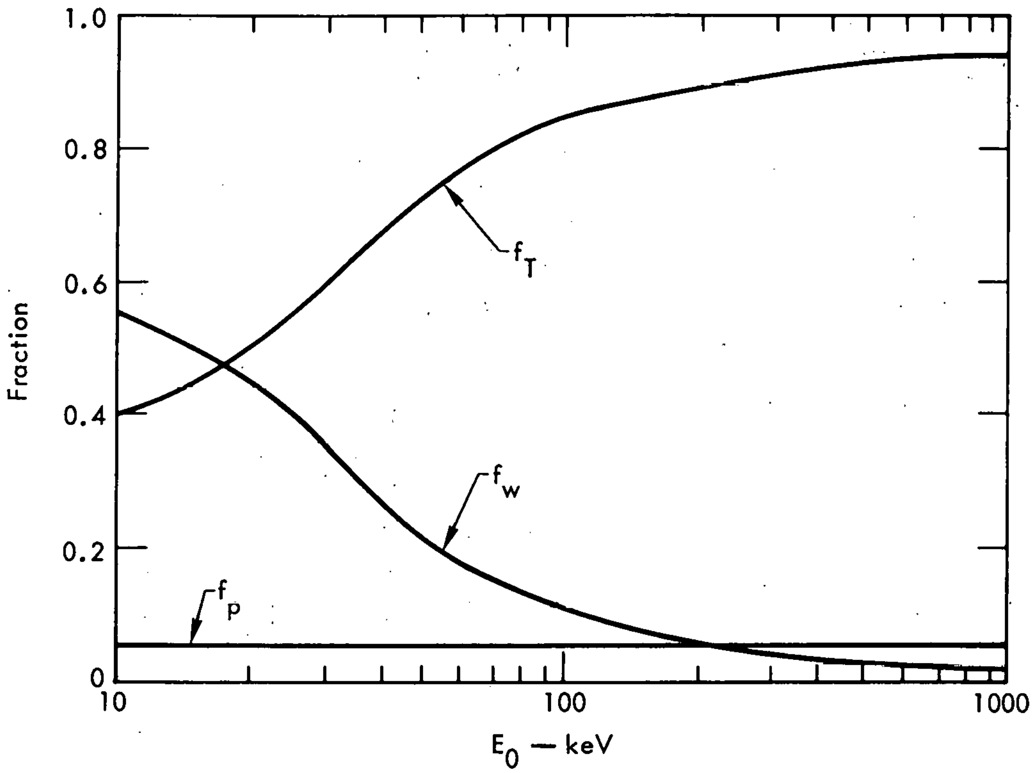

Fig. 5. Fraction of injected deuterium beam that is trapped (f_T), penetrates the plasma (f_p), and charge-exchanges without reionization (f_w) as a function of the injected deuterium atom energy for a mirror reactor with

$$\lambda \equiv \frac{\langle\sigma v\rangle_T \, nD}{v_o} = 3.$$

Figure 6 shows the overall efficiency of a deuterium atom injection system as a function of the injected deuterium atom energy for a variety of deuterium ion types. The circulating power and circulating current of the injection system are shown in Figs. 7 and 8, respectively. Since the use of D^+ gives high efficiencies at low injection energies and D^- gives high efficiencies at high injection energies, we will use these ions for the remainder of this discussion.

EFFECT OF PERTURBATIONS OF THE PLASMA PARAMETERS ON NEUTRAL BEAM TRAPPING IN THE REACTOR PLASMA

A fraction of the neutral beam that enters the reactor plasma is trapped in the plasma. The remainder of the neutral beam either penetrates through the plasma or charge-exchanges with the plasma ions without undergoing a reionizing collision before escaping to the reactor first wall. Thus

$$f_T + f_p + f_w = 1, \tag{7}$$

where f_p is the fraction of the neutral beam that penetrates through the plasma.

Riviere[4] has estimated the fraction of the neutral beam that penetrates a reactor plasma as

$$f_p = \exp\left[-\int_0^D \frac{n\,\langle\sigma v\rangle_T}{v_o}\,dx\right] \tag{8}$$

for a beam diameter much less than the plasma diameter. D is the reactor plasma diameter, n is the reactor plasma density, v_o is the velocity of the injected atoms, and $\langle\sigma v\rangle_T$ is the total reaction rate coefficient for collisional processes. For $\langle\sigma v\rangle_T$ assumed constant, the integral can be replaced with $Dn\langle\sigma v\rangle_T/v_o$, where n is an averaged density.

Hunt[5] estimates the fraction of the injected beam striking the reactor first wall as the product of the fraction of the injected neutral

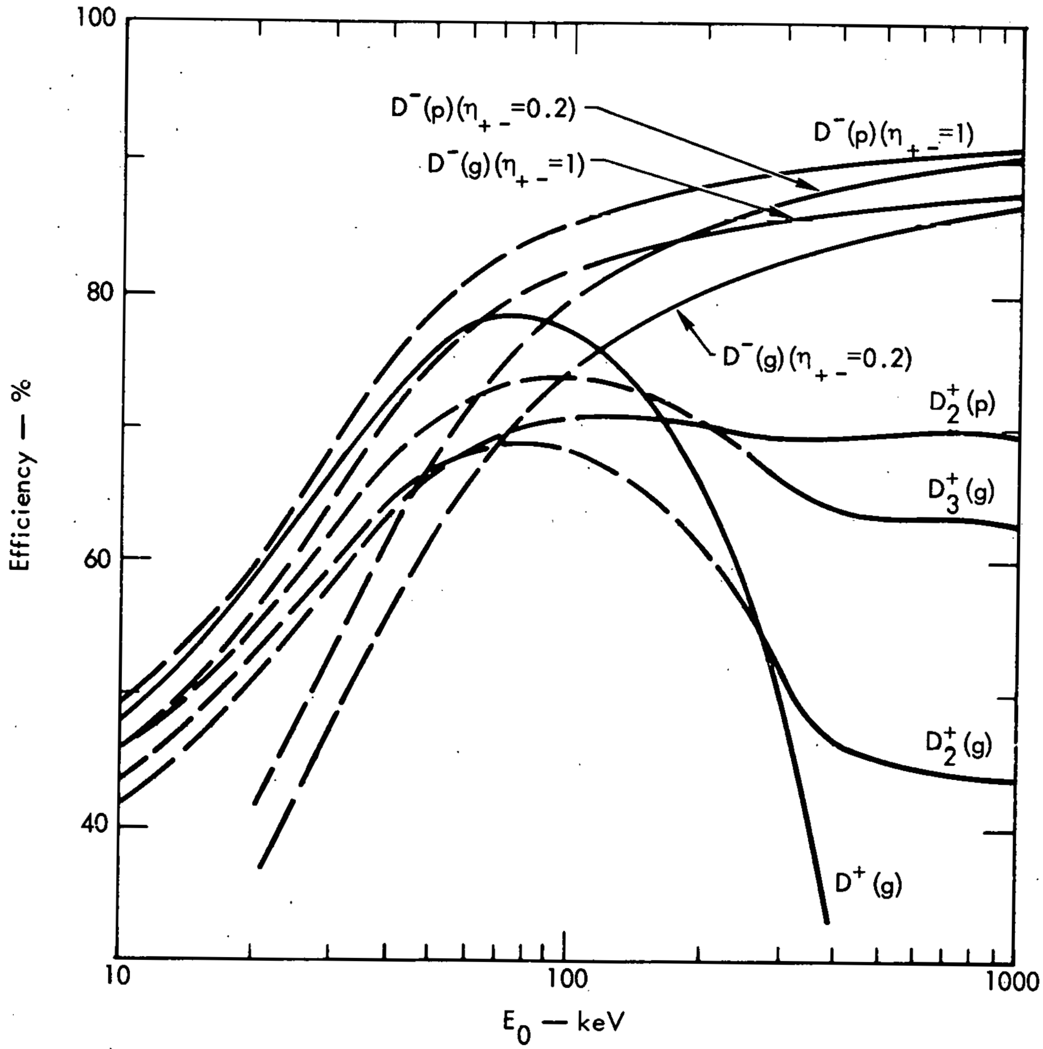

Fig. 6. Injection system efficiency as a function of injected deuterium atom energy with q = 0.5 keV, η_{Ti} = 0.25 (i = 1,2,3,4), η_{Ti} = 0.45 (i = 5,6,7), η_{D1} = 0.9, η_{D2} = 0.7, η_{a2} = 0.92. (For η_{+-} = 0.2, η_{a1} = 0.92, E^+ = 1.5 keV; for η_{+-} = 1, η_{a1} = η_{+-}, E^+ = 0).

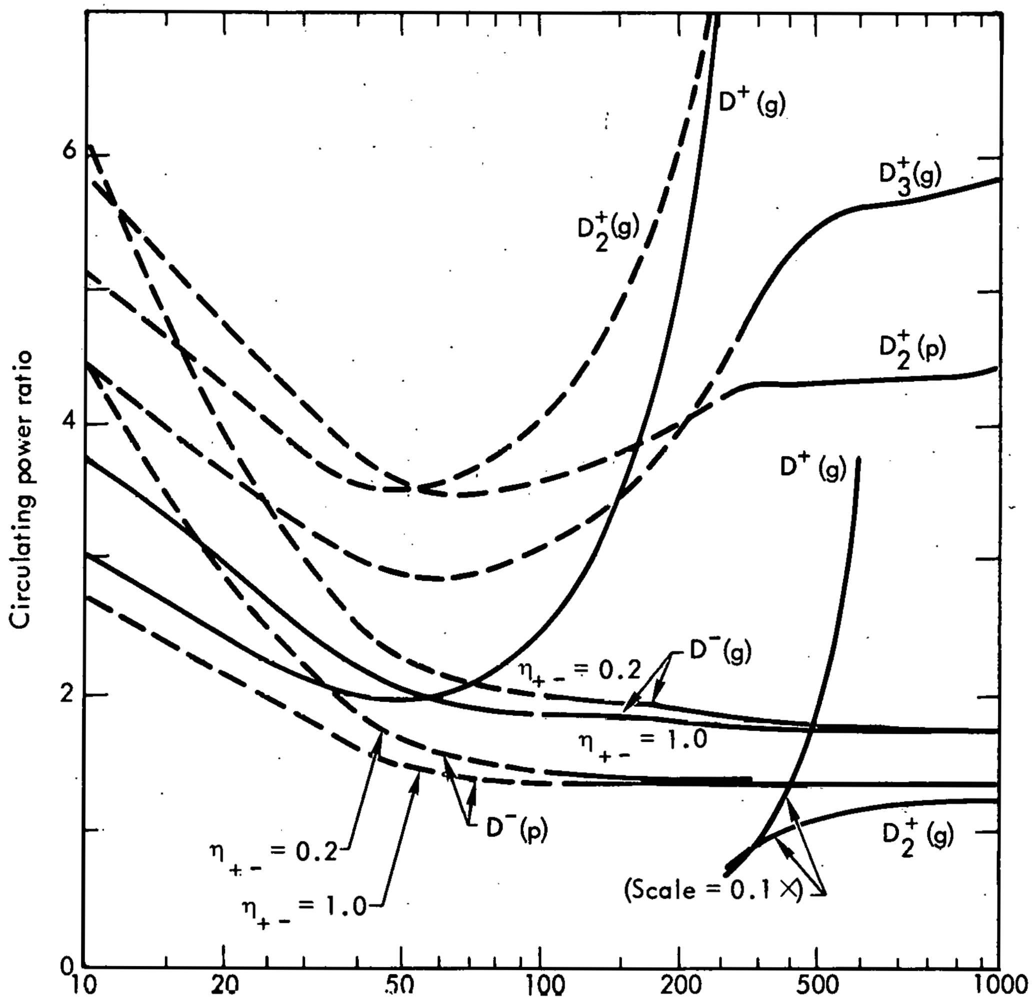

Fig. 7. Ratio of accelerator power to trapped power as a function of injected deuterium atom energy, η_{a2} = 0.92.

