

## Formation, stability and momentum transport characteristics of impurity-induced snakes in Alcator C-Mod

L. Delgado-Aparicio<sup>1</sup>, R. Granetz<sup>2</sup>, J. Rice<sup>2</sup>, Y. A. Podpaly<sup>2</sup>, M. L. Reinke<sup>2</sup>,  
M. Bitter<sup>1</sup>, E. Fredrickson<sup>1</sup>, D. Gates<sup>1</sup>, M. Greenwald<sup>2</sup>, K. Hill<sup>1</sup>, E. Marmor<sup>2</sup>,  
N. A. Pablant<sup>1</sup>, S. Scott<sup>1</sup>, R. Wilson<sup>1</sup>, and S. Wolfe<sup>2</sup>

<sup>1</sup>Princeton Plasma Physics Laboratory, Princeton, NJ, USA

<sup>2</sup>MIT - Plasma Science and Fusion Center, Cambridge, Massachusetts, USA

### 1. MOTIVATION.

A small but long-lived helical perturbation dubbed a *snake* was first found at JET following the injection of a high-speed frozen deuterium pellet [1]. More than two decades have passed since their discovery and observation in every major fusion facility. However, the description of the *snake* formation, stability criteria as well as its impact on the background plasma has remained elusive. The role of impurity density, resistivity, collisionality and momentum exchange with the background plasma can now be described using an adequate suite of spectroscopic diagnostics that included AXUV bolometers, SXR tomography and a high-resolution x-ray crystal imaging spectrometer [2].

### 2. SNAKES IN C-MOD.

*Snakes* have been observed at C-Mod even in the absence of injection of frozen deuterium pellets, especially after the release of high-Z impurity flakes from the tiles covering

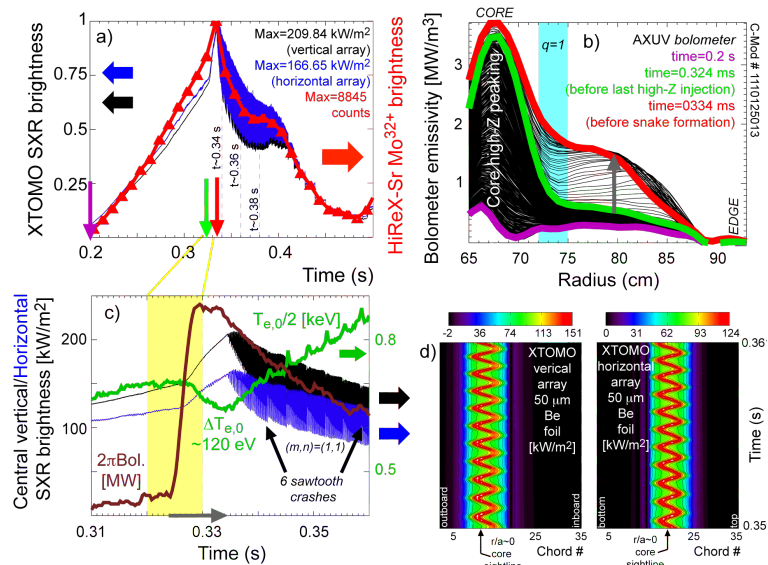


Fig. 1. SXR and bolometric signatures associated to the formation and sustainment of the  $(m,n)=(1,1)$  snake.

the vacuum vessel [3,4]. Typical waveforms from the line-integrated soft x-ray and AXUV bolometer measurements are shown in Figures 1-a) and -b); Figure 1-c) depicts the clear correlation between the divertor bolometer data indicating a last impurity injection before the *snake* formation and the 120 eV drop on the core electron temperature. This description is consistent with having an impurity source cooling the  $q=1$  surface, increasing the local resistivity and causing a drop in the current density that eventually leads to the formation of a

magnetic island that “traps” the impurities from the background plasma [3,4]. The typical  $m=1$  snake-like pattern shown in Figure 1-d) is formed by an enhancement of the impurity density in a small flux tube on the  $q=1$  surface which rotates toroidally in the field of view of the SXR arrays. Moreover, the normalized time history of the molybdenum brightness depicted in Figure 1-a) was measured by a core-viewing sightline of the x-ray imaging spectrometer, and shows a remarkable agreement with the central normalized brightness measured by the XTOMO cameras [3,4]. It is therefore safe to assume that most of the core emission is strictly from molybdenum charge states. The impurity

peaking at the center of the Mo *snake* is such that its SXR emissivity is approximately four times higher than that of the unperturbed background plasma (see Figure 2). This *snake* travels in the electron diamagnetic drift direction and considering an average toroidal transit time of  $t \sim 0.185\text{--}0.2$  s, we obtain velocities of the order of 21–23 km/s, which are consistent with the toroidal velocity measured from the x-ray line Doppler shifts.

