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MIXED SPECIES IN INTENSE NEUTRAL BEAMS*

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ABSTRACT

Present high-current ion sources for neutral injection experiments accelerate a mixture of atomic and molecular hydrogen species that are converted into neutral particles with different energies and neutralization efficiencies. Beam composition can have important effects on injection system efficiency, vacuum system design, and first-wall loading. Measured and inferred neutralization efficiencies for the LBL high-current sources are given.

INTRODUCTION

One way of maintaining a hot magnetically confined plasma is by injecting new, high-energy material into it. An intense high-energy neutral beam becomes ionized and trapped when it impinges upon a lower-energy plasma within the confinement field and not only replaces lost ions, but also heats the plasma. This approach is being used for Baseball II, 2XII, Ormak, ATC, and other machines around the world.

Neutral beam systems, now under discussion for fusion experiments and reactors, require tens to hundreds of megawatts of electrical power. The choice and control of the atomic and molecular ion species in the plasma source can have an important effect on the capital and operating costs, with or without recovery of the energy of the non-neutralized fraction of the beam. (In the former case, electrostatic energy recovery from a mono-energetic ion beam could be straightforward, but the necessity to disperse fractional energy beams would cause additional complexity.) The required amount of cold gas in the neutralizing cell varies with ion energy and species, and in turn affects the cost of the large vacuum system. Neutrals with different energies will be trapped at different plasma radii; in particular, low-energy atoms will be trapped at large radii and increase the power loading on limiters and first walls. Finally, we note that the trapping of an injected H_2 or D_2 molecule produces (by dissociation) an energetic atom that may escape to the wall.

BEAM SPECIES AND NEUTRALIZATION

Deuterium ions, in a deuterium arc or glow discharge, exist principally in four forms. The positively charged D^+, D_2^+, and D_3^+ atomic and molecular ions, and the negatively charged D^- ion. Each of these ions, when extracted from the plasma and accelerated to form a high-energy beam, may be electrically neutralized in part by capturing an electron from a neutral gas target, by dissociation, or by losing an electron to the target. For collisionally thick targets, the competition between electron-capture-and-loss collisions establishes an

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equilibrium balance of positive, negative, and neutral particles in the emerging beam.

For a beam which contains no molecular ions, the collision-induced changes in the various charge states of the beam are described by the set of equations

$$\frac{dF_i}{d\pi} = \sum_{j\neq i} F_j\sigma_{j,i} - F_i \sum_{j\neq i} \sigma_{i,j} \qquad i,j = D^+,\ D^0,\ D^-, \tag{1}$$

where F_i is the fraction of the beam in charge state i, $\sigma_{i,j}$ is the cross section for a collision in which the energetic particle changes its charge from i to j, and π is the target line density of the neutralizer (molecules/cm^2).

For a beam of diatomic molecules there are two such sets of equations, one for the molecular species and another for the atomic dissociation fragments at one-half the molecular energy:

$$\begin{aligned} \frac{dF_k}{d\pi} &= F_\ell\sigma_{\ell,k} - F_k\left(\sigma_{k,\ell} + \frac{1}{2}\sum_i \sigma_{k,i}\right) && k,\ell = D_2^+,\ D_2^0 \\ \frac{dF_i}{d\pi} &= \sum_{j\neq i} F_j\sigma_{j,i} - F_i \sum_{j\neq i} \sigma_{i,j} + \sum_k F_k\sigma_{k,i} && i,j = D^+,\ D^0,\ D^-. \end{aligned} \tag{2}$$

Here $\sigma_{k,i}$ is the cross section for the production of the atomic species i from the molecular species k (e.g., production of D^0 from D_2^+). Since two atomic species result from the dissociation of one diatomic molecule, this definition of $\sigma_{k,i}$ yields the factor 1/2 in the molecular equation.

