Onset conditions of helical cores in tokamaks for extrapolation to ITER

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Helical cores, or “snakes”, have been observed in many tokamak devices over the years [1, 2, 3] and numerically reconstructed for recent discharges at DIII-D [4]. Helical cores have been found to both improve and degrade confinement through different mechanisms. Theoretical predictions and supporting experiments at MAST find that fast ion confinement degrades significantly with helical cores [5]. On the other hand, the flux pumping mechanism [6] keeps the q profile above unity without sawteeth crashes and is beneficial for maintaining high performance discharges [3]. Their impact on ITER has not yet been fully quantified, but numerical studies of onset conditions suggest that ITER could be highly susceptible to helical core formation.

Helical snakes like the one shown in Fig 1 have been often observed in Alcator C-Mod ohmic discharges during the plasma current ramp-up phase or early in the plasma current flat-top. The mode spontaneously forms and remains active for tens of milliseconds. Typically the mode starts out as an ideal displacement of flux surfaces in the plasma core, as has been measured and confirmed by tomographic inversion. After some time the mode smoothly transitions into a crescent shape accompanied by the onset of sawteeth [2]. Here we focus on such a typical case in C-Mod discharge 1120208028.

The mode onset is between 0.31 s and 0.32 s into the discharge. The soft-X-ray (SXR) as well as the Electron Cyclotron Emission (ECE) diagnostics clearly show the snake in the plasma core, as shown in Fig 1 by SXR emission. The mode rotates with the core of the plasma at about 4 kHz. The displacement of the magnetic axis is well resolved, especially in the SXR data due to the Molybdenum impurity radiation in the core, and has a magnitude of about 1.5 cm.

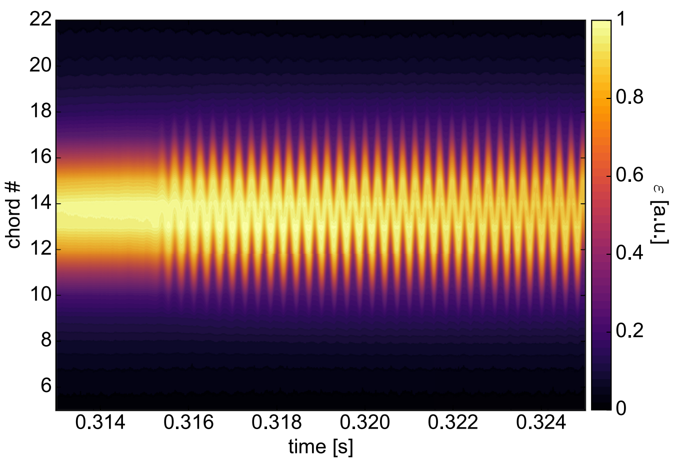

Figure 1: *Helical core in C-Mod shot 1120208028, measured by SXR Array 1; strongest emission is on axis.*

Using the SXR data around 0.33 s the helical core equilibrium was reconstructed by the V3FIT code [7], following the same procedure as was used previously in the DIII-D tokamak [8]. C-Mod's SXR arrays 1 and 3 are used in the reconstruction. Both arrays are at the same toroidal location but view the plasma from the top and low-field-side respectively. In order to provide 3D data to V3FIT four evenly spaced time slices within one rotation period of the helical core around 0.33 s are chosen and identified as an equivalent of four identical diagnostic sets at four different toroidal locations throughout the vessel. During the reconstruction V3FIT adjusts the current density profile as well as the toroidal phase of the helical core with respect to the diagnostic locations to minimize the χ^2 between measured and synthetic signals. After each modification, the 3D equilibrium is reconverged and the synthetic signals evaluated. The final result is the minimum in χ^2 and therefore, within error bars, a best possible match between model and data. Using the same procedure, a total of four equilibria at times between 0.31 s and 0.34 s were reconstructed. The helical core has not yet formed at 0.31 s, which results in an axisymmetric reconstructed equilibrium, but all other time slices reconstruct to 3D helical core equilibria, similar to the one shown in Fig. 2 for 0.33 s.

