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Energy confinement time in magnetic fusion

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The single most important scientific question in magnetic fusion research may be confinement in a fusion plasma. A theory is presented for quantitative calculations of confinement time limits for plasma thermal energies in magnetically confined thermonuclear fusion reactors. The theory is based on radiation reaction associated with spontaneous electron cyclotron radiation as described by the Larmor formula. Good agreement is found between the theory and the measurements of energy confinement times from the early TFTR D-T fusion experiment and the recent Wendelstein 7-X hydrogen plasma experiment. A new, advanced Lawson criterion for D-T ignition is derived. A fundamental limit of fusion energy gain is predicted, which is consistent with the latest magnetically confined D-T fusion energy record achieved experimentally at JET.

In a magnetically confined plasma, 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. In the leading order of 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. It is readily shown that the confinement time of plasma thermal energy is simply given by[1]

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

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

For comparison between theory and experiment, it is essential to use high quality data showing how plasma parameters vary after supplied heating power is turned off. Figure 1 shows comparison between theory and experiment for data shown in Figs. 2 and 3.

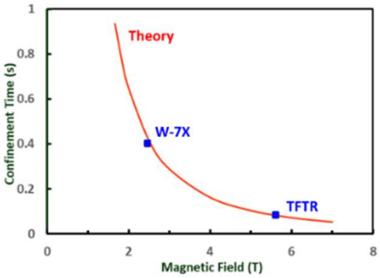

Figure 1 Theory versus experiment chart[1].

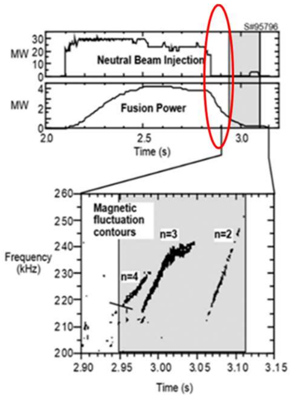

Figure 2 TFTR experimental data[2].

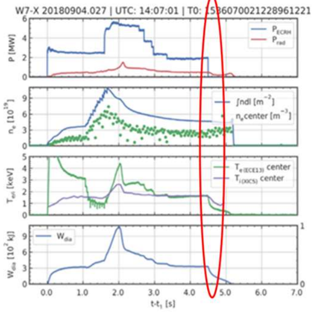

Figure 3 Wendelstein 7-X experimental data[3].

At the optimal temperature of 14 keV for D-T fusion, the advanced Lawson criterion for ignition becomes simply[1]

$$\beta \equiv \frac{p}{p_{mag}} \geq 0.92 = 92\% \qquad (2)$$

with the so-called β parameter measuring the thermal pressure $p = 2nk_BT$ relative to the magnetic pressure $p_{mag} = B^2/2\mu_0$. The upper limit of fusion energy gain is $Q_{Limit} \approx 5\beta/0.92 = 5.4\beta$.

The latest D-T fusion energy record[4] achieved experimentally at the Joint European Torus (JET) with sustained $Q = 0.33$ for 5 s appears to be consistent with the advanced Lawson criterion. Indeed, the theoretical limit is $Q_{Limit} = 0.35$ taking the JET geometric parameters $R = 3$ m and $a = 1.25$ m and the associated MHD stability limit $\beta = 6.4\%$.

References

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