The efficiency of neutral beam injectors for fusion reactors

by

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SYMBOLS

B	blanket parameter
E	neutral beam particle energy, keV
E'	energy of the ion beam leaving the positive ion source, keV
E_I	amount of beam energy entering the plasma, MJ
E'_I	amount of beam energy trapped in plasma, MJ
E_{max}	maximum energy used by the ion source, MJ
E_r	energy recovered by the injector system, MJ
E_T	total energy used by the injector system, MJ
E_{th}	energy recovered by the thermal converter in the double-charge exchange injector, MJ
f_n	efficiency of the neutralizer (power neutral beam/ power ion beam)
f_+	fraction of the power leaving the neutralizer that is available for direct conversion
f_t	fraction of the neutral beam transmitted through the drift tube
I	beam current of the ion source, kA
I_{eq}	neutral beam strength, equivalent amps
m_a	effective power multiplication factor for the negative-ion accelerator stage
N_I	number of injectors in the system
P_I	power of the neutral beam entering the plasma, MW
P'_I	power trapped in plasma, MW
P_{max}	maximum power used by the ion source, MW
P_r	power recovered by the injector system, MW
P_T	total power used by the injector system, MW

Q	fusion energy/energy input
t_h	time in reactor cycle needed for neutral beam injection, sec
t_i	injector pulse length, sec
t_r	total reactor operating time, sec
δ_I	duty factor for an injector (time operating/(time operating + time for unscheduled and scheduled maintenance))
η_D	direct converter efficiency at neutralizer outlet
η_{DC}	plasma direct converter efficiency
η_e	electrical efficiency for an injector (energy injected/(energy used - energy recovered))
η_e'	heating efficiency of a neutral beam injector (energy trapped in plasma/(energy used - energy recovered))
η_{ie}	ion source electrical efficiency (energy in ion pulse/energy used)
η_{ip}	ion source power efficiency (power in ion beam/power used)
η_m	power efficiency of the double-charge exchange cell
η_o	overall plant efficiency (electrical energy/fusion and/or fission energy)
η_p	power efficiency for one injector (power injected/(power used - power recovered))
$\bar{\eta}_s$	net efficiency of energy storage or conversion from another source for the energy transfer system
η_{th}	thermal cycle efficiency

I. INTRODUCTION AND LITERATURE SURVEY

The basic concept behind the first generation of fusion reactors is conceptually simple, the idea being to economically produce net energy from the thermonuclear reaction given by

$$D_1^2 + T_1^3 \rightarrow He_2^4\ (3.52\ \text{MeV}) + n_o^1(14.05\ \text{MeV}) + 17.57\ \text{MeV} \quad (1)$$

Magnetic confinement is one of the methods that can be used to harness the fusion energy. In this system the plasma is surrounded by a vacuum, vacuum wall, cooling system, blanket, shield, and magnetic coils. The plasma producing components have to supply the following conditions

1. Ion and electron temperatures high enough for plasma ignition.
2. Sufficient plasma particle density and confinement time.

To achieve breakeven a reactor must be able to provide a fusion reaction rate large enough so the power generated just equals the power losses. Breakeven has not occurred in magnetic systems such as the tokamak, θ-pinch, and mirror machines because all the necessary plasma conditions cannot be simultaneously produced.

The temperature of a magnetic confined plasma is determined by a reactor power balance. For thermal equilibrium there must be balance between the power losses from bremsstruhlung and synchrotron radiation, ion and election diffusion, and the power deposited in the plasma by α heating or other heating mechanisms. Ohmic or resistive heating has proved successful for preliminary plasma heating, but is incapable of raising the plasma temperature to thermonuclear levels. So there needs to be a method to bridge the gap between ohmic heating and the point where α heating overcomes the total radiation and particle losses.

The injection of energetic neutral beams across the confining magnetic field is one method of plasma heating. When the neutrals enter the plasma they are ionized by charge exchange and electron ionization (19)[1]. The collisions of energetic ions and plasma ions have the effect of producing a high energy tail in the maxwellian distribution of energies in the plasma (11). The plasma temperature rises due to the additional average isotropic energy per ion contributed by the distorted tail.

There are several basic requirements for the neutral particles. They include sufficient energy for plasma penetration and a total power input necessary for reasonable heating times. Also in most systems using several injections, beam

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[1] Number in parentheses refers to reference position in the literature cited.

orientations should be used that induce the smallest instabilities in the plasma. For high heating efficiencies it is required that most of the energetic ions be in confined orbits.

The first set of experiments using neutral injectors failed to ignite the plasma (10, 9, 1). However, favorable plasma heating rates were achieved with few harmful effects. Results showed the expected high energy ion tail. Only minor plasma instabilities were noticed. For the tokamak, injection antiparallel to the plasma current proved to be slightly less efficient than parallel injection, but this was expected to approach the same efficiency for larger plasma currents. The primary limitations were the small amount of injected power and short pulse times.

To reach ignition a neutral beam power input of tens of megawatts will probably be necessary. For this case, and for steady-state injection where the neutral beam will overcome energy losses, particle losses, and will be used for plasma fueling, the efficiency of the injector is of primary importance. Hovingh and Moir (14) have studied injector efficiency for mirror reactors where effective use of recirculated power is necessary. Extensive energy recovery techniques were employed. The general conclusion was that the first injectors would be quite efficient but as the energy of the beam increased new designs would have to be used to maintain high efficiencies.

The purpose of this study is to find the reasons for the power losses in various neutral injectors and to predict the efficiency of the present and future types. Results will rely on both establish performance and some theoretical predictions. After a thorough understanding of the problem has been achieved, recommendations will be given for the best type of injector for use in the reactors that are expected to reach plasma ignition.

II. NEUTRAL BEAM INJECTOR REQUIREMENTS FOR FUSION REACTORS

The performance objectives for a neutral beam injector system are dictated by the associated reactor. To ignite and sustain the desired plasma conditions the particle energy and beam power are the important factors. The particle energy required is dependent on the fuel cycle, plasma state, reactor type, and the power plant characteristics. For plasma ignition power inputs should be large enough for short heating times. When the beam is used in steady state injection, the power input to the plasma must equal the leaked power minus the fraction of the fusion power given to the trapped particles.

Because the injected neutral beam is one factor that determines the plasma conditions, it is instrumental in raising the Q value of the plasma, where Q is defined as the ratio of the fusion energy to the energy input. Some general requirements for plasma conditions and neutral beam particle energy can be set in order to reach a specified Q. Table 1 shows the approximate beam requirements grouped according to low, moderate, and high Q values.

The lowest energy requirement for D-T fuels is for a counterstreaming-ion tokamak and a two-component plasma with energy clamping. The former uses counter-injected D° and T°

Table 1. Neutral beam energy requirements for D and T fuels (16)

Reactor or plasma type	Specified Q	Approx. beam energy needed
Counterstreaming-ion tokamak (15)	low $Q=1$	D° 100 keV T° 150 keV
Two-component plasma with energy clamping	low $Q=1$	D° 100 keV
Mirror reactor D and T plasma	low $Q=1$	$D^{\circ}>100$ keV
Two-component plasma	moderate $1 < Q \leq 5$	D° 200-400 keV
Two-component plasma or normal D and T plasma	high $Q \geq 10$	$D^{\circ}>400$ keV

neutral beams to reach Q values of 1 to 3. The latter uses a two-component plasma in which energetic D° is injected in a cold T target plasma. An auxiliary input energy is added to retard the slowing down of the ionized beam. Mirror machines are limited to Q values near 1 and will probably be required to have a fairly energetic beam to maintain high ion temperatures in the plasma. Even greater beam energies are needed for the moderate and high Q values, with the two-component plasma having smaller beam energy requirements.

It is likely that extensive use of advanced energy conversion and recovery systems will be necessary for workable power plants with Q values near 1. In the event a tokamak with a Q near 10 was used, a binary thermal conversion cycle might be sufficient. If neutral beam injectors were used as the main power input into the plasma, rough values for the overall injector efficiency can be found for both cases.

A fraction of the total energy released by the D-T cycle is in charged particles, so thermal and direct energy conversion devices can be used. Bottoming cycles for the direct converter, blanket multiplication, and energy recovery for the wasted neutral beam energy will increase plant efficiency even further. With the above systems and assuming that the radiation power losses are made up by charged particle input from neutral injection, then an expression for the overall plant efficiency, η_o, is (16)

$$\eta_o = \frac{(1 + B)\eta_{th} - \frac{1}{Q}\left[\frac{1}{\eta_e'} - (\eta_{DC} + (1 - \eta_{DC})\eta_{th})\right]}{(1 + B)} \qquad (2a)$$

B is the blanket parameter (which depends on the blanket multiplication factor), η_{th} and η_{DC} are the thermal cycle and direct converter efficiencies respectively, and η_e' is the effective neutral beam heating efficiency when the untrapped portion of the neutral beam has been taken into account.

