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D. L. JASSBY

PLASMA PHYSICS LABORATORY

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PRINCETON UNIVERSITY
PRINCETON, NEW JERSEY

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D. L. JASSBY

Plasma Physics Laboratory, Princeton University
Princeton, New Jersey [illegible]

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D. L. JASSBY

Plasma Physics Laboratory, Princeton University
Princeton, New Jersey 08540

ABSTRACT

The optimal performances of 12 types of fusion devices are compared with regard to neutron production rate, neutrons per pulse, and fusion energy multiplication, Q_p (converted to the equivalent value in D-T operation). The record values in all categories are held by the beam-injected tokamak plasma, followed by other beam-target systems. The achieved values of Q_p for nearly all laboratory plasma fusion devices (magnetically or inertially confined) are found to roughly satisfy a common empirical scaling, $Q_p \sim 10^{-6} E_{in}{}^{3/2}$, where E_{in} is the energy (in kilojoules) injected into the plasma during one or two energy confinement times, or the total energy delivered to the target for inertially confined systems. Fusion energy break-even ($Q_p = 1$) in any system apparently requires $E_{in} \sim 10{,}000$ kJ.

I. INTRODUCTION AND DEFINITIONS

Neutrons generated by fusion reactions have potential application in fissile and tritium breeding, radiation testing, isotope production, radiotherapy, and thermochemical processes. In assessing the potential of a fusion device to perform as the neutron source of a fissile breeder, for example, important figures of merit include the time-averaged neutron source strength, the time-averaged neutron wall loading, the fusion energy multiplication, Q_p, and the plant electrical energy multiplication, Q_E. Except for beam-target systems utilizing solid or gas targets, present devices have extrordinarily low duty factors and inefficient means of plasma heating and confinement, so that the performance parameters are at best several orders of magnitude smaller than those of practical interest. Nevertheless, to obtain a perspective on the potential of fusion devices for near-term applications, it is instructive to compare neutron production parameters for the presently most successful fusion-neutron sources.

Figures of merit for fusion-neutron sources can be defined as follows:

$$F_n = \text{neutron production rate (n/s)} \qquad (1)$$

(This quantity is useful only for quasi-steady or long-pulse devices.)

$$N_p = \text{neutron production per pulse} \qquad (2)$$

$$Q_p = \frac{\text{fusion power}}{\text{injected heating power}} \qquad (3)$$

for quasi-steady devices, or

$$Q_p = \frac{\text{fusion energy per pulse}}{\text{heating energy per pulse}} \qquad (4)$$

for pulsed systems.

$$Q_E = \frac{\text{Recoverable electrical power output}}{\text{Total input electrical power}} \qquad (5)$$

for quasi-steady devices, or

$$Q_E = \frac{\text{Recoverable electrical energy per pulse}}{\text{Total input electrical energy per pulse}} \qquad (6)$$

for pulsed systems.

2. COMPARISON OF MAXIMUM NEUTRON YIELDS

2.1 Conditions for Maximum Neutron Production

Table 1 lists relevant parameters for the best performer of each class of fusion device that is known to produce significant yields of fusion neutrons. (There are two entries in the category of ohmic-heated tokamaks.) The conditions shown are those that have resulted in maximum N_p or F_n. These conditions are invariably near, if not identical to, those that give maximum Q_p.

The following notes apply to Table 1:

(1) For tokamaks, P_{in} is the sum of the ohmic-heating power and injected neutral-beam power (P_{beam}) during quasi-steady conditions.

(2) For pulsed systems, E_{in} is the total energy delivered to the target (pellet, foil, or electrodes).

(3) For the quasi-steady systems, E_{in} is the beam energy injected throughout the period during which steady plasma conditions are being reached and then maintained for 1 τ_E, where τ_E is the energy confinement time, plus the estimated additional energy needed to produce the target plasma. It does not include the magnetic energy involved in setting up a plasma current.