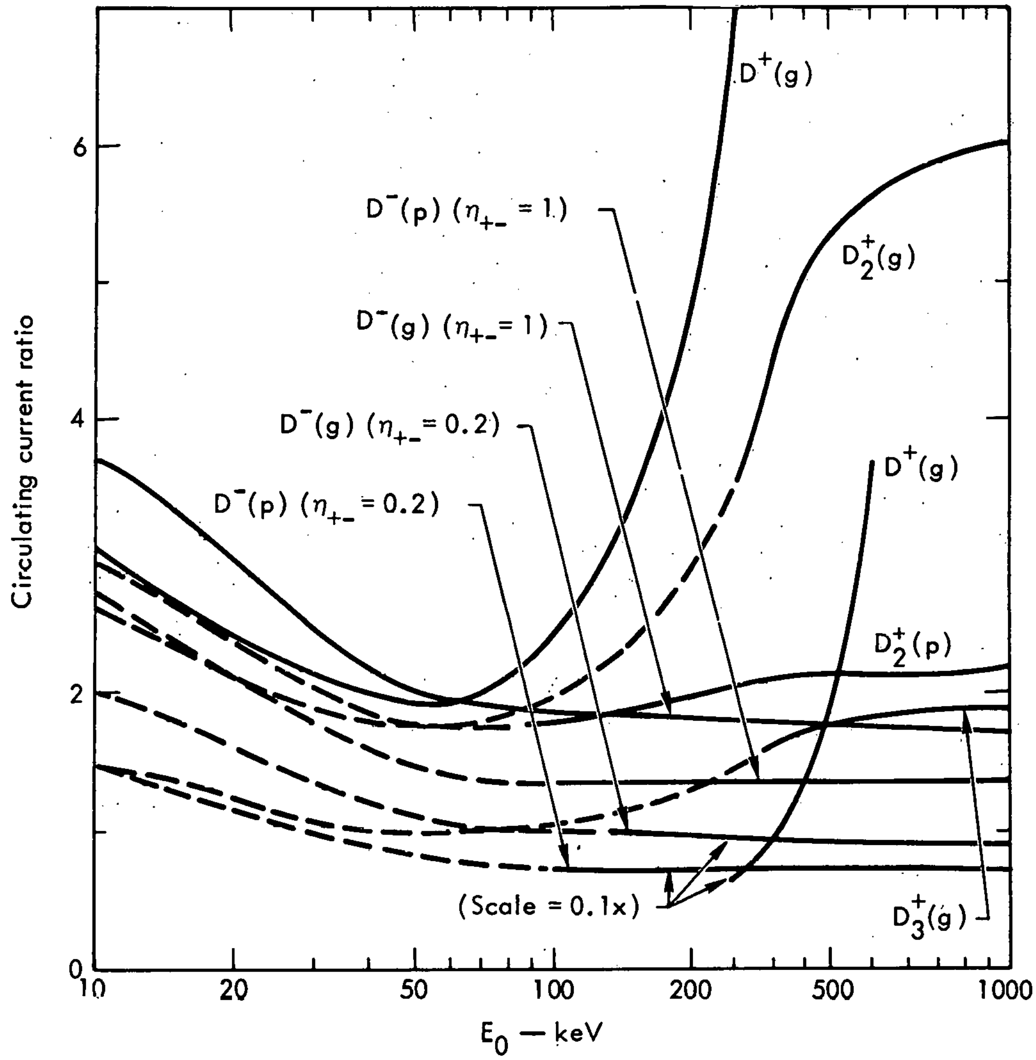

Fig. 8. Ratio of the source beam current to the trapped beam current as a function of the injected deuterium atom energy, $\eta_{a2} = 0.92$. (For $\eta_{+-} = 1$, $\eta_{a1} = \eta_{+-}$, $E^+ = 0$; for $\eta_{+-} = 0.2$, $\eta_{a1} = 0.92$, $E^+ = 1.5$ keV.)

beam that undergoes charge-exchange in the plasma and the probability that the neutrals formed by charge-exchange will not be reionized in the plasma. That is,

$$f_W = \left\{ \frac{<\sigma v>_{cx}}{<\sigma v>_T} \left[1 - \exp\left(- \frac{Dn<\sigma v>_T}{v_o} \right) \right] \right\} \exp\left[-\frac{1}{2} \left(\frac{Dn<\sigma v>_T}{v_o} \right) \left(\frac{<\sigma v>_i}{<\sigma v>_T} \right) \right], \tag{9}$$

where $<\sigma v>_{cx}$ is the total reaction rate coefficient for charge exchange, $<\sigma v>_i$ is the total reaction rate coefficient for ionization by both ions and electrons, and

$$<\sigma v>_T = <\sigma v>_i + <\sigma v>_{cx} .$$

Note the assumption that the randomly directed neutrals have an average path length equal to the radius of the reactor plasma.

Combining Eqs. (7)-(9) shows the fraction of the injected neutral beam that is trapped to be

$$f_T = \left[1 - \exp\left(- \frac{Dn<\sigma v>_T}{v_o} \right) \right] \left\{ 1 - \frac{<\sigma v>_{cx}}{<\sigma v>_T} \exp\left[-\frac{1}{2} \left(\frac{Dn<\sigma v>_T}{v_o} \right) \left(\frac{<\sigma v>_i}{<\sigma v>_T} \right) \right] \right\}. \tag{10}$$

Perturbing the beam balance, from Eq. (7),

$$\frac{\delta f_T}{f_T} = - \left[\frac{f_p}{f_T} \cdot \frac{\delta f_p}{f_p} + \frac{f_w}{f_T} \cdot \frac{\delta f_w}{f_w} \right]. \tag{11}$$

For an invariant fraction of the beam penetrating the plasma such that

$$\frac{\delta f_p}{f_p} = 0,$$

then

$$\frac{\delta f_T}{f_T} = - \frac{f_w}{f_T} \cdot \frac{\delta f_w}{f_w} . \tag{11a}$$

Rewriting Eqs. (8) and (9) as

$$f_p = \exp(-\gamma) \tag{8a}$$

$$f_w = \frac{\langle\sigma v\rangle_{cx}}{\langle\sigma v\rangle_T} \left[1 - \exp(-\gamma)\right] \exp\left[-\frac{1}{2} \gamma \frac{\langle\sigma v\rangle_i}{\langle\sigma v\rangle_T} \right], \tag{9a}$$

where

$$\gamma \equiv \frac{Dn\langle\sigma v\rangle_T}{v_o} \tag{12}$$

then

$$\frac{\delta f_p}{f_p} = -\gamma \frac{\delta\gamma}{\gamma} \tag{13}$$

and

$$\frac{\delta f_w}{f_w} = \left\{ \frac{\langle\sigma v\rangle_{cx}}{\langle\sigma v\rangle_T} \frac{\gamma}{f_w} \exp\left[-\gamma\left(1 + \frac{\langle\sigma v\rangle_i}{\langle\sigma v\rangle_T}\right)\right] - \frac{1}{2} \frac{\gamma \langle\sigma v\rangle_i}{\langle\sigma v\rangle_T} \right\} \frac{\delta\gamma}{\gamma}$$

$$+ \left[1 - \frac{\langle\sigma v\rangle_{cx}}{\langle\sigma v\rangle_T} \left(1 - \frac{1}{2} \frac{\gamma \langle\sigma v\rangle_i}{\langle\sigma v\rangle_T}\right)\right] \frac{\delta \langle\sigma v\rangle_{cx}}{\langle\sigma v\rangle_{cx}} - \frac{\langle\sigma v\rangle_i}{\langle\sigma v\rangle_T}$$

$$\times \left[\frac{1}{2}\gamma - \left(1 - \frac{1}{2} \frac{\gamma \langle\sigma v\rangle_i}{\langle\sigma v\rangle_T}\right)\right] \frac{\delta \langle\sigma v\rangle_i}{\langle\sigma v\rangle_i} , \tag{14}$$

where

$$\frac{\delta\gamma}{\gamma} = \frac{\delta n}{n} + \frac{\delta D}{D} + \frac{\langle\sigma v\rangle_i}{\langle\sigma v\rangle_T} \frac{\delta \langle\sigma v\rangle_i}{\langle\sigma v\rangle_i} + \frac{\langle\sigma v\rangle_{cx}}{\langle\sigma v\rangle_T} \frac{\delta \langle\sigma v\rangle_{cx}}{\langle\sigma v\rangle_{cx}} . \tag{15}$$

Combining Eqs. (8) through (15) gives the perturbation of the trapping fraction for perturbations in the plasma parameters.

The perturbations of the fraction of the randomly directed neutrals to the wall are of the same sign as a perturbation in the charge-exchange rate coefficient, but of the opposite sign as perturbations in the other plasma parameters for deuterium atoms between 10 keV and 1000 keV. The perturbations of the trapping fraction are of the opposite sign as a perturbation in the charge-exchange rate coefficient, but of the same sign as perturbations of the other plasma parameters.

Figure 9 shows the perturbation of the trapping fraction and the unreionized charge-exchange particles striking the first wall as a function of deuterium atom energy for the plasma with $\gamma = 3$, using Riviere's[4] summary of reaction rate parameters for a mirror reactor shown in Fig. 10. The unperturbed trapping fraction and the fraction of the unreionized charge-exchange particles striking the first wall are shown in Fig. 5.

EFFECT OF PERTURBATIONS OF THE INJECTION SYSTEM COMPONENT PERFORMANCES ON THE OVERALL INJECTION SYSTEM PERFORMANCE

Consider a fixed mass ratio of source ion to injected atom and a fixed energy of the source ion into the alkali metal vapor cell. The perturbation of the injector efficiency for a fixed injection energy as a function of the perturbations of the injection system component efficiencies is given by

$$\frac{\delta\eta}{\eta} = A\,\frac{\delta q}{q} + B\,\frac{\delta\eta_{a1}}{\eta_{a1}} + C\,\frac{\delta\eta_{+-}}{\eta_{+-}} + D\,\frac{\delta\eta_{a2}}{\eta_{a2}} + E\,\frac{\delta f_n}{f_n} + F\,\frac{\delta f_T}{f_T}$$

$$+ G\,\frac{\delta f_w}{f_w} + H\,\frac{\delta\eta_{T1}}{\eta_{T1}} + K\,\frac{\delta\eta_{T2}}{\eta_{T2}} + N\,\frac{\delta\eta_{T3}}{\eta_{T3}}$$

$$+ P\,\frac{\delta\eta_{T4}}{\eta_{T4}} + R\,\frac{\delta\eta_{T5}}{\eta_{T5}} + S\,\frac{\delta\eta_{T6}}{\eta_{T6}} + U\,\frac{\delta\eta_{T7}}{\eta_{T7}} + W\,\frac{\delta\eta_{D1}}{\eta_{D1}} + Y\,\frac{\delta\eta_{D2}}{\eta_{D2}}, \qquad (16)$$

where

$$A = -\frac{q}{\Phi\,\eta_{a1}\,\eta_{+-}\,ME}\,(1 - \eta_{T1})$$

$$B = -A + \frac{E^{+}}{\Phi ME}\left(\frac{1 - \eta_{T2}}{\eta_{a1}\eta_{+-}}\right)$$

$$C = B + \frac{E^{+}}{\Phi ME}\left(\frac{\eta_{T2} - \eta_{T3}}{\eta_{+-}}\right)$$

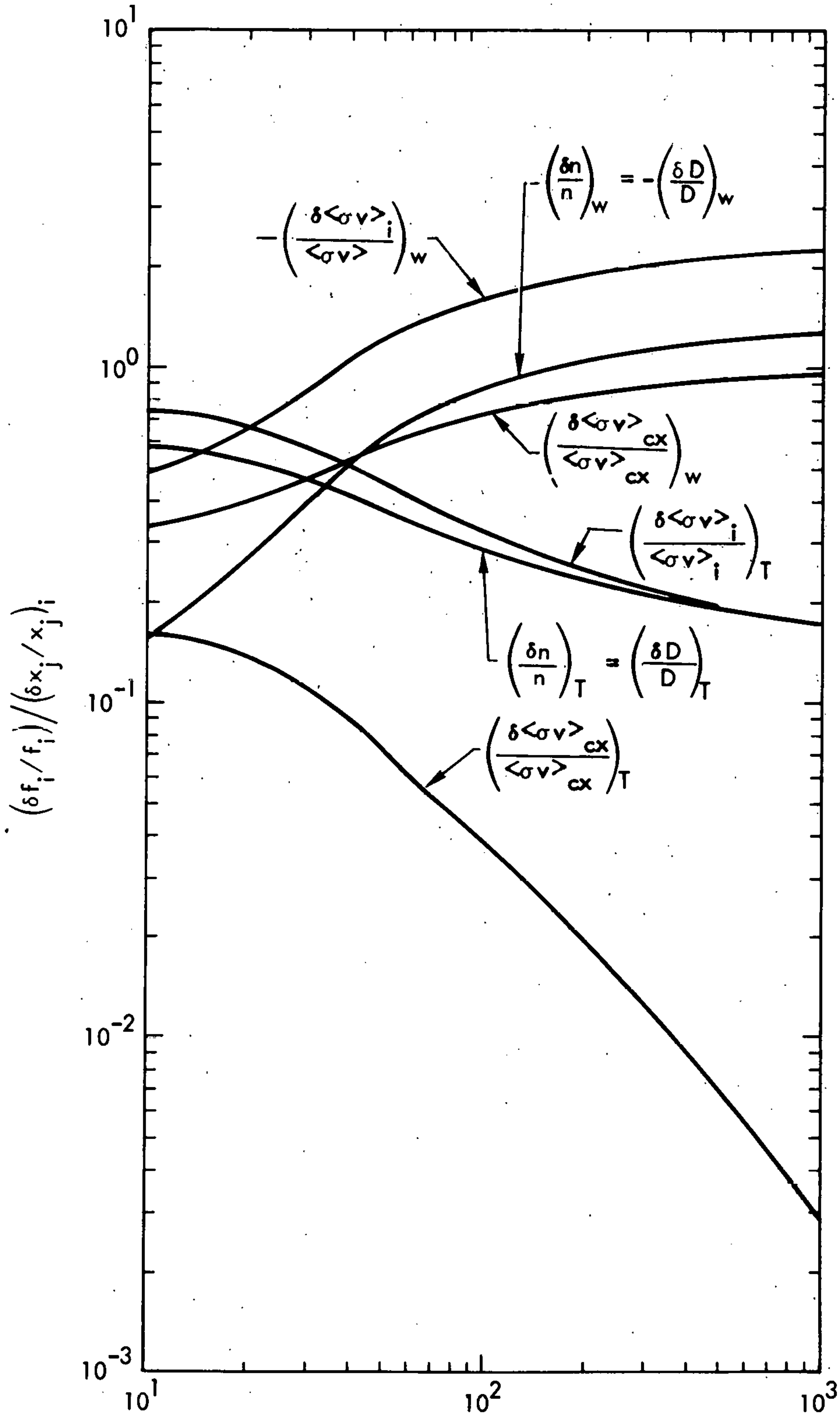

Fig. 9. Normalized rate of change of the trapping fraction (i = T) and wall loading (i = w) to various plasma parameters as a function of the injected deuterium atom energy,

