APPLICATION OF SMALL-SIGNAL FUSION ENERGY GAIN

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ABSTRACT

The measured burnup fraction of the 1-MeV tritons produced in a deuterium tokamak plasma, multiplied by 17.5, is essentially the small-signal fusion energy gain g_T for an ideal 1-MeV triton beam injected into the deuterium plasma. The measured g_T can be converted directly into the two-component fusion energy gain that would be realized if a lower energy tritium beam were injected into the plasma, or if a deuterium beam were injected into a tritium target plasma having the same parameters as the actual deuterium plasma. Under certain conditions, $g_T \geq 1$ can be obtained by injection of a low-current 225-keV tritium beam into a hot deuterium plasma, thereby verifying that the plasma has the essential characteristics needed for achieving macroscopic fusion energy "break-even."

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1. SMALL-SIGNAL ENERGY GAIN

1.1 Definitions

The fusion power amplification factor of a reacting plasma is usually defined as

$$Q_p = \frac{P_{fus}}{P_{in}} = \frac{\text{fusion power}}{\text{total heating power}} \quad (1)$$

A high-temperature deuterium or deuterium-tritium plasma can also serve as an amplifier of incremental injected power, ΔP_{in} , or energy, ΔU_{in} . A "small-signal" input is one that does not measurably affect the plasma power balance or macroscopic plasma parameters. We define the *small-signal fusion power gain* $g_T(E_0)$ for a triton current I_b injected at energy E_0 into a deuterium plasma as

$$g_T(E_0) = \frac{\Delta P_{fus}}{\Delta P_{in}} = \frac{I_b \tau_s (n_d + n_{dh}) \langle \sigma v \rangle E_f}{E_0 I_b} \quad (2)$$

where $\langle \sigma v \rangle$ is the fusion reactivity of the steady-state distribution of tritons with the target deuterons of density n_d and beam-injected deuterons (if any) of density n_{dh} , τ_s is the triton slowing-down time, and E_f is the fusion energy release per reaction (17.6 MeV). Thermalized tritons are excluded from the calculation of $\langle \sigma v \rangle$, which includes only decelerating ions with $E \geq 2T_i$ [1]. Here ΔP_{in} is a tiny fraction of the P_{fus} needed to maintain the operating point (n_e , T_e , T_i) of the fusion amplifier.

If a short pulse of beam energy $\Delta U_{in} = E_0 \int I_b(t) dt$ is injected, we define the *small-signal fusion energy gain* as

$$g_T(E_0) = \frac{\Delta U_{fus}}{\Delta U_{in}} = \frac{\int I_b dt (n_d + n_{dh}) \langle \sigma v \rangle \tau_s E_f}{E_0 \int I_b dt}, \quad (3)$$

where $\langle \sigma v \rangle$ is the average reactivity of an injected triton during its slowing-down time τ_s , and is the same as the reactivity in Eq. (2). Thus the two values of g_T are identical. In the second case, the pulse of fusion energy from which g_T is determined will lag the injected energy pulse, because of the typically long slowing-down time of injected particles. Figure 1 illustrates these concepts.

Analogous definitions of $g(E_0)$ apply for energetic deuterons injected into a deuterium, tritium, or ^3He plasma, and for energetic tritons injected into a tritium or ^3He plasma.

In the discussion herein, the incremental injected energy comes from neutral beams or charged fusion-reaction products. (We refer to the neutral beam as a "probe beam," as its power is sufficiently small so as not to disturb the plasma parameters.) Similar considerations apply to energy injected by other means, for example, by incremental RF power that resonates with a tritium or ^3He minority-ion species in a predominately deuterium plasma. In any case, the temperature of the target plasma can be maintained by high-power neutral beam injection, by radiofrequency (RF) waves, or possibly by ohmic heating alone.