In order to find approximate overall injector efficiencies, representative values for B, η_{th}, Q, and η_{DC} must be found (16). For a mirror reactor operating with a Q equal to one, the thermal and direct converter efficiencies would be near 45% and 70% respectively. A bottoming cycle would be included for the plasma direct converter. With a natural uranium blanket the blanket parameter would be around 10. Substituting these values into Equation 2a indicates that an injector efficiency of about 70% would be needed to maintain an overall plant efficiency of 40%. An injector efficiency of less than 40% would seriously reduce the plant efficiency.

A second case would be a tokamak with a Q value equal to 10. An advanced thermal cycle with an efficiency of 50% would be the only method used for electrical production. Thus, Equation 2a reduces to

$$\eta_o = \eta_{th} - \frac{1}{Q}\left[\frac{1}{\eta_e'} - \eta_{th}\right] \qquad (2b)$$

The injector efficiency needed for a plant efficiency of 45% would be over 90%. An injector efficiency of 50% would reduce the plant efficiency to 35%.

The two examples of selected reactors give only approximate indications of the efficiencies required. Obviously, for some cases such as a neutral beam injector used for short pulses, the efficiency need not be high because the amount of energy wasted is not excessive. On the other hand, for steady-state injection, especially when Q is low and no blanket multiplication is used, injector efficiencies of at least 80% are called for.

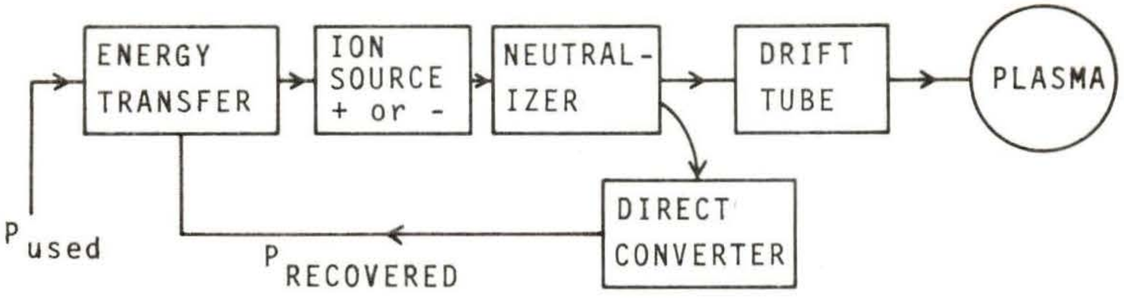
III. COMPONENT PERFORMANCE

A. Ion Sources

Two general classes of neutral beam injectors that could possibly be efficient at high beam energies are shown in Figure 1. The first class uses a positive or negative ion source producing ions of energy E(keV) that are neutralized in a gas or plasma cell. The ions not neutralized will be collected by a direct converter at the neutralizer outlet. The neutral component proceeds through the drift tube to the plasma. Both the power from the converter and outside source must be channeled through an energy storage or dc-dc conversion system, whose function is to make the power sources compatible with the power supplies.

A second class uses a low energy positive ion source fed into a double-charge exchange cell which produces a certain fraction of negative ions. The positively charged ions and neutral atoms are separated for input into a thermal converter. A second acceleration stage accelerates the negative ions to an energy E(keV). Similar to the first class the negative ions are neutralized in the cell. The neutrals proceed through the drift tube, while a fraction of the positive ion power is converted to direct current by a direct converter. Power from the direct converter, thermal converter, and outside source must be channeled through the energy

I SINGLE–CHARGE EXCHANGE



II DOUBLE–CHARGE EXCHANGE

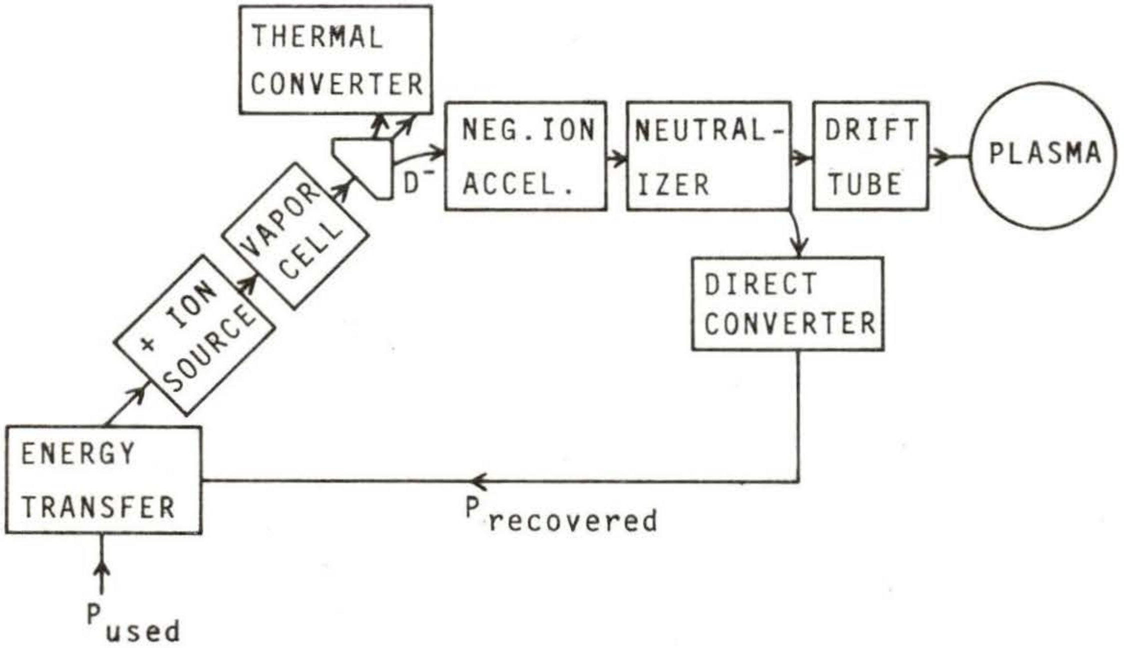


Figure 1. Neutral beam injector classes

transfer system.

An ion source consists of a plasma source and a system for extracting and accelerating the ions. Positive ion sources have been built with the largest beam power, of which the duoPIGatron and filament are the types used for neutral injectors.

The duoPIGatron ion source is a PIG discharge with a duoplasmatron source as the plasma feed. The heated filament in the duoplasmatron strips electrons from the neutral gas which are then accelerated and constricted in the region of an anode by a potential and inhomogeneous magnetic field. The increased electron energy produces additional ionizations. The partially ionized gas diffuses through a small aperture in the region of an intermediate electrode and target cathodes. This section of the source is essentially a PIG discharge producing oscillatory electrons between the target cathodes, causing additional ionizing collisions in the plasma. The filament positive ion source produces a quiescent plasma in an arc chamber with a high current discharge emitting cathode. No external magnetic fields are applied. The ionization results from electron collisions. Both sources can be built with similar beam energies and power, the main difference is that the filament type has a slightly more uniform and stable plasma extraction area.

The duoPIGatron and filament sources use a three element accel-decel electrode configuration for the extraction and accelerating system. An accel grid operating at a positive voltage with respect to the third grid at ground extracts and accelerates the positive ions from the plasma. An intermediate suppressor (decel) grid at a negative potential prevents backstreaming electrons from the neutralizer cell from striking the source elements. This method of electrostatic focussing will accelerate all single and molecular ions of the same charge. For use in estimating power consumption, the major power supplies for the positive ion sources are listed in Table 2.

Table 2. Major power supplies for positive ion sources

DuoPIGatron	Filament
arc	arc
gas supply	gas supply
filament	filament
magnet (2)	accel
accel	gradient
decel	suppressor (decel)

There are several causes for inefficiencies in positive ion sources. Only a portion of the energy used to form the plasma is removed by the extracted ions. For both the duoPIGatron and filament ion sources only about 50% of the molecular gas fed to the source is extracted as ions. This allows the flow of gas into the extractor establishing an ambient neutral background density. Some of the accelerated ions might undergo charge exchange producing low energy ions and neutral particles. The low energy ions will be accelerated by the electric field in the gap and collide with a grid. A significant number of secondary electrons are formed by the sputtering, which in turn bombard other grids. The net result is a power loading and current drain in the extraction system. Another major source of power loss is high beam divergence. The magnitude of the above effects can be significant. For short pulse times the energy used to form the plasma can be much larger than the amount contained in the accelerated beam. Typical power losses in the extractor system are 5 to 10% of the total ion beam power.

The magnetron is currently the most powerful of the negative ion sources. It uses a cesium covered cathode surface that is bombarded with fast positive and neutral particles diffusing into mutually perpendicular magnetic and electric fields. The negative ions formed on the cathode surface are then extracted and accelerated. The limitations of the magnetron are thermal loads on the cathode surface, low power output, and poor gas efficiencies compared to the positive ion sources.

Properties of positive and negative ion sources are depicted in Table 3. The beam power and pulse length are the most important factors for the source performance. It should be noted that several species fractions consisting of singular and molecular ions are produced in the positive ion sources. More recent filament and duoPIGatron sources have the advantage of several orders of magnitude more beam power than the magnetron types.