$$\lambda \equiv \frac{Dn\langle\sigma v\rangle_T}{v_o} = 3.$$

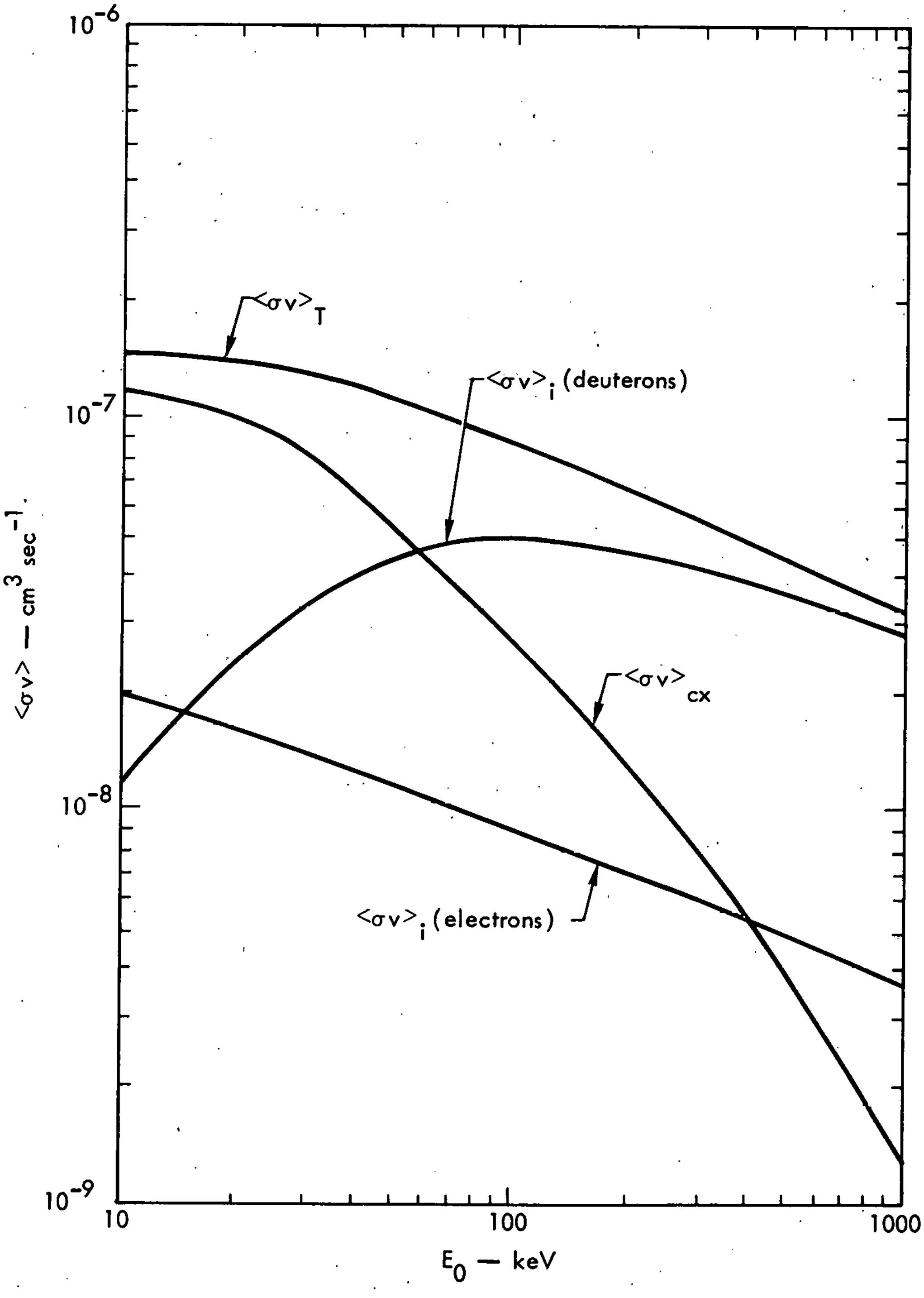

Fig. 10. Summary of reaction rate coefficients for a deuterium atom beam with energy E_0 entering a mirror reactor plasma with electron temperature = $E_0/7$, mirror ratio = 3, and rejection of forward scattered neutrals from charge exchange within a cone semi-angle = 0.2.

$$D = 1 + \left(\frac{E^+}{ME} - 1\right) \frac{\eta_{a2}\eta_{T4}}{\Phi} + \frac{\eta_{a2}}{\Phi} \left\{(1 - f_n) P_{rn}\right.$$

$$\left. + f_n \left[(1 - f_T - f_w) P_{rp} + f_w \eta_{T6}\right]\right\}$$

$$E = 1 + \frac{\eta_{a2} f_n}{\Phi} \left[f_w \eta_{T6} + (1 - f_T - f_w) P_{rp} - P_{rn}\right]$$

$$F = 1 - \frac{\eta_{a2} f_T f_n}{\Phi} P_{rp}$$

$$G = - \frac{\eta_{a2} f_w f_n}{\Phi} [P_{rp} - \eta_{T6}]$$

$$H = \frac{q \eta_{T1}}{\Phi \eta_{a1}\eta_{+-} ME}$$

$$K = \frac{E^+}{\Phi ME} \left(\frac{1 - \eta_{a1}}{\eta_{a1}}\right) \frac{\eta_{T2}}{\eta_{+-}}$$

$$N = \frac{E^+}{\Phi ME} \left(\frac{1 - \eta_{+-}}{\eta_{+-}}\right) \eta_{T3}$$

$$P = -\left(\frac{E^+}{ME} - 1\right) \frac{(1 - \eta_{a2})}{\Phi} \eta_{T4}$$

$$R = \frac{\eta_{a2}\left(1 - f_n\right)\left(1 - \eta_{D1}\right)\eta_{T5}}{\Phi}$$

$$S = \frac{\eta_{a2} f_n f_w \eta_{T6}}{\Phi}$$

$$U = \frac{\eta_{a2} f_n (1 - f_T - f_w)(1 - \eta_{D2}) \eta_{T7}}{\Phi}$$

$$W = \frac{\eta_{a2}\eta_{D1} (1 - f_n)(1 - \eta_{T5})}{\Phi}$$

$$Y = \frac{\eta_{a2}\eta_{D2} f_n (1 - f_T - f_w)(1 - \eta_{T7})}{\Phi},$$

where

$$P_{rn} = \eta_{D1} + (1 - \eta_{D1}) \eta_{T5}$$

$P_{rp} = \eta_{D2} + (1 - \eta_{D2})\, \eta_{T7}$

Φ is denominator of Eq. (1).

For ions produced directly from the source,

$$\frac{\delta\eta}{\eta} = A\,\frac{\delta q}{q} + D\,\frac{\delta\eta_{a2}}{\eta_{a2}} + E\,\frac{\delta f_n}{f_n} + F\,\frac{\delta f_T}{f_T} + G\,\frac{\delta f_w}{f_w} + H\,\frac{\delta\eta_{T1}}{\eta_{T1}} + P\,\frac{\delta\eta_{T4}}{\eta_{T4}} + R\,\frac{\delta\eta_{T5}}{\eta_{T5}} + S\,\frac{\delta\eta_{T6}}{\eta_{T6}} + U\,\frac{\delta\eta_{T7}}{\eta_{T7}} + W\,\frac{\delta\eta_{D1}}{\eta_{D1}} + Y\,\frac{\delta\eta_{D2}}{\eta_{D2}}\,, \qquad (17)$$

with $\eta_{+-} = \eta_{a1} = 1$, $E^+ = 0$, and Φ is the denominator of Eq. (2).

From Eq. (11a) for an invariant fraction of the beam penetrating through the plasma

$$\frac{\delta f_T}{f_T} = -\frac{f_w}{f_T} \cdot \frac{\delta f_w}{f_w}\,. \qquad (18)$$

Thus, in Eqs. (16) and (17) the term

$$F\,\frac{\delta f_T}{f_T} + G\,\frac{\delta f_w}{f_w} = \left[F - \frac{f_T}{f_w}\,G\right] \frac{\delta f_T}{f_T} \qquad (19)$$

can be used for the case where an invariant fraction of the beam penetrates through the plasma.

From Eq. (3), the fractional charge in the circulating power is

$$\frac{\delta\left(\frac{P_{acc}}{P_T}\right)}{\left(\frac{P_{acc}}{P_T}\right)} = -\left[\frac{\delta\eta_{a2}}{\eta_{a2}} + \frac{\delta f_n}{f_n} + \frac{\delta f_T}{f_T} + \frac{\frac{E^+}{ME}\left(\frac{1}{\eta_{a1}\eta_{+-}}\right)}{1 + \frac{E^+}{ME}\left(\frac{1 - \eta_{a1}\eta_{+-}}{\eta_{a1}\eta_{+-}}\right)} \left(\frac{\delta\eta_{+-}}{\eta_{+-}} + \frac{\delta\eta_{a1}}{\eta_{a1}}\right)\right]. \qquad (20)$$

For large injection energies such that $E \gg E^+$, perturbations in the efficiencies of the accelerator a1 and the alkali metal vapor cell do not have as much leverage on change in the circulating power as perturbations in the efficiency of the accelerator a2 or the fraction of the beam neutralized or trapped. For the case where the injection system uses ions directly from the source,

$$\frac{\delta\frac{P_{acc}}{P_T}}{\frac{P_{acc}}{P_T}} = -\left[\frac{\delta\eta_{a2}}{\eta_{a2}} + \frac{\delta f_n}{f_n} + \frac{\delta f_T}{f_T}\right], \tag{21}$$

so that perturbations in the component performances have equal leverage on the change of the injection system circulating power.

From Eq. (5), the fractional change in the circulating current is

$$\frac{\delta\frac{I_{source}}{I_{trapped}}}{\frac{I_{source}}{I_{trapped}}} = -\left[\frac{\delta\eta_{a1}}{\eta_{a1}} + \frac{\delta\eta_{+-}}{\eta_{+-}} + \frac{\delta\eta_{a2}}{\eta_{a2}} + \frac{\delta f_n}{f_n} + \frac{\delta f_T}{f_T}\right]. \tag{22}$$

Perturbations in the component performances have equal leverage on the change of the circulating current.

The effects of perturbations of the various component performance on the injection system efficiency are shown in Figs. 11-22 as a function of injected deuterium atom energy for systems using D^+ and D^- ions. The results are normalized so that each of the figures represents a plot of the alphabetic constant of a term in Eq. (16). Figure 23 shows the effects of a perturbation of the trapping fraction on the wall loading fraction for a fixed fraction of the beam penetrating the plasma.

Figure 24 shows the effects of perturbations in the performance of various components on the efficiency of an injector system using D^+. Figures 25 and 26 show the effects of perturbations in the performance of various components on the efficiency of an injector system using D^- with $\eta_{+-} = 0.2$ and $\eta_{+-} = 1.0$, respectively. The effects on the efficiency of an injector system of perturbations in the performance of various components are not shown in Figs. 24-26 for effects <1%.

