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Simulations of fusion reactions under thermal and non-thermal equilibrium distributions in tokamaks

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The fusion reaction rate, serving as a core metric for evaluating plasma energy output, critically determines both the power amplification factor (Q-value) of fusion devices and the self-sustaining conditions and stability of burning plasmas. Traditional theories, based on Maxwell-Boltzmann distribution assumptions, simplify fusion reaction rates into global integral quantities. However, this framework faces challenges when auxiliary heating techniques—such as neutral beam injection (NBI) and ion cyclotron resonance heating (ICRH)—introduce energetic non-thermal particles. The dynamic interplay between fast ions and background thermal ions significantly alters velocity-space distribution functions, thereby triggering non-thermal equilibrium fusion reactions.

This study utilizes a self-developed Particle Tracing Code (PTC), which incorporates Monte Carlo methods, to systematically investigate the evolution of fast-ion distributions under NBI and combined ion cyclotron resonance frequency (ICRF) heating conditions. By simulating particle dynamics during auxiliary heating, the research quantified the impact of these distributions on fusion reaction rates and compared contributions from thermonuclear, beam-target, and beam-beam reactions nder NBI operation. As shown in Fig. 1a, the variation of fusion reaction rate coefficients with ion temperature under different beam parameters in the HL-3 tokamak is revealed, while Fig. 1b demonstrates the variation of fusion reaction rates with core ion temperature under varying NBI parameters. Additionally, energy spectra and slowing-down processes of fusion products are analyzed.

Integration of ICRF heating uncovered synergistic effects between NBI and ICRF, quantitatively demonstrating enhanced heating efficiency during combined operation. These findings provide theoretical foundations for optimizing fusion performance and auxiliary heating system design, while establishing a scientific basis for improving energy output efficiency in future fusion experiments.

References
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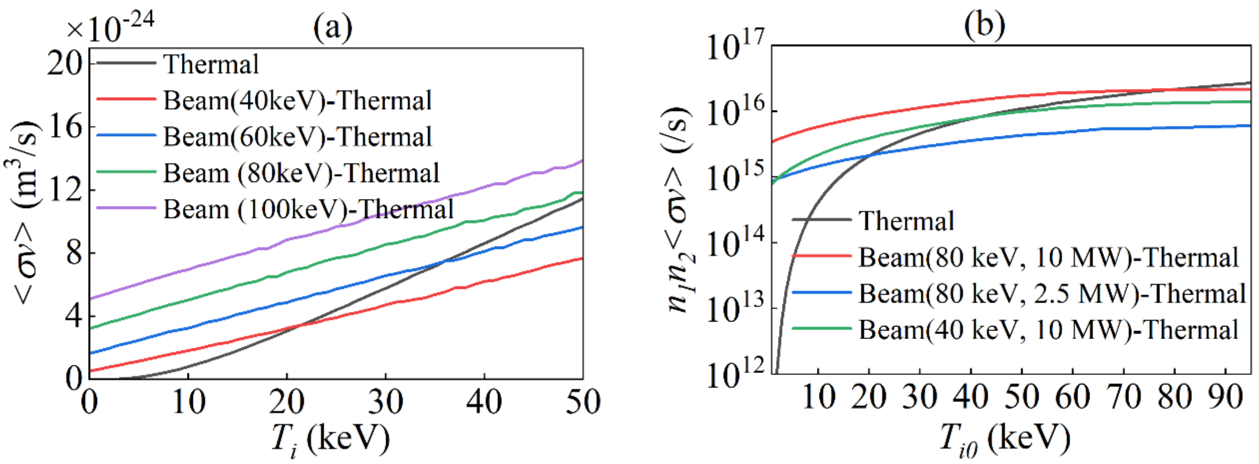

Figure 1. (a) Variation of reaction rate coefficients with ion temperature for HL-3 thermal fusion and beam-thermal fusion under different beam parameters; (b) Variation of reaction rates with core ion temperature for thermal fusion and beam-thermal fusion under varying beam parameters.