(4) The electron temperature T_e is specified only for the quasi-steady systems, as the electron velocity distribution is usually nonMaxwellian for the pulsed systems. All the devices listed have nonMaxwellian ion energy distributions, with the exceptions of the ohmic-heated tokamak, the theta-pinch, and the laser-heated pellets.

In the following compilation, no distinction is made between thermonuclear and nonthermonuclear fusion neutrons.

2.2 Summary of Record Neutron Yields

Table 2 ranks the 13 fusion devices of Table 1 in the order of their achieved Q_p. Also given are the highest values of F_n achieved to date for the long-pulse machines. The record F_n (1.5×10^{14} n/s) is held by the beam-injected PLT tokamak at Princeton.(1,2) For these record conditions in PLT, approximately 50% of the neutron production is due to beam-target reactions between the fast ions formed by injection of neutral D^o beams and the deuterons in the target plasma.(1) Almost all the remaining neutron production is due to reactions between circulating fast ions, with a very small fraction due to reactions among the Maxwellian target ions. If the PLT target plasma had been tritium, it is expected that F_n would have been of the order of 10^{16} n/s. (The D-T reaction rate is two orders of magnitude larger than the D-D reaction rate.) The new Rotating-Target Neutron Source (RTNS-II) at Livermore,(3) which consists of a 400-keV deuteron beam bombarding a tritiated target, should soon generate a continuous F_n of 4×10^{13} n/s at 14 MeV – which is below the record value in PLT obtained using only deuterium fuel.

Table 2 also gives N_p, the record neutron production per pulse, for each device. Presentday long-pulse plasma systems have very low duty factors ($\sim 10^{-3}$), so that N_p is perhaps a more relevant parameter than F_n in comparing the performances of all fusion systems. The largest $N_p = 1.5 \times 10^{13}$ has also been obtained in PLT, surpassing by one order of magnitude the erstwhile record performance of the dense plasma focus.(4) The principal source of neutrons in the plasma focus is also thought to be a beam-target reaction.(5,6)

By way of comparison with the data summarized herein, a so-called "neutron bomb"(7) generates at least 10^{24} fusion neutrons (i.e., a few grams). This yield is equivalent to that which would be obtained from the TFTR machine presently under construction,(8) if it could be operated continuously in the D → T mode for one day!

3. LIMITING PERFORMANCE OF BEAM-TARGET SYSTEMS

It is evident from Table 2 that the largest DT-equivalent values of Q_p have so far been obtained in various beam-target systems. Even in the plasma focus the bulk of the neutron production is apparently due to beam-target reactions.(5) In the solid-target system, Q_p is limited fundamentally to a value near the presentday performance of 0.002; this limit is due to the slowing-down of the energetic ions by ionization of the target atoms (especially those of the metal substrate) and by Coulomb interaction with the cold target electrons.(9) Ionization losses can be reduced by a large factor by using a gaseous target,(10) so that the fast-ion slowing-down time is extended, and Q_p is increased by a factor of at least 3. However, values of Q_p exceeding 1 or 2% can be attained only by going to a plasma target where ionization losses are very small in steady state, and the electrons can be heated substantially, so that the fast-ion slowing-down time is greatly enhanced. This process is the basis of the TCT concept,(11) and is also closely related to the operation of the classical mirror machine. The reasons for the relatively poor performance of mirror machines to date (see Table 2) are primarily an inability to raise the electron temperature above 200 eV,(12) and secondarily the use of relatively low neutral-beam energies (20 keV).

The maximum Q_p that is theoretically attainable in an *optimized* beam plasma-target system is about 2.5. In the dense plasma focus where the ion beams are spontaneously produced by instabilities, the beam-target reactions cannot be optimized, so that the largest Q_p ultimately attainable in the focus is probably significantly less than unity. On the other hand, Q_p in a beam-driven tokamak plasma can be raised above 2.5 if the $n\tau_E$ of the plasma can be sufficiently increased, and possibly also at a more modest $n\tau_E$ by using both D and T injection.(13) In both cases thermonuclear reactions then become dominant. In fact, there is in principle no limitation to the value of Q_p that is attainable with a neutral beam-heated tokamak neutron source.