Likewise, for an initial beam of D_3^+ ions, there is one equation for the triatomic molecular ions (there is no reliable evidence of a stable D_3^0 molecule), a set of equations for the diatomic molecular dissociation fragments at 2/3 of the D_3^+ energy, and a third set for the atomic fragments at 1/3 of the D_3^+ energy:

$$\frac{dF_{D_3^+}}{d\pi} = -F_{D_3^+}\left(\frac{1}{3}\sum_i \sigma_{D_3^+,i} + \frac{2}{3}\sum_k \sigma_{D_3^+,k}\right)$$

$$\frac{dF_k}{d\pi} = F_\ell\sigma_{\ell,k} - F_k\left(\sigma_{k,\ell} + \frac{1}{2}\sum_i \sigma_{k,i}\right) + F_{D_3^+}\sigma_{D_3^+,k} \qquad \begin{aligned} k,\ell &= D_2^+,\ D_2^0 \\ i,j &= D^+,\ D^0,\ D^- \end{aligned}$$

$$\frac{dF_i}{d\pi} = \sum_{j\neq i} F_j\sigma_{j,i} - F_i \sum_{j\neq i} \sigma_{i,j} + \sum_k F_k\sigma_{k,i} + F_{D_3^+}\sigma_{D_3^+,i} \tag{3}$$

It is clear that for a particular neutralizer a host of cross-section data is required to determine the neutralization efficiency. These data are not always available for an arbitrary choice of neutralizers, so it is not possible at this time to do a systematic study. Enough sample calculations have been carried out, however, to indicate that D_2 is representative of the better gas neutralizers. (For D^- and the molecular ions, plasma targets

should be more efficient than gas neutralizers.[1] Such targets have not been tried yet and will not be discussed here.) Our choice of the appropriate cross sections for D_2, gleaned from the literature, is given in Table I. The cross sections and the uncertainty estimates in Table I are based on comparisons of various published values[2] of the same quantities, and on extrapolations if no measurements exist; they are not to be considered "best values", i.e., no evaluations of the various experiments have been made. (Note that most cross sections are not known very accurately.) As an example appropriate to energies assumed in calculations for two-component experiments, the neutralization efficiency vs D_2 target thickness obtained from Eqs. (1), (2), and (3) is shown in Fig. 1 for 200 keV/deuteron beams (200-keV D^+ and D^-, 400-keV D_2^+, and 600-keV D_3^+). The results are presented this way, since it is the deuteron which eventually will be trapped and heat the plasma. The horizontal scale is the target thickness for a D_2 neutralizer. The logarithmic vertical scale is the neutral power conversion efficiency, η (power in neutral beam/power in incident ion beam). For the incident molecular ions the power in the neutral beam is obtained by summing the contributions from 200-keV D^0 and 400-keV D_2^0.

The maxima at intermediate neutralizer thickness in the molecular-ion curves of Fig. 1 result from the presence of D_2^0 molecules which exist at low target thicknesses but are destroyed by dissociation in thick targets. These maxima become less pronounced at lower energies and disappear below about 130 keV/deuteron. At even lower energies (below about 75 keV/deuteron) the η vs π curves for the molecular ions lie below the D^+ curve, i.e., low-energy molecular-ion beams require larger values of π than do D^+ beams to achieve the same neutralization efficiencies. This effect is illustrated in Fig. 2, where we show the target thickness for "optimum" neutral production for the three species as a function of energy. (Optimum neutral production is defined as the maximum value of η if a maximum exists, otherwise it is 95% of the equilibrium η.) The curves cross over at about 75 keV/deuteron. Above this energy the molecular ions can be neutralized with thinner targets than can the D^+ ions.

The maximum neutralization efficiency for each species is shown as a function of energy in Fig. 3. At low energies, each beam produces the same result. It is only above about 75 keV that D^- starts to show any advantage, and above 130 keV/deuteron that D_3^+ or D_2^+ produces more neutral power than D^+. At higher energies, the D^- beam looks the best; however, since no one has yet produced an intense negative-ion beam at high energies, the rest of the discussion will deal exclusively with positive beams.

MIXED BEAMS

Positive-ion beams extracted from a deuterium plasma generally contain a mixture of all three positive ions. For example, the 10-A neutral beam source developed at LBL[3] typically produces a mixture of neutral particles from a 20-keV ion beam which is 75% D^+, 15% D_2^+, and 10% D_3^+. (The beam composition of the scaled up 50-A source[3] is probably similar, but has not been measured yet.) Alteration of the composition by a change in ion-source operating conditions has been explored only to a limited extent; e.g., when arc parameters were changed while the total beam power to a calorimeter plate was kept constant, it was possible to raise the D_2^+ fraction to 22% (67% D^+, 22% D_2^+, and 11% D_3^+), but it was not possible to increase the D^+ fraction appreciably. (When hydrogen is used in the source, the measured mixture is 60% H^+, 20% H_2^+, and 20% H_3^+.) Other kinds of high-current-density ion sources, e.g., the ORNL "duoPIGatron",[4] also produce mixed-species beams.

