ENERGY BALANCE OF NUCLEAR-FISSION REACTIONS (dt) IN THE BEAM-TARGET SYSTEM

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In connection with the prospects of obtaining beams of high-energy ions and neutrals with currents in the tens of amperes, and plans for using such beams for plasma heating [1, 2], there is practical interest in the question of the energy balance for dt reactions occurring during interactions of accelerated deuterons with a tritium plasma target [3]. Dawson et al. [4] have considered the conditions for a positive energy balance in such reactions in a pure tritium target.

The present paper evaluates the critical parameters of a similar plasma-beam system, taking into account the effect of deuteron accumulation in the target.

We will find the dt reaction intensities IB and the deuteron stopping time \( \tau_d \) in a thick, fully ionized tritium target:

\[
IB = \int_0^E n \frac{(2E/M)^{1/2} \sigma(E) dE}{(-dE/dt)};
\]

\[
\tau_d = \int_0^E dE/(-dE/dt).
\]

Here, \( E \) (eV), \( M \), and \( I \) are the energy, mass, and flux of deuterons, respectively; \( n \) (cm\(^{-3}\)) is the density of the target; \( \sigma(E) \) and \( B \) are the effective cross section and yield of the dt reaction; \( (-dE/dt) \) is the stopping loss rate for the deuteron [3]:

\[
(-dE/dt) = \frac{1.0 \times 10^{-9} n E \ln \Lambda}{T_e^{3/2} (1 + 2.7 \times 10^{-4} E/T_e^{3/2})^{3/2}} + \frac{8.5 \times 10^{-9} n \ln \Lambda}{E^{1/2}} \text{ eV/sec},
\]

where \( T_e \) is the electron temperature of the target (\( T_e \ll E \)) in eV; \( \ln \Lambda \) is the Coulomb logarithm.

Figure 1 shows the values of \( B \) and \( n\tau_d \) calculated from Eqs. (1)-(3). The data on the cross section \( \sigma(E) \) are taken from [5]: \( \ln \Lambda = 18; \ T_e = 5-8 \text{ keV}; \ n = 10^{14}-10^{16} \text{ cm}^{-3} \). Similar results having accuracy of 20\% were obtained when finding \( (-dE/dt) \) from the solution of the Fokker-Planck equation [6]. The effect of deuteron accumulation in the target can be taken into account with sufficient accuracy by introducing the factor \( (1 - \alpha) \) into Eq. (1), where \( \alpha \) is the relative deuteron density. In this case, \( n \) in Eqs. (1)-(3) signifies the overall plasma density.

The condition for positive energy balance in the stationary plasma-beam system has the form:

\[
[IB (1 - \alpha)] W_n \eta_p + p \eta_p = \frac{P}{\eta} \geq 1\text{E}.
\]

where \( p = 3\pi T_e V/\tau \geq 1\text{E} \) is the power input to the target (\( T_e \approx T_e \)); \( W_n \) is the reaction energy; \( \eta_p \) and \( \eta_n \) are the plasma-energy and reaction-product conversion efficiencies, respectively; \( \eta_p \) is the average efficiency of the injector and the additional means for heating the target; \( V \) is the target volume; \( \tau \) is the energy time for plasma confinement.

From Eq. (4) we can obtain estimates of the critical target and beam parameters:

\[
\alpha \pi \geq \frac{3 (\pi \tau) T_e Q}{\alpha_1 (1 - \alpha) W_n \eta}.
\]

Fig. 1. Dependence of $n_T$ and B on the deuteron energy $E$ and the target electron temperature $T_e$. The deuteron energies are: 1) 50; 2) 100; 3) 200; 4) 400; 5) 1000 keV.

Fig. 2. Lawson curves for thermal ($Q = 2$) and beam (C region filled) reactors:

$\alpha = \alpha_1$ when $\tau \leq \tau_1$; $\alpha = \alpha_1(\tau/\tau_1)$ when $\tau > \tau_1$.

$$\frac{B}{E} \geq \frac{Q}{(1-\alpha)W_n};$$

$$I = \frac{\alpha n^2 \eta_1}{nT_1};$$

where $Q = (1 - \eta_p\eta_d)/\eta_n\eta_d$; $\alpha_1 = n_1/\eta_1$; $n_1 = I\tau_1/V$ is the high-energy deuteron density in the target.

Equation (6) establishes a lower limit for the target temperature, which has a minimum when $E \approx 200$ keV, which is in accordance with the results of [4]. It follows from Eqs. (5) and (6) that taking deuteron accumulation into account ($\alpha = 0$) leads to increased critical values for $T_e$ and $n_T$.

The quantity $\alpha$ cannot be as small as we wish. Equations (5) and (6) and the natural requirement $\alpha_1 \leq \alpha$ limit $\alpha$ with a lower bound of $\alpha_{\text{min}} = (1/2)(1 - (12T_eQ/W_nB))$ and upper bound $\alpha_{\text{max}} = 1/2$, at which the absolute minimum of $n_T$ is reached.

Figure 2 depicts the region C of $n_T$ and $T_e$ values which satisfy Eqs. (5) and (6) for $E = 200$ keV, $Q = 2$ ($\eta_n = 1/3$, $\eta_p = 2/3$, $\eta_d = 3/4$) and $W_n = 2.4$ MeV. In this case, $T_e(\text{min}) \approx 6.5$ keV. The minimum for $n_T$ ($\sim 10^{18}$ cm$^{-3}$ sec) is attained when $T_e \approx 9$ keV and $\alpha = \alpha_1 \approx 1/3$.

For comparison we show the A region for $n_T$ and $T_e$ ($T_i = T_e$) values of the plasma in a thermal reactor with $Q = 2$. It is clear from Fig. 2 that the conclusion of [4] concerning easing the Lawson criterion in a beam system holds when the final deuteron density is taken into account, if $\alpha_1$ is not too small ($\alpha_1 \approx 1.5 \times 10^{-5}$). The best approximation of the plasma parameters in existing and planned experimental installations to the C region occurs when $\alpha = \alpha_1 \approx 0.1$.

We will estimate the size of the beam current. It follows from Eq. (7) that, when $n \approx 10^{14}$ cm$^{-3}$, $\alpha_1 = 0.1$, $T_e = T_e(\text{min})$, and under the conditions of Fig. 2, the unit current is $I/V \approx 8.3 \times 10^{-6}$ A/cm$^3$. When $V \approx 10^8$ cm$^3$, a current of $I \approx 8.3$ A is required. Obtaining such currents is feasible with modern technology.

In conclusion, we note that the position of the C boundary in Fig. 2 is significantly dependent on several factors. Thus, increasing deuteron stopping due to collective processes (which are especially dangerous when large $\alpha_1$ are of interest), the presence of heavy impurities, etc., cause decreased output of the B reaction and, yet, push the C boundary closer to the thermal-reactor A region. This effect can be compensated to a certain extent by increasing the energy-conversion efficiency (decreasing $Q$) and the effective value of $W_n$ (for example, through fission reactions).

**LITERATURE CITED**