B. Neutralizer and Drift Tube

The neutralizer functions as a converter of high energy atomic or molecular ions into high energy atoms and molecules. Neutralization can be accomplished in the cell by either a gas or plasma, gas cells being the type generally used in neutral injectors. Since future reactor designs will generally inject deuterium in the plasma, consideration will only be given to D° injection. Table 3 indicates that D_1^+, D_2^+, D_3^+ or D^- are the ion species emitted by the source. Conversion to neutral atoms can be obtained by a capture of an electron by a positive ion or removing an electron from a negative ion. Diatomic and triatomic ions produce neutral atoms and molecules from a series of dissociation and neutralization reactions. The molecular dissociations forming neutral components are

Table 3. Neutral beam injector performance

Experiment	Ion beam energy Ion beam strength Pulse length	Ion species fractions	Neutral components
BNL magnetron (18) [surface plasma]	30 keV 0.9 A 20 ms	H^-	
Cleo tokamak (1) [duoPIGatron]	25 keV 3 A 50 ms	75% H^+ 25% H_2^+	70% H° - 25 keV 30% H° -12.5 keV
Ormak (9) [duoPIGatron]	20 keV 6.2 A 300 ms	$D_1^+ D_2^+, D_3^+$	D° or D_2° at 28, 13.8 and 9.3 keV
LBL 10-A (8) [filament]	20 keV 10 A 20 ms	75% D^+ (67%)[a] 15% D_2^+ (22%)[a] 10% D_3^+ (11%)[a]	57% D° - 20 keV 21% D° - 10 keV 19% D_2° - 6.7 keV 1% D_2° - 13 keV
LBL 50-A (2) [filament]	20 keV 50 A 10 ms	76% D^+ 22% D_2^+ 2% D_3^+	50% D° - 20 keV 34% D° - 10 keV 4% D° - 6.6 keV 4% D_2° - 20 keV 1% D_2° - 13 keV

[a] Arc parameters changed, power output kept constant.

$$\begin{aligned}
&D_2^+ \rightarrow D^\circ + D^+ \\
&D_2^+ \rightarrow 2D^\circ + \text{electron capture} \qquad (3) \\
&D_3^+ \rightarrow D_2^+ + D^\circ \\
&D_3^+ \rightarrow D_2^\circ + D^+
\end{aligned}$$

The atomic species will produce neutral atoms at full energy. Half-energy atoms or full-energy molecules are produced by the diatomic ionic species. Similarly, the triatomic dissociations will yield molecular dissociations at 2/3 and atomic fragments at 1/3 the original ion energy.

The neutral beam leaving the neutralizer is composed of the neutral particles D° and D_2° at different energies depending on the type and extracted energy of the ion from which they were formed (See Table 3). The neutralizer efficiency, f_n, is defined as the ratio of the power of the neutral beam leaving the neutralizer to the power of the ion beam entering the neutralizer. Actual efficiencies are dependent on the neutralizer cell thickness (D_2 molecules/cm^2), the beam species, and the energy of the beam since the cross-sections are energy dependent. It is usually the practice to optimize the target thickness of the gas cell for a particular ion species and energy. However, some restrictions are realized because of physical limitations on very large cell lengths and reionization of the neutral particles.

Neutralizer efficiencies as a function of energy for typical species fractions are shown in Figure 2. The efficiency was taken to be the ratio of the total neutral beam power at all energies to the ion beam power entering the neutralizer. Neutralization of positive ions results in considerable power losses at high beam energies. The higher neutralization efficiency of negative ions can be utilized by two methods. The first is to develop an efficient and powerful negative ion source for input into the neutralizer. A double-charge exchange cell for positive to negative ion conversion prior to the neutralizer can also be used. Technology for the first method does not exist. Components for a double-charge exchange injector have been individually developed, but need to be proved practical in an actual injector.

The final loss of beam power in the injector system is in the drift tube. Slow gas emitted from the neutralizer builds up in the drift tube inducing ionizing collisions with part of the energetic neutral beam. The magnetic field of the reactor then deflects the ions which eventually results in sputtered particles from the tube walls. This process occurs even when a direct converter on ion deflector is used at the neutralizer outlet. With good gas pumping techniques and proper tube materials the losses can be reduced to less than 10% of the neutral beam power.

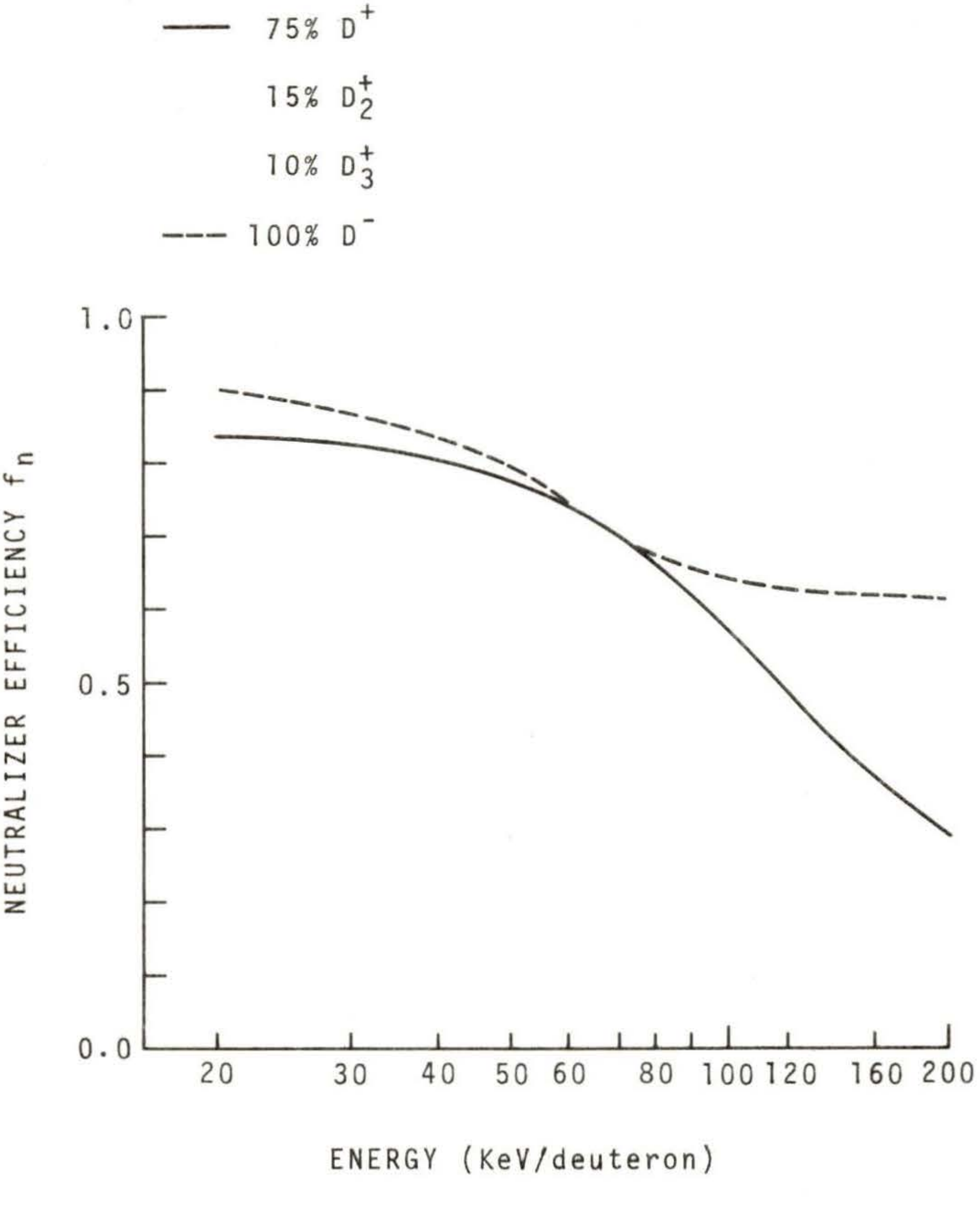


Figure 2. Neutralizer efficiency vs. beam energy for typical ion species (8)

C. Related Components

Two important performance-related facilities for an injector are the energy storage (or conversion device) and the direct converter. Most injectors have not been able to get the necessary power from continuous power supplies, with their high transfer efficiencies of ∿95%, and have been forced to use capacitive discharge systems. Capacitive systems can not be expected to produce a great amount of energy for long periods of time because of low energy density and consequent large size. Properties of more advanced systems with greater energy densities are listed in Table 4. Large amounts of stored energy and high transfer efficiencies are at least theoretically possible. However, for some types the net efficiency (energy generated/electrical input) can be considerably lower than the transfer efficiency. There are also problems with the development of switches for the large output currents and compatibility with the injector. Most injector power supply specifications will require fast current rise-times and falltimes, low voltage ripple, and short repetition periods.