Unwanted ion species can, in principle, be rejected at low energy by a magnetic selection process. However, to minimize space-charge blowup, present

high-power-density beam systems have the neutralizer immediately following the last element of the extraction system. Consequently, no momentum selection of the ions is possible and the neutral beam (which represents about 90% of the beam power at 20 keV) is produced from all three ions. From the composition of the accelerated ion beam and Eqs. (1)-(3), we can calculate the neutral beam composition: With a 20-kV extraction potential, and a neutralizer thickness of $7 \times 10^{15}/cm^2$, the neutral-particle current composition is 57% 20-keV D^0, 21% 10-keV D^0, 19% 6.7-keV D^0, 1% 20-keV D_2^0, and 2% 13-keV D_2^0.

Let us now consider the neutralization efficiency of such a mixed-ion beam if it were accelerated to higher energies (by adding accelerating stages to the present source). Since the next large CTR experiments will require multi-megawatt beams of 30- to 80-keV H^0 or D^0 atoms, we will focus our attention on this energy range.

Tables II and III show calculated efficiencies for producing the desired D^0 and H^0 beams under various conditions as well as the power produced in neutrals of other energies. This power invested in neutrals other than the desired ones is important because lower-energy particles may be trapped at large radii and end up mostly as a load on the vacuum walls or the plasma limiters.

The top line of each section of the tables shows what could be achieved with a pure deuteron or proton beam of the desired energy. This is followed by the efficiency we could achieve with actually observed mixtures of the various beam components at two different accelerating voltages. The achievable neutral power is given at two reasonable neutralizer thicknesses: 5×10^{15} molecules/cm^2 and 10^{16} molecules/cm^2 (for 80-keV H^0 production the target thicknesses have been increased to 10^{16} and 2×10^{16} molecules/cm^2).

In the last column we show the beam current that the ion source must produce in order to obtain 1 MW of neutral power at the specified energy; this is a lower limit, since it assumes that the beam optics are good enough to deliver the beam with 100% efficiency through beam-line apertures.

DISCUSSION

In Fig. 4 we show an example of the power flow in a neutral beam system where 1 MW of 80-keV D^0 atoms is desired. We assume the ion species composition of an LBL source[3] (we do not know of any high-current ion sources with more favorable ion species composition). Assuming no losses, the ion-beam power must be 2.1 MW extracted from the ion source. Following the neutralizer (thick enough to give at least 95% of the equilibrium D^0 fraction), 0.65 MW is in positive ions that must be dumped on some surface. From an economic standpoint, it is desirable to recover the energy of the ion beam, e.g., by electrostatic deceleration;[5] from an engineering standpoint it would be much easier if essentially all of the ions had the same momentum.

Of the 1.45 MW in the neutral beam--again assuming no losses due to some of the neutral beam striking apertures--1 MW is at the desired energy, and 0.45 MW is at lower energies. Since the neutral-particle penetration thickness (ions/cm^2) in a fusion-experiment plasma is approximately proportional to the neutral energy for a given species,[6] lower-energy neutrals will be trapped at larger radii, and may be lost rapidly to the wall (e.g., by charge exchange).

The possibility of having nearly monoenergetic neutral atomic beams is clearly desirable, and the need for research toward this end is indicated. There may be ways to enhance the D^+ fraction in an ion source, e.g., by constructing the arc chamber and gas feed lines of heated tungsten; but for the

present, realistic mixtures of species must be considered when mating neutral beam systems with CTR confinement devices.

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TABLE LEGENDS

Table I. Cross sections[2] used in calculations (10^{-17} cm^2/D_2 molecule).

Table II. Neutralization efficiencies for the production of 30-, 40-, and 80-keV D^0 beams from ion beams containing D^+, D_2^+, and D_3^+.

Table III. Neutralization efficiencies for the production of 30-, 40-, and 80-keV H^0 beams from ion beams containing H^+, H_2^+, and H_3^+.

