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A comprehensive map of micro-instabilities in multi-species plasmas

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In magnetic fusion, where high temperature plasmas must be efficiently confined, understanding the transport physics of multi-species plasmas—including not only bulk ions and electrons, but also impurity ions entering from the device walls and fusion reactions—is one of the most significant issues. In particular, achieving selective exhaust of impurity ions while allowing bulk ions to accumulate in the core is essential for realizing a reactor, since impurities degrade fusion efficiency through radiation losses and other factors.

However, micro-instabilities driven by plasma density and temperature gradients often induce turbulent transport, thereby degrading plasma confinement performance. In multi-species plasmas, the presence of multiple gradients further complicates the structure of these instabilities. For example, the toroidal impurity mode (tIM) [1,2] has been discussed as a type of the micro-instability that arises under an idealized density profile, in which bulk ions are peaked and impurity ions have a hollow profile in the core region. The density gradients that drive such instabilities are determined by quasi-neutrality condition, which must be satisfied across all particle species, as follows:

$$\frac{R_0}{L_{ne}} = (1 - f_c)\frac{R_0}{L_{ni}} + f_c\frac{R_0}{L_{nZ}} \ , \qquad (1)$$

where R_0 is the torus major radius, L_{ns} the density gradient lengths for species s, $f_c = Zn_z/n_e = 1 - f_i$ is charge concentration of impurity ion with charge Z. Equation (1) represents the case of a plasma consists of three species of electron, bulk ion and impurity ion. In this work, we provide a detailed analysis of "comprehensive stability map" for the micro-instabilities in a multi-dimensional parameter space, using linear gyrokinetic simulations. The parameter space consists of the gradients of plasma temperature and density for each particle species, while satisfying the quasi-neutrality conditions described above.

The figure shows the relationship between the maximum growth rates of tIM instability under flat temperature profiles and the quasi-neutrality condition in the space of the density gradients of each particle species [3]. Here, carbon ion $(Z = 6)$ and hydrogen ion are employed as impurity and bulk ions, respectively. Under the quasi-neutrality condition with a fixed impurity charge concentration f_c, the growth rate varies widely in the parameter space. This result suggests that attention should be paid to the individual density gradients rather than to the impurity charge concentration alone. It can be observed that as f_c increases, the tIM grows with a constant electron density gradient, while the mode tends toward a reduction in instability when the hydrogen density gradient is kept constant. In particular, the hydrogen density gradient has a significant impact on the growth rate of tIM, and this effect is stronger than that of the impurity charge concentration. Additionally, we found that when finite temperature gradients are present, i.e., when both ion temperature gradient (ITG) mode and tIM coexist, the resulting instability is not simply the sum of the two modes.

The detailed, comprehensive stability map may help guide operational scenarios where micro-instabilities can be controlled, for example, by actively varying impurity density.

References

[1] J. Q. Dong and W. Horton, Phys. Plasmas **2**, 3412 (1995).
[2] M. Muto and K. Imadera, Phys. Plasmas **30**, 072303 (2023).
[3] Y. Ito, "Effects of temperature and density gradients on micro-instabilities in multi-species plasmas," Master's Thesis in Nagoya University (2025).

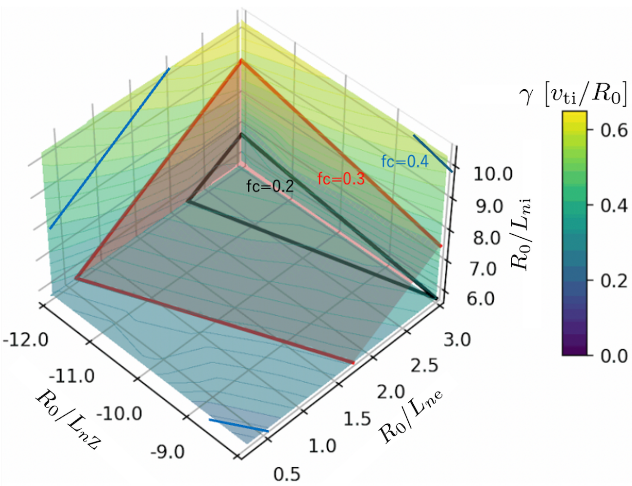

Figure: Maximum growth rate of toroidal impurity mode in the space of each density gradient of electron, hydrogen, and impurity ions. The planes represent the surfaces of the quasi-neutrality conditions with $f_c = 0.2$ (black colored), $f_c = 0.3$ (red), and $f_c = 0.4$ (blue).