ASH EXHAUST CAUSES A LIMITATION IN STEADY-STATE TOKAMAK-FUSION REACTORS

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Abstract

Ash exhausts from the tokamak fusion reactors will interact with magnetic fields and induces electric currents there. It is proved, for typical parameters under steady-state condition, there exists a confliction between the minimum exhausted velocity and the maximum permissible velocity for equlibrium and stability requirements.

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After recent progress in plasma confinement and heating in tokamaks, and with the current construction of large tokamak experiments aimed at demonstrating that plasmas can be heated up to fusion temperature and confined for fusion-relevant times at least for D + T reaction, the ash exhaust problem must be considered more carefully. For steady-state tokamak reactors, a method for driving toroidal current either by neutral injection or by r. f. travelling wave, etc. and refuelling by injection pellets deeper into the plasma are necessary. Then the ash must be exhausted steadily as a radial outward velocity along the minor radius. The macroscopic movement of ash will interact with both the poloidal and toroidal fields and induces electric currents there. We know already, the poloidal beta (β_p) is connected directly with the currents and their distributions, so there must exist some relationships between the ash remove velocity and the most important parameters of tokamak plasmas.

For simplicity, we use the constant current density model to estimate the main effects roughly, the real distribution of currents will only modify a little by changing the constant. The poloidal current denisty

$$j_t = j_{t1} + j_{t2} \tag{1}$$

j_{t1} — toroidal current density induced by external sources

j_{t2} — toroidal current density induced by plasma velocity ($\sigma v_n B_p$)

From equilibrium analysis of toridal plasmas

$$\begin{aligned} \beta_p &= \frac{<\Delta p>}{\left(\frac{B_p^2}{2\mu_0}\right)_a} \\ &= \frac{2\pi \int_0^a \left[\int_0^r (j_t B_p - j_p B_t)\, dr\right] r\, dr}{\pi a^2 \cdot \left(\frac{B_p^2}{2\mu_0}\right)_a} \\ &= 1 - \frac{8}{3}\frac{j_p}{j_t} q_a \frac{R}{a} \end{aligned} \tag{2}$$

here R — major radius, a — minor radius, q_a — safety factor at a, t, p are denoted to toroidal and poloidal components respectively.

Since $j_p = -\sigma v_n B_t$ for steady case, minus sign means plasma poloidal current is on the diamagnetic direction for outward flow. Neglecting the small difference between $\sigma_{\|}$ and $\sigma_{\perp}$. From (1) and (2) we obtain

$$\frac{j_{t2}}{j_{t1}} = \left[\frac{8}{3}\frac{(q_a\frac{R}{a})^2}{\beta_p - 1} - 1\right]^{-1}$$

$$\approx \frac{3(\beta_p - 1)}{8(q_a\frac{R}{a})^2} \tag{4}$$

for typical tokamak conditions. The poloidal current induced by plasma movement must be one or two orders of magnitude less than the current induced by external sources. Since $j_{t2} \ll j_{t1}$,

$$j_{t2} = \sigma v_a B_p \approx \sigma v_n \frac{\mu_0 j_{t1} \cdot \pi a^2}{2\pi a}$$

$$\frac{j_{t2}}{j_{t1}} = \frac{\mu_0 \sigma v_n a}{2} \tag{5}$$

substitute (5) to (4) and finally we obtain

$$\mu_0 \sigma v_n a \approx \frac{0.75(\beta_p - 1)}{q_a^2(\frac{R}{a})^2} \tag{6}$$

for typical reaction case,

$$T \sim 10\,keV, \quad \frac{R}{a} \sim 3, \quad q_a \sim 3,$$
$$\beta_{p\,max} \sim \frac{R}{a}, \quad a \sim 1\,m, \quad \mu_0 = 4\pi \times 10^{-7} H/m$$

the electrical conductivity ($T \sim 10\,keV$)

$$\sigma_{spitzer} \sim 10^9\,mho/m$$

then from (6)

$$(v_n)_{max} \approx 1.5 \times 10^{-5}\,m/s$$

even for the case, that the anomaly factor of σ is ten, the $(v_n)_{max}$ still can't exceed $1.5 \times 10^{-4}\,m/s$.

For D+T reactor,

$$T \sim 10keV$$
$$n \sim 10^{20}\,m^{-3}$$

the average velocity v^{D-T} is $1.6 \times 10^6\,m/s$, and since the reaction mean path λ is $10^8\,m$ so the reaction life time

$$\tau_R \sim \frac{\lambda}{v_{D-T}} \sim 60\,sec.$$

and the ash remove average velocity

$$(v_{ash})_{min} \sim \frac{a}{\tau_R} \sim \frac{1}{60} \sim 1.6 \times 10^{-2}\, m/sec.$$

After the thermonuclear reaction is completed, the ash must exhaust with a radial outward velocity near $1.6 \times 10^{-2}\, m/sec.$ along the minor radius. But from equilibrium and stability analysis it can't exceed much more than $3 \times (10^{-4} - -10^{-5})\, m/sec.$ under typical conditions. The difference is near two or three orders of magnitude. So no steady-state tokamak fusion reactor will be possible with presently estimated possible parameters if this exhaust method is proposed.

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