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ENERGETIC PARTICLE BEAMS AND FUSION DEVICES

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ABSTRACT

Energetic neutral beams are being considered both for filling and heating fusion devices. Rough estimates of beam current and energy are derived for open and closed magnetic geometries. In addition, the use of beams to effect energy multiplication schemes or stationary Tokamak experiments are briefly summarized. The problems of neutral beam production as a function of beam energy and ion specie is also discussed. The state-of-the-art for ion beam production at ORNL concludes the report.

INTRODUCTION

An energetic beam is a prime candidate for filling and/or heating existing and proposed fusion devices. The purpose of this paper is to tabulate the beam requirements estimated by various researchers and to show the relevance of the energetic beam development work in the ORNL Controlled Thermonuclear Research Program to the desired goals.

I. Mirrors

Many people,[1,2,3] have contributed to the consideration of filling a magnetic mirror by beam injection. One may estimate the beam current and energy requirements by considering the rate equation for a D,T reaction. For example (50% D, 50% T).

$$\frac{dn_i}{dt} = S_i - n_i^2 \frac{\langle \sigma v \rangle}{2} - \frac{n_i}{\tau_i} \qquad (1)$$

where S_i = injected current density,

$n_i^2 \frac{\langle \sigma v \rangle}{4}$ = time rate of change on ions/volume by fusion (2 ions burned/fusion),

τ_i = ion confinement time, and n_i/T_i = loss rate.

At equilibrium

$$\frac{dn_i}{dt} = 0$$

and

$$S_i = \frac{n_i^2 \langle \sigma v \rangle}{2} + \frac{n_i}{\tau_i} \, .$$

The fractional burnup,

$$f = \frac{S_i - L}{S_i} = \frac{1}{1 + \frac{2}{n_i \tau_i <\sigma v>}} \approx \frac{1}{2} n_i \tau_i <\sigma v> = \frac{\tau_i}{2\tau_f} \quad (2)$$

where $\tau_f \equiv (n_i <\sigma v>_f)^{-1}$.

For a mirror at temperatures below several hundred keV, $f < 1\%$ and

$$S_i \approx \frac{n_i}{\tau_i} .$$

The injected current I is

$$I = S_i \; Ve = \frac{n_i Ve}{\tau_i} , \quad (3)$$

where V = plasma volume.

From Fokker-Planck calculations we have[4]

$$n_i \tau_i = 4.6 \times 10^{11} \; \frac{T^{3/2} \log R}{\ell n \; \Lambda}$$

where T is in keV.

When R=3, $\ell n \Lambda = 15$ we obtain

$$n_i \tau_i = 1.5 \times 10^{10} \; T^{3/2} .$$

Substituting in (3) we find

$$I = \frac{n_i^2 Ve}{1.5 \times 10^{10} \; T^{3/2}} .$$

In terms of fusion power, P_f

$$P_f = \frac{1}{4} n_i^2 <\sigma v> Q \; Ve,$$

where Q is in eV. we have

$$I = 2 \times 10^{-2} \; \frac{P_f}{T^{3/2}}$$

where $Q = 1.7 \times 10^7$ eV and

$\langle\sigma v\rangle = 8 \times 10^{-16}$ cm^3/sec, a rough average over the high energy range of T tabulated in Table 1 and likely for mirror reactors.

The resulting values of I for the indicated values of P_f and T are shown in Table 1.

Table 1. Power Requirements for Mirror Reactor

$P_f(MW_{th})$	T(keV)	I(kA)	$P_{injected}/P_f$
10^4	100	200	2
	400	25	1
	1000	6	0.6
10^3	100	20	2
	400	2.5	1
	1000	0.6	0.6
10^2	100	2	2
	400	0.35	1
	1000	0.06	0.6

One concludes that hundreds to thousands of amps are required at energies greater than or equal to 100 keV. Since high magnetic fields are present, these beams will have to be neutral atoms. Production of the beams and problems in converting ions to neutrals are considered in Section III. The ratios of $P_{injected}$ to P_f shown in Table 1 result in a pessimistic view on mirror fusion reactors. The situation is even worse when one considers thermal efficiency and beam injection efficiency.

R. F. Post[5] argues that direct conversion of the mirror losses may make a mirror device economically feasible. However the efficiency of direct conversion has not yet been experimentally determined.