1.2 Energy Gain of D-D Tritons

The $D(d,p)T$ reaction in a deuterium plasma injects a 1-MeV triton "beam" into the plasma. A fraction F_b of the thermalizing tritons burns up by the reaction $T(D,n)\alpha$ to produce 14-MeV neutrons. Actual values of $g_T(1000)$ can be derived from measurements of F_b :

$$g_T(1000) = \frac{\text{D-T neutron yield} \times 17.6 \text{ MeV}}{\text{D-D neutron yield} \times 1.01 \text{ MeV}} = F_b \times 17.5 \quad (4)$$

The denominator is the total amount of injected triton energy over one or more pulses. (The cross sections for the triton-producing and neutron-producing D-D reactions are very nearly the same.) The tritons have a nominal energy of $E_0 = 1.01$ MeV, but in fact are born with a broad energy spectrum, which depends on the energy of the reacting deuterons.

1.3 Objectives

The purpose of this paper is to show that:

- 1) The measured burnup fraction of D-D tritons, F_b , can be converted directly to $g_D(E_0)$ for deuterons injected into a pure-tritium target plasma having the same parameters as the deuterium plasma.
- 2) The measured F_b can be converted directly to the $g_T(E_0)$ that would be measured for a tritium beam of energy E_0 injected into the same deuterium plasma. Under certain conditions, achieving $g_T(E_0) \geq 1$ can be used to demonstrate a type of fusion energy "break-even."

2. PREDICTION OF SMALL-SIGNAL GAINS

2.1 Variation of Gain With Temperature

Figure 2(a) shows $g_T(E_0)$ for monoenergetic tritons injected into a deuterium plasma, while Fig. 2(b) shows $g_D(E_0)$ for monoenergetic deuterons injected into a tritium plasma. The curves are calculated for spatially uniform temperature $T_e = T_i$, using the beam-target reactivities discussed in Ref. 1.

Some important points to note are the following:

- 1) The assumptions in deriving $\langle \sigma v \rangle$ and τ_s are that the slowing-down rates of energetic ions are classical, and that no energetic ions are lost from the plasma before slowing down.
- 2) If a fraction of the injected tritons have prompt orbit losses, then $\langle \sigma v \rangle$ is unchanged, but I_b or $\int I_b dt$ must be multiplied by $(1 - \text{loss fraction})$.
- 3) g_D is the usual two-component fusion energy gain for a single energetic deuteron slowing down in a tritium plasma [2]. g_D equals the macroscopic fusion power amplification factor, Q_p , when 1) injected D beams supply all the power to the plasma, and 2) beam-beam and thermonuclear reactions are negligible.
- 4) Both g and Q_p are strong functions of T_e and weak functions of T_i [1,2].
- 5) If the neutral beams have multiple energy species, then

$$g = f_1 g(E_0) + f_2 g(E_0/2) + f_3 g(E_0/3) \quad , \quad (5)$$

where f_i is the fraction of total injected power at E_0 , etc.

2.2 Determination of Equivalent g_D and Q_p

The T_e in Fig. 2 corresponds to an average temperature, $\langle T_e \rangle$, which is the actual $T_e(r)$ weighted over the profile according to some power of plasma density. In the case of the D-D tritons in a beam-heated plasma, T_e is weighted as the sum of the target and energetic deuteron densities $= n_d + n_{dh}$. When $Z_{eff} = 1$ and no H is present, $n_d + n_{dh} = n_e$.

Figure 2(b) can be used to determine the Q_p that would be measured with D injection into a pure-T target plasma (no thermonuclear or beam-beam reactions), simply by finding the $\langle T_e \rangle$ corresponding to the measured $g_T(1000)$. Note that it is not necessary to know the actual profile of T_e to deduce g_D . All that one need assume is that the density profile of the slowing-down tritons, taking their orbits into account, is essentially the same as the fast-deuteron density profile, $n_{dh}(r)$.

Similarly, dilution of the target plasma by impurity ions, which enters Eqs. (2) and (3) via $(n_d + n_{dh})\tau_S$, will have nearly equivalent effects on $g_T(1000)$, $g_T(E_0)$, and $g_D(E_0)$, reducing all gains by the factor $(1 - Z n_Z/n_e) = (n_d + n_{dh})/n_e = N_d$.