Table I

Cross Sections for Calculations

(10^{-17} cm^2/D_2 molecule)

	D^+		D^0		D^-		D_2^+			D_2^0			D_3^+			
Energy keV/deut	σ_{10}	σ_{1-1}	σ_{01}	σ_{0-1}	σ_{-10}	σ_{-11}	$\sigma_{D_2^0}$	σ_{D^0}	σ_{D^+}	$\sigma_{D_2^+}$	σ_{D^0}*	σ_{D^+}	$\sigma_{D_2^0}$	$\sigma_{D_2^+}$	σ_{D^0}	σ_{D^+}
10	83	0.13	8.0[b]	1.6	100	8.5	46	74	22	7.7	25	3.3	35	11	72	11
20	80	0.45	9.3[a]	2.5	108	9.0	36	83	22	12	(17)	4.9	41	12.5	91	16
50	47	0.80	13	1.6	85	8.5	16	63	24	19	(9.5)	7.0	30	10.8	83	21
100	17	0.10	14	0.75	65	8.0	4.3	35	24	19	(7.3)	6.9	10	8.2	50	24
200	2.5[a]	0.01	10.8	(0.25)	47	(7.2)	0.7	13[c]	19	15	5.0	5.8	3.5	5.6	25	22.3
500	0.046[a]	(0)	6.0	(0.06)	25	(6.0)	(0.04)	3.7[c]	10	7.0	3.2	3.8	1.1	3.0	13	15
1000	0.0012	(0)	3.3	(0.02)	15	(5.2)	(0.006)	2.0[c]	5.6	4.2	2.2	2.4	0.63	1.8	6.5	7
Estimated uncertainties	±10%	±30%	±10%	±20%	±15%	±10%	±10%	±10%	±20%	±20%	±25%	±25%	±20%	±15%	±10%	±10%

Estimated uncertainties are as shown under each column except as noted.

[a] ±15%

[b] +10-50%

[c] ±20%

() Parentheses indicate extrapolations or interpolations where no uncertainty can be assigned.

σ_{ij} (i,j = 1,0,-1) indicates cross section for change from charge state i to j.

σ_{D^0}, σ_{D^+}, etc. symbolize cross sections for the production of D^0, D^+, etc.

*Reaction $D_2^0 \rightarrow D^0 + D^+$ only.

Table II

Desired D atom energy (keV)	Ion beam composition (%)			Accelerator voltage (kV)	Fraction of power neutralized (%)				Required amperes from ion source to produce 1 MW neutral power at the desired energy
					$\pi = 5 \times 10^{15}$ mol/cm^2		$\pi = 10^{16}$ mol/cm^2		
	D^+	D_2^+	D_3^+		at desired energy	at other energies	at desired energy	at other energies	
30	100			30	83		84		40
	75	15	10	30	62	22	63	23	53
	67	22	11	60	18[a]	55	19[b]	58	88
40	100			40	80		83		30
	75	15	10	40	60	22	62	22	40
	67	22	11	80	17[c]	46	18[d]	51	69
80	100			80	56		62		20
	75	15	10	80	41	20	46	21	27
	67	22	11	160	12[e]	22	13[f]	26	48

(a) includes 3.5% of beam power in 60 keV D_2

(b) includes 1.5% of beam power in 60 keV D_2

(c) includes 3% of beam power in 80 keV D_2

(d) includes 1% of beam power in 80 keV D_2

(e) includes 4% of beam power in 160 keV D_2

(f) includes 3% of beam power in 160 keV D_2

Table III

Desired H atom energy (kev)	Ion beam composition (%)			Accelerator voltage (kV)	Fraction of power neutralized (%)				Required amperes from ion source to produce 1 MW neutral power at the desired energy
					$\pi = 5 \times 10^{15}$ mol/cm^2		$\pi = 10^{16}$ mol/cm^2		
	H^+	H_2^+	H_3^+		at desired energy	at other energies	at desired energy	at other energies	
30	100			30	68		71		47
	60	20	20	30	41	33	43	36	78
	60	20	20	60	13[a]	35	14[b]	41	119
40	100			40	56		63		40
	60	20	20	40	33	32	37	34	68
	60	20	20	80	11[c]	24	13[d]	30	96
					($\pi = 10^{16}$ mol/cm^2)		($\pi = 2 \times 10^{16}$ mol/cm^2)		
80	100			80	25		29		43
	60	20	20	80	15	28	18	28	69
	60	20	20	160	6.4[e]	12	6.3	13	98

