Fast ion stability and wall heat loading in stellarators

Alpha particle physics remains one of the most important scientific frontiers in the development path of fusion as a future energy resource. Fast ion driven instabilities have been observed for nearly all stellarator experiments in which energetic tail heating populations are present. These instabilities have generally been related to shear Alfvén or other MHD modes that are resonantly destabilized either through passing or trapped particle precessional resonances. Regimes have been observed both where the effects of such modes are relatively benign, as well as cases where they lead to drops in neutron emission, lowered core confinement, and measured increases in fast ion losses at the vacuum chamber wall.

Fast ion drive suppression through high density ignition

Through high density operation stellarators offer an effective means for avoiding these instabilities and maintaining acceptable wall/divertor heat loads. High density regimes have been achieved in the W7-AS experiment's HDH regime[1] with densities up to 4×10^{20} m^{-3} and in the LHD experiment's SDC regime[2] with densities up to 1×10^{21} m^{-3}. If these regimes can be extrapolated to stellarator reactors, they can significantly reduce the potential for fast ion instabilities and the associated localized wall heating from fast ion losses. This is related to the scaling of the slowing down-time ($\tau_{s,fast} \propto T_e^{3/2}/n_e$) and steady-state fast ion density ($n_{fast} = \tau_{s,fast} n_e^2 \langle \sigma v \rangle / 4$ with the background plasma density and temperature. Higher densities in a stellarator reactor and the lower required ignition temperatures significantly decrease the slowing-down time, which lowers n_{fast} and T_{fast} (i.e., through the decreased tail component on the slowing-down distribution). These factors then reduce the drive ($\propto d\beta_{fast}/dr$) for fast ion instabilities. Also, since the density of the resident fast ion component is reduced, the potential for large fast ion losses from other mechanisms, such as unconfined orbit loss, and MHD activity in the thermal plasma is greatly reduced.

Fast ion stability research thrusts

Since the accessibility requirements and physics of high density regimes in stellarators are not yet well understood and plasmas will have to be heated through a sequence of lower densities to attain these regimes, an active experimental and theoretical program to understand and predict fast ion instabilities in 3D configurations will be important for the future of the stellarator concept. An experimental program is already underway and should benefit from interaction with similar activities in tokamak research. Continued refinement in the spatial, velocity and time resolution of fast ion diagnostics will be essential in understanding these phenomena and their implications and control in future devices. The theory/modeling of fast ion instabilities in stellarators has made progress at mode identification,[3,4,5,6] linear thresholds,[7] and fast ion loss prediction.[8] Further improvements will be needed in these areas along with a greater focus on the nonlinear physics in order to attain the desired predictive capabilities. Since stellarators encompass a wide range of magnetic geometries and symmetries, a larger set of Alfvén instabilities can be present than in tokamaks; however, due to the larger number of potential modes the opportunities for parasitic (continuum) damping are also greater. These issues will require advancements in computational MHD/kinetic analysis tools and close collaboration with experiments. In addition, since the structure and stability of fast ion driven modes can be influenced by the stellarator's 3D magnetic field structure, it has been suggested that a target for energetic particle instability suppression (through a mode density function) can readily be developed[6] and should be included in future stellarator physics optimization efforts.

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