### 3. TEARING MODE FORMATION AND STABILITY

Data from C-Mod impurity-induced *snakes* agree with the hypothesis that the formation of the tearing mode is caused by a localized current drop on the  $q=1$  surface and that resistivity plays a fundamental role in both the formation and sustainment of these islands [5]. An extended Modified Rutherford Equation (MRE) can provide a convenient framework to study the effect of impurity radiation and cooling on the island size. In the absence of neoclassical driving and stabilizing terms, the time evolution of the width of the island is,

$$\frac{\tau_R}{r_s} \frac{d\omega}{dt} \approx r_s \Delta' + C_1 \bar{\omega} + \frac{C_2}{\bar{\omega}}, \quad \bar{\omega} \equiv \omega/r_s, \quad C_1 = 3(r_s^2/s) \tilde{P}_{rad}/\chi_{\perp,eff}^{island} n_e \langle T_e \rangle, \quad C_4 \approx 5.43g[s(r_s)] \tilde{Z}_{eff}/Z_{eff} \quad (1)$$

The second term in the RHS characterizes the linear dependence between the island growth rate and island size through a dimensionless variable  $C_1 \propto \delta P_{rad}$ , where  $\delta P_{rad} > 0$  is the net radiated power density carried by the island [3,4]. The third term takes into account the enhancement of impurity density at the center of the island with respect to that of its surroundings through a dimensionless variable  $C_2 \propto \delta Z_{eff}/Z_{eff}$  [6,7]. With a  $s \sim 0.2$  at  $R \sim 0.73$  m and  $\chi_{e,0}$  and  $T_{e,0}$  of the order of 0.5 m<sup>2</sup>/s and 1.5 keV, the term  $C_1$  is  $\sim 5.4$ . On the other hand,

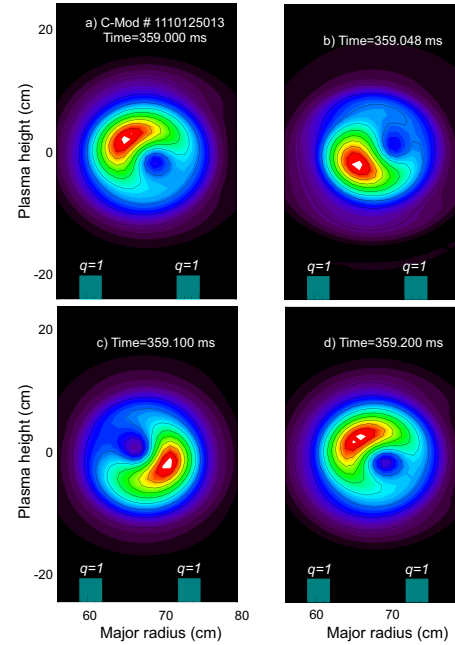


Fig. 2. Fast SXR tomographic reconstructions of Mo island.

the function  $g(s)$  is  $\sim 10$  while the experimentally inferred  $\delta Z_{eff}/Z_{eff}$  from the bolometer measurements shown in Figure 3, is as high as 40% [3,4]; with these data we can safely conclude that  $C_2 \in [10.9, 21.7]$ , which is at least twice to four times bigger than  $C_1$ . Therefore, the  $\delta P_{rad}$  term is not a dominant factor but rather only a correction to a stronger effect given by the  $\delta Z_{eff}$  term. A detailed discussion of the stability of the  $m=1$  mode is included in references [3,4]. The ability to predict the appearance of these modes is an important issue for advanced tokamak operation scenarios since their coupling to other modes can be a cause of plasma disruptions. Verifying this relationship between the island growth rate and the island-size is important, as it predicts that even ITER may be susceptible to tearing mode destabilization by impurity radiation. A systematic study of the role of impurities affecting the tearing mode onset and evolution by providing an enhanced radiation and associated cooling rates have not been taken into account yet for the developed ITER scenarios [8,9].