Because there is a unique relation between F_b and $\langle T_e \rangle$, the gain curves in Fig. 2 can be replotted with F_b as the variable, as shown in Fig. 3. Then the gain for any injected beam can be deduced directly from the measured F_b without first finding the intermediate parameter $\langle T_e \rangle$.

2.3 Principal Nonideal Effects

Prompt orbit losses. First-orbit losses of tritons become significant at $I_p < 1.5$ MA [3-5]. For tokamaks with I_p considerably smaller than 1 MA, prompt losses can be several tens of percent or more, and the proposed method cannot be used unless the prompt loss fraction is well known and corrected for.

Profile differences. In practice, the triton *birth profile* is likely to be more peaked than $n_{dh}(r)$, but this discrepancy is compensated by the larger triton orbits.

Triton accumulation. If the thermalized D-D tritons build up in the plasma for times long compared with their slowing-down time, then in the case of long-pulse plasmas an appreciable fraction of the 14-MeV neutron production may eventually arise from reactions involving thermalized tritons. This problem can be avoided by measuring F_b with active neutron detectors for a time $\sim \tau_s$. (Presentday beam-heated tokamaks may encounter the opposite problem: The pulse duration after beam injection is insufficiently long for F_b to attain its full potential magnitude.)

Significant density of beam-injected ions. This consideration applies only if F_b is measured in plasmas heated by D beams. The average speed of the fast deuterons is much closer to the speed of the target ions than to the average speed of the slowing-down tritons. Thus for reaction with the 1-MeV tritons the beam deuterons can be regarded as part of the deuterium target-ion population. Figures 2(a) and 3(a) give an accurate estimate of the $g_T(E_0)$ that would be measured for an injected low-power tritium beam, without having to know n_{dh}/n_e . However, Figs. 2(b) and 3(b) give an accurate prediction of g_D only if the correct n_{dh}/n_e is included in N_d .

Energization of D-D tritons. An error will be introduced if the bulk plasma is heated by ion cyclotron waves that resonate with the D-D tritons in some region of the plasma.

3. ILLUSTRATION USING TYPICAL TFTR CONDITIONS

3.1 Using The Measured $\langle T_e \rangle$

The density-averaged T_e for the TFTR conditions giving the highest D-D neutron intensities to date is in the range 3 to 3.6 keV [6,7]. These plasmas,

which are heated by D neutral beam injection, are characterized by $n_d/n_e \sim 0.6$ and $n_{dh}/n_e \sim 0.12-0.16$ [6,8]. Table I summarizes the expected values of F_b for D-D tritons and the g_D for TFTR heating beams injected into a tritium target plasma with the same parameters as the present deuterium plasmas (including impurity content). A g_D of 0.23 would be realized with a low-current (probe) neutral beam having the 1986 injector energy and species mix, while $g_D = 0.43$ would be obtained with the 1987 injector characteristics. These values would be substantially higher if the impurity level (including hydrogen) could be reduced. The g_D -values would represent the Q_p for the same plasma heated by D beam injection, if deuterium could be prevented from building up in the tritium target plasma. Also given in Table I are the g_D and g_T for ideal 150-keV D and 225-keV T beams having no fractional-energy species.

3.2 "Black-Box" Method

In the actual application of the technique discussed in this paper to find g_D or g_T , there would be no direct use of $\langle T_e \rangle$. One needs to measure only F_b , and not inquire into T_e , impurity content, or any other parameter. *The deuterium plasma can be regarded as a "black box," which emits just 2.5-MeV and 14-MeV neutrons. One needs only the ratio of these quantities (F_b) to derive all the small-signal gains, using Fig. 3. The quantity T_e is used simply as a parameter that links Fig. 2 and Fig. 3. (To predict g_D accurately, it may be necessary to estimate n_{dh}/n_e , as noted above.)*

Preliminary measurements of F_b in TFTR, obtained with scintillation counters [9] and activation foils [10], were generally in the range 0.1 to 1%. For the proposed technique to be useful, accurate measurements of F_b are needed, preferably using both activation foil sets and real-time detectors such as

scintillators [11] and time-of-flight instruments. A serious problem in applying the predictive technique at $I_p = 0.8$ to 1 MA, where the best TFTR plasma performance is often found [6-8], is that a large fraction of the D-D tritons escape from the plasma at this relatively low current [3-5].