The most promising direct converter for beam energy recovery is the in-line, nonintercepting type (6). The energy conversion technique is one of electrostatic deceleration of positive ions with direct particle collection. Good features

Table 4. Pulsed-power supplies (17)

Type	Energy density	Transfer time	Approx. max. stored energy	Energy transfer efficiency
Capacitive	low	fast	10 MJ	∿90%
Inductive	medium	medium	100 MJ	25%
Inductive with capacitive transfer	medium	medium	100 MJ	25-100%
Inertial	high	slow-medium	10,000 MJ	∿90%

are a lack of interference with the magnetic field of the reactor and low power loads. Direct conversion efficiencies of about 70% should be realized with the efficiency defined as

$$\eta_D = \frac{\text{collected power - load on electrode power supply}}{\text{total ion beam power}} \qquad (4)$$

A double-charge exchange cell is used to convert low energy positive ions into positive, negative, and neutral particles. Cs or alkali-metal vapor cells have been used. Before the negative ions are accelerated to a higher energy, the positive and neutral particles must be separated. A thermal conversion unit can be used to recover some of the wasted energy. Double-charge exchange cells have an efficiency of about 20%, with several in series improving the efficiency further.

IV. SYSTEM REQUIREMENTS

An injector system, consisting of one or several injectors, will need to input a certain beam power and total energy into the plasma. Defining P_I(MW) as the power of the neutral beam entering the plasma that is necessary to sustain the desired plasma conditions, untrapped particles and other losses considered, then P_I can be supplied by a single injector or a system whose total power equals the needed power input. Similarly, the required energy, E_I(MJ), can be produced by one or more injectors.

The two classes of neutral beam injectors can be used in two general types of injector systems. The first type is a steady-state mirror reactor where injection would be used for the entire operating cycle. A pulsed-tokamak reactor, where the neutral beam will probably ignite the plasma, is the second type. Important parameters concerning both systems are the number of injectors needed and efficiency at which the neutral beam is produced.

A. Steady-State Injection

For continuous injection into a mirror reactor the following conditions hold

$$t_h \simeq t_r \simeq t_i \qquad (5)$$

Assume for simplicity sake that only one powerful injector is needed for the system. For single-charge exchange injectors the power needed and energy input are given by

$$P_I = EIf_n f_t \qquad (\mathrm{MW}) \tag{6}$$

$$E_I = EIf_n f_t t_i \qquad (\mathrm{MJ}) \tag{7}$$

Defining the power efficiency as the power injected divided by the power used minus the power recovered, yields the following expressions

$$\eta_p = \frac{P_I}{\dfrac{P_{max}}{\bar{\eta}_s} - \bar{\eta}_s EI\eta_D f_t} \tag{8a}$$

$$P_{max} = \sum_{i=1}^{N} V_i\,(\mathrm{kV})\,I_i\,(\mathrm{kA}) \qquad (\mathrm{MW}) \tag{8b}$$

P_{max} is the maximum power used by the injector. The sum over i is taken to include N injector related power supplies such as beam, direct converter, neutralizer cell, and pump systems.

For energy storage and cost considerations the expression for the electrical efficiency, η_e, is

$$\eta_e = \frac{E_I}{\frac{E_{max}}{\bar{\eta}_s} - \bar{\eta}_s E I \eta_D f_t t_i} \qquad (9a)$$

$$E_{max} = \sum_{j=1}^{N} V_j(\text{kV}) I_j(\text{kA}) t_j(\text{sec}) \qquad (\text{MJ}) \qquad (9b)$$

The summation is over the energy used by the j power supply operating for a time t_j.

Using the above efficiencies gives the total power and energy consumed by the injector

$$P_T = \frac{P_I}{\eta_p} \qquad (\text{MW}) \qquad (10)$$

$$E_T = \frac{E_I}{\eta_e} \qquad (\text{MJ}) \qquad (11)$$

In addition, the power and energy trapped in the plasma are given by

$$P_I' = \eta_p' \, P_I \qquad (\text{MW}) \qquad (12)$$

$$E_I' = \eta_e' \, E_I \qquad (\text{MJ}) \qquad (13)$$

For the injector type using double-charge exchange, the needed input quantities are

$$P_I = E' I \eta_m m_a f_n f_t \qquad (\text{MW}) \qquad (14)$$

$$E_I = P_I t_i \qquad (\mathrm{MJ}) \tag{15}$$

The power efficiency of the double-charge exchange cell is η_m, and m_a is the effective power multiplication factor for the negative-ion accelerator stage boosting the particle energy to E(keV).

Similar to the previous injector type, the power efficiency, with recovered power P_r, is

$$\eta_p = \frac{P_I}{P_{max}/\bar{\eta}_s - P_r} \tag{16a}$$

$$P_r = \bar{\eta}_s E' I[(1 - \eta_m)\eta_{th} + \eta_m m_a f_+ \eta_D] \qquad (\mathrm{MW}) \tag{16b}$$

The thermal efficiency of the converter for the D^+ and $D°$ particles, which should be nearly equal to the reactor thermal efficiency, is η_{th}.

The expression for the electrical efficiency of the double-charge exchange injector is complicated by the fact that the response time of the thermal converter will probably differ from the injector pulse length. Defining $\bar{E}_{th}$ as the amount of energy in MJ recovered by the thermal converter, then the electrical efficiency is

$$\eta_e = \frac{E_I}{\dfrac{E_{max}}{\bar{\eta}_s} - \bar{\eta}_s[\bar{E}_{th} + E' I \eta_m m_a f_+ \eta_D t_i]} \tag{17}$$

The total power and energy used by the second class is given by Equations 10 and 11, with the substitution of the appropriate efficiencies.

B. Pulsed Injection

The neutral beam injection system for a pulsed tokamak will probably be used for plasma ignition. Depending on the type of injector, the pulse length might not be equal to the heating time, so the following conditions apply

$$t_i \le t_h < t_r \tag{18}$$

Assuming injectors of the same design are used and the duty cycle for a single injector is greater than t_h, then the number of injectors needed in the rotating system is a function of the injector pulse length. The system number for the first class of injectors is

$$t_i = t_h \qquad N_I = \frac{P_I}{EIf_n f_t \delta_I} \tag{19a}$$

$$t_i \le .5t_h \qquad N_I = \frac{P_I t_h}{EIf_n f_t \delta_I t_i} \tag{19b}$$

$$.5t_h < t_i < t_h \qquad N_I = \frac{2P_I}{EIf_n f_t \delta_I} \tag{19c}$$

If the computed N_I is not an integer, then it should be rounded to the next highest whole number.

If the pulse length of all the injectors is approximately equal, each will be operating near the optimum range, and the power efficiency and electrical efficiency of the system should be near that of a single injector. Defining $\bar{t}_i$ as the average pulse length of the rotating system, then the maximum power and total energy used are

$$P_T = \frac{N_I E I f_n f_t}{\eta_p} \quad \text{(MW)} \tag{20}$$

$$E_T = \frac{N_I E I f_n f_t \bar{t}_i}{\eta_e} \quad \text{(MJ)} \tag{21}$$

The derived equations for the double-charge exchange injector are similar in principle to the first class. Again the number of injectors necessary is a function of the pulse length of a single injector. With N_I rounded to the next highest integer, when necessary, the expressions are

$$t_i = t_h \qquad N_I = \frac{P_I}{E' I \eta_m m_a f_n f_t \delta_I} \tag{22a}$$

$$t_i \leq .5 t_h \qquad N_I = \frac{P_I t_h}{E' I \eta_m m_a f_n f_t \delta_I t_i} \tag{22b}$$

$$.5 t_h < t_i < t_h \qquad N_I = \frac{2 P_I}{E' I \eta_m m_a f_n f_t \delta_i} \tag{22c}$$

$$\frac{\#\ \text{of D or T}}{\text{sec}} \approx \frac{I_{eq}\, f_t}{e} \qquad (26)$$

where e is the electron charge in coulombs. Equation 26 partially neglects the presence of neutral molecules in the beam. However, the error is less than 10% because according to Berkner et al. (8) the power contained in the molecular components is small.

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V. NEUTRAL BEAM INJECTOR PERFORMANCE

The equations derived in Chapter IV can be used to determine existing injector performance. Only positive ion sources and gas neutralizer cells using deuterium were considered, because the major advances have been in these areas. The best obtainable performance for a particular ion source was used as data selection criteria. The neutralizer performance is based on the calculated power efficiencies, rather than on experimental values. Moreover, it was assumed that the differences between duoPIGatron and filament sources were small, so that the positive ion source data could be gathered into one group.