II. Tori

Unlike the mirror, we start with a dense, relatively cold plasma which is to be heated by injection of energetic ions. The rate of heating of the plasma electrons and ions can be written[6] as

$$\frac{dT_e}{dt} = \gamma\frac{\eta J^2}{n} + K_1 \frac{E_o I}{nVe} - K_2 \frac{T_e - T_i}{\tau_{ei}} - K_3 T_e^{3/2} \qquad (4)$$

$$\frac{dT_i}{dt} = K_2 \frac{T_e - T_i}{\tau_{ei}} + K_4 \frac{E_o I}{nVe} - \frac{T_i}{\tau_E} \qquad (5)$$

Here we find the first term of Eq. (4) to be the rate of ohmic heating, the second term the energy transfer to electrons from beam ions, the third term the energy loss rate to ions and the last term represents the bremsstrahlung loss. Equation (5) has a similar set of terms except the ion energy loss rate is due to ion thermal conductivity as given by the GSK theory.

To find an approximate solution to these equations we over simplify, set $T_e = T_i$, and obtain the steady state solution for fixed T_i:

$$I = \frac{nVeT_i}{K_4 E_o \tau_E}. \qquad (6a)$$

Here K_4 is the fraction of energy from beam ions transferred to plasma ions which can be obtained from Sigmar and Joyce[7] as a function of temperature. Since the product of energy confinement time and plasma density must exceed the Lawson limit, where we assume the particle confinement time is equal to or greater than the energy confinement time, then

$n\tau_E \gtrsim 2 \times 10^{14}$. While this Lawson limit is a function of temperature, it has a broad minimum near 25 keV.

With this as a basis we can use the fusion power as a scaling point to substitute in (6a) for n_i^2

$$I = \frac{4P_f}{<\sigma v>Q} \quad \frac{T_i}{K_4 E_o n\tau_E} . \tag{6b}$$

As stated above, K_4 is not constant. However, putting $T_e \approx T_i$ is a simplification which neglects energy transfer from electrons to ions. Within the desired accuracy of our calculation, we put $K_4 \approx 0.5$ for the range of E_o considered. Inserting numbers for a DT reaction where again we take $Q = 1.7 \times 10^7$ eV and allow $<\sigma v>$ and $n\tau_E\big|_{\text{Lawson}}$ to vary with T_i we find that $T_i/(<\sigma v>n\tau_e)$ is approximately constant in the range $10 \lesssim T_i \lesssim 20$ keV. This means that P_{injected}/P_f is approximately constant and is about 0.14 in this range. Table 2 shows the current and power requirements gotten in this way and indicates the necessary power for heating a toroid is an order of magnitude less than for filling mirror reactors with the same power output.

Table 2. Power Requirements for Toroidal Reactors with 10 keV $\lesssim T_i \lesssim$ 20 keV.

$P_f(MW_{th})$	T(keV)	I(kA)	$P_{injected}/P_f$
10^4	100	14	.14
	400	35	.14
	1000	1.4	.14
10^3	100	1.4	.14
	400	0.35	.14
	1000	0.14	.14
10^2	100	0.14	.14
	400	0.035	.14
	1000	0.014	.14

Many considerations enter when trying to optimize the plasma density. Time dependent solutions of Eqs. (4) and (5) suggest that low densities (3.5×10^{13} cm^{-3}) are more desirable for ohmic ignition; also low densities are desirable because of radiation damage effects on the walls. On the other hand, increasing the density causes the injected current to decrease for fixed reactor power as can be seen from Eq. (6b). Other effects such as trapping length and fueling suggest additional criterion for injection. For instance, Riverie[8] shows that to obtain sufficient penetration of neutral particles for fueling, beam energies of 1 MeV are required. At these energies, the conversion of ion beams to neutral beams is a problem and will be discussed in Section III.

D.C. Tokamak

In 1969, Ohkawa[9] proposed using beams to produce the toroidal current where the beams would augment or substitute for the azimuthal electric field produced initially by a transformer. The ohmic current to be maintained decays because of the momentum loss between electrons and ions via Coulomb collisions. An electric field driven by a changing flux is required to maintain this current. By considering injection of a high and low energy beams in opposite directions, Ohkawa derives the currents necessary for the plasma electrons and ions to receive momenta through Coulomb interaction from the respective high and low energy beams. Injection in opposite directions at different energies is required to limit net momentum transfer to ions. From power and current consideration for a 10^3 MW_{th} reactor, Ohkawa's numbers indicate beams on the order of 1 MeV at 10 to 10^2 A are necessary.