(a) includes 4% of beam power in 60 keV H_2

(b) includes 2% of beam power in 60 keV H_2

(c) includes 2.5% of beam power in 80 keV H_2

(d) includes 1% of beam power in 80 keV H_2

(e) includes 1% of beam power in 160 keV H_2

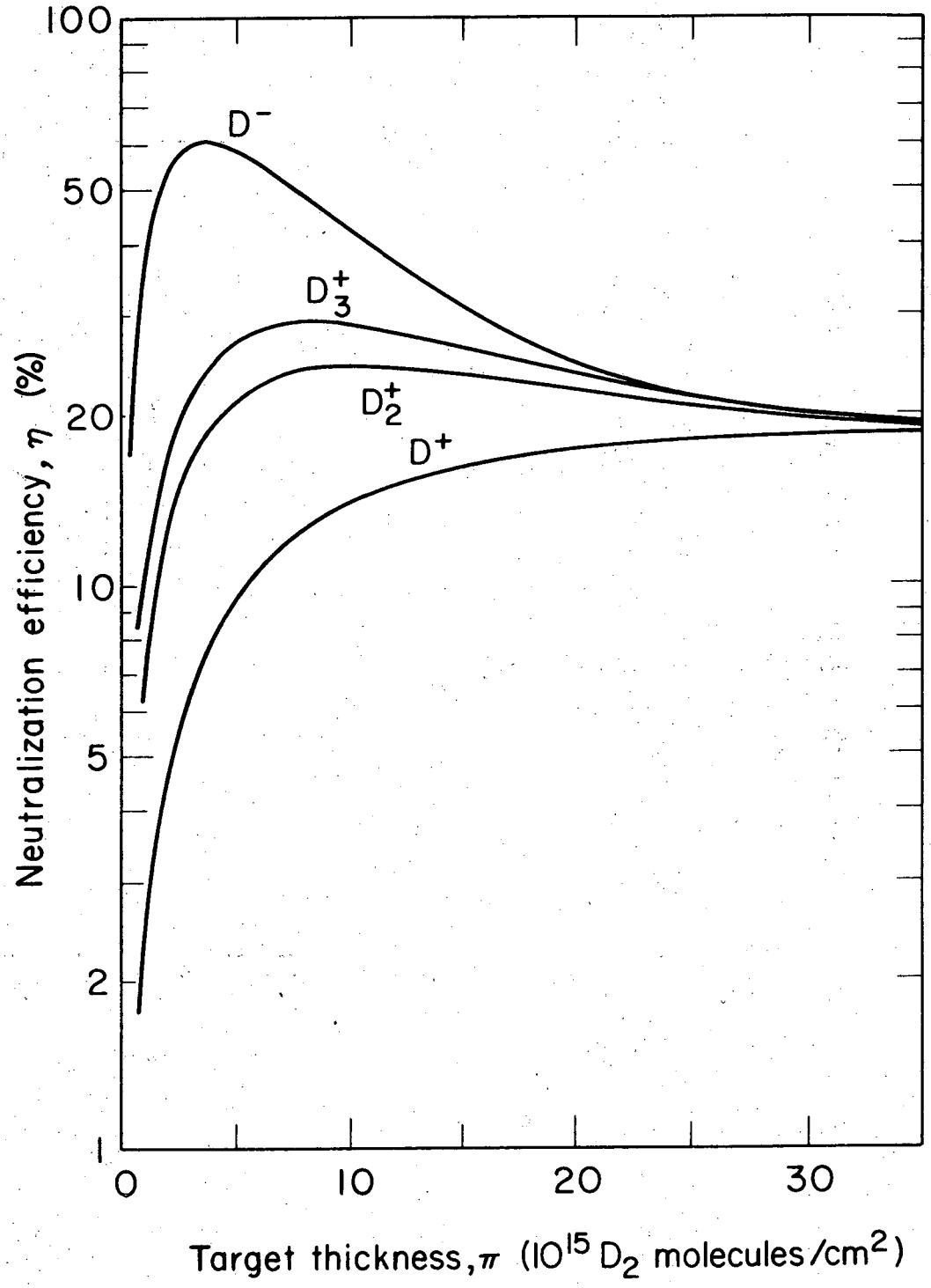
FIGURE LEGENDS

Fig. 1. Neutralization efficiency η (power in neutral beam/power in initial ion beam) vs D_2 neutralizer thickness for each of the four beams; 200-keV D^+, 400-keV D_2^+, 600-keV D_3^+, and 200-keV D^-.