The predicted injector power efficiency without energy storage or direct conversion for a positive-ion filament source is given by (7)

$$\eta_p = \frac{f_n(E)}{f_n(E) + 2.5/E + .075} \qquad (27)$$

E is the beam energy in keV and $f_n(E)$ is the neutralizer power efficiency for the correct species fractions at the energy E. Figure 3 contains the predicted power efficiency curves versus beam energy. The predicted ion source performance was obtained by setting $f_n(E) = 1$ in Equation 27. An estimate of the total injector efficiency was found by using the typical species fractions 75% D^+, 15% D_2^+, and

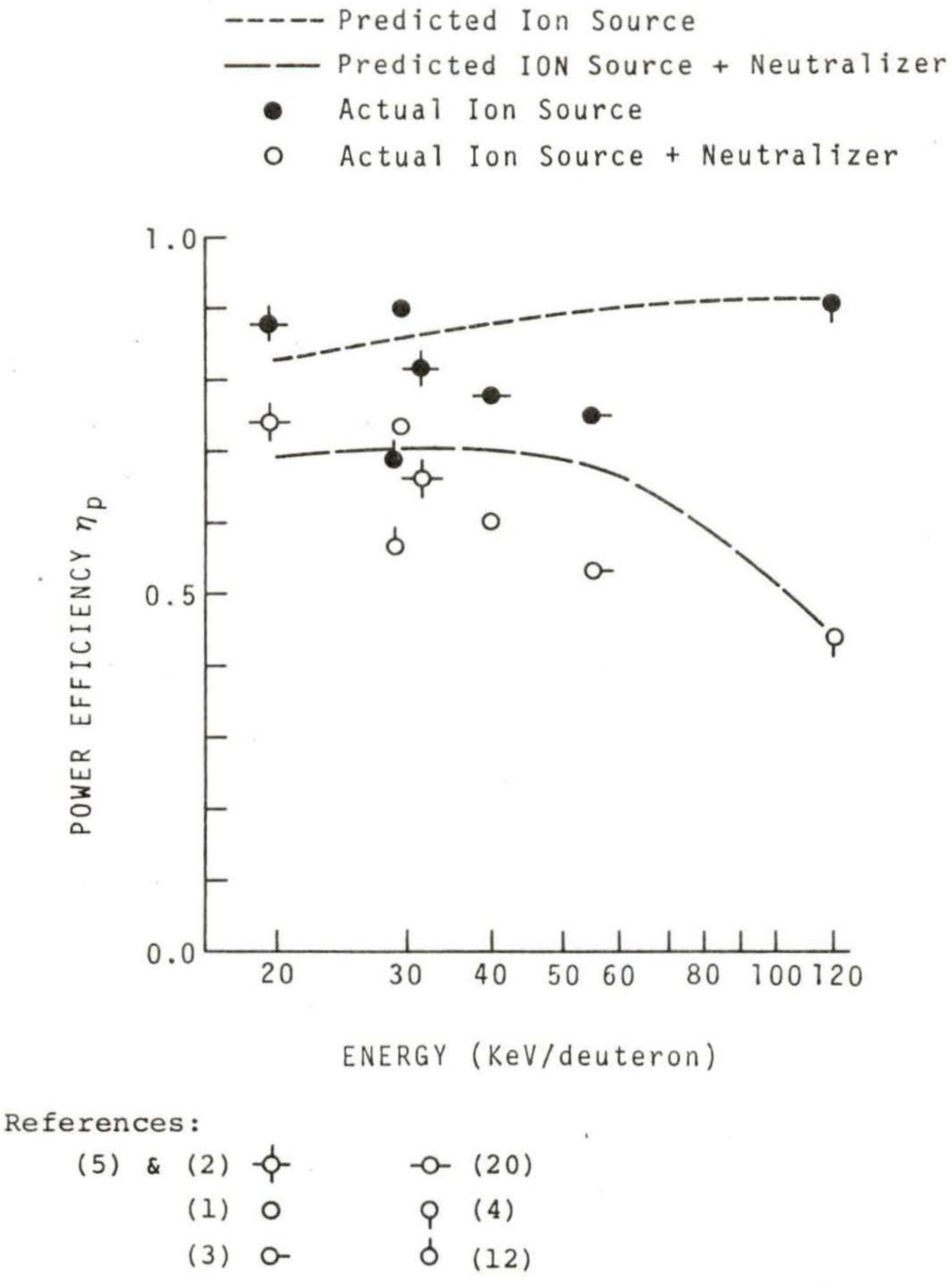

Figure 3. Power efficiency vs. beam energy

10% D_3^+ to compute $f_n(E)$.

Equations 8a and 8b can be utilized to find the actual power efficiencies of positive ion sources. P_I is taken to be the beam power. Since the transfer system efficiency and power recovery should not be considered, the simplifications are

$$P_r = 0 \qquad \bar{\eta}_s = 1 \qquad f_t = 1.0 \tag{28}$$

Moreover, the injector power efficiencies can be estimated by multiplying the ion source efficiency by the appropriate $f_n(E)$ for the typical species fractions. Figure 3 shows that with the exception of the source with the most energetic beam, the ion source power efficiency has not increased with increasing beam energy. The total injector efficiency has dropped, due to neutralizer power losses, and might be lower than the predicted values.

The same equations can also be used to plot the ion source power efficiency versus the power contained in the ion beam. Figure 4 contains the power efficiencies versus ion-beam power for positive ion sources. Conditions listed in Equation 28 apply. The ion source efficiencies increase slightly with increasing ion power because the proportion of the power used by the accelerator stages, which is nearly equal to the beam power, increases relative to the power needed to produce the plasma. The ion source power efficiency

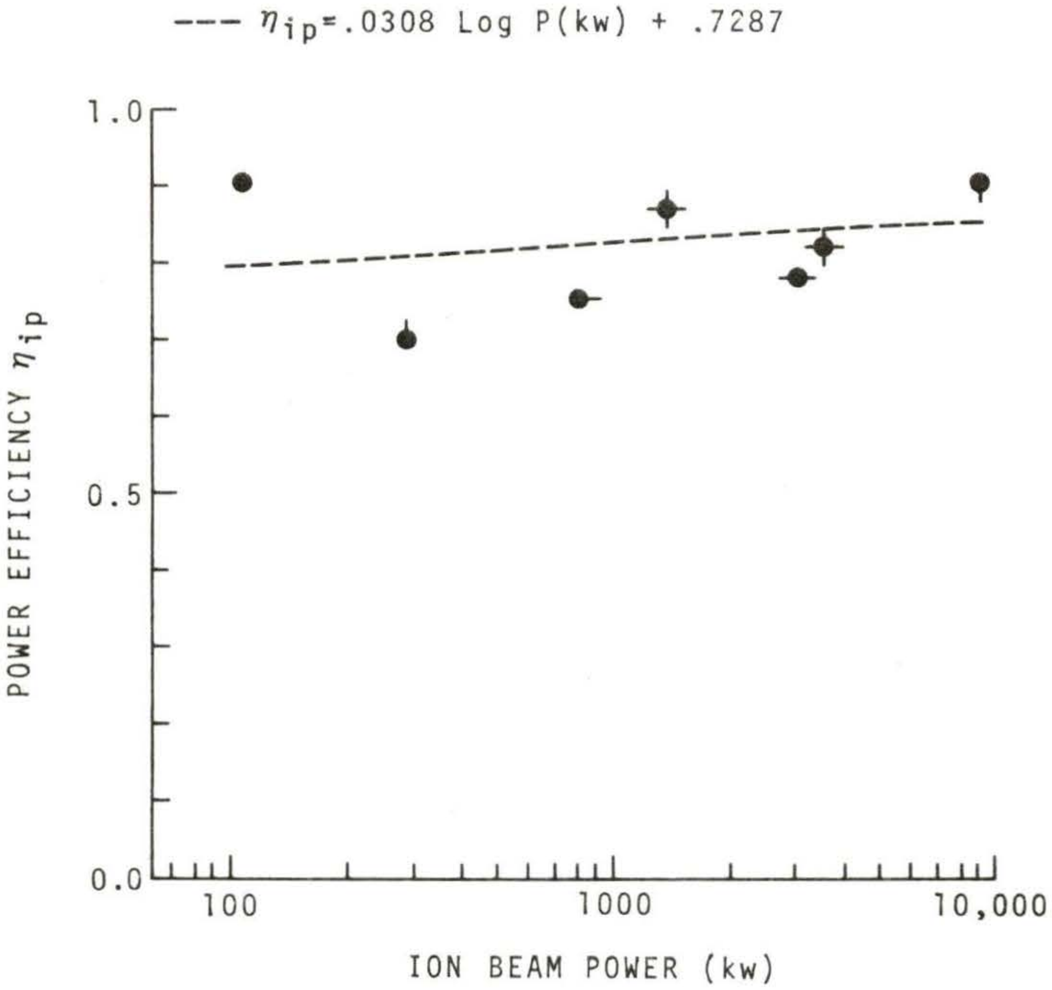

Figure 4. Power efficiency vs. ion-beam power for positive ion sources

is approximately given by the least-squares fitted equation

$$\eta_{ip} = .0308 \text{ Log } P_I(\text{kW}) + .7287 \qquad (29)$$

for ion beam powers of 100 to 10,000 kW.