In TFTR experiments to date, the maximum ratio of tritium density to deuteron density in the target plasma is $n_t/n_d \sim 10^{-5}$, assuming that all the D-D tritons produced in the 0.5-s beam pulse thermalize and remain in the plasma. The τ_s for the tritons in beam-heated plasmas considerably exceeds 0.5 s, so that n_t/n_d is likely to be much smaller than 10^{-5} . (In fact, when the beam pulse occurs toward the end of the discharge, the tritons have insufficient time to decelerate.) Hence the (D $\rightarrow$ T⁺) beam-target reaction rate is much less than 0.1% of the D-D reaction rate, and therefore much less than 10% of the expected reaction rate of the D-D tritons (T⁰ $\rightarrow$ 100% D⁺). This effect may have to be taken into account at much longer beam pulse lengths.

4. DEMONSTRATION OF SMALL-SIGNAL ENERGY GAIN > 1

Achieving $g = 1$ with an injected T or D probe beam would verify that the plasma has the essential characteristics required for macroscopic two-component fusion energy break-even, or $Q_p = 1$. Achieving $g_T = 1$ can be accomplished by injecting a low-current tritium beam into a deuterium target plasma heated by deuterium neutral beams, RF waves, or by ohmic heating. The principal condition is that $\langle T_e \rangle$ be sufficiently large.

The $g_T = 1$ demonstration could in principle be done with the D-D tritons themselves. However, an exceptionally large T_e is required to achieve the 6% burnup of 1-MeV tritons corresponding to $g_T = 1$ (see Fig. 3), so that use of a lower energy tritium beam is probably essential.

4.1 Gain of 225-keV Triton Beam

Table I indicates that for the best TFTR conditions achieved to date, a 225-keV tritium beam would give $g_T = 0.57$, while reducing the impurity content (including hydrogen) would increase g_T to as much as 0.76. An 80% increase in F_b , corresponding to an increase in $\langle T_e \rangle$ from 3.6 keV to 8.3 keV, is required for $g_T = 1.0$ to be obtained with 225-keV beams with the present plasma impurity concentration (see Figs. 2 and 3 for $N_d = 0.75$). If the target plasma were purely deuterium, then a $\langle T_e \rangle$ of only 5.3 keV would be required.

If a significant toroidal electric field is present and the beam is injected in the direction of the field (i.e., co-injection), then τ_s and g_T can be enhanced considerably. The problem of triton buildup in the target plasma will also be alleviated by the longer τ_s (see below).

Beam-Heated Plasmas. As do the 1-MeV tritons, the beam-injected tritons will interact with both the bulk deuterons (density = n_d) and the thermalizing beam deuterons (n_{dh}). However, for a fair demonstration it is important to minimize reactions between *thermalized tritons* and the fast deuterons injected by the heating beams. (Otherwise, a false differential energy "gain" could be realized simply by injecting a tritium pellet!) The measured g_T must be multiplied by a correction factor that is readily shown to be $1/[1 + (\tau_p/\tau_s)n_{dh}/(n_d + n_{dh})]$, where τ_p is the confinement time of a thermalized triton. If $\tau_p \sim \tau_s$, the multiplying factor is typically 0.8 to 0.9. (For D-D tritons, $\tau_s \gg \tau_p$ and the correction factor is 1. For injected pellets, $\tau_s = 0$ and the correction factor is 0.)