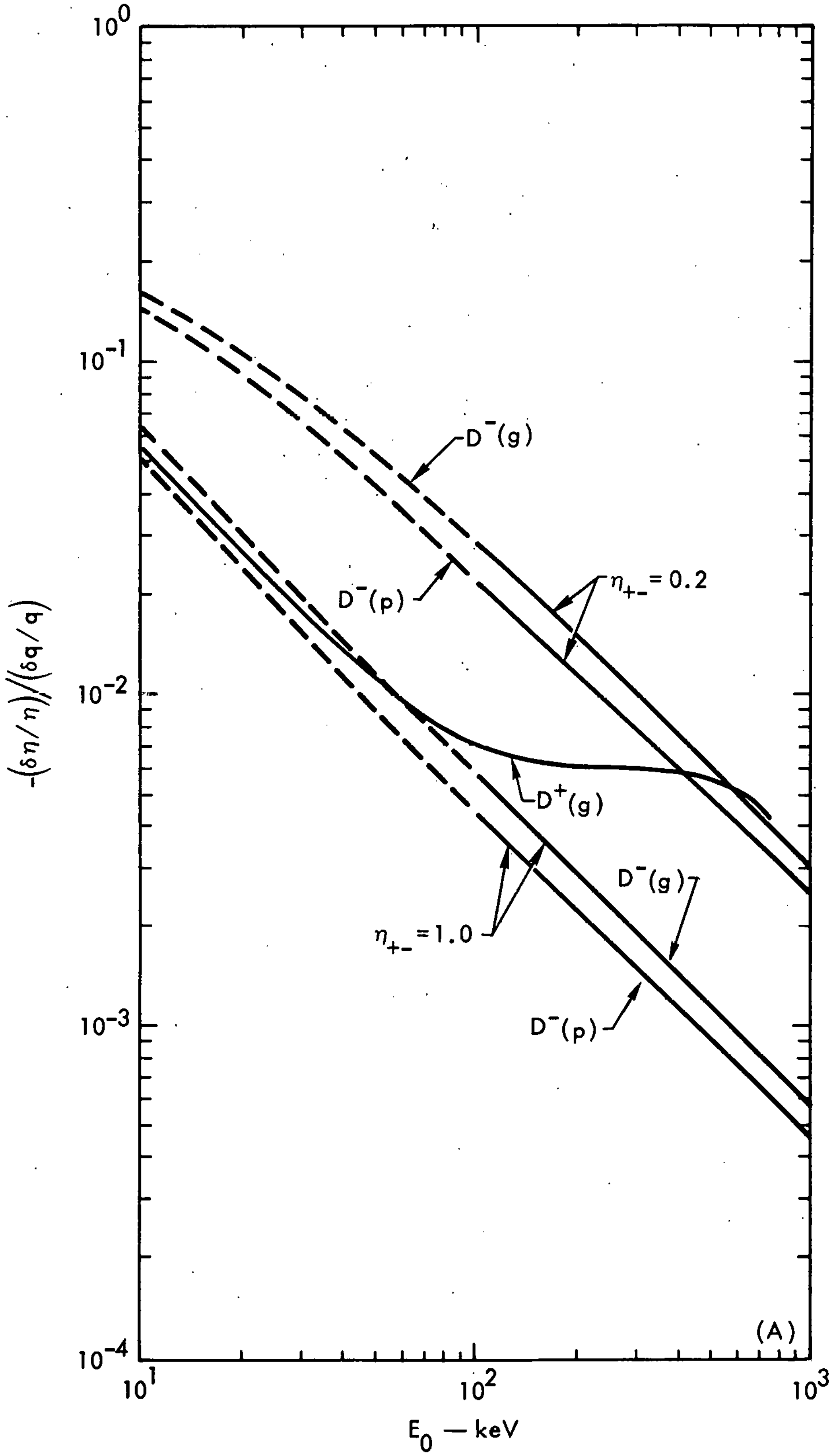

Fig. 11. Normalized rate of change of the injector system efficiency to the source energy required to produce an ion as a function of the injected deuterium atom energy, q = 500 eV/ion.

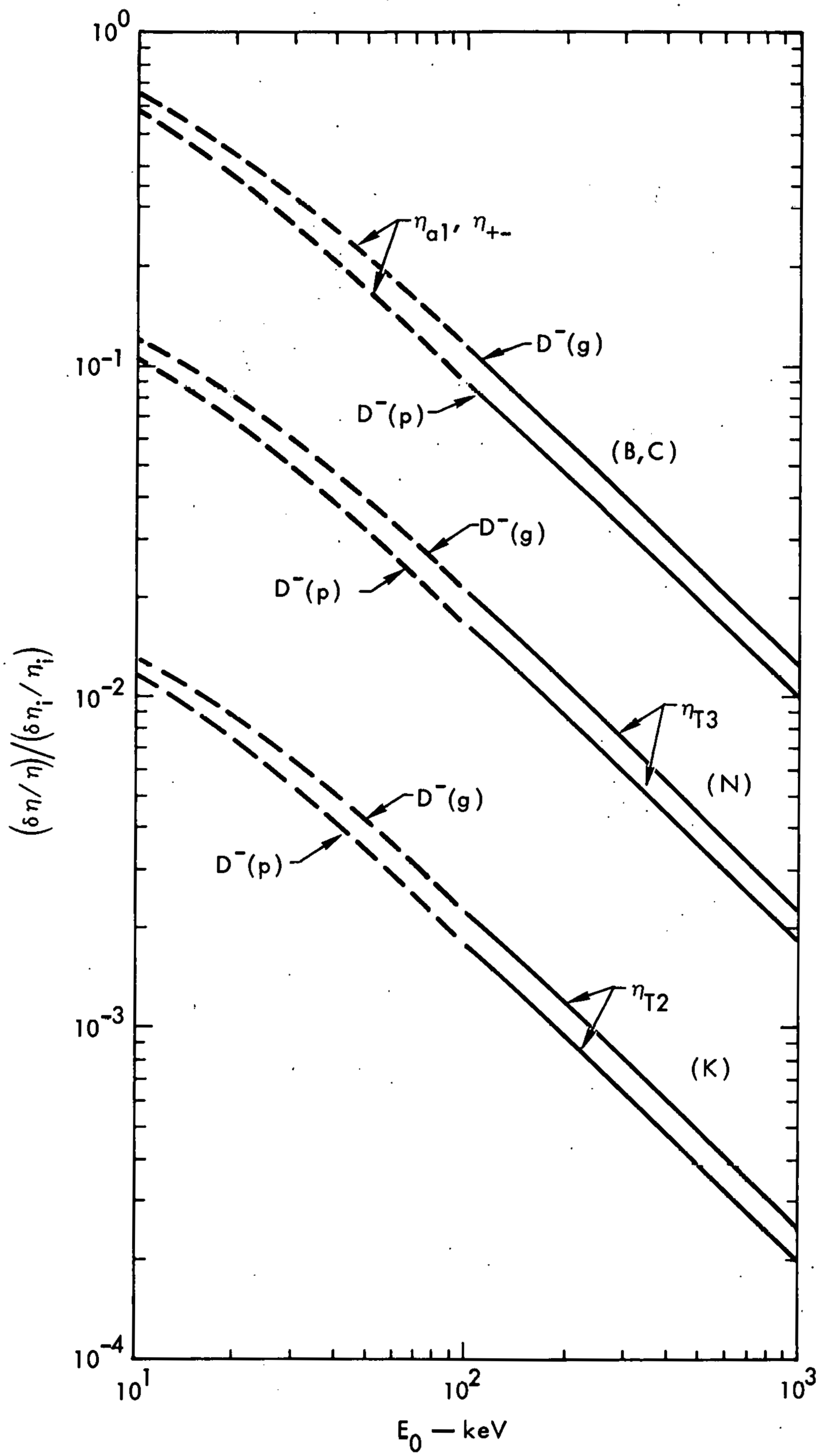

Fig. 12. Normalized rate of change of the injector system efficiency to various component efficiencies as a function of the injected deuterium atom energy for negative ions produced in an alkali metal vapor cell, $\eta_{+-} = 0.2$, $\eta_{a1} = 0.92$, $\eta_{T2} = \eta_{T3} = 0.25$.

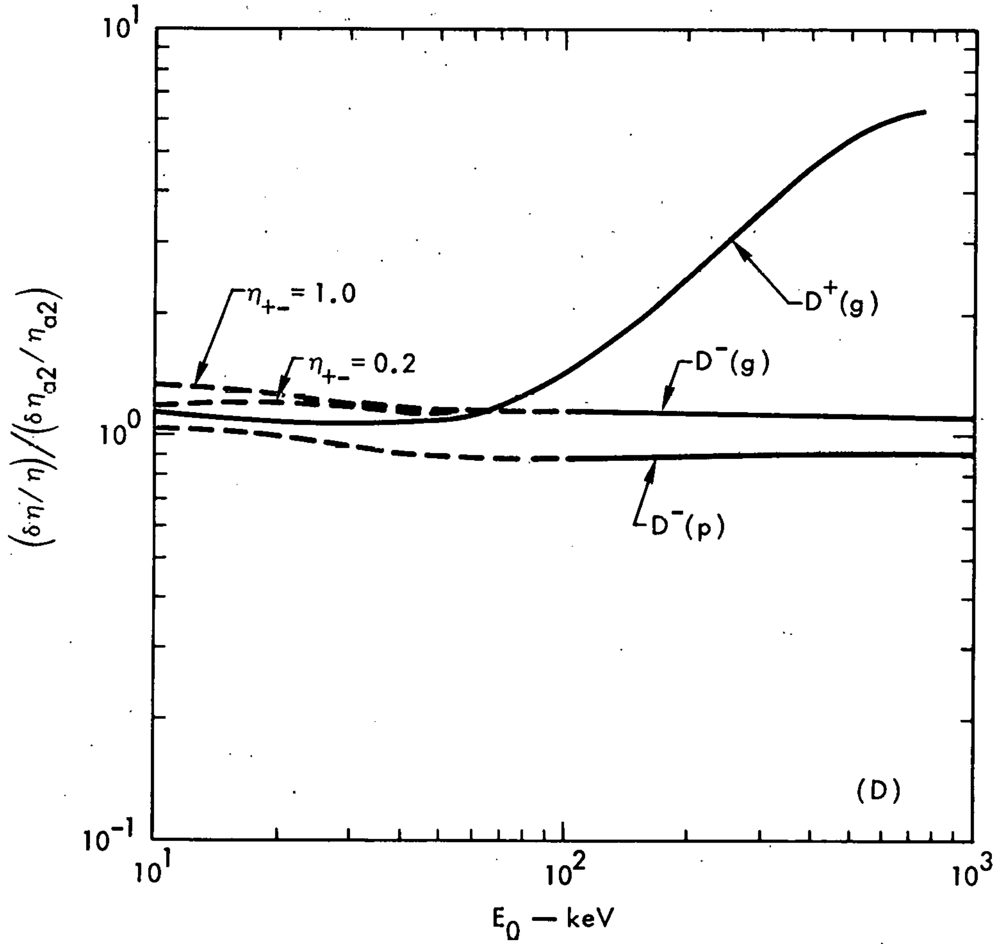

Fig. I3. Normalized rate of change of the injector system efficiency to the accelerator efficiency as a function of the injected deuterium atom energy, $\eta_{a2} = 0.92$.

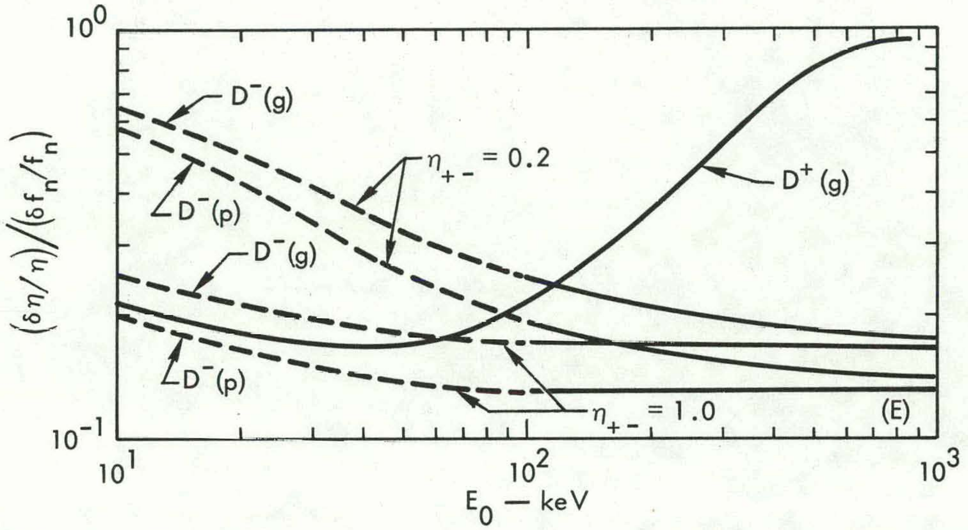

Fig. 14. Normalized rate of change of the injector system efficiency to the neutralizer power efficiency as a function of the injected deuterium atom energy.

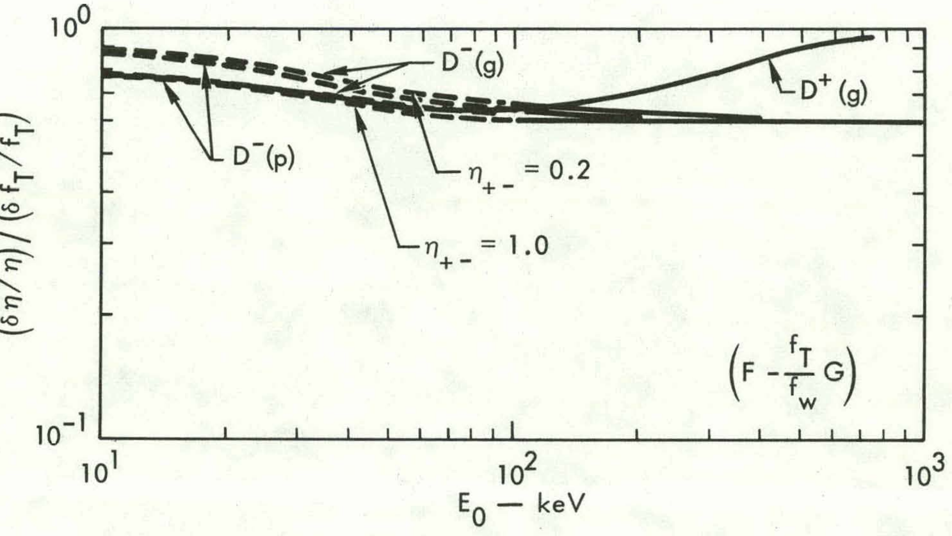

Fig. 15. Normalized rate of change of the injector system efficiency to the trapping fraction as a function of the injected deuterium atom energy for an invariant penetration fraction of 5%.