The electrical efficiency versus the total ion or neutral beam energy content can be obtained by using Equations 9a and 9b. The procedure is similar to the previous case, where E_I is taken to be the total energy in the beam pulse. Other conditions are

$$E_r = 0 \qquad \bar{\eta}_s = 1 \qquad f_t = 1 \qquad (30)$$

Figure 5 shows the electrical efficiency increasing sharply with increasing energy in the beam pulse. The increase is smaller with the neutralizer because of the power losses in the gas cell. The increase in the electrical efficiency occurs because the accelerator stages in the source use large amounts of power for short periods and when the total energy in the pulse is small, the energy consumed to heat the filaments and create the plasma can be greater than the amount needed to accelerate the ions. An expression, obtained from a least-squares fit, for the electrical efficiency of positive ion sources from 5 to 4,000 kJ is

$$\eta_{ie} = .2666 \text{ Log } E_I(\text{kJ}) - .1061 \qquad (31)$$

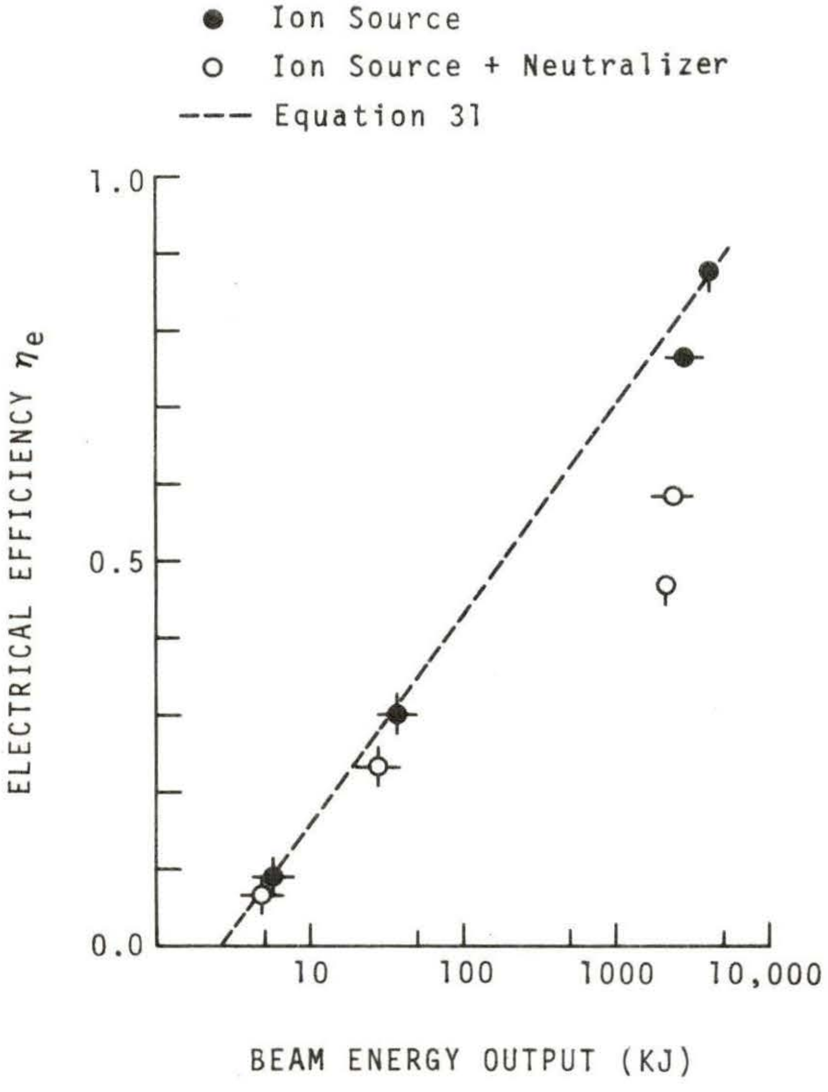

Figure 5. Electrical efficiency vs. beam energy output

The results of this section do not seriously contradict the predicted positive ion source performance. Slight discrepancies are expected due to differences in source conditioning and unexpected scaling effects. However, the results do show that due to short pulse lengths, ion sources have not yet reached their maximum electrical efficiencies. For long pulses the electrical efficiency should approach the power efficiency. The ion source electrical efficiencies in Figure 5 are less than the corresponding power efficiencies.

VI. PROJECTED INJECTOR PERFORMANCE

In order to predict injector efficiencies several assumptions regarding future component performance must be made. The assumptions used are consisted with the present properties and probable future properties of the injector components. Both classes of neutral beam injectors are considered. Some general assumptions regarding the systems are:

1. There is a constant 5% loss of neutral beam power in the drift tube.
2. Positive ion sources produce a beam consisting of 75% D^+, 15% D_2^+, and 10% D_3^+. A gas cell is used for neutralization.
3. Negative ion sources produce a 100% D^- beam.
4. All systems used a direct converter with a constant efficiency of 70% over the full range of beam energies.
5. The power and energy used by all equipment, besides the power supplies listed in Table 2, is negligible.

A. Single-Charge Exchange Injectors

Equation 27 gives the predicted ion source plus neutralizer performance. When $f_n(E)$ is equal to one, the ion source power efficiency is obtained. The ion source power efficiency can also be expressed by

$$\eta_{ip} = \frac{EI}{P_{max}} \tag{32}$$

Solving for P_{max} and using the predicted trend for η_{ip} in Equation 8a yields the power efficiency as a function of beam energy and component properties

$$\eta_p = \frac{f_n f_t}{\frac{1}{\bar{\eta}_s}\left[1 + \frac{2.5}{E} + .075\right] - \bar{\eta}_s \eta_D f_+} \qquad (33)$$

Figure 6 contains the power efficiency plotted against beam energy for positive ion-based neutral injectors. The fraction of the charged beam leaving the neutralizer, which is available for direct conversion, was taken as the part of beam at full energy. This is consistent with the use of simple versions of direct converters. Figure 6 indicates that the injector efficiency is low at 200 keV even with direct-converter power recovery. The power efficiency is also very sensitive to the transfer system efficiency. Overall storage or conversion efficiencies of around 70% are needed for efficient injectors.

Equation 29 indicates that the positive ion-based injector power efficiency is expected to remain fairly constant as the injector power is increased and other component properties kept constant. From the previous calculations the beam energy and transfer system efficiency will cause the largest variation in the injector power efficiency.

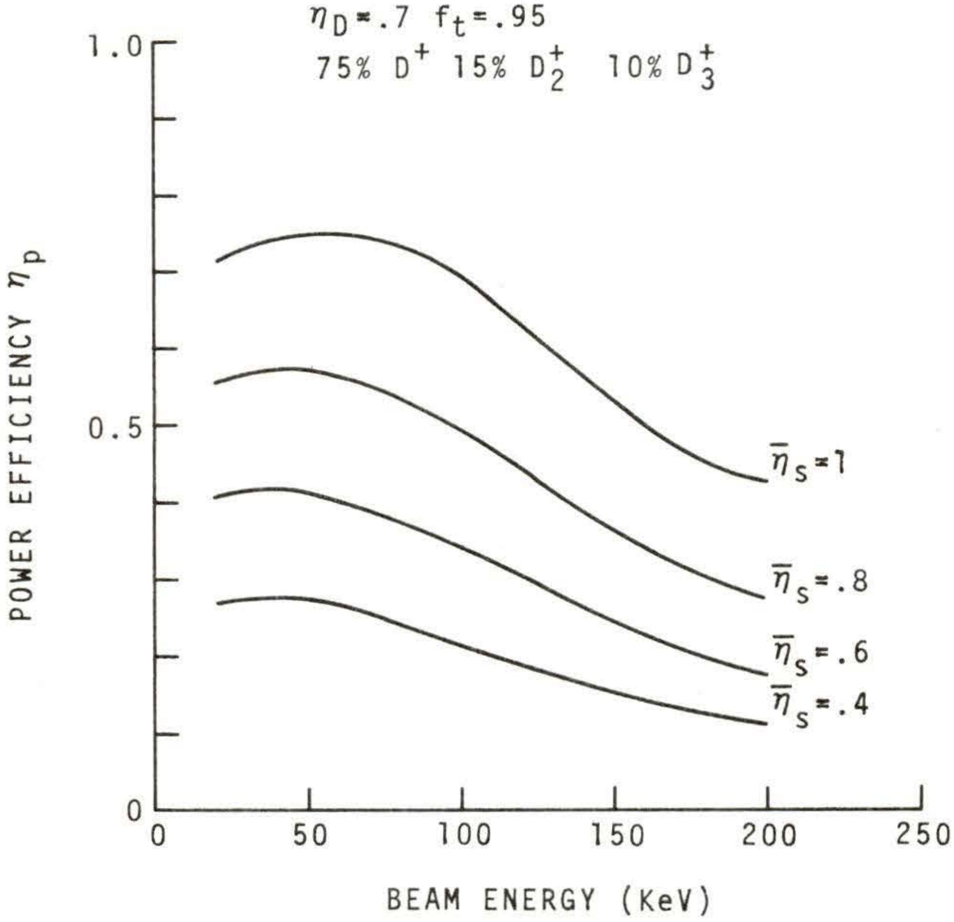

Figure 6. Predicted power efficiency vs. beam energy for positive ion-based injectors

To determine the variation of injector electrical efficiency with injected energy the electrical efficiency of the ion source must be known. Using Equation 31, the maximum energy used by the ion source can be given by

$$E_{max} = \frac{EIt_i \text{ (MJ)}}{.2666 \text{ Log } EIt_i \text{(MJ)} - .6937} \tag{34}$$