In the beam-injected 2XIIB mirror machine,(14) and in the PLT tokamak with both co- and counter-injection,(1) it is observed that $F_n \propto P_{beam}^{2 \rightarrow 2.5}$. This scaling is in quantitative agreement with that expected theoretically from beam-target and "beam-beam" nuclear reactions involving *classically behaving* injected fast ions. In the dense plasma focus (DPF), an empirical scaling law for neutron production(15) has been found to be $N_p \propto E_{in}^{2.1}$. This scaling is difficult to explain quantitatively, as the formation of the energetic ion beams which account for the bulk of the fusion reactions is a poorly understood phenomenon. The predicted extrapolations in performance of the DFP have been based almost entirely on this empirical scaling, but the most recent experiments indicate that the strong energy dependence of neutron yield weakens at high input energies.(16) By way of contrast, there is no hint that the scaling of neutron performance in the tokamak system deviates from theoretical prediction at high injection powers.(1) In extrapolating the performance of the beam-injected tokamak, the critical question is whether the high T_e and high degree of plasma purity needed for $Q_p \gtrsim 1$ can be achieved.(17) These two plasma conditions are related, and potential obstacles to their realization appear amenable to plasma engineering solutions, such as the provision of a magnetic divertor.

For presentday neutron applications, the solid-target, gas-target, and DPF systems all have the advantage over competing neutron sources that Q_E is relatively close to Q_p, and in fact is much larger than Q_E in the beam-injected tokamak, because of the energy dissipation in the tokamak magnetic coil systems. Furthermore, the solid-target and gas-target systems can be operated steady state.

4. FUSION ENERGY MULTIPLICATION VERSUS ENERGY INPUT TO PLASMA

4.1 Experimental Scaling

Table 3 shows how the measured neutron yield varies as a function of the injected beam power or energy directed onto the target, for those fusion systems where such scalings have been determined (tokamak, mirror machine, DPF, and laser/pellet). Note that $F_n \propto P_{beam}^2$ is essentially equivalent to $N_p \propto E_{in}^2$, so that these four systems have approximately the same type of energy dependence. The scaling of Q_p is obtained by dividing either by P_{beam} or E_{in}.

Figure 1 shows the measured Q_p versus energy E_{in} for the nine plasma systems of Tables 1 and 2. (In determining Q_p for the Theta Pinch, it is assumed that only 0.1 E_{in} is delivered to the plasma.) For the quasi-steady systems, E_{in} is the heating energy required to initiate the target plasma, added to the injected energy during one or two energy confinement times (essentially the total pulse length in presentday systems). Evidently, the performance of most of these systems is very roughly consistent with a *common* empirical scaling, $Q_p \sim 10^{-6} E_{in}^{3/2}$, where E_{in} is expressed in kilojoules. A heuristic explanation for part of this scaling is the following:

The neutron production during one energy confinement time in a deuterium plasma of volume V and total ion population N is

$$N_p = \frac{1}{2}\frac{N^2}{V}\langle\sigma v\rangle\,\tau_E \qquad (7)$$

where $\langle\sigma v\rangle$ is the fusion reactivity for the ion velocity distribution of the plasma. Profile effects (which are important in practical systems) can be accounted for roughly by using in Eq. (7) the values $V = V'$ and $N = N'$ that are appropriate to the neutron-producing hot central region. In the temperature range of interest (5 to 20 keV) the temperature dependence of $\langle\sigma v\rangle$ for a Maxwellian ion population varies(18) from T_i^3 to T_i^2, and is taken here as

$2 \times 10^{-21} T_i^{5/2}$ cm^3/s, with T_i in keV (neutron branch only). It should be noted that the "equivalent temperature" of presentday beam-target plasma systems, which have significant populations of ions with energies of several tens of kilovolts, is found to be in the range 8 to 20 keV. (For example, in the central region of the beam-injected PLT plasma(1) as well as in the 2XIIB plasma,(14) the average ion energy is about 13 keV at the highest injection powers.) Assuming that $T_e \sim 1/2\ T_i$, then $E_{in} \sim 3 \times 10^{-19} N T_i$, with E_{in} in kJ. Then Eq. (7) becomes

$$N_p \sim 2 \times 10^{25}\, E_{in}^{5/2}\, \frac{\tau_E}{V'} \left(\frac{N'}{N}\right)^2 \frac{1}{N^{1/2}} \qquad (8)$$