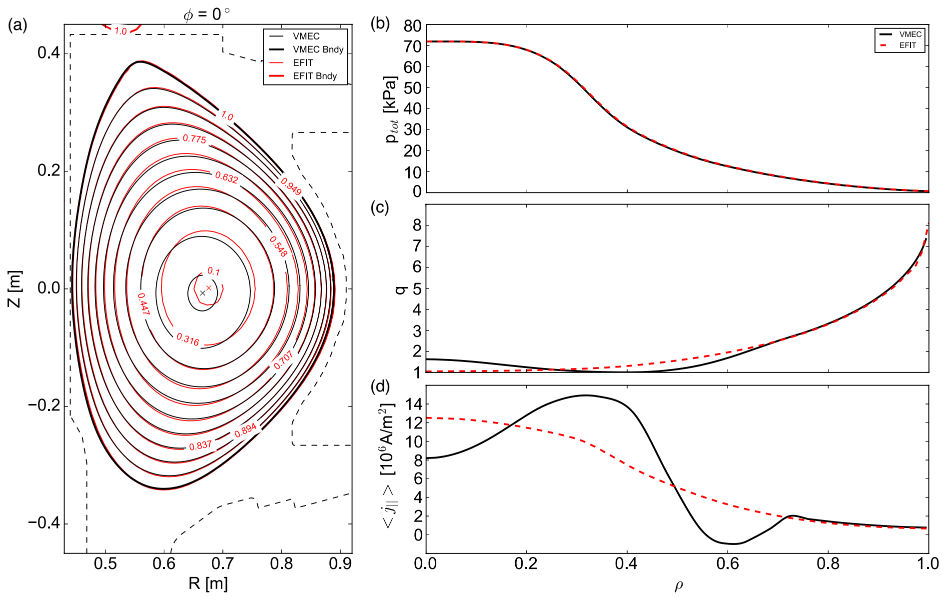

Figure 2: *C-Mod 3D equilibrium reconstruction (black) at 0.33 s compared with kinetic EFIT (red). (a) X-section, (b) pressure profile, (c) q-profile, (d) parallel current density.*

Figure 2 compares the reconstructed 3D equilibrium (black) with the axisymmetric EFIT equilibrium at the same time slice (red). The cross section in (a) clearly shows the displacement of the flux surfaces near the magnetic axis with an axis displacement of 1.42 cm. The pressure profile in (b) matches, since it is given as a fixed input to the reconstruction. V3FIT reconstructs the current density profile (d) between $\rho = 0$ and $\rho = 0.7$, while then (PAR)VMEC [9] computes the flux surfaces and q-profile (c) self-consistently. The q-profile shows a significant reversed shear with $q_{min} = 1.005$ at $\rho_{qmin} = 0.4$ and $q_0 = 1.63$. Note that q_{min} is larger than 1, which agrees with the sawteeth-free progression of the discharge. The current density is significantly different between EFIT and the reconstruction. Unfortunately there is no MSE data for this shot to locally constrain the q-profile and therefore the current density additionally during the reconstruction. Nevertheless, in agreement with numerical predictions [8], a reversed shear q-profile is needed to match the helical core in the equilibrium to the measured data.

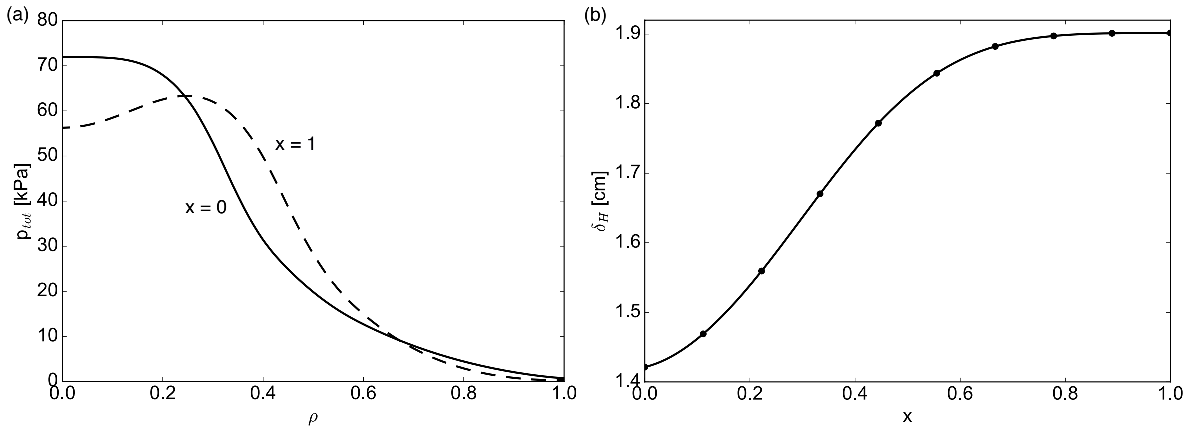

Figure 3: *(a) Possible pressure profiles at 0.33 s: (solid) standard monotonic profile, (dashed) hollow profile. (b) Change of helical core size with continuous change in pressure profile from monotonic* $(x = 0)$ *to hollow* $(x = 1)$.