This equation is valid from .01 to .63 MJ. For injected energies greater than .63 MJ, η_e is expected to asymptotically approach an average power efficiency of 90%. Figures 7 and 8 contain plots of Equation 9a with the appropriate values of E_{max} substituted. The two variables are the beam energy and transfer system efficiency. The dashed lines in both figures represent the approximate points where the pulse times are too short to be practical. Also included are the maximum attainable electrical efficiencies. This is just the power efficiency read off Figure 6 using the appropriate beam energy and transfer system efficiency. Results indicate that injectors of 60, 120, and 180 keV need an injected total energy greater than 10 MJ to realize their full efficiency. This corresponds to pulse lengths of about 10 seconds for the above energies. An injector having a beam energy of 240 keV would reach maximum efficiency in a relatively short pulse length, but would have a poor electrical efficiency. Energy transfer system efficiencies below 80% will seriously reduce the

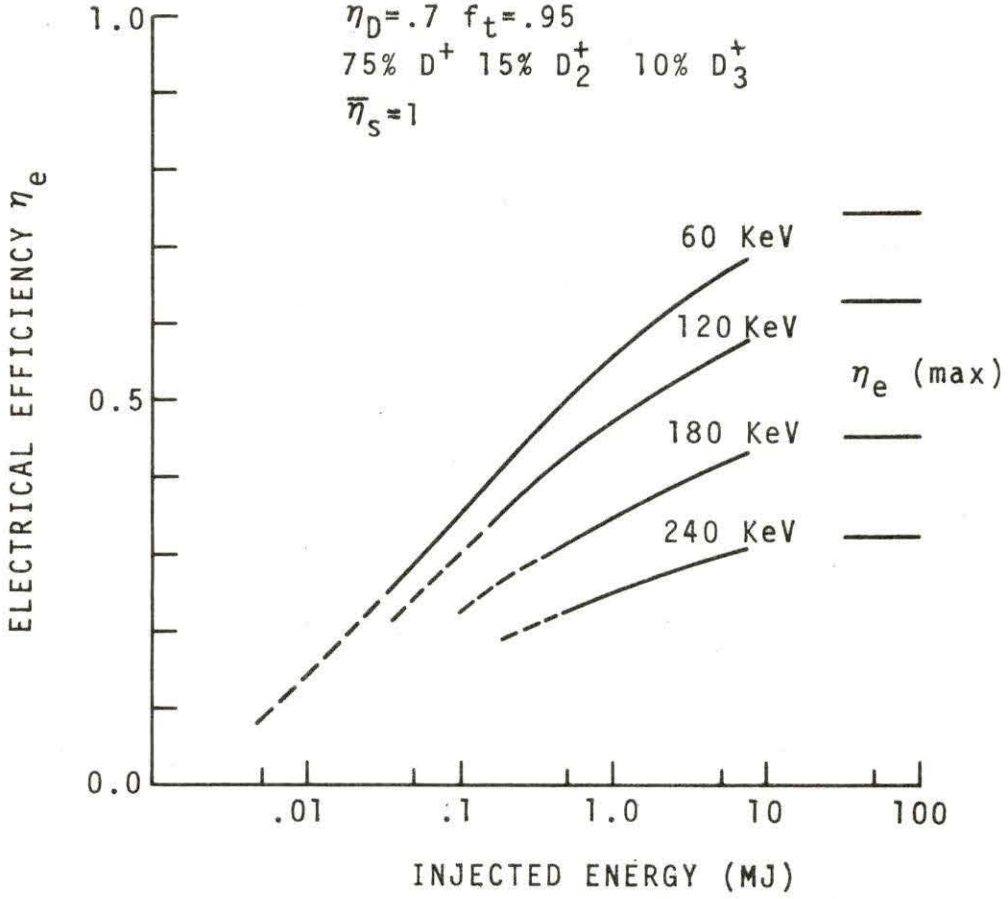

Figure 7. Predicted electrical efficiency vs. injected energy for positive ion-based injectors

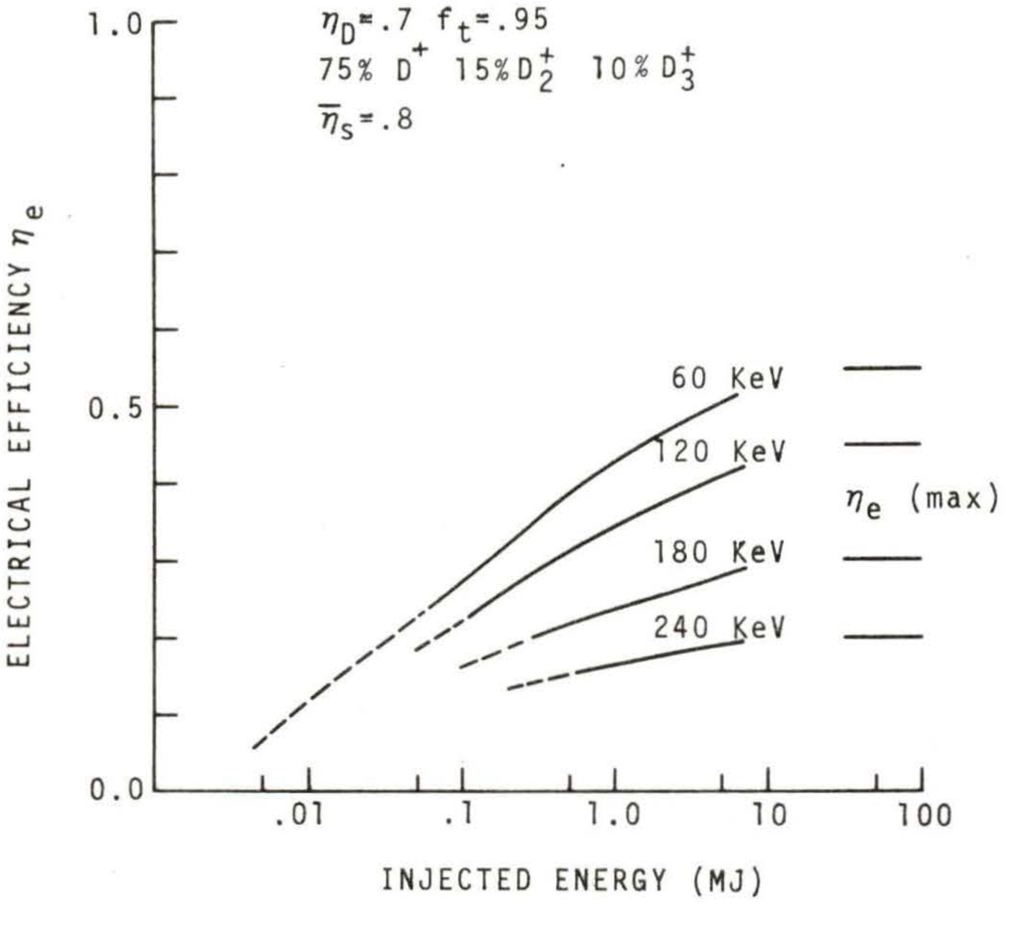

Figure 8. Predicted electrical efficiency vs. injected energy for positive ion-based injectors

electrical efficiencies.

The last single-charge exchange injector to be considered is a negative ion source with a gas neutralizer. Since large scale negative ion sources have not been developed, it is necessary to pick values for the ion source power efficiency and assume that it remains constant over the range of beam energies. Substituting P_{max} from Equation 32 into Equation 8a yields

$$\eta_p = \frac{f_n f_t}{\dfrac{1}{\eta_{ip}\bar{\eta}_s} - \bar{\eta}_s \eta_D f_+} \qquad (35)$$

Figure 9 contains plots of power efficiency versus beam energy for various values of η_{ip} and $\bar{\eta}_s$. The fraction of the power leaving the neutralizer that is available for direct conversion was taken to be the entire charged portion. Figure 9 indicates that fairly low ion source efficiencies can be tolerated and that the injector power efficiency remains nearly constant over a large range of beam energies. No information can be given on the electrical efficiency of the negative ion-based injectors.

B. Double-Charge Exchange Injector

The double-charge exchange injector is a method of taking advantage of the high neutralization efficiency of D^- ions.