Fig. 2. Neutralizer thickness for optimum neutral production vs beam energy for each of the three beams D^+, D_2^+, and D_3^+. Where no maximum in η vs π exists we choose π for 95% of equilibrium η.

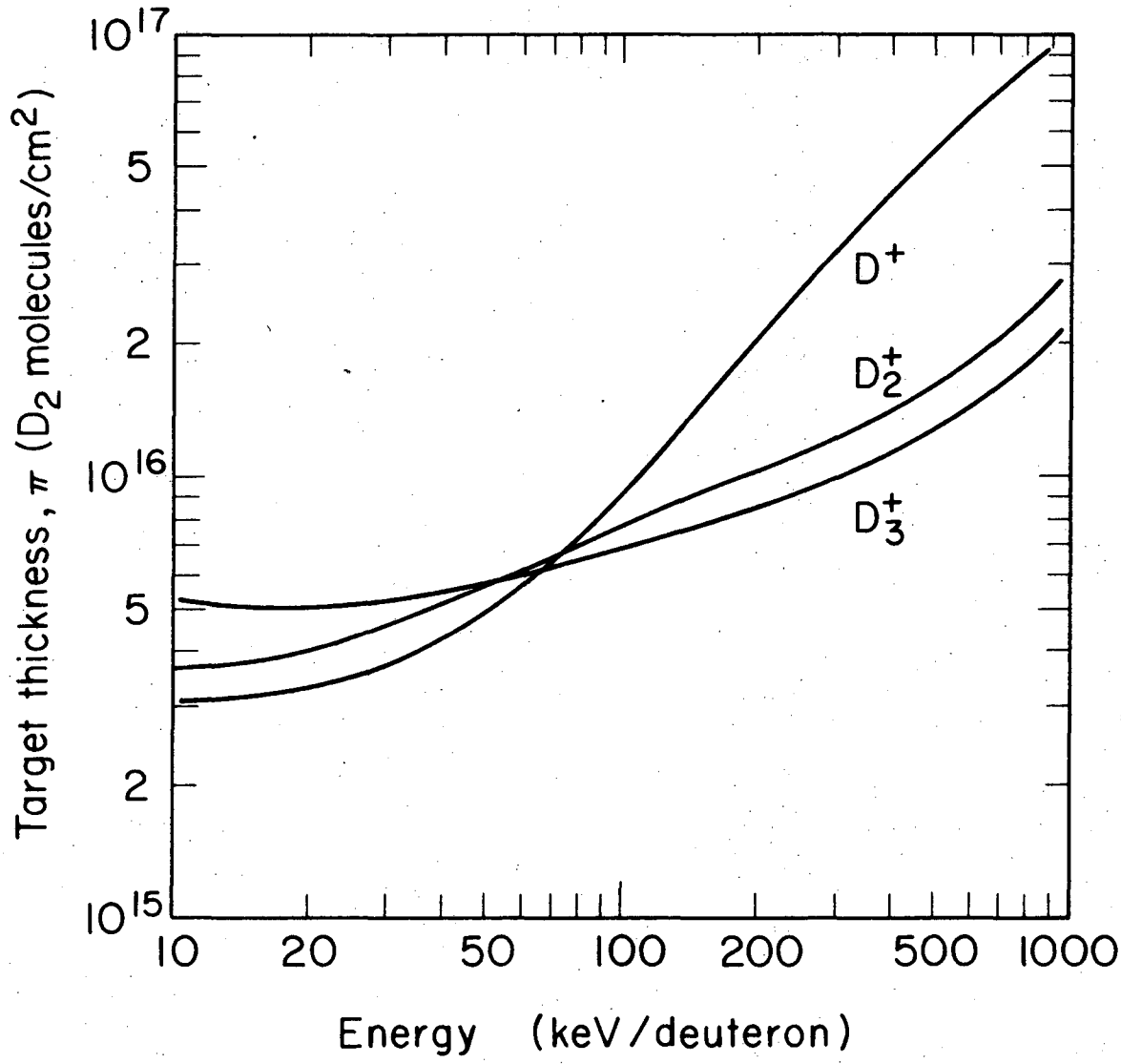
Fig. 3. Maximum neutralization efficiency in D_2 vs beam energy, for each of the four beams, D^+, D_2^+, D_3^+, and D^-.