Recently, Callen and Clarke[10] considered the slowing down time of a beam injected into a toroidal plasma. They point out that during the slowing down time, the beam ions constitute a stored azimuthal current. Once the momentum of the beam ion is reduced to that of the bulk plasma, the contribution of the ion to the particle current ceases. For a 30 keV beam in a 1 keV plasma of 5×10^{13} cm^{-3}, they calculated a slowing down time of $\tau \approx 50$ msec. Sigmar[11] and Hogan are considering the beam produced stored current as the 'seed' for producing a bootstrap current.[12] Preliminary calculations indicate a current multiplication of the injected current by about $10^3 - 10^4$ from stored current and 10 from the bootstrap current. Thus 10 amperes of neutral beam produced current would be 10^5 amperes of toroidal current. The beam also has the effect of monotonically increasing the angular momentum of the bulk plasma. It is not clear what the consequences of this effect will be.

Energy Multiplier

Several people have considered schemes for producing fusion energy in devices which contain a warm, dense plasma below the ignition temperature. Recently, Dawson et al[13] calculated the fusion probability factor of a beam slowing down in a bulk plasma as a function of n, τ and T_e. Neglecting the energy requirements to maintain the bulk plasma, they determine that it is possible to efficiently obtain a significant fusion power output before the beam energy or fusion probability drops too low. They specify the desirability of having neutral beams in the 100 to 300 keV energy range with 100 - 1000 A currents.

Clarke[14] has added an interesting extension to Dawson's proposal which in some respects is the inverse of Ohkawa's idea. Clarke suggests utilizing the azimuthal electric field to maintain the energy of the beam in Dawson's energy multiplier scheme. In this way the fusion probability of the injected beam may be maintained at its maximum value, thereby affording about a 50% increase in the energy multiplication.

III. Ion to Neutral Conversion

It is apparent that all energetic particle beams must start out as ions, which are electrostatically accelerated. In order to penetrate the magnetic confining regions of the plasma, it is necessary to convert these beam ions to neutral atoms outside of the confining magnetic field. The atoms are reconverted to ions inside the plasma, thereby satisfy Liouville's theorem. The process of ionizing the neutral beam inside the plasma is important to our considerations insofar as the mean free path of the energetic neutral is on the order of the plasma radius. This condition will set a lower limit on the beam energy. Of more importance technologically is the ion to neutral conversion and the restrictions it imposes on the ion specie as a function of beam energy. For reactor purposes, the neutral atom beams required lie in the 100 keV - 1 MeV energy range with currents in the 1000 A - 100 A range. The curves[3] in Fig. 1 illustrate very clearly the difficulty to be encountered in producing such neutral atom beams. For both positive ions D^+ and D_2^+ the conversion efficiency is poor at ion energies above 100 - 200 keV and are at best 20% to 30%. Conversion of D_3^+ may be somewhat better depending upon unknown plasma effects in the conversion cell.

The conversion efficiency for D^- looks good. However, in choosing a D^- beam one has merely shifted his problems from the conversion cell to the ion source and extraction region. The difficulties in producing D^-