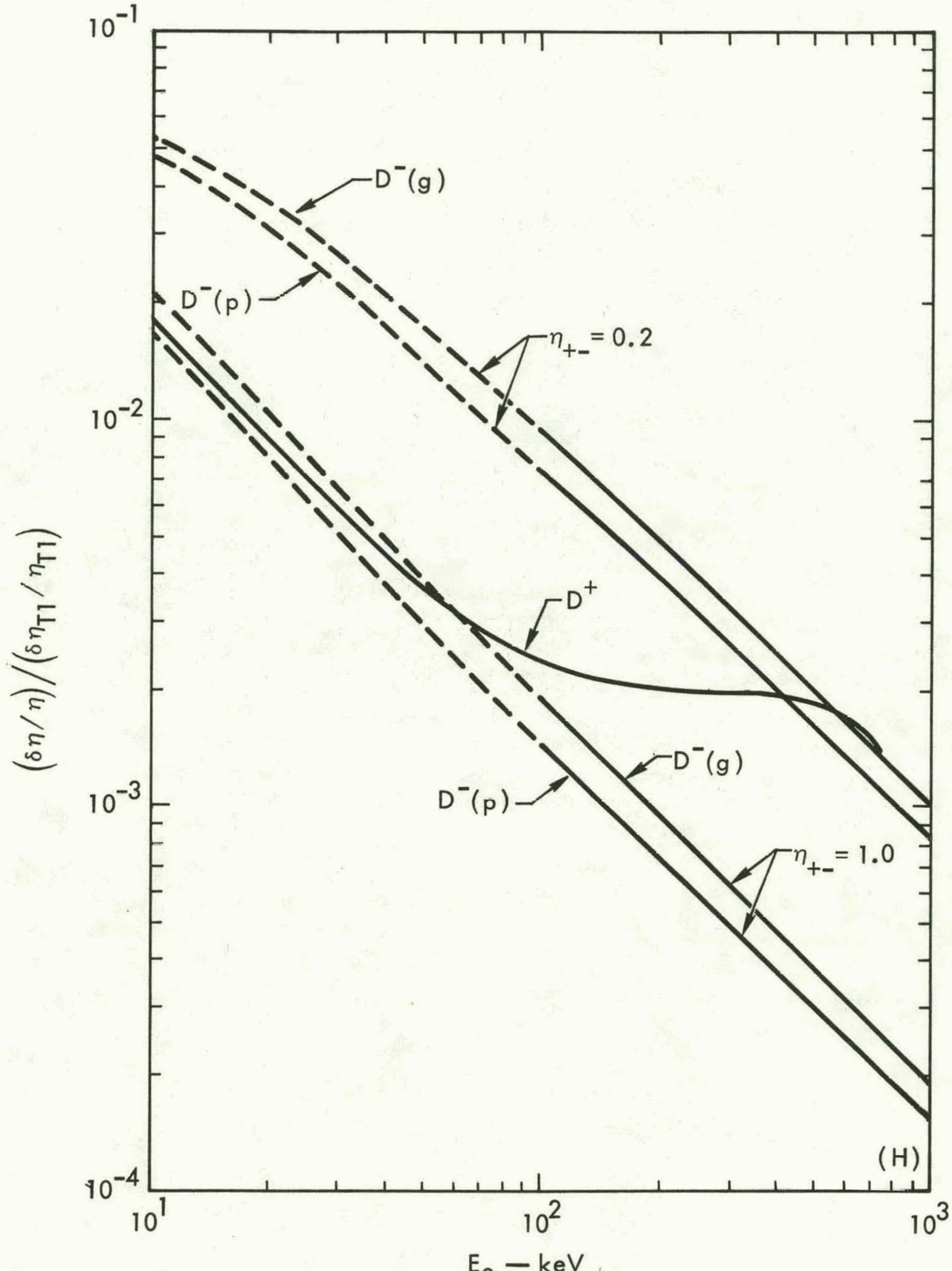

Fig. 16. Normalized rate of change of the injector system efficiency to the efficiency of the source-loss thermal converter as a function of the injected deuterium atom energy, $\eta_{T1} = 0.25$.

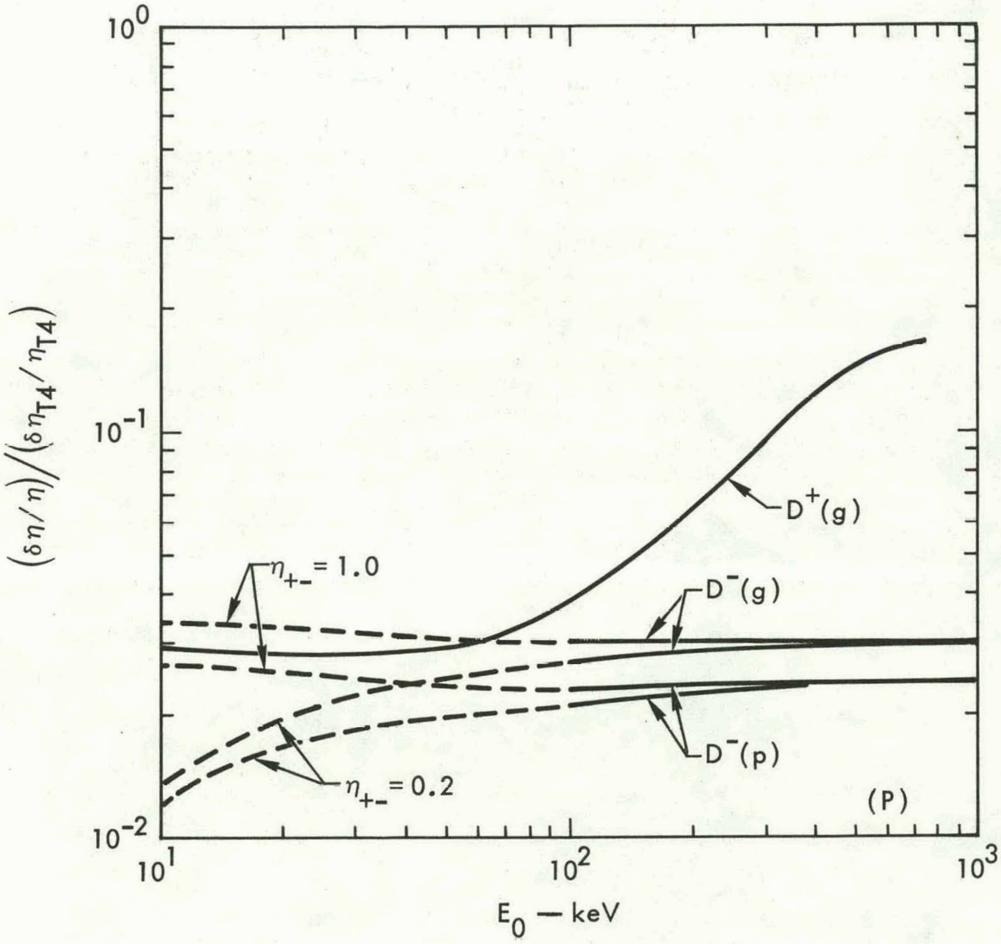

Fig. 17. Normalized rate of change of the injector system efficiency to the efficiency of the accelerator-loss thermal converter as a function of the injected deuterium atom energy, $\eta_{T4} = 0.25$.

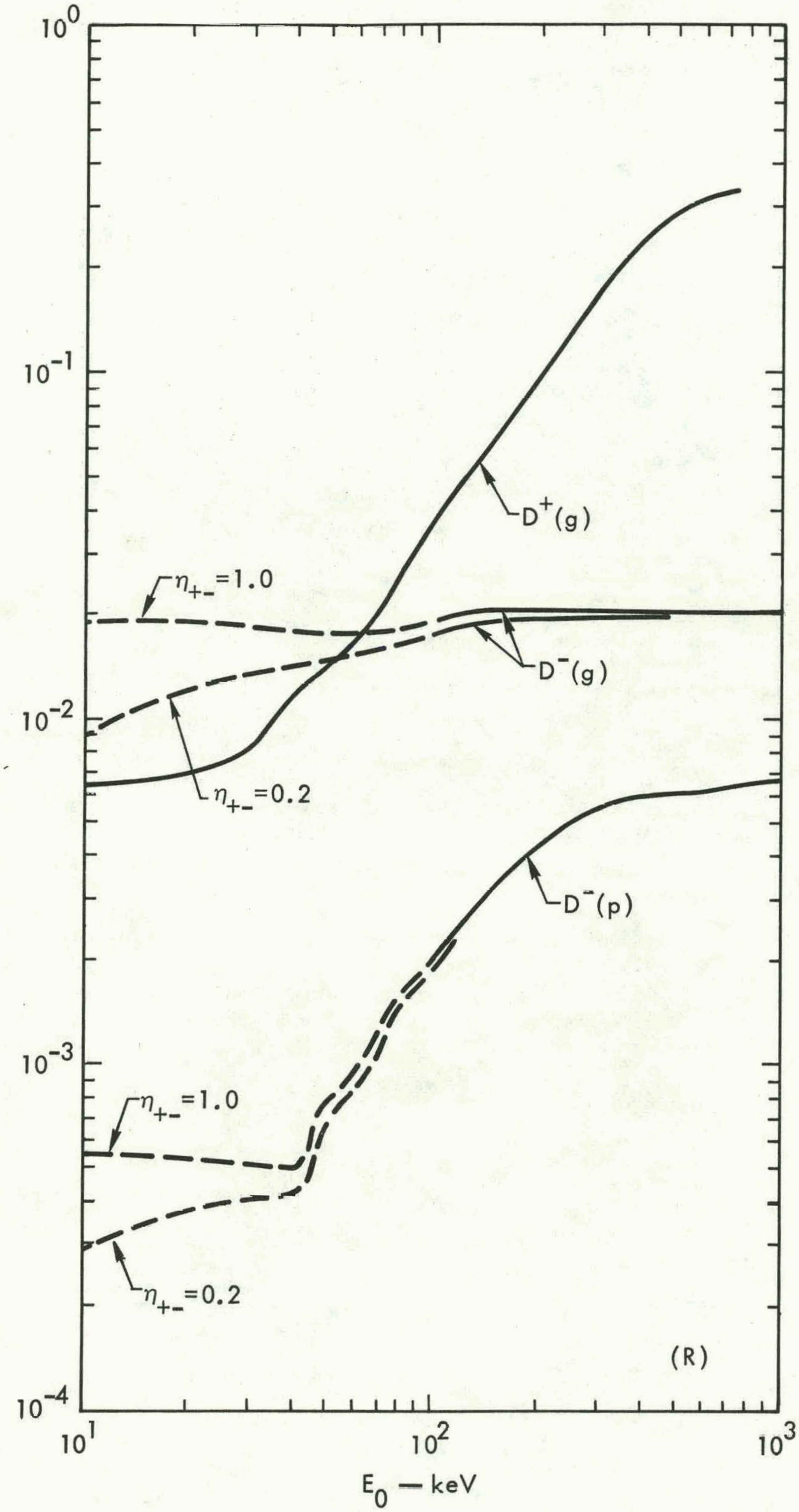

Fig. 18. Normalized rate of change of the injector system efficiency to the efficiency of the neutralizer-loss, direct-converter-loss thermal converter as a function of the injected deuterium atom energy, $\eta_{T5} = 0.45$.

