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 $I_B$ and the deuteron stopping time $\tau_1$ in a thick, fully ionized tritium target:

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

$$\tau_1 = \int_0^E \frac{dE}{(-dE/dt)}.$$  

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]:

$$(-dE/dt) = \frac{1.6 \times 10^{-9} \eta_n \ln \Lambda}{T_e^{3/2} (1 + 2.7 \times 10^{-14} E/T_e^{3/2})} + \frac{8.5 \times 10^{-10} \eta \ln \Lambda}{E^{1/2}} \text{ eV/sec},$$

where $T_e$ is the electron temperature of the target ($T_e, T_1 \ll E$) in eV; $\ln \Lambda$ is the Coulomb logarithm.

Figure 1 shows the values of $B$ and $n\tau_1$ calculated from Eqs. (1)-(3). The data on the cross section $\sigma (E)$ are taken from [5]; $\ln \Lambda = 18; T_e = 5-8$ keV; $n = 10^{14}-10^{15}$ 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

$$[I_B (1 - \alpha) W_0 \eta_0 + \rho \eta_p \eta_l] \eta_1 > p,$$

where $p = 3nT_eV/\tau \geq IE$ is the power input to the target ($T_1 \approx T_e$); $W_0$ is the reaction energy; $\eta_p$ and $\eta_0$ are the plasma-energy and reaction-product conversion efficiencies, respectively; $\eta_l$ 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:

$$n \tau > \frac{3 (\sigma \tau_1) T_0 \theta}{\alpha_1 (1 - \alpha) W_0}.$$

Fig. 1. Dependence of $nT_1$ 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 $\tau > \tau_1$.

\[ \frac{B}{E} > \frac{Q}{(1-\alpha)W_n}; \]

\[ \frac{I}{V} = \frac{\alpha_1n^2}{nT_1}; \]

where $Q = (1 - \eta_p\eta_u)/\eta_n\eta_u$; $\alpha_1 = n_1/n$; $n_1 = \ln_{\tau}/V$ 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 $nT_1$.

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 $\alpha_{\min} = (1/2)(1 - (12T_eQ/W_nB))$ and upper bound $\alpha_{\max} = 1/2$, at which the absolute minimum of $nT_1$ is reached.

Figure 2 depicts the region C of $nT_1$ and $T_e$ values which satisfy Eqs. (5) and (6) for $E = 200$ keV, $Q = 2$ ($\eta_n = 1/3$, $\eta_p = 2/3$, $\eta_u = 3/4$) and $W_n = 2.4$ MeV. In this case, $T_e(\min) \approx 6.5$ keV. The minimum for $nT_1(\approx 10^{18} \text{ cm}^{-3}\cdot\text{sec})$ is attained when $T_e \approx 9$ keV and $\alpha = \alpha_1 \approx 1/3$.

For comparison we show the A region for $nT_1$ and $T_e$ ($T_1 = T_e$) 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 ($\alpha_1 > 1.5 \times 10^{-5}$). 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 $n \approx 10^{14} \text{ cm}^{-3}$, $\alpha_1 = 0.1$, $T_e = T_e(\min)$, and under the conditions of Fig. 2, the unit current is $I/V \approx 8.3 \times 10^{-6}$ A/cm$^3$. When $V \approx 10^6 \text{ cm}^3$, 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**