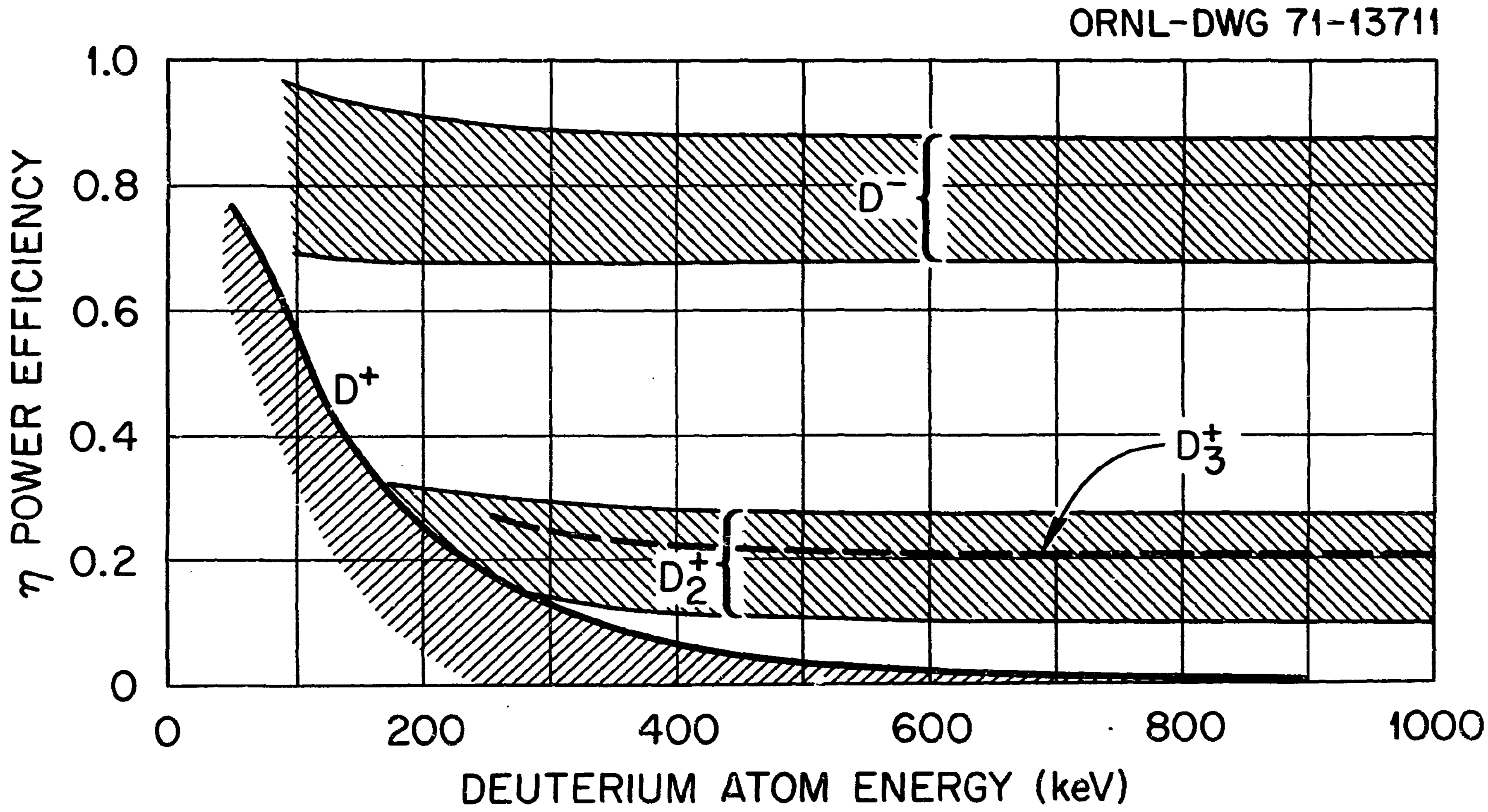

Fig. 1. Efficiency vs Neutral Beam Energy for Neutralization of D_1^+, D_3^+, D_2^+ and D^- in Hydrogen. For the last three beams an optimum target thickness is taken. The range of values for D_2^+ and D^- is due to uncertainty in the degree of ionization of the target gas, a fully ionized gas giving the highest value in each case. The cross sections for D_3^+ breakup on plasma are not known to sufficient accuracy to enable the range to be stated in this case. [Ref. 3]

ions may be appreciated by looking at Fig. 2.[15] This figure shows the conversion efficiency for incident low energy D^+ ions. The maximum conversion efficiency is about 20% in cesium. The problem is twofold: 1) production of large D^+ ion currents at ∿ 1 kV; and 2) acceleration of D^- ions without expending huge amounts of energy on unwanted electrons. The conversion loss is at ∿ 1 keV ion energy whereas for D^+ and D_2^+, the conversion loss is at ∿ 100 keV ion energy. However, we lose in using D^- ions compared to D^+ and D_2^+ because it is much more difficult to extract bright beams at 1 kV than at 100 kV. In either case we need an ion flux from the source on the order of 4 to 5 times greater than the neutral atom flux to be injected. Direct conversion[3] of the unconverted D^+ or D_2^+ ion at $\gtrsim$ 100 kV might play a decisive role not only in the feasibility of mirrors but also in the choice of ion species for beams > 100 keV, when reactor prototypes are constructed.