The standard kinetic EFIT reconstruction procedure for C-Mod enforces a monotonic pressure profile. Due to the strong core radiation due to impurities, ECE data suggests a hollow pressure profile during the helical core formation though. Two different pressure profiles at 0.33 s are shown in Fig. 3(a). For the analysis the monotonic profile is continuously morphed into the hollow one by $p = (1-x)p_{monotonic} + x\,p_{hollow}$, using the dimensionless parameter x. For $x = 0$ the pressure is the monotonic profile and for $x = 1$ it becomes the hollow one. Keeping every other input fixed from the reconstructed helical core equilibrium, we can model helical core equilibria with VMEC by only changing the pressure. Figure 3(b) shows the evolution of the magnetic axis displacement δ_H with x. The displacement monotonically increases by about 34% with the pressure profile becoming hollow, which indicates a significantly stronger drive of the kink. This shows that a hollow pressure profile, as caused by the strong impurity radiation in the plasma core, is favorable for helical core formation.

The threshold for the spontaneous symmetry breaking is determined using VMEC scans, beginning with reconstructed 3D equilibria from DIII-D and Alcator C-Mod based on observed internal 3-D deformations. The helical core is a saturated internal kink mode; its onset threshold, shown by the black line in Fig. 4, is proportional to $(dp/d\rho)/B_t^2$ around $q = 1$. Below the threshold, applied 3-D fields can drive a helical core to finite size, as in DIII-D. The helical core size thereby depends on the magnitude of the applied perturbation. Above it, a small, random 3-D kick causes a bifurcation from axisymmetry and excites a spontaneous helical core, which is independent of the kick size. The onset threshold is very sensitive to the q-shear in the core. Helical cores occur frequently in Alcator C-Mod during ramp-up when slow current penetration results in a reversed shear q-profile, which is favorable for helical core formation.

The markers in Fig. 4 show the operational conditions of discharges in DIII-D, C-Mod and ITER relative to the helical core onset threshold. DIII-D shot 164661 is marginally stable, but driven by applied 3D fields [8]. Four time slices for C-Mod discharge 1120208028 show how the discharge transitions across the onset threshold, resulting in the snake shown in Fig. 1. Key features that enable the transition include the reversed shear q-profile as well as the hollow pressure profile. Both are expected to occur in ITER due to the slow current penetration into the core as well as core radiation due to Tungsten impurities. An ITER mock-up discharge with a subtle reversed shear q-profile but still a monotonic pressure profile is significantly above the onset threshold.

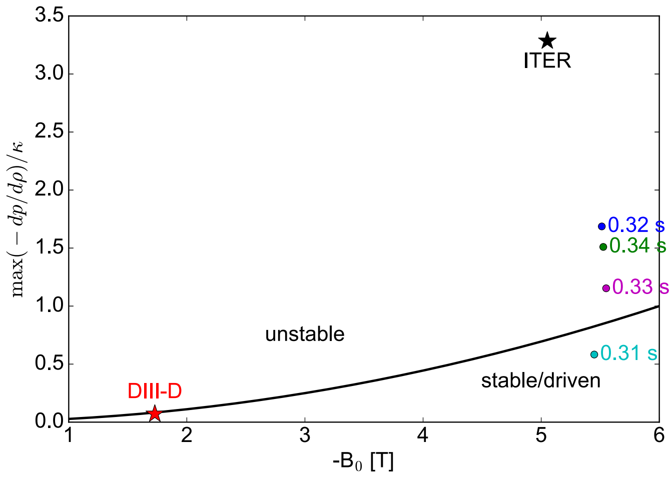

Figure 4: *Onset of helical cores for an ITER mock-up discharge (15 MA, H-mode), compared to DIII-D and 4 different time slices of C-Mod discharge 1120208028. The y-axis is normalized so that all thresholds coincide.*

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