#### 4. MHD-INDUCED MOMENTUM TRANSPORT.

The interplay between the 3D nature of non-axisymmetric MHD perturbations and the bulk plasma can degrade rotation, and can lead to a self-feeding process which actually deteriorates the overall plasma confinement. An interesting feature inferred from the Doppler-shift of the  $\text{Mo}^{32+}$  emission-line is that toroidal rotation remains invariant from the time of the *snake* creation until its disappearance at 0.42 s as shown in Figure 4-a). Moreover, it is only after the *snake* disappears that the core rotation increases +40 km/s in the co-current direction, which is characteristic of the strong  $I_p$  dependence of L-mode rotation [10]. The velocity profiles shown in Figure 4-b) confirm the increment of +40-50 km/s at the core, but also indicate a change of +90 km/s at the location where the *snake* was originally observed. This significant increment might suggest that the 3D MHD perturbed fields could have experienced torques associated to both resonant and non-resonant effects. The constancy of the plasma angular momentum density for the range of times where the *snake* was present can correspond to a delicate balance between the torques associated to the 3D induced NTV and the Reynolds tensor, both of which depend on the existence of a non-zero ion temperature gradient [3,4,11]. The data from the HiReX-Sr spectrometer shown in Figure 4-c), confirm for the first time the

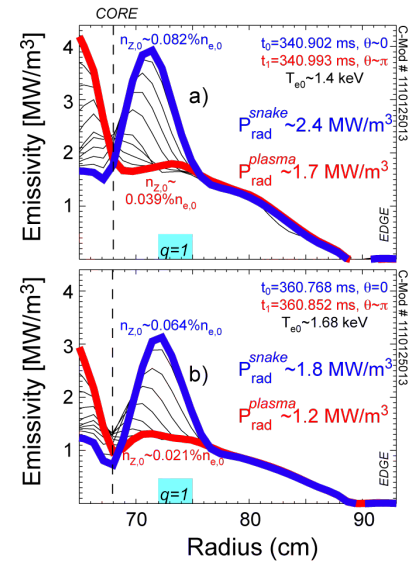


Fig. 3. Fast bolometric reconstruction of Mo island.

presence of an ion temperature gradient as high as 35 keV/m outside the  $q=1$  surface during the times where the *snake* is present, therefore, a balance between the 3D induced NTV and the torque from the Reynolds tensor could have been at play. The ability to predict if the presence of tearing modes will also impact toroidal rotation and momentum transport in L- and H-mode plasmas is also of concern for ITER scenarios due to the small amount of external momentum input from the neutral beam and the potential drag of the intrinsic torque by 3D non-axisymmetric fields [3,4].

## 5. SUMMARY.

Impurity-induced  $m=1$  *snakes* are observed in Alcator C-Mod, caused by the release of molybdenum *flakes* from the tiles covering the vacuum vessel. The tearing mode formation can be explained with an extended Modified Rutherford Equation in which the saturated island width depends on the typical  $\Delta'$  term and the local changes of  $\delta Z_{eff}$  and  $\delta P_{rad}$ . Their stability criteria are satisfied by an enhanced plasma pressure and plasma resistivity on the center of the island in agreement with compressible resistive MHD models. The interplay between the 3D non-axisymmetric mode and toroidal rotation is apparently mediated by the existence of  $\nabla T_i$ -dependent torques associated with neoclassical toroidal viscosity and the Reynolds stress.

## 6. REFERENCES

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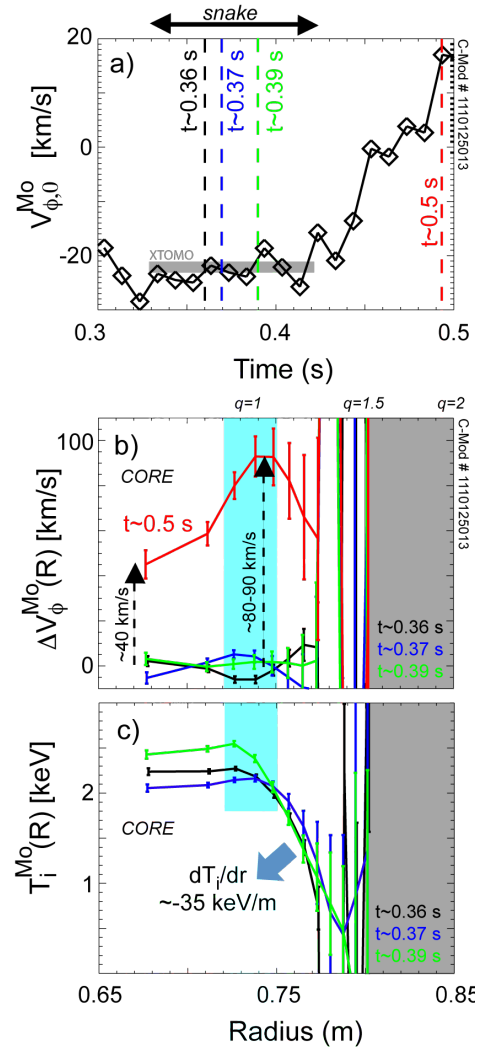


Fig. 4. Fast bolometric reconstruction of Mo island.