Limits of energy confinement time and fusion energy gain in magnetic confinement fusion

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Abstract

A theoretical upper limit of energy confinement time in a magnetic confinement fusion (MFC) reactor is predicted based on radiation reaction associated with spontaneous electron cyclotron radiation (SECR). Agreement is found between theory and experiments at the Tokamak Fusion Test Reactor (TFTR), the DIII-D tokamak, the Joint European Torus (JET), and the Wendelstein 7-X stellarator. A theoretical limit of D-T fusion energy gain is predicted, offering plausible explanations for the sustained D-T fusion energy gain of $Q = 0.19$ in TFTR, the equivalent D-T fusion energy gain of $Q = 0.32$ inferred from D-D fusion in DIII-D, and the new D-T fusion energy record in JET with $Q = 0.33$ sustained for 5 seconds.

1. Introduction - Fusion energy is a promising candidate for clean energy. There have been new fusion energy records achieved in thermonuclear fusion experiments recently [1,2]. In magnetic confinement fusion (MCF), energy confinement time is the single most important scientific issue [3]. It is intimately related to fusion energy gain.

The physics of energy confinement is complex [4]. Traditionally, tokamak and stellarator designs rely on empirical scaling laws for estimating energy confinement time. The most widely accepted scaling laws are the ITER98 empirical energy confinement scaling for tokamaks [5] and the ISS04 empirical energy confinement scaling for stellarators [6]. Both empirical scaling laws involve multiple physical quantities, geometrical parameters, and fitting coefficients. While instabilities, disruptions, turbulence, charged-particle transport, and Rutherford-scattering-type bremsstrahlung radiation have received most attention in energy confinement studies [4], spontaneous electron cyclotron radiation (SECR) has been widely treated as mostly reabsorbed by plasmas [7-9]. The validity of such treatment has not been verified experimentally and is questionable in the context of the present paper.

2. Theoretical upper limit of energy confinement time - In a magnetically confined plasma consisting of hydrogen isotopes, an electron gyrates in the magnetic field and spontaneously emits cyclotron radiation. It loses its perpendicular kinetic energy $E_{e\perp}$ via cyclotron radiation emission according to the Larmor formula [10]. In the leading-order approximation, the electrons in the plasma are isothermal, and the total kinetic energy of an electron on average is $E_e \approx 3E_{e\perp}/2$. The ions and electrons tend to thermalize among themselves on a time scale shorter than or comparable to the characteristic time scale over which the electrons lose their energies via cyclotron radiation, such that $E_i \approx E_e = E$, where E_i is the total kinetic energy of an ion on average. It is reasonable to assume that the energy loss rate of an ion is about the same as that of an electron on average. Furthermore, it is assumed that SECR reabsorption and other energy loss mechanisms are small. Under these assumptions, it readily follows that the upper limit of energy confinement time is [11]

$$\tau_E \equiv -\frac{E}{dE/dt} = \frac{3c}{4\omega_c^2 r_e} = \frac{2.6\ \mathrm{second}}{B_{\mathrm{Tesla}}^2}, \qquad (1)$$

where c is the speed of light, $r_e = e^2/4\pi\varepsilon_0 m_e c^2 = 2.8 \times 10^{-15}$ m is the classical electron radius, $\omega_c = eB/m_e$ is the electron cyclotron frequency, and B is the central (or toroidal) magnetic field. At $B = 1$ T, $\tau_E = 2.6$ s.

3. Comparison between theory and experiment - For comparison between theory and experiment, it is essential to analyze high quality data showing how plasma parameters vary immediately after supplied heating power is turned off in a high-performance plasma discharge. Figure 1 summarizes the comparison between theory and experiments at the tokamaks TFTR [3], DIII-D [12], and JET [13] and the stellarator Wendelstein 7-X [14]. The experimental data analyses for TFTR and Wendelstein 7-X has been discussed [11]. The experimental data for DIII-D plasma discharge #87977 with $\tau_E = 0.4$ s at a toroidal magnetic field of 2.15T is extracted from [12]. In recent JET experimental plasma discharge #99869 [13], the measured D-T fusion power decreases exponentially as the NBI heating power was abruptly reduced at $t = 13.0$ s. From the time scale over which the fusion power decreased, as calculated using the experimental fusion power $P_1 = 5.6$ MW at $t = t_1 = 13.0$ s and fusion power $P_2 = 2.1$ MW at $t = t_2 = 13.24$ s, the experimental energy confinement time is estimated to be $\tau_E = (t_2 - t_1) ln\,(P_1/P_2) = 0.24$ s. This result agrees with the theoretical $\tau_E =$ 0.22 s for a toroidal magnetic field of 3.45 T in this experimental plasma discharge.

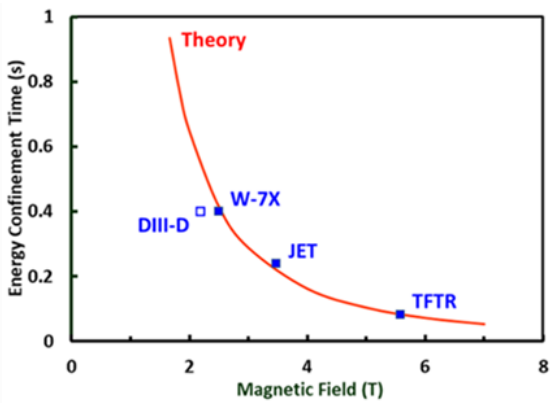

Fig. 1 Comparison between theory and experiment on energy confinement time. The solid curve is the theoretical upper limit. The solid square dots are the analyzed TFTR, JET, W-7X experimental data as labelled, and the open square dot is the reported DIII-D data.