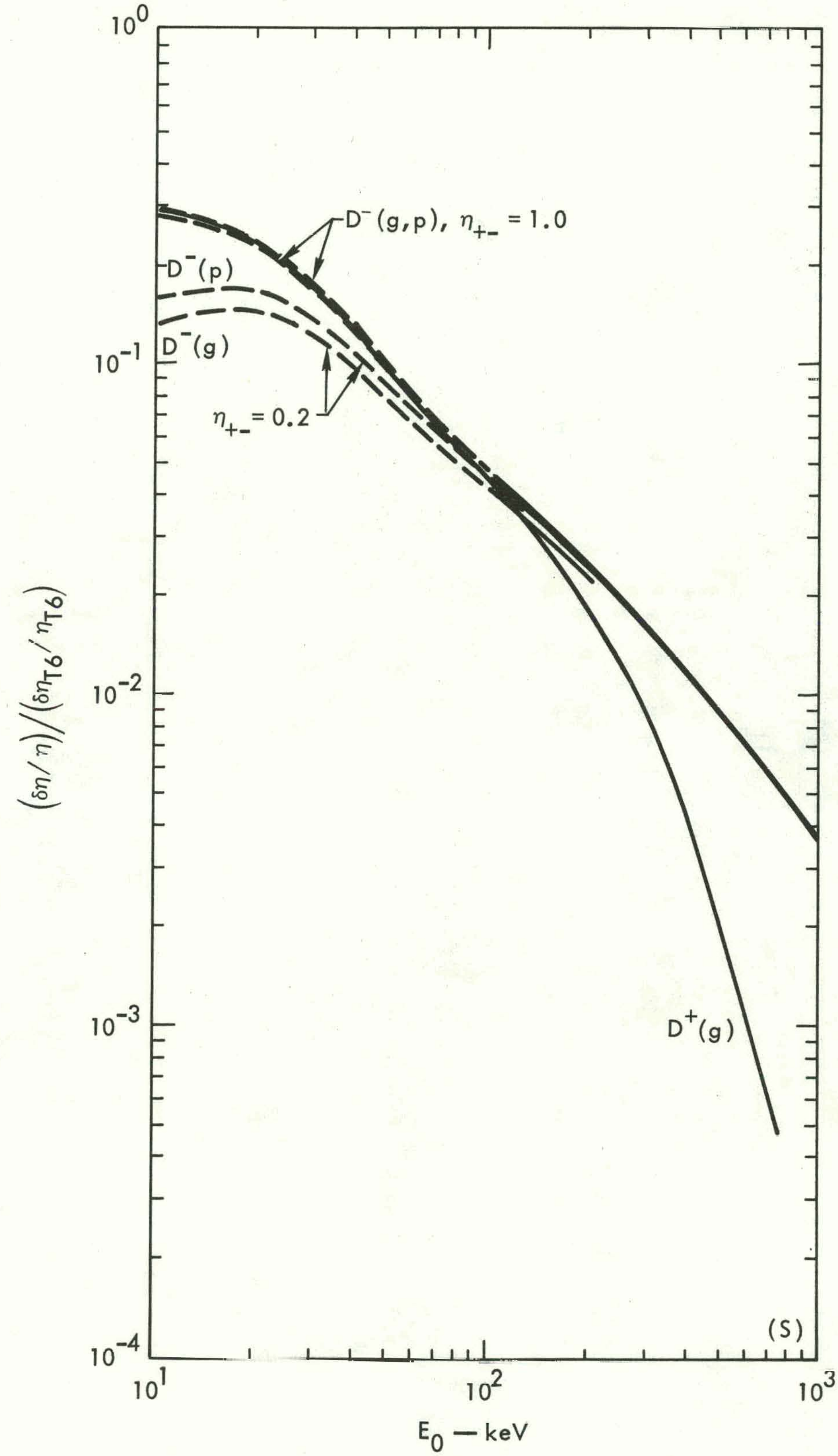

Fig. 19. Normalized rate of change of the injector system efficiency to the efficiency of the reactor thermal converter as a function of the injected deuterium atom energy, $\eta_{T6} = 0.45$.

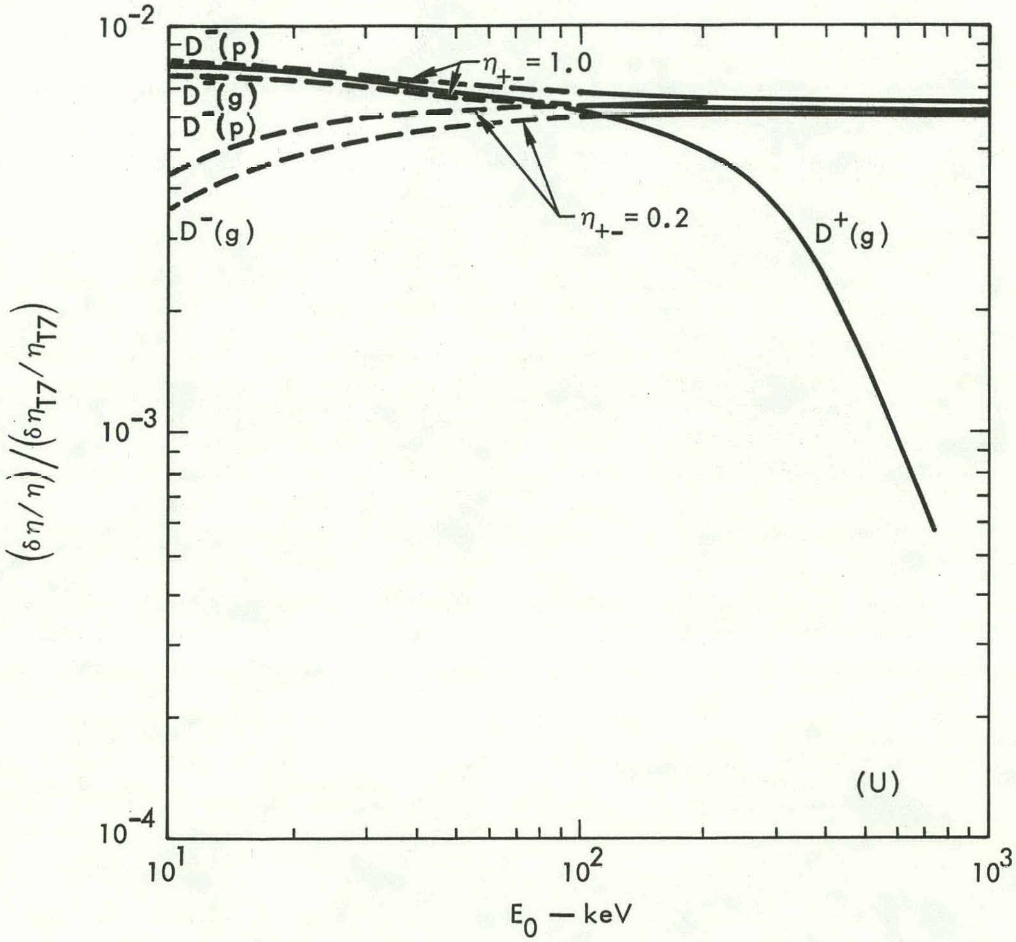

Fig. 20. Normalized rate of change of the injector system efficiency to the efficiency of the penetrating beam-direct-converter-loss thermal converter as a function of the injected deuterium atom energy $\eta_{T7} = 0.45$.

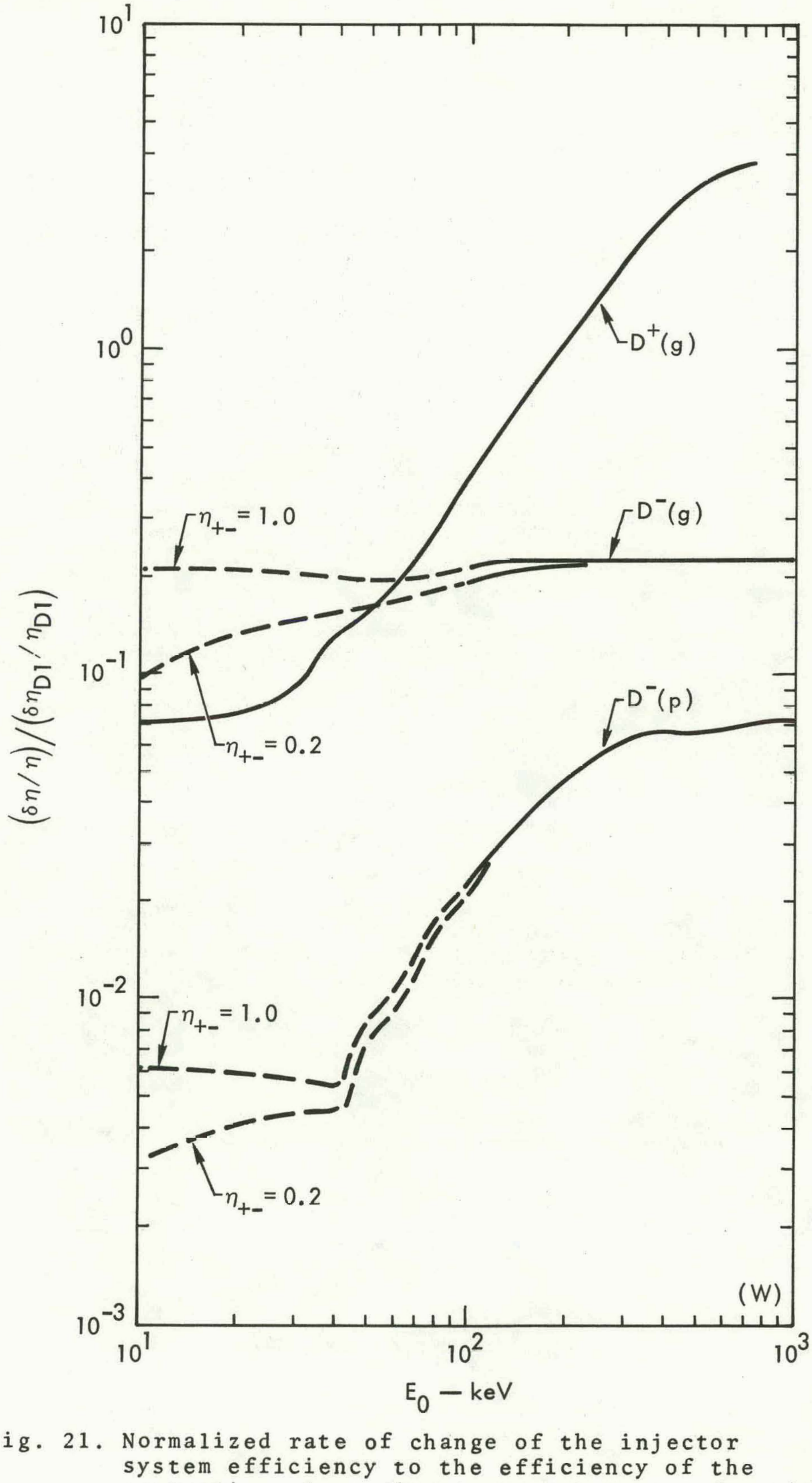

Fig. 21. Normalized rate of change of the injector system efficiency to the efficiency of the neutralizer-loss direct converter as a function of the injected deuterium atom energy, $\eta_{D1} = 0.9$.

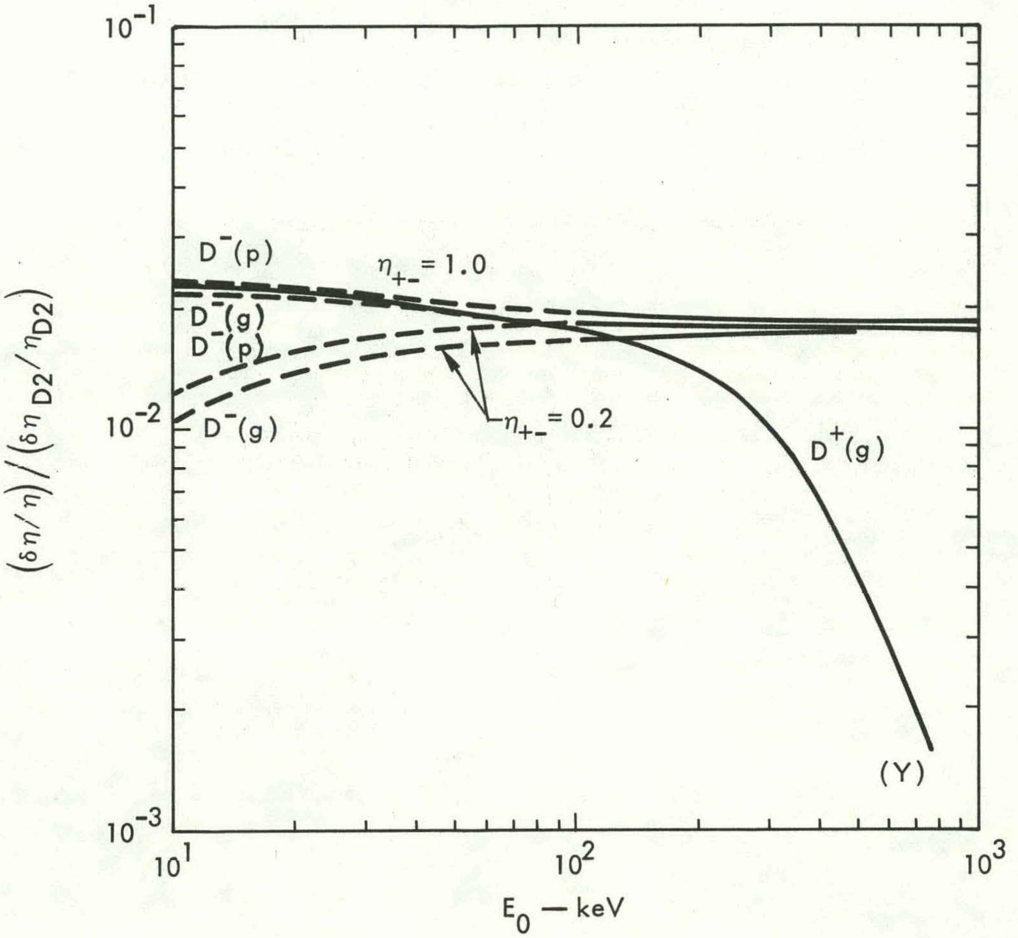

Fig. 22. Normalized rate of change of the injector system efficiency to the efficiency of the penetrating-beam direct converter as a function of the injected deuterium atom energy for $\eta_{D2} = 0.7$.