The unwanted reactions can be largely avoided if the D heating beams are turned off upon injection of the tritium beam; most of the energetic deuteron population will thermalize much faster than the 225-keV tritons. When the D beams are turned off, TFTR experience shows that T_e stays flat or even rises for the first 50 ms, then drops by 1 keV at 100-150 ms after beam turn-off, and by 2

keV at 200 ms after beam turn-off [7]. This rate of fall probably would have an acceptably small effect on g_T .

RF-Heated Plasmas. To obtain an accurate determination of g_T , the RF waves must not resonate with the injected tritons. The probe beam can operate continuously, as long as the number of tritons building up in the bulk plasma remains well below $I_b \tau_S R_G$, where $R_G \sim 10$ is the ratio of beam-target to thermonuclear reactivity [1]. This condition is equivalent to $\tau_p / \tau_S \ll R_G$.

Ohmic-Heated Plasmas. Conceivably $g_T = 1$ could be attained in plasmas heated solely by ohmic heating with very high current density, although impurity ions would have to be added to increase the plasma resistivity. Such impurities should have moderate Z (20-30) in order to minimize dilution of the deuterium target plasma and still be nearly fully ionized to minimize radiation loss.

Tritium Target Plasmas. $g_D = 1$ could be demonstrated by injecting a low-current deuterium beam into a tritium target plasma heated by tritium neutral beams, RF waves, or by ohmic heating. A much larger tritium inventory would be required than in the case of the tritium probe beam.

4.2 Required Probe Beam Current, I_b

I_b must be sufficiently large so that the incremental 14-MeV neutron production will greatly exceed the background level from the burnup of D-D tritons. In TFTR deuterium plasmas with the capability of showing $g_T \sim 1$, the 1-MeV triton production rate will be in the range 2 to $5 \times 10^{16}/s$ (4-10 mA). Taking into account that, at a given T_c , the fractional burnup for 1-MeV tritons is 2 to 3 times that for 225-keV tritons, $I_b \sim 200$ mA will be adequate. With $I_b < 1$ A, the required tritium inventory will be small, and neutron activation of the

tokamak components will not increase significantly above the level caused by D-D neutrons.

A modulated probe beam might appear attractive as a way of reducing I_b still further. However, modulation may not be useful in short-pulse machines because of the time delay of the 14-MeV neutron signal resulting from the lengthy slowing-down time of injected tritons (> 0.1 s). Modulation may be effective when a continuous measurement of g_T is to be used as part of a temperature control circuit for either a deuterium or D-T long-pulse burning plasma. Note that even an ignited plasma may have $g_T \sim 1$ if its $\langle T_e \rangle$ is relatively low.

A negative-ion-based neutral beam is preferable to avoid the complications of interpreting results that would be introduced by the fractional-energy components of positive-ion-based neutral beams.

5. CONCLUSIONS

The measured burnup fraction, F_b , of the 1-MeV tritons produced in a deuterium plasma can be directly converted to the fusion energy gains of deuteron or triton probe beams injected into tritium or deuterium target plasmas, respectively, having exactly the same parameters as the existing deuterium plasma. Application of this technique requires no measurement other than the ratio of 14-MeV to 2.5-MeV neutron flux, which gives F_b . Three conditions are that the orbit losses of tritons are negligible, radial transport during slowing-down is small, and the density profile of the D-D tritons is the same as that of beam-injected ions. Accurate measurements of F_b are required in order that this method can correctly predict the fusion energy gain of D or T probe beams.

A low-current (<1 A) tritium beam with $E_0 = 225$ keV can be used to demonstrate small-signal fusion energy gain g_T exceeding unity in a deuterium plasma heated by D beams or RF waves. In the beam-heated case, the D beams must be turned off as soon as the tritium probe beam is injected, or a correction must be made to the measured g_T . In the best TFTR conditions achieved to date, $g_T = 0.57$ would be realized. To reach $g_T = 1$ requires a doubling of the electron temperature, or elimination of impurity content together with a 50% increase in temperature.