Fig. 4. Power flow diagram for a 1-MW, 80-keV D^0 injection system. (The ion species composition of an LBL source has been assumed.) Estimates for relative penetration thicknesses, P.T. (ions/cm^2), were obtained from Sweetman.[6]



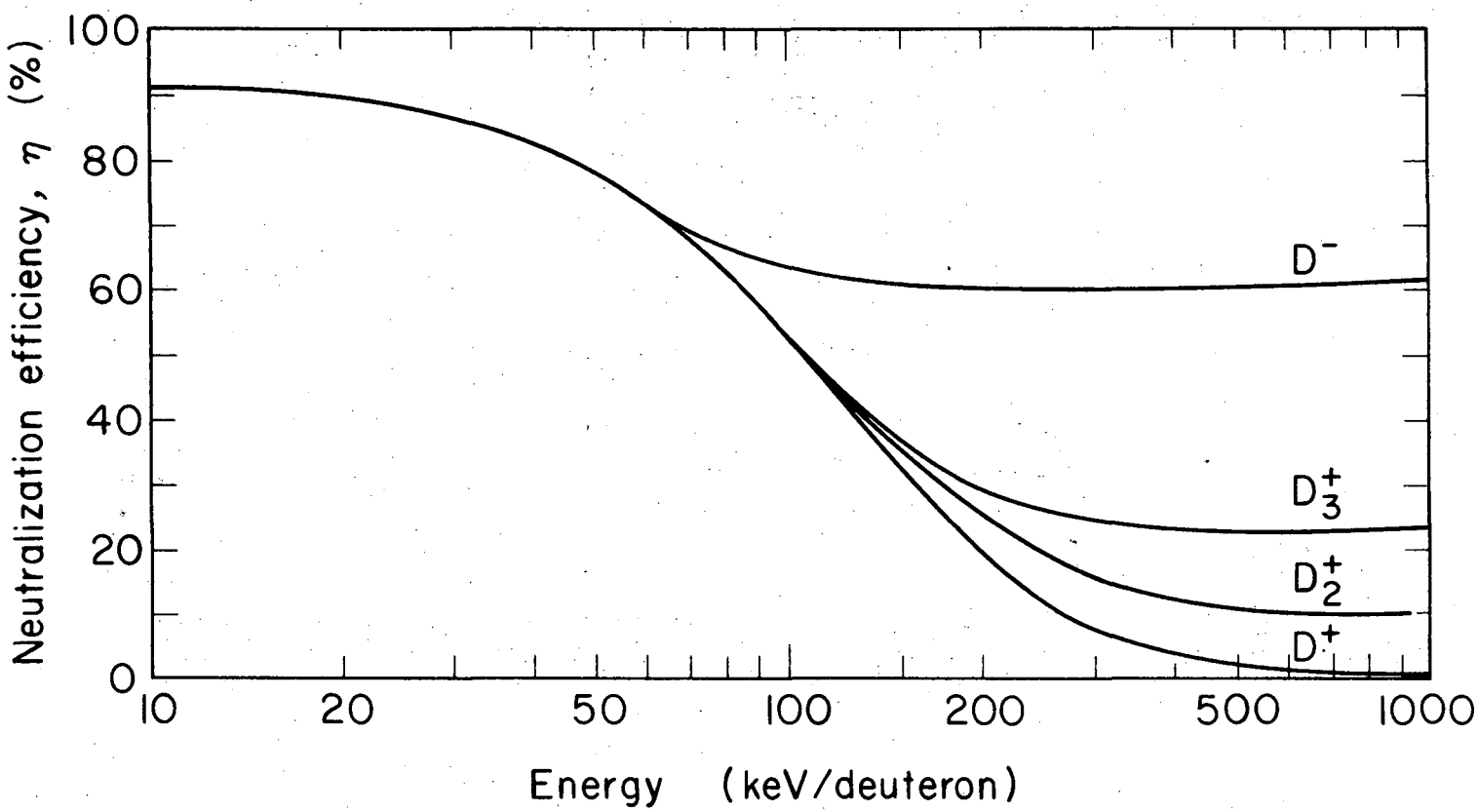
XBL 743-2708

Fig. 1.



XBL 743-2710

Fig. 2.



XBL 743-2709

Fig. 3.