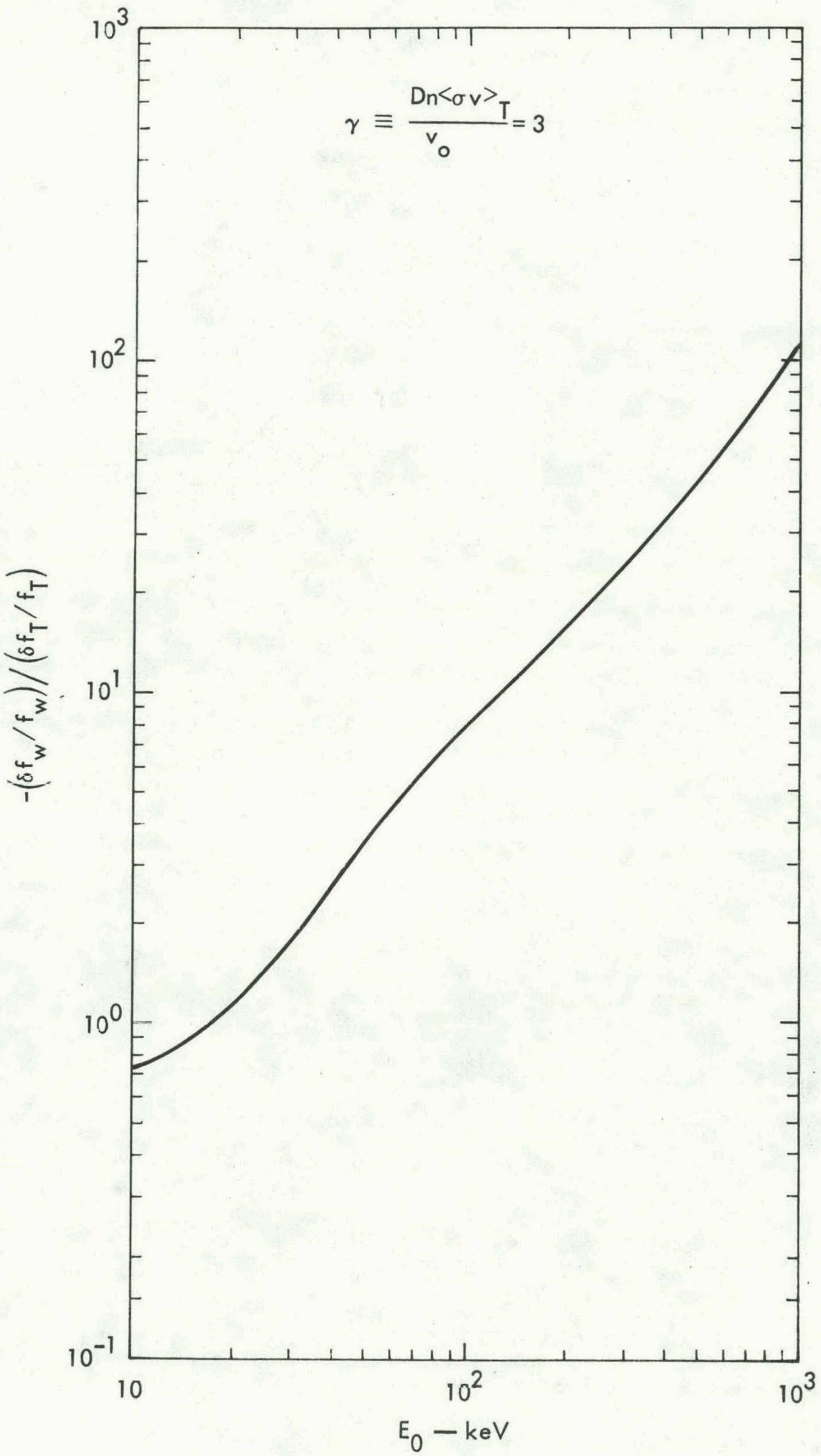

Fig. 23. Normalized rate of change of the injected beam charge-exchange loss fraction to the trapping fraction as a function of the injected deuterium atom energy for a penetration fraction of 5%.

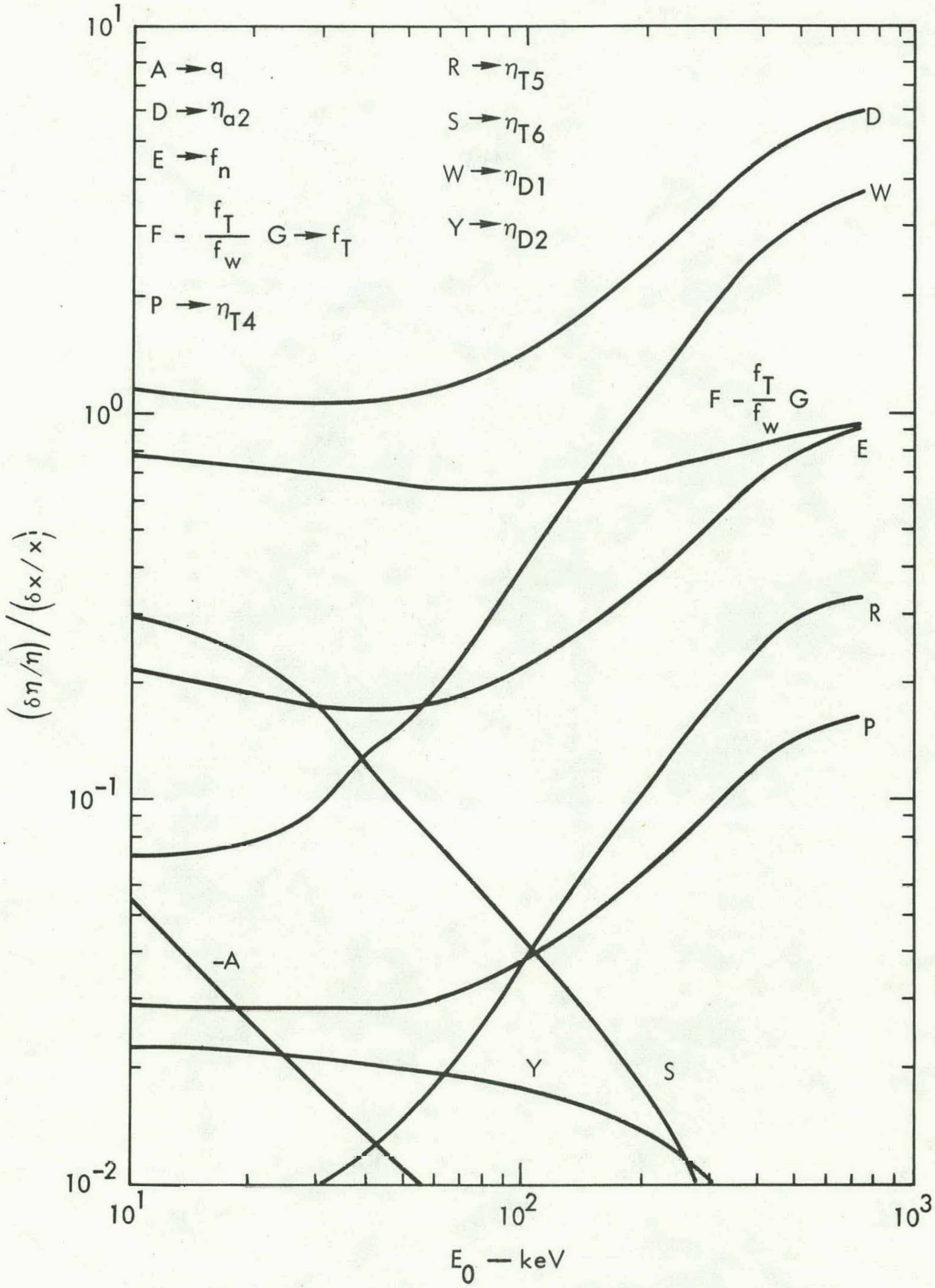

Fig. 24. Normalized rate of change of the injector system efficiency to the efficiency of various injector components as a function of injected deuterium atom energy for a system using D^+. g denotes gas neutralizer; p denotes plasma neutralizer.

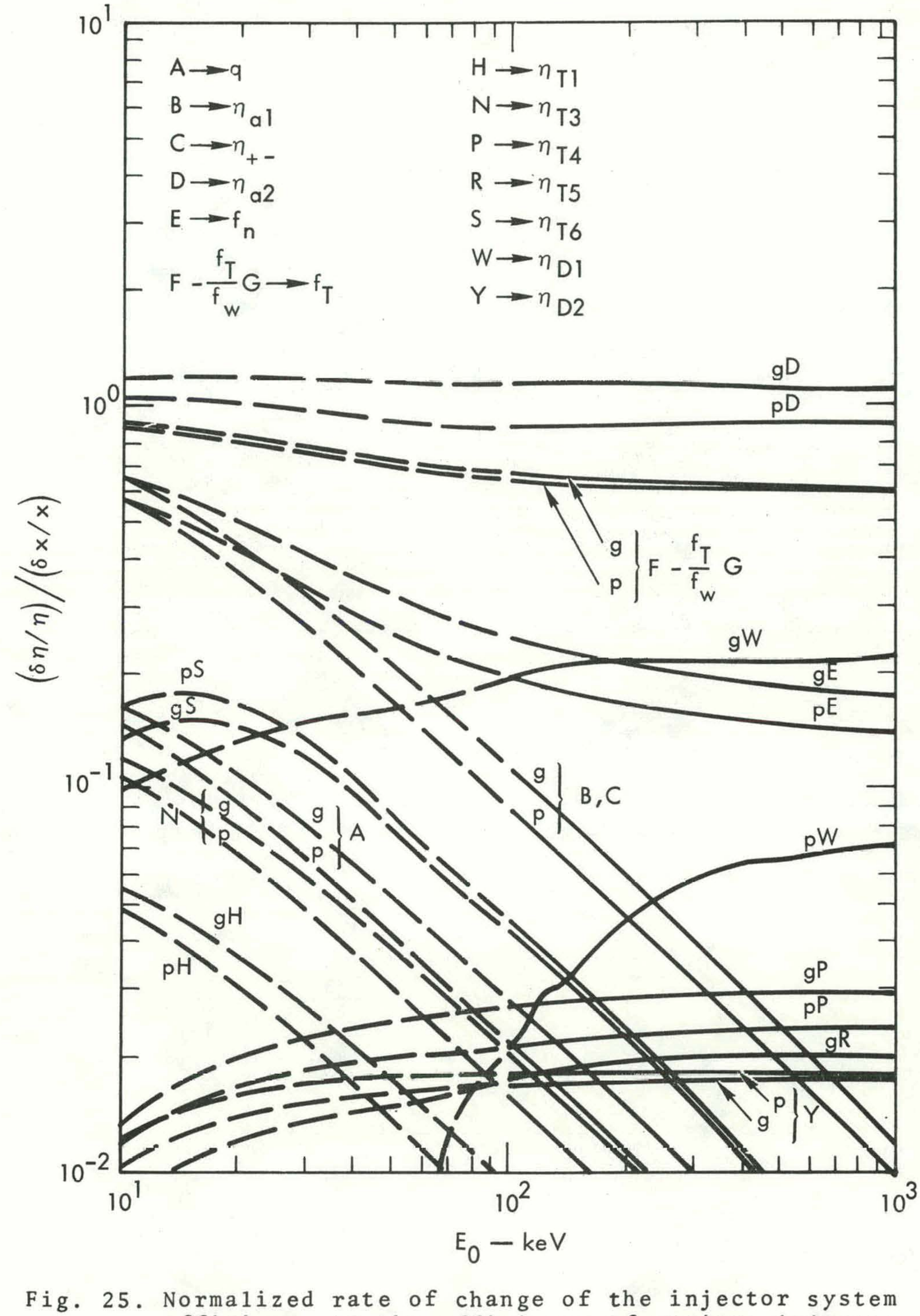

Fig. 25. Normalized rate of change of the injector system efficiency to the efficiency of various injector components as a function of injected deuterium atom energy for a system using D^-, $\eta_{+-} = 1.0$. g denotes gas neutralizer; p denotes plasma neutralizer.