Since $Q_p \propto N_p/E_{in}$, the empirical $E_{in}^{3/2}$ dependence of Q_p for a given type of system follows if $\tau_E \propto V' N^{1/2} \propto n_e^{1/2} V^{3/2}$. This latter dependence is known to be roughly valid for tokamaks,(19) but it is not clear why this quantity times $(N'/N)^2$ should remain within a range of one order of magnitude for most magnetically or inertially confined fusion systems.

4.2 Break-Even Requirement

The data in Fig. 1 suggest that in almost any fusion system, Q_p can be increased by delivering more energy to the target plasma or pellet. However, this energy must be delivered in 1 or 2 τ_E (or in one disassembly time), so that for systems with poor energy confinement, the power requirements become prohibitively large.

The observed scaling of Q_p implies that to reach $Q_p = 1$, a total energy of 10 MJ must be injected or delivered to the target in a time of the order of τ_E. The original design of the TFTR(8) specified a beam power of 20 MW for 0.5 sec, or an energy of 10 MJ in a time of 1 to 2 τ_E. Hence this prescription seems remarkably close to the energy and power requirements needed for achieving $Q_p = 1.0$, according to Fig. 1.

It has been recognized that laser-pellet systems might also require at least 10 MJ of beam energy to reach break-even, if an exploding-pusher target must be used.(20) However, it is hoped that the ablatively driven implosion technique(21) will enable $Q_p = 1$ (as defined here) to be attained with only a very small fraction of 10 MJ. Nevertheless, this implosion technique has not yet proved capable of generating high temperatures, and one notes that the proclaimed energy requirement for break-even has jumped upward almost yearly from 1 kJ in the early 1970s(21) to at least 300 kJ today.(22)

Proponents of the CO_2-laser and electron-beam pellet heating systems, on the other hand, have affirmed that 1 to 10 MJ is in fact required for reaching $Q_p = 1$ by their techniques.(23) Of course, this energy must be delivered in less than 1 disassembly time ($\sim$1 ns).

5. DISCUSSION

Many analyses of fusion-driven breeder systems have shown that $Q_p \gtrsim 1$ and $Q_E \gtrsim 0.5$ are required for approximate economic viability, in addition to other restrictions on the capital cost of the plant per unit fusion power capacity.(4) It appears from the demonstrated performances tabulated in Table 2 that the beam-driven tokamak system is the best near-term candidate for achieving $Q_p \gtrsim 1$. The superiority of the beam-injected tokamak system in reaching significant values of Q_p is due in part to the ability of the plasma to accept large amounts of injected energy within one energy confinement time without causing a deterioration in confinement, and also to the ability of this system to produce and sustain a high electron temperature, which is crucial to the maintenance of high average ion energies with minimal external power investment. The agreement of the measured neutron yields on PLT with theoretical expectation suggests that prediction of the neutron production of future beam-injected tokamak devices can be made with confidence, provided that the required electron temperatures can be attained.

However, enormous advances must be made in both plasma and reactor engineering in order to achieve quasi-steady operation and $Q_E \gtrsim 0.5$. These requirements include notably the development of the means of steady-state heat and particle removal from the torus and of steady-state impurity control; efficient, steady-state neutral-beam injectors; steady-state toroidal-field coils with low power dissipation; and optimal remote maintenance and assembly procedures to minimize downtime. The solid-target and gas-target neutron sources are likely to remain the favored systems for most fusion-neutron applications until *high-duty-factor* beam-injected tokamaks are developed.

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Table 1.

