Thermal Instability in Magnetically Confined Toroidal Plasmas Induced by Radiative Emission of Highly Charged Ions

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Excessive heat load on divertor plates in magnetically confined fusion reactors poses significant risks, potentially leading to substantial damage and jeopardizing stable reactor operation. One promising approach for mitigating this heat load is the cooling of peripheral plasmas through radiative emission from deliberately introduced highly charged ions, known as impurities. Impurities with low atomic number (Z) are preferred to avoid unintended cooling of the hot core plasma, as high-Z impurities can result in excessive radiation at the high temeprature range of order of several keV.

The cooling function (L), defined as the sum of all impurity line radiations, exhibits a notable dependence on electron temperature (T_e). Initially, L increases with T_e as electrons in plasma attain sufficient energy to excite orbital electrons in impurity ions, resulting in radiation through subsequent de-excitation. However, as the impurity charge states progress to closed-shell configurations (e.g., He-like shell), excitation energies rise and radiation significantly diminishes, causing L to decrease by orders of magnitude. Consequently, low-Z impurities show peak radiation efficiency at electron temperatures around 10–30 eV, followed by a decline as T_e approaches 100 eV.

This temperature-dependent behavior of L is a critical factor in the thermal instability of plasmas. When the condition $\frac{\partial}{\partial T}\left(\frac{L}{T_e}\right) < 0$ is met, plasma cooling accelerates in a runaway manner until reaching a new thermal equilibrium [1]. Our study investigates the thermal instability in magnetically confined toroidal plasmas, focusing on the role of peripheral magnetic field structures where radiative cooling predominantly occurs.

In the Large Helical Device (LHD) experiment at NIFS, Japan, the thermal instability growth rate γ_{th} was analyzed during radiative cooling operation with carbon impurities as a major impurity originating from graphite divertor plates. As plasma density increased, edge T_e gradually decreased with fixed heating power, enhancing total plasma radiation according to the function $n_e n_{imp} L(T_e)$, where n_e and n_{imp} are densities of electrons and impurities, respectively. During cooling, γ_{th} became positive in the peripheral region, with the unstable zone moving radially inward until plasma collapse due to uncontrollable radiation occurred.

Interestingly, introducing magnetic perturbation fields stabilized radiative cooling by altering edge magnetic topology. The resulting "magnetic island," analogous to phase-space structures in nonlinear Hamiltonian systems, consist of X-points (hyperbolic singular point) and O-points (elliptic cell) surrounded by separatrices. By inspecting energy transport at the island, the γ_{th} becomes large at the O-point and the X-point, where the stabilizing effect by energy transport is reduced significantly because of the singularities. Thermal instability analysis within the island revealed that while radiation intensified, γ_{th} at the O-point became negative, reaching thermal stability. Thermal condensation at the O-point led to reduced T_e (down to several eV) and increased density (up to 10^{20} m^{-3}), avoiding the unstable condition $\frac{\partial}{\partial T}\left(\frac{L}{T_e}\right) < 0$.

Details of this analysis will be presented and the thermal equilibrium achieved during radiative cooling operations will be discussed at the conference.

[1] S.A. Balbus, The Astrophysical Journal **303**, L79 (1986) L79.