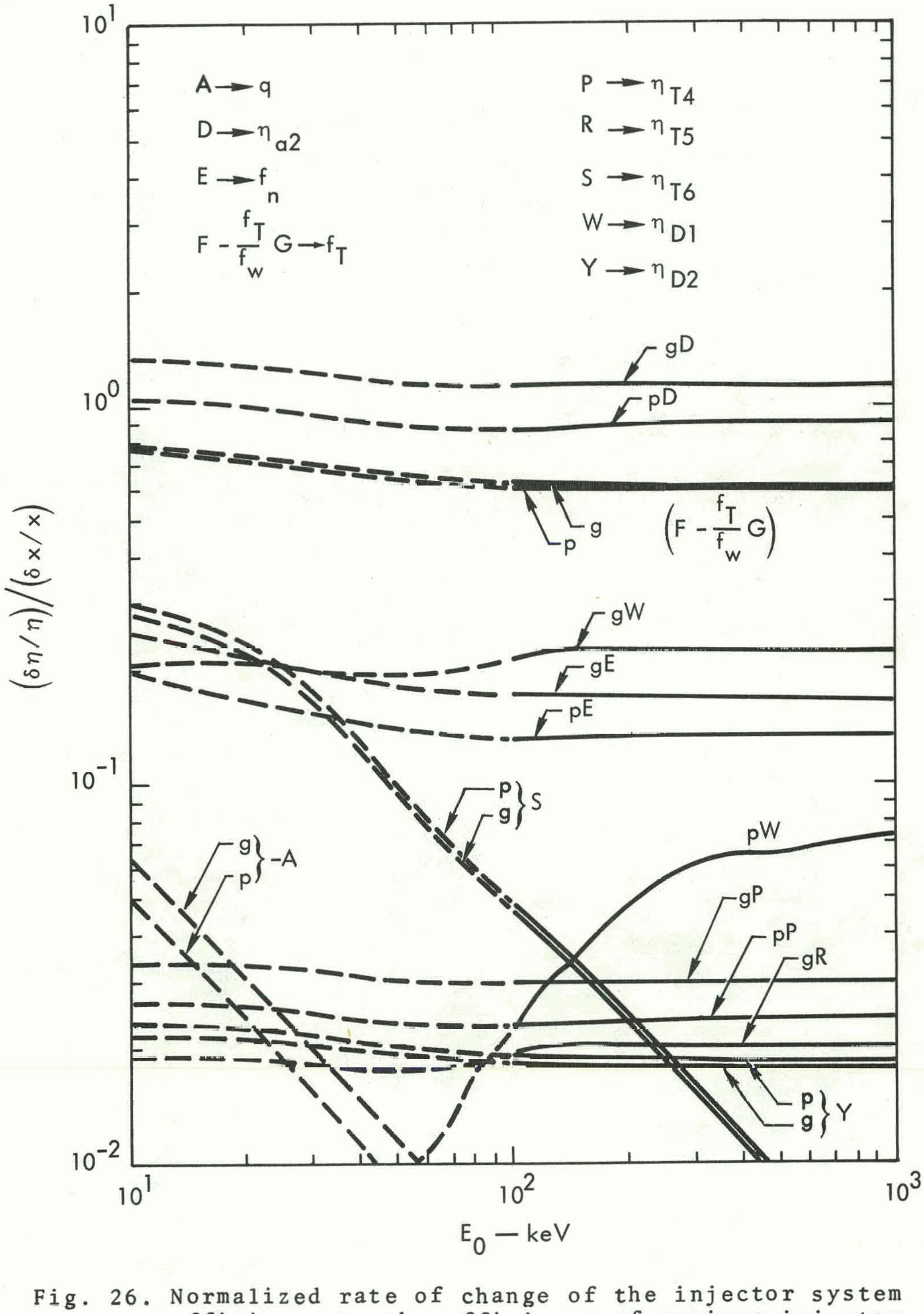

Fig. 26. Normalized rate of change of the injector system efficiency to the efficiency of various injector components as a function of injected deuterium atom energy for a system using D^-, η_{+-} = 1.0. g denotes gas neutralizer; p denotes plasma neutralizer.

DISCUSSION

With the assumptions made in this study, we can make a number of important generalizations for neutral deuterium injection:

Trapping Fraction

The most effective way to increase the trapping fraction of a plasma is to increase the ionization reaction rate coefficient.

Circulating Power

1. The accelerator performance (η_{a2}), neutralizer efficiency (f_n), and the trapping fraction (f_T) all have equal leverage on the circulating power.
2. The performances of η_{a2}, f_n, and f_T all have greater leverage on the circulating power than the alkali metal vapor cell efficiency (η_{+-}) and the pre-accelerator efficiency (η_{a1}).

Circulating Current

The performances of η_{a1}, η_{a2}, η_{+-}, f_n, and f_T all have equal leverage on the circulating current.

Injection Efficiency

1. In general, independent of ion type, the component performances with the largest leverage on the system efficiency are, in decreasing order, the accelerator efficiency (η_{D2}), the trapping fraction (f_T), the neutralizer loss direct conversion (η_{D1}), and the neutralizer power efficiency.
2. At low energies, independent of ion type, the performance of the reactor thermal converter (η_{T6}) and the source (q) are important.

As an example, consider a neutral injection system that injects 500 keV deuterium atoms produced from negative deuterium ions neutralized in an electron gas. From the injection system with

$q = 0.5$ keV/ion

$\eta_{a1} = \eta_{a2} = 0.92$

$\eta_{T1} = \eta_{T2} = \eta_{T3} = \eta_{T4} = 0.25$

$$\eta_{T5} = \eta_{T6} = \eta_{T7} = 0.45$$
$$\eta_{D1} = 0.90$$
$$\eta_{D2} = 0.70$$
$$f_n = 0.878 \qquad \text{(Fig. 4)}$$
$$\left.\begin{array}{l} f_w = 0.02 \\ f_T = 0.93 \\ f_p = 0.05 \end{array}\right\} \qquad \text{(Fig. 5)}$$
$$\eta_{+-} = 0.2$$

the injection system efficiency is 88.7% (from Fig. 6). The equation in Fig. 1 shows the reactor system efficiency to be 30.6%. Figure 27 plots the ratio of the difference between the trapped power and the accumulated losses through the system to the trapped power. Also,

$$A = -4.81 \times 10^{-3} \qquad \text{(Fig. 11)}$$
$$B = C = 1.93 \times 10^{-2} \qquad \text{(Fig. 12)}$$
$$D = 9.03 \times 10^{-1} \qquad \text{(Fig. 13)}$$
$$E = 1.47 \times 10^{-1} \qquad \text{(Fig. 14)}$$
$$F - \frac{f_T}{f_w} G = 6.01 \times 10^{-1} \qquad \text{(Fig. 15)}$$
$$H = 1.60 \times 10^{-3} \qquad \text{(Fig. 16)}$$
$$K = 3.85 \times 10^{-4} \qquad \text{(Fig. 12)}$$
$$N = 3.54 \times 10^{-3} \qquad \text{(Fig. 12)}$$
$$P = 2.35 \times 10^{-2} \qquad \text{(Fig. 17)}$$
$$R = 5.96 \times 10^{-3} \qquad \text{(Fig. 18)}$$
$$S = 8.77 \times 10^{-3} \qquad \text{(Fig. 19)}$$
$$U = 6.41 \times 10^{-3} \qquad \text{(Fig. 20)}$$
$$W = 6.56 \times 10^{-2} \qquad \text{(Fig. 21)}$$
$$Y = 1.83 \times 10^{-2} \qquad \text{(Fig. 22)}$$

Thus, combining Eqs. (16) and (19),

$$\frac{\delta\eta}{\eta} = 0.903 \frac{\delta\eta_{a2}}{\eta_{a2}} + 0.601 \frac{\delta f_T}{f_T} + 0.147 \frac{\delta f_n}{f_n} + \left[6.56 \frac{\delta\eta_{D1}}{\eta_{D1}} + 2.35 \frac{\delta\eta_{T4}}{\eta_{T4}}\right.$$

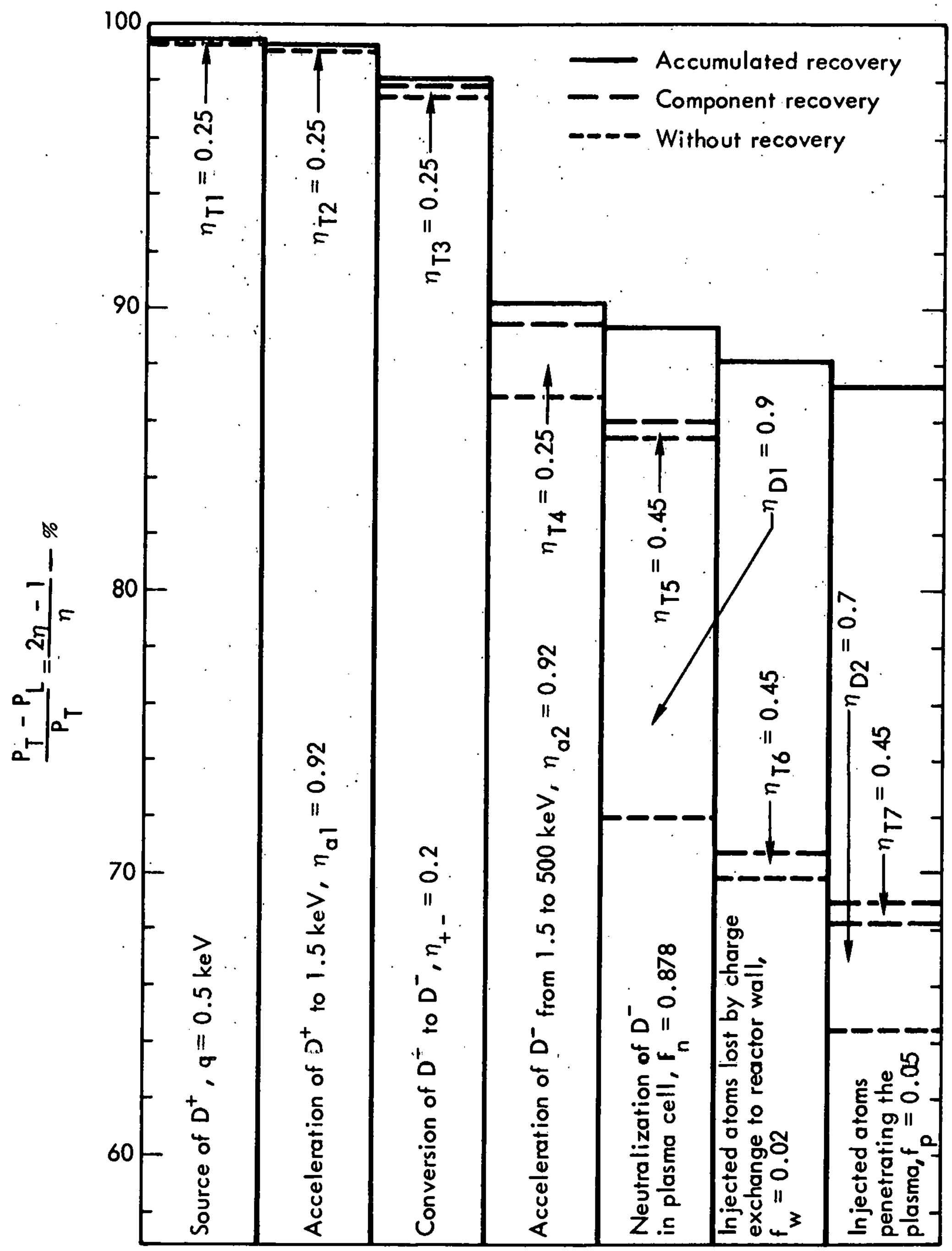

Fig. 27. Ratio of trapped power minus losses to trapped power of a particle passing through the injection system.

$$+ 1.93 \left(\frac{\delta\eta_{a1}}{\eta_{a1}} + \frac{\delta\eta_{+-}}{\eta_{+-}} \right) + 1.83 \left. \frac{\delta\eta_{D2}}{\eta_{D2}} \right] \times 10^{-2}$$

$$+ \left[8.77 \frac{\delta\eta_{T6}}{\eta_{T6}} + 6.41 \frac{\delta\eta_{T7}}{\eta_{T7}} + 5.96 \frac{\delta\eta_{T5}}{\eta_{T5}} - 4.81 \frac{\delta q}{q} \right.$$

$$\left. + 3.54 \frac{\delta\eta_{T3}}{\eta_{T3}} + 1.60 \frac{\delta\eta_{T1}}{\eta_{T1}} \right] \times 10^{-3} + 3.85 \times 10^{-4} \frac{\delta\eta_{T2}}{\eta_{T2}} .$$

If the primary acceleration efficiency can be increased by 1% while the performance of the remainder of the injector components is held fixed, then

$$\frac{\delta\eta_{a2}}{\eta_{a2}} = 0.01,$$

so the new accelerator efficiency is

$$\eta'_{a2} = \eta_{a2} \left[1 + \frac{\delta\eta_{a2}}{\eta_{a2}} \right] = 0.92 \left[1.0 + 0.01 \right] = 0.9292.$$

Thus

$$\frac{\delta\eta}{\eta} = 0.903 \times 0.01 = 0.00903,$$

so the new injection efficiency is

$$\eta' = \eta \left[1 + \frac{\delta\eta}{\eta} \right] = 1.00903 \ \eta.$$

Since the earlier injection efficiency was 88.7%, the new injection efficiency is 89.5%.

Using the equation from Fig. 1, with $\eta_I = 0.887$

$$\frac{\delta\eta_{sys}}{\eta_{sys}} = 2.64 \frac{\delta\eta}{\eta} = 2.64 \times 0.00903 = 0.0239.$$

The new system efficiency is

$$\eta'_{sys} = \eta_{sys} \left[1 + \frac{\delta\eta_{sys}}{\eta_{sys}}\right] = 1.0239\ \eta_{sys}.$$

From the equations on Fig. 1 with η_I = 88.7%, the original system efficiency is 30.6%. Thus the new system efficiency is 31.4%.

CONCLUSIONS

This analysis of the effects of the various component performances on the efficiency of a neutral beam injector system demonstrates the importance of the design of accelerators and direct converters for the injector system. Also important are the design of the beam neutralizer and the selection of the plasma parameters that determine the beam trapping fraction. For high energy neutral beam injection (>100 keV) using D^- ions, the performances of the source and the energy recovering system for producing negative ions become relatively unimportant in relation to the energy recovery system for the accelerated particles.

The injection of high energy neutrals into a themonuclear reactor requires large energy conversion and vacuum systems and efficient accelerators. The results shown in this paper should be useful in designing a cost-effective high energy neutral injector system for a thermonuclear reactor.

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