The required plasma parameters for achieving $g_T = 1$ are as difficult to reach as those needed for demonstrating $Q_p = 1$. The ability to achieve $g_T = 1$ in a deuterium plasma will verify that the plasma has the characteristics needed to show actual energy break-even in a D-T plasma.

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Appendix A

Principal Symbols Used

E_f	Energy release per fusion reaction (MeV)
E_0	Energy of probe neutral beam (keV)
F_b	Probability of burnup of D-D triton while thermalizing
$g_D(E_0)$	Small-signal gain for deuteron beam injected into a tritium plasma
$g_T(E_0)$	Small-signal gain for triton beam injected into a deuterium plasma
I_b	Current of probe neutral beam (A)
n_d	Density of thermal deuterons (cm^{-3})
n_{dh}	Density of energetic deuterons (cm^{-3})
N_d	$(n_d + n_{dh})/n_e$
Q_p	Fusion power/total plasma heating power
$\langle T_e \rangle$	Density-averaged electron temperature (keV)
T_i	Temperature of thermal ions (keV)
$\langle \sigma v \rangle$	Fusion reactivity (cm^3/s)
τ_s	Slowing-down time of energetic ion (s)

Table I

**EXPECTED TRITON BURNUP AND SMALL-SIGNAL FUSION GAINS
FOR BEAM-HEATED TFTR PLASMAS IN MID-1986**

Peak T_e (measured [7])	5.5 to 6.5 keV	
Density-averaged $\langle T_e \rangle$	3.0 to 3.6 keV	
Expected $g_T(1000)/N_d$, from Fig. 2	0.31 to 0.38	
n_d/n_e	0.60 ^a	
$N_d = (n_d + n_{dh})/n_e$	0.70-0.75 ^a	
Expected burnup fraction of D-D tritons, $F_b = g_T/17.5$	0.013 to 0.016	
$\langle T_e \rangle$	<u>3.6 keV</u>	<u>3.6 keV</u>
Impurity dilution factor, N_d	0.75	1.0
Impurity dilution factor, $N_t = n_t/n_e$	0.60	1.0
F_b	0.016	0.021

Information below is obtained from Fig. 3

$0.50g_D(92) + 0.35g_D(46) + 0.15g_D(31)$ [mid-1986 neutral beams]	0.23	0.38
$0.80g_D(120) + 0.20g_D(60)$ [mid-1987 neutral beams]	0.43	0.72
$g_D(150)$	0.55	0.91
$g_T(225)$	0.57	0.76

^a Deduced from measured plasma parameters [6-8].

DEUTERIUM-TRITIUM
POWER AMPLIFIER

DEUTERIUM
POWER AMPLIFIER

MACROSCOPIC FUSION POWER AMPLIFICATION

$$Q_p = \frac{P_{fus}}{P_{in}} \geq 1$$

$$Q_p = \frac{P_{fus}}{P_{in}} \ll 1$$

SMALL-SIGNAL FUSION ENERGY GAIN

$$g = \frac{\Delta U_{fus}}{\Delta U_{in}} \geq 1$$

$$g = \frac{\Delta U_{fus}}{\Delta U_{in}} \geq 1$$

Fig. 1. Definitions of fusion power amplification factor, Q_p , and small-signal fusion energy gain, g .

Fig. 2. Small-signal fusion gain $g_T(E_0)$ for tritium beam injection into a deuterium target plasma, and $g_D(E_0)$ for deuterium beam injection into a tritium target plasma. E_0 is the injection energy of the probe beam. $N_D = (n_d + n_{dh})/n_e$ and $N_T = n_t/n_e$. Zero-dimensional calculation.

Fig. 3. Small-signal fusion gain $g_T(E_0)$ for $T^0 \rightarrow 100\% D^+$, and $g_D(E_0)$ for $D^0 \rightarrow 100\% T^+$, as a function of the fractional burnup of D-D tritons (1 MeV) slowing down in a deuterium plasma of the same characteristics. E_0 is the injection energy of the probe beam. $N_D = (n_d + n_{dh})/n_e$ and $N_T = n_t/n_e$.

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