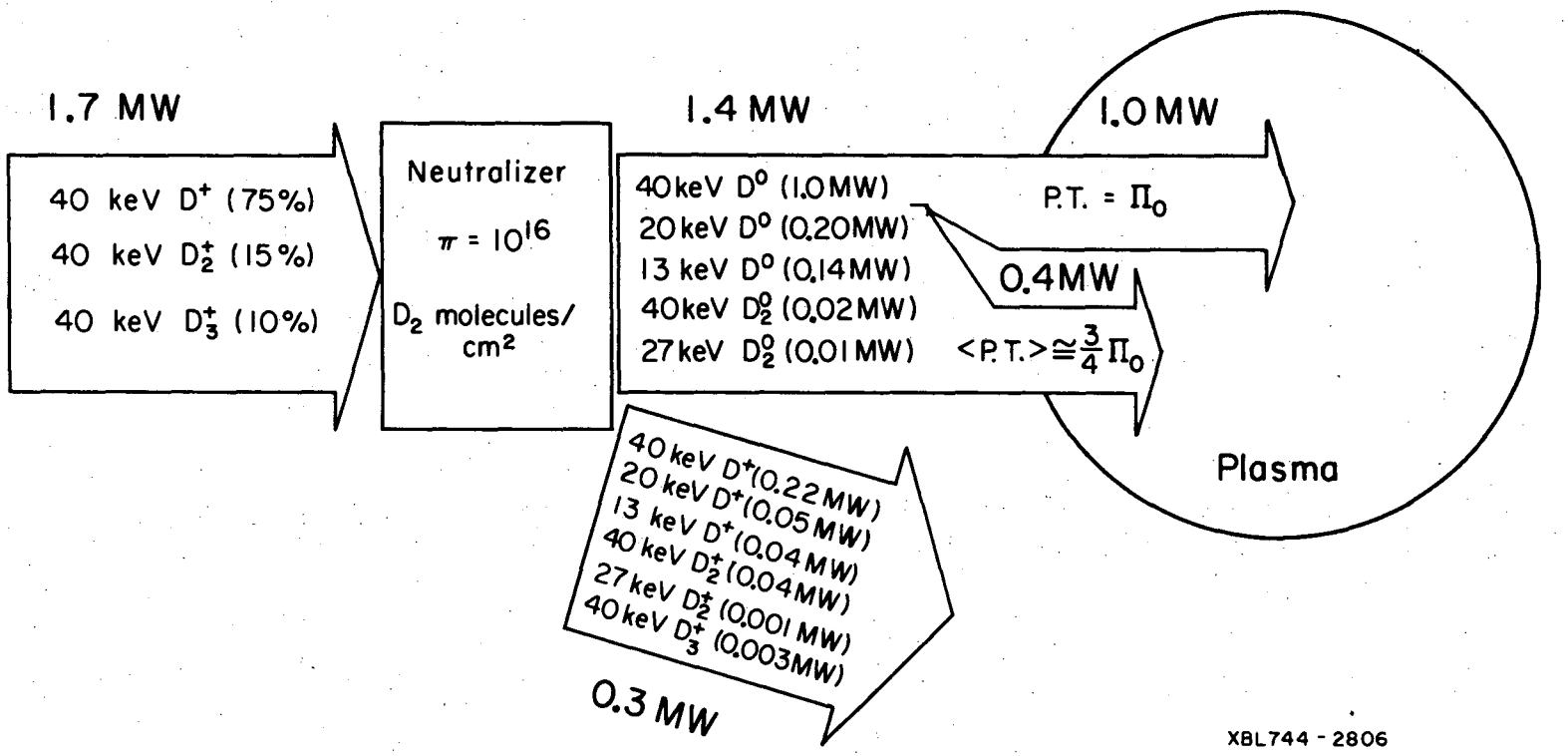

1.7 MW
40 keV D+ (75%)
40 keV D2+ (15%)
40 keV D3+ (10%)
Neutralizer
π = 10^16
D2 molecules/cm2
1.4 MW
40keV D0 (1.0MW)
20keV D0 (0.20MW)
13 keV D0 (0.14MW)
40keV D20 (0.02MW)
27keV D20 (0.01MW)
1.0MW
P.T. = Π0
0.4MW
<P.T.> ≅ 3/4 Π0
Plasma
40 keV D+(0.22MW)
20 keV D+(0.05MW)
13 keV D+(0.04MW)
40 keV D2+(0.04MW)
27 keV D2+(0.001MW)
40 keV D3+(0.003MW)
0.3 MW
XBL744-2806

Fig. 4.

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