OPERATING CONDITIONS FOR RECORD NEUTRON YIELDS

A. Quasi-Steady Fusion Devices

					Ion or Neutral Beam Parameters					
Type	Device	Reference	Year	Fuel	Voltage (kV)	Power (MW)	Pulse Length (ms)	P_{in} (MW)	E_{in}^* (kJ)	T_e (eV)
Beam/Solid Target	RTNS-II	[1]	1979	D → T	400	0.06	dc	0.06	–	0.03
Beam/Gas Target		[2]	1976	D → T	210	0.8 kW	dc	0.8 kW	–	0.05
Ohmic-Heated Tokamak	PLT	[3]	1978	D	–	–	–	0.55	250	1100
Ohmic-Heated Tokamak	Alcator A	[4]	1978	D	–	–	–	0.35	30	900
Beam-Injected Tokamak	PLT	[5]	1978	D → D	39	2.3	150	2.8	600	3500
Beam-Injected Mirror Machine	2XIIB	[6]	1977	D → D	20	5.5	10	5.5	40	150
RF-Injected Tokamak	Alcator A	[7]	1978	D	2.5 GHz	0.1	15	0.45	30	1000

*Energy input to reach maximum plasma temperature, and maintain for 1 confinement time.

Table 1. (Cont'd)

B. Pulsed Fusion Devices

Type	Device	Reference	Year	Fuel	E_{in}^* (kJ)	Pulse Length (ns)
Dense Plasma Focus	DPF-6-1/2	[8]	1973	D	420	200
Theta Pinch (Linear)	Scyllac	[9]	1972	D	2800	5000
Laser/Pellet Short λ	SHIVA	[10]	1978	DT	2.6	0.1
Laser/Pellet Long λ	HELIOS	[11]	1978	DT	2.4	0.75
REB/Exploding Wire	Gamble II	[12]	1973	D	50	50
REB/Foil	Reiden III	[13]	1978	D	3.2	80

REB ≡ Relativistic Electron Beam.

*Energy delivered to electrodes, pellet, wire or foil.

In calculating Q_p for the Theta Pinch, it is assumed that only 0.1 E_{in} is delivered to the plasma.

Table 2.

RECORD FUSION-NEUTRON PRODUCTION IN EXPERIMENTAL DEVICES

Device	Type	Year	D-D Neutrons Per Second	D-D Neutrons Per Pulse	Q_p	Equivalent Q_p in D-T
PLT [5]	Beam-Injected Tokamak	1978	1.5×10^{14}	1.5×10^{13}	5×10^{-5}	0.017
[2]	Beam/Gas Target	1976	2×10^{12} in D-T	continuous operation	-	0.007
RTNS-II [1]	Beam/Solid Target	1978	4×10^{13} in D-T	continuous operation	-	0.002
DPF-6-1/2 [8]	Dense Plasma Focus	1973	-	2×10^{12}	7×10^{-6}	0.002
Gamble II [12]	REB/Exploding Wire	1973	-	1×10^{11}	2×10^{-6}	6×10^{-4}
Alcator A [7]	RF-Injected Tokamak	1978	2×10^{11}	2×10^{9}	5×10^{-7}	1×10^{-4}
Reiden III [13]	REB/Foil	1978	-	1×10^{9}	4×10^{-7}	1×10^{-4}
SHIVA [10]	Laser/Pellet (Short λ)	1978	-	3×10^{10} in D-T	-	5×10^{-5}
PLT [3]	Ohmic-Heated Tokamak	1978	1×10^{11}	5×10^{10}	2×10^{-7}	5×10^{-5}
Alcator A [4]	Ohmic-Heated Tokamak	1978	7×10^{10}	2×10^{9}	2×10^{-7}	5×10^{-5}
2XIIB [6]	Mirror Machine (Beam-Injected)	1977	4×10^{11}	3×10^{9}	1×10^{-7}	3×10^{-5}
Scyllac [9]	Theta Pinch (Linear)	1972	-	7×10^{9}	3×10^{-8}	1×10^{-5}
HELIOS [11]	Laser/Pellet (long λ)	1978	-	5×10^{8} in D-T	-	7×10^{-7}