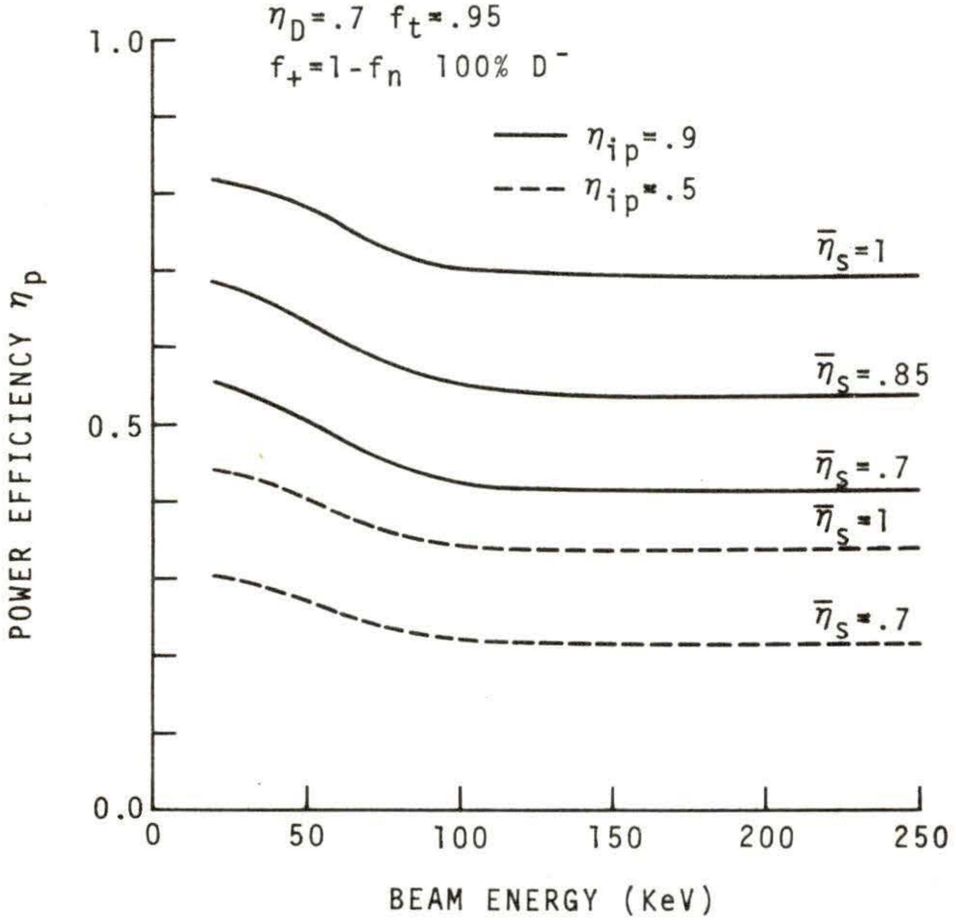

Figure 9. Predicted power efficiency vs. beam energy for negative ion-based injectors

The following model has been adopted to represent a developed injector.

A high current positive ion source is used to produce $E' = 2\text{keV}$ ions with a power efficiency of 90%. The positive ions are focussed on a vapor cell where partial double-charge exchange conversion occurs. The second accelerator stage increases the negative ion beam energy to E(keV), while losing 7% of the beam power. The effective power multiplication factor for the second accelerator stage is then

$$m_a = \frac{.93\ E}{E'} \tag{36}$$

The total source power efficiency can then be written as

$$\eta_{ip} = \frac{1 + .93\eta_m(m_a - 1)}{1.11 + \eta_m(m_a - 1)} \tag{37}$$

Other necessary information is the power recovered by the thermal converter at the vapor cell outlet. Assuming that 30% of the available power is recovered, and substituting the above information into Equation 16a gives the injector power efficiency

$$\eta_p = \frac{\dfrac{\eta_m(.93\ m_a + .07)f_n f_t}{1.11 + \eta_m(m_a - 1)}}{\bar{\eta}_s} - \dot{P}_r \tag{38a}$$

where

$$\dot{P}_r = \bar{\eta}_s[(1 - \eta_m)(.3) + \eta_m(.93m_a + .07)\eta_D f_+] \qquad (38b)$$

Figure 10 contains plots of Equation 38a for various values of η_m and $\bar{\eta}_s$. All the charged portion of the beam was available for direct conversion. Variations in the vapor cell power efficiency only slight effect the injector efficiency. This is evidenced by the fact that the two values of η_m in Figure 10 produce nearly the same injector efficiency for most beam energies. However, the injected neutral beam power is proportional to the efficiency of the vapor cell, requiring high current positive ion sources if η_m is small. Similar to the previous injector types, a transfer system efficiency greater than 75% is needed for good injector power efficiencies.

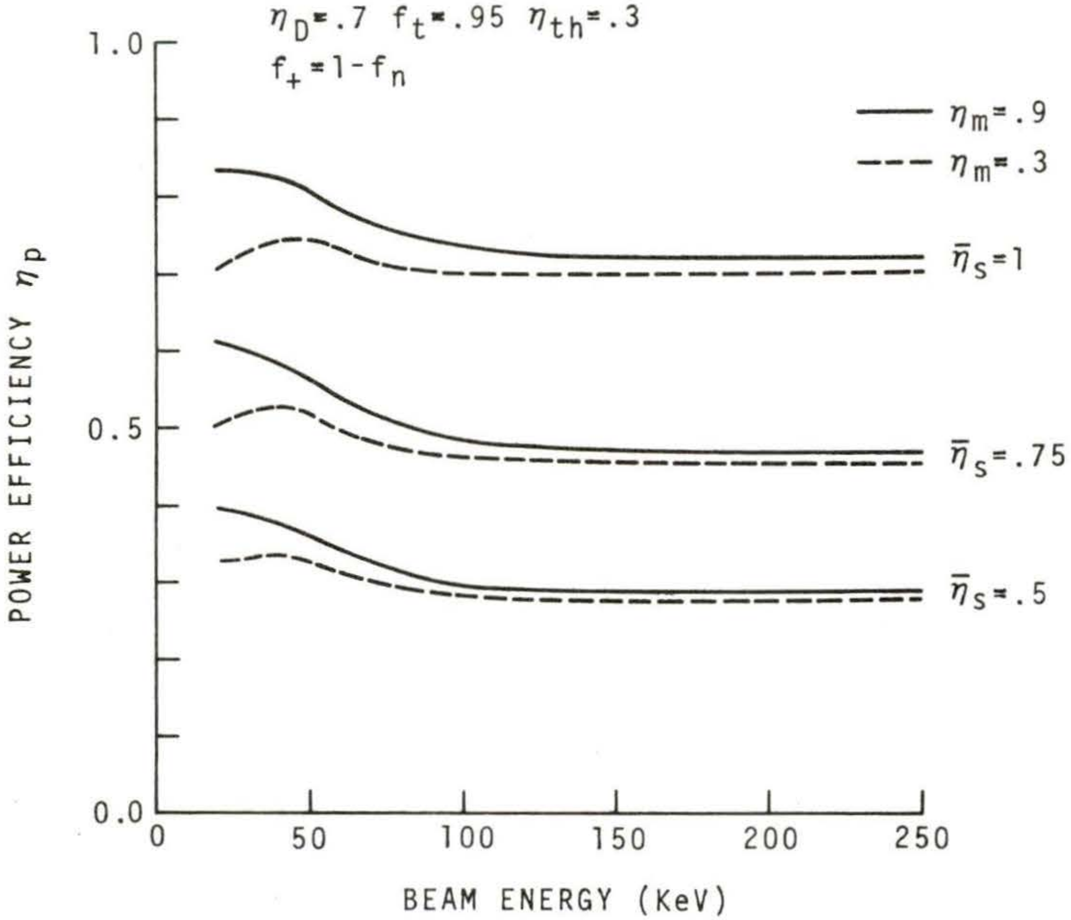

Figure 10. Predicted power efficiency vs. beam energy for double-charge exchange injectors

VII. CONCLUSIONS AND SUGGESTIONS FOR FUTURE WORK

A. Conclusions

The recommendations for the most efficient injectors can be grouped according to the beam energy. The groups consist of beam energies greater than or less than 100 keV.

1. Positive and negative ion neutralization have similar efficiencies for beam energies less than 100 keV. Since reasonably powerful and reliable positive ion sources have been developed in that energy range, no added benefits will be realized with the use of other source types. Above 100 keV the efficiency of positive ion-based injectors falls rapidly. However, if a maximum injector power efficiency of about 50% can be tolerated, beam energies approaching 200 keV can still be employed.
2. Negative ion-based and double-charge exchange injectors have the highest power efficiencies for beam energies above 100 keV. For both types, the injector power efficiency is essentially independent of the neutralizer, because the negative ion neutralization efficiency is nearly constant from 100 to 1,000 keV. In addition, the double-charge exchange injector is likely to have less neutral

beam power than the negative ion-based type.

Besides the mentioned recommendations, some important observations from this study are:

1. The actual positive ion source power efficiencies were found to be slightly lower than the predicted values.
2. Injector power efficiencies will be greater than 80% only for low beam energies and transfer system efficiencies near 100%.
3. Negative ion-based and double-charge exchange injectors are likely to have electrical efficiencies less than the corresponding power efficiencies for short pulse lengths.
4. Transfer system efficiencies have a significant effect on all injector types. A transfer system efficiency less than 80% will reduce most injector power efficiencies to 50% or less.

B. Suggestions for Future Work

The following are suggestions for future work related to this study:

1. More data need to be collected on the power consumption of all the injector related components and methods to reduce the consumption during different injector operating modes.

2. A more exact model needs to be developed to predict the scaling effects of positive ion sources.
3. Theoretical or experimental studies have to be performed to design and predict the efficiency of the beam direct converter at all beam energies.

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