NONLINEAR MAGNETOHYDRODYNAMIC MODELLING OF IDEAL BALLOONING MODES IN HIGH-BETA WENDELSTEIN 7-X PLASMAS

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The stellarator is one of the most promising concepts for future fusion reactors. The high-performance operation of the advanced Wendelstein 7-X (W7-X) stellarator has profound implications on the viability of the stellarator concept, and its success critically depends on maintaining magnetohydrodynamic (MHD) stability at high beta (the ratio of plasma to magnetic pressure). To evaluate the impact of the MHD instabilities that may be triggered, we have undertaken state-of-the-art MHD simulations of W7-X plasmas above the designed 5% beta-limit. Ideal ballooning modes occur as linear theory predicts, but saturate nonlinearly at relatively low levels without inducing large-scale crashes. This suggests that the W7-X optimization for MHD stability is successful beyond expectation, and enhances the appeal of the stellarator approach to steady-state fusion reactors. That said, such nonlinear stability is not guaranteed in stellarators, for more significant profile change occurs when a low-order resonance is induced by a more peaked pressure profile, and interchange modes cause a major pressure crash in an alternative, unoptimized W7-X configuration. This work marks a significant advance in stellarator MHD modelling, which is enabled by the recent extension of the M3D-C^1 code to stellarator geometry.

Stellarator plasmas have shown nonlinear stability when driven beyond linear stability thresholds in experiments, which, if understood, could be exploited to expand the operation windows. In addition, stellarator designs could employ nonlinear stability considerations to relax linear stability constraints, which often can be too restrictive and costly. However, modelling MHD activities in stellarators has been difficult due to the lack of nonlinear codes that can effectively treat realistic stellarator geometry and transport timescales. To develop such a capability, we have extended the M3D-C^1 code to allow non-axisymmetric domain geometry [1]. We introduce a set of logical coordinates, in which the computational domain is axisymmetric, to utilize the existing finite-element framework of M3D-C^1. A C^1 coordinate mapping connects the logical domain to the non-axisymmetric physical domain, where we use the M3D-C^1 extended MHD models essentially without modifications. The implementation of this approach has been verified by several numerical tests, including simulations of the heating, destabilization, and equilibration of a stellarator plasma with strongly anisotropic thermal conductivity, and of the relaxation of stellarator equilibria to integrable and non-integrable magnetic field configurations in realistic geometries. To validate this new capability, we have simulated the sawtooth-like crashes observed in W7-X experiments with electron cyclotron current drive [2]. The near-axis current drive gives rise to two ι=1 resonances in the equilibrium rotational transform profile so that two consecutive (1,1) internal kink modes are seen in the simulations. A small-amplitude crash at the inner resonance occurs first, which may correspond to the sawtooth precursors observed in the experiments. A bigger crash at the outer resonance then flattens the core temperature profile, which shows semi-quantitative agreements with experimental measurements on metrics such as the crash amplitude and the inversion radius of the temperature change. These results also illustrate a likely mechanism of the current-drive-induced sawtooth-like crashes in W7-X.

Using the stellarator extension of M3D-C^1, we have performed the first nonlinear MHD simulations of pressure-driven instabilities in high-beta W7-X plasmas [3]. In the standard configuration (EIM), we first consider a broad pressure profile that is favourable for achieving high volume-averaged beta (5.4%), as shown by the black dashed curve in Figure 1(b). The corresponding rotational transform profile in Figure 1(a) shows no low-order resonance. The simulation agrees with the design analyses that ideal ballooning modes become linearly unstable as Figure 2(a) shows, but predicts nonlinear saturation at benign levels with mild confinement degradation as Figure 2(b) shows, which is much less severe than the original expectation of losing the plasma column. This suggests that W7-X may be able to operate at or slightly above the designed beta-limit while avoiding major MHD events, but by no means implies that nonlinear stability is guaranteed. The latter point is exemplified by simulating a different equilibrium with a peaked profile and lower volume-averaged beta (4.0%) shown by the black dash-dot curve in Figure 1(b). The corresponding rotational transform profile in Figure 1(a) shows the presence of an ι=5/6 low-order resonance. Figure 2(c) shows that the ballooning mode structure is much more radially extended, and Figure 2(d) shows that the nonlinear dynamics induces substantial degradation in the core.

The contrast is more evident in Figure 1(b), which shows that the peaked pressure profile is subject to more significant change than the broad profile. In addition, we also consider an alternative, unoptimized configuration (TEH) with nearly zero magnetic shear, in which ideal interchange modes trigger a major pressure crash at beta= 1%. These results suggest that MHD stability should still be treated seriously in stellarator operation and design, for which nonlinear modelling using tools like M3D-C[1] can play an instrumental role.

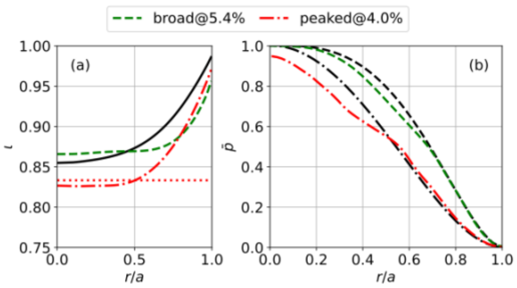

Figure 1 (a) The rotational transform profiles in the simulated EIM equilibria with different pressure profiles and beta values. The vacuum profile (solid) is shown for comparison, and the dotted line marks the ι=5/6 resonance. (b) The final shapes of the normalized pressure profile in the simulations, with the initial shapes (black) shown for comparison.

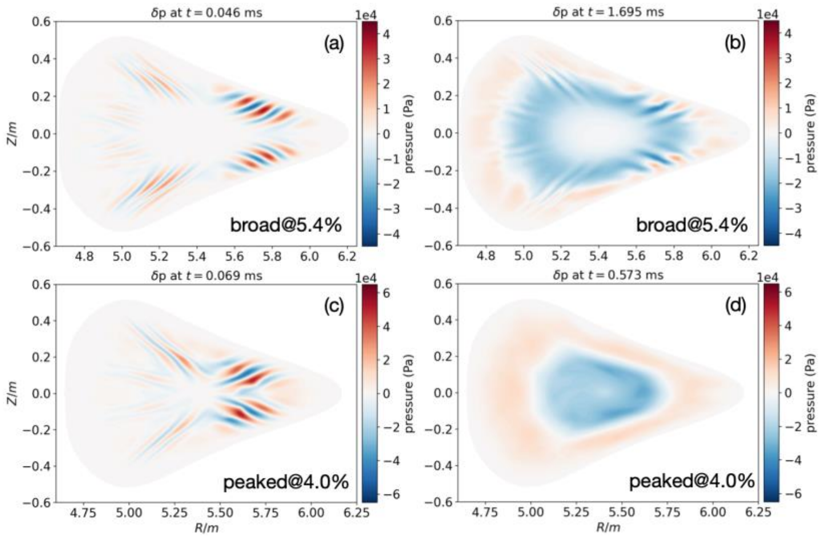

Figure 2 Snapshots of the pressure change in two EIM simulations with different pressure profiles and beta values: (a) and (c) show mode structures at the end of the linear growth phase, while (b) and (d) show saturated states at the end of the simulations. Note the different scales in the color bars.

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