IV. Ion Beam State-of-the-Art at ORNL

The ORNL, CTR ion beam program is actively engaged in the development of energetic, multiampere neutral beams. The status of this work is presented in ORNL-3472. Briefly, this work may be summarized in the following:

A simple, flexible and efficient ion source has been built and named a duoPIGatron. The source consists of a duoplasmatron ion source feeding a PIG discharge system. The extraction electrodes are multiaperture and are arranged in an accel-decel arrangement with a 5 cm diameter. One ampere beams are extracted in steady state operation with ion energies of from 1.5 to 5 keV. Four ampere beams are extracted for 0.1 sec pulses and 10% duty cycle at ion energies of 20 to 40 keV. At 30 to 40 keV $\approx$ 60% of the ion beam is within a half angular divergence of 1.2° with

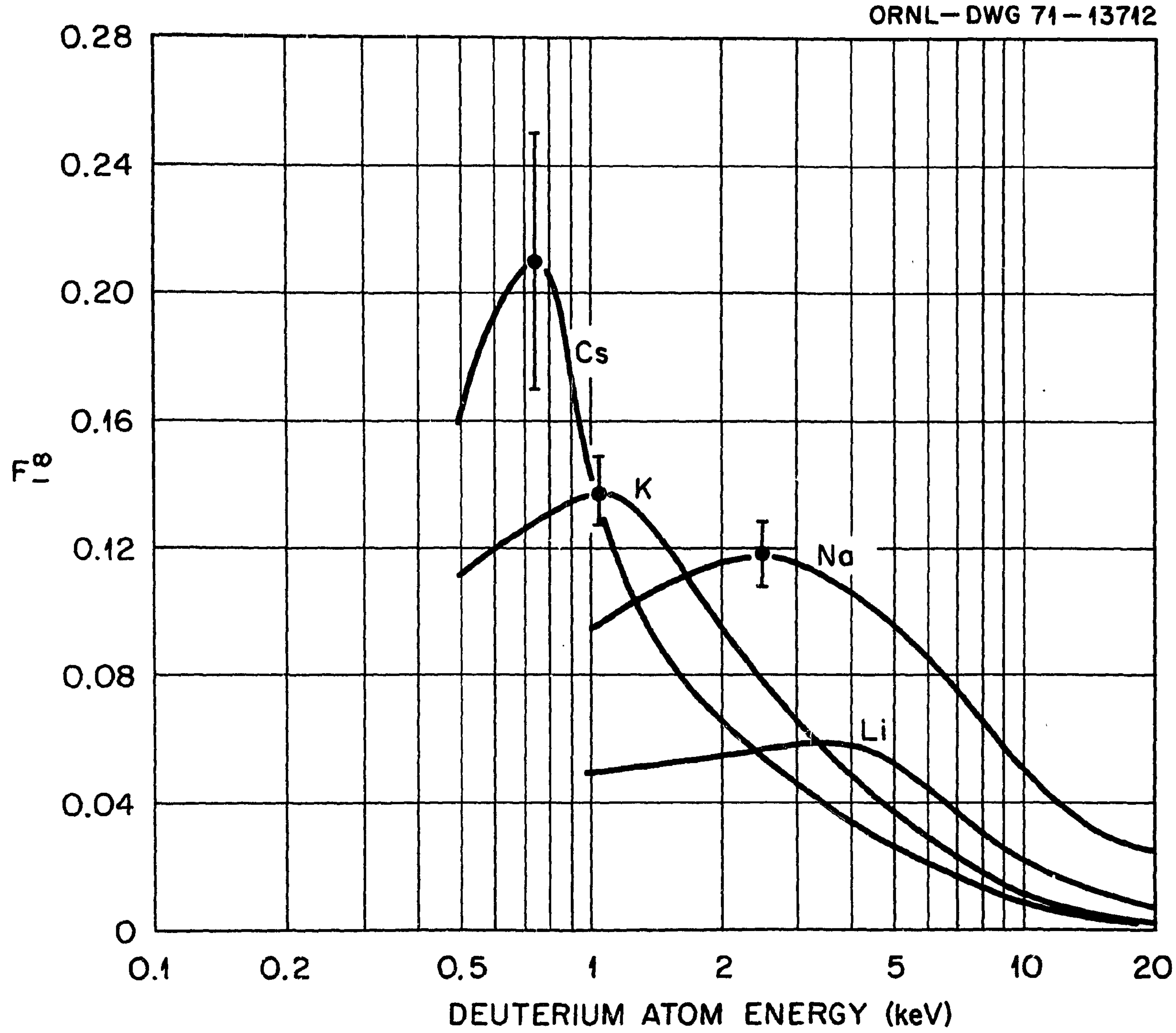

Fig. 2. Negative Ion Equilibrium Fractions for Incident Protons and Alkali-Metal-Vapor Targets. [Ref. 14]

no magnetic lens. Using a hydrogen gas cell this system produces 2.6 A (equivalent) of 17.5 and 35 keV H^o particles within a half angular divergence of 1.2°

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