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Table 3

MEASURED SCALINGS OF FUSION-NEUTRON YIELDS

Device Type	Neutron Production	Q_p
Beam-injected tokamak[a]	$F_n \propto P_{beam}^{2 \rightarrow 2.5}$	$P_{beam}^{1 \rightarrow 1.5}$
Beam-injected mirror[b]	$F_n \propto P_{beam}^{5/2}$	$P_{beam}^{3/2}$
Dense Plasma Focus[c]	$N_p \propto E_{in}^{2.1}$	$E_{in}^{1.1}$
Laser/Pellet[d]	$N_p \propto E_{in}^{2 \rightarrow 3}$	$E_{in}^{1 \rightarrow 2}$

Note: The symbols F_n, N_p, P_{beam}, and E_{in} are defined in Sections 1 and 2.1 of the text.

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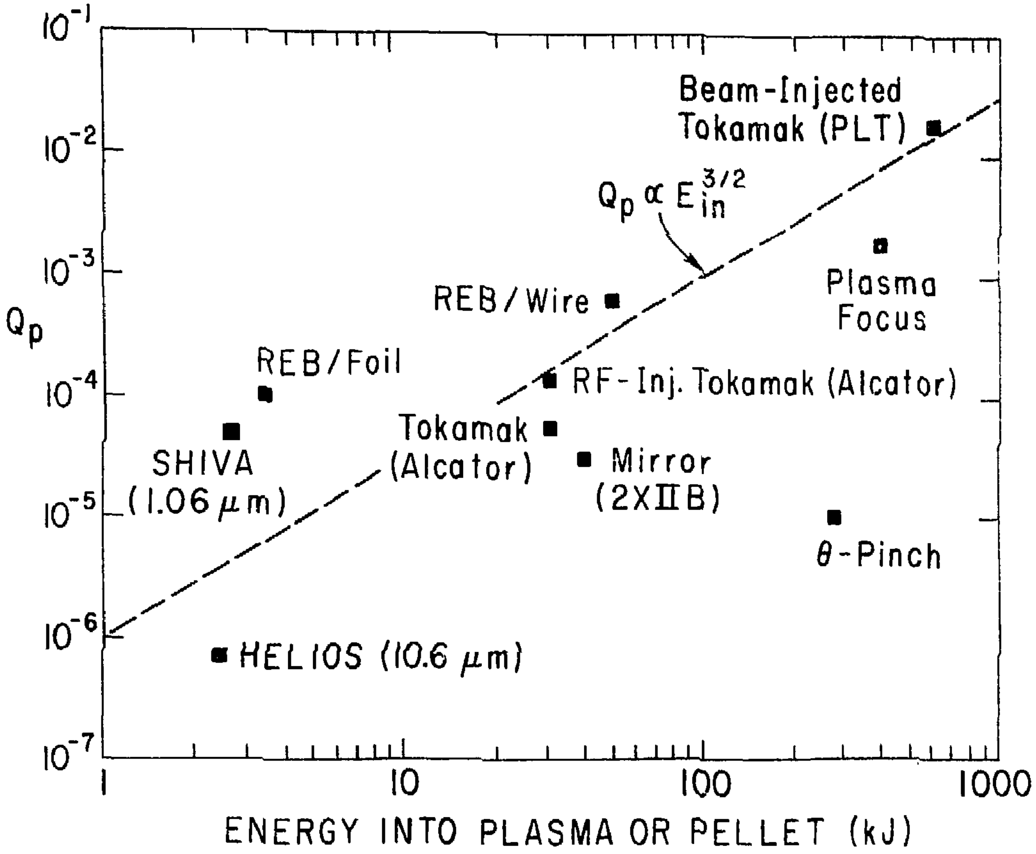

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Fig. 1. Record values of fusion power multiplication or fusion energy multiplication versus energy E_{in} injected into the plasma or delivered to the pellet, foil, wire, or electrodes. See definitions of Q_p and E_{in} in Sections 1 and 2.1 . For systems that have used only deuterium, the equivalent Q_p in D-T is given.

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