Predictive simulation of global instabilities in Tokamaks

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The macroscopic dynamics of instabilities in tokamaks are well described by the magnetohydrodynamic (MHD) equations, which are obtained by integrating velocity moments of the Boltzmann equations for the electrons and ions over velocity space and combining this with the low-frequency Maxwell Equations [1]. In this talk, we are concerned with solving these equations numerically to predict the onset and saturation amplitude of instabilities.

There are many simpler sets of equations that make additional approximations to more efficiently describe a given tokamak instability. Some of these, that others will discuss, are called “reduced MHD”, or “the island evolution equation”, or “the Porcelli model”, etc. These simpler, model equation sets, are extremely useful for understanding the basic physics of certain instabilities. However, the approach of our SciDAC project, The Center for Extended Magnetohydrodynamic Modeling”, is to solve the full 3D MHD equations without making other approximations and keeping all the geometric detail. This is much more compute intensive than applying the simpler models, but can lead to new discoveries of phenomena that are absent in the simplified models, and can provide quantitative results for direct comparison with experiments over a wide range of parameters.

All modern tokamaks with elongated cross sections are unstable to a “vertical instability” which is an axisymmetric nearly rigid motion of the plasma column. These instabilities are stabilized by a two-tier approach. A conducting metallic structure, normally the vacuum vessel, slows the instability growth rate down to the L/R time of the vessel, and then a feedback system using the poloidal field coils is used to provide complete stability. This instability is well described by 2D MHD codes [2].

3D tokamak instabilities that are described by these same equations include the sawtooth oscillation, kink and ballooning modes, tearing modes, edge localized modes (ELMs) and resistive wall modes (RWM). The latter are the 3D analogue of the vertical instability. The instabilities with the slowest growth rates are the most challenging to simulate because of the problems of accurately computing the small driving force and the associated long integration times. This has led us to develop fully implicit time integration methods [3,4] and to use high-order finite elements and a representation for the velocity field that permits plasma motions that do not compress the toroidal field to a high order of accuracy.

We describe recent progress in the calculation of linear stability properties and the nonlinear evolution of ELMS, in the simulation of feedback control of neoclassical tearing modes, in calculating properties of the sawtooth, including kinetic effects, and in the prediction of the onset of non-resonant m=1 ideal modes. We are also applying these codes to calculate the forces on the vacuum vessel when the plasma undergoes a major disruption.

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