On the kink formation and stability of impurity ‘snakes’ in Alcator C-Mod

L. Delgado-Aparicio\textsuperscript{1,2}, L. Sugiyama\textsuperscript{3}, R. Granetz\textsuperscript{2}, J. E. Rice\textsuperscript{2}, Y. A. Podpaly\textsuperscript{2}, M. L. Reinke\textsuperscript{2}, D. Gates\textsuperscript{1}, W. Bergerson\textsuperscript{4}, M. Bitter\textsuperscript{1}, E. Fredrickson\textsuperscript{1}, C. Gao\textsuperscript{2}, M. Greenwald\textsuperscript{2}, K. Hill\textsuperscript{1}, A. Hubbard\textsuperscript{2}, J. W. Hughes, E. Marmar\textsuperscript{2}, N. A. Pablant\textsuperscript{1}, S. Scott\textsuperscript{1}, R. Wilson\textsuperscript{1}, S. Wolfe\textsuperscript{2} and S. Wuktich\textsuperscript{2},

\textsuperscript{1}PPPL, \textsuperscript{2}MIT-PSFC, \textsuperscript{3}MIT-LNS, \textsuperscript{4}UCLA

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Background

1. Snake oscillations are characterized by a small region of localized and enhanced plasma density that rotates within the field of view of various diagnostics and is radially concentrated on, or inside the $q=1$ surface.

2. Impurity snake modes were first seen at Doublet-III [high-Z impurity accumulation: Jahns, NF’82] and PLT [high-Z laser blow-off injection: Cohen, APS-DPP’83)].

3. D$_2$ pellet-induced snakes were first seen at JET (Weller, PRL ‘87) as a persistent density perturbation at a rational $q$-surface.

4. Snakes have been a common feature in every major tokamak fusion experiment, as well as in spherical tori and reversed field pinches.
Motivation for new studies of snakes

① The formation of the snake, the reasons for its improved stability and its impact on the background plasma are still unknown.

② New diagnostics with adequate spatial resolution can be used for the first time to study the role of $P_{\text{rad}}$, $n_z$, $v_{e,i}$, $\eta$, $v_\phi$, $p=nT$ and $Z_{\text{eff}}$.

③ Simulations of ideal-MHD equilibrium states have reproduced the ‘original’ snakes observed at JET (Cooper, PRL’10, NF’11) and predicted the helical ITER equilibria (Cooper, PPCF’11).

④ There are growing concerns that these 3D structures (e.g. triggered by particle fueling or impurity accumulation) could enhance the redistribution of fast ions ($r_{q=1,\text{ITER}} \sim 1 \text{m}$).

⑤ Novel nonlinear M3D simulations that separately evolves density and temperature are now available.
(1,1) snake modes in C-Mod are routinely observed on a number of diagnostics.

1. Observed during the current ramp-up phase or early in the plasma current flattop.

2. The high-$T_{e,\text{edge}}$ increases high-Z impurity erosion $\Rightarrow$ allow on-axis impurity peaking.
Suite of novel diagnostics installed in Alcator C-Mod enables new snake 3D studies
VUV/SXR survey spectroscopy shows that Mo is the main high-Z impurity before snake formation.

① Typical enhancement of Mo-line emission from core accumulation is $\times 4-10$

② Lack of emission from stainless steel constituents
High resolution x-ray imaging spectrometer monitors He-like and H-like Ar, as well as Ne-like molybdenum ($\text{Mo}^{32+}$).

Similar systems have been installed in NSTX, LHD, KSTAR and EAST.
Molybdenum from the metal walls is responsible for the enhanced SXR and $P_{\text{rad}}$.

Brightness of $\text{Mo}^{32+}$ peaking at the core before "snake" is observed.
Enhanced SXR brightness is well correlated with an increase in Mo$^{32+}$ line intensity.

Conclude that the “snake-like” pattern in the brightness data is formed by a small region of localized and enhanced molybdenum density.
In few words: Snake formation can be considered as a multi-stage process.

Sawtooth-free kink-like state have lifetimes spanning from few to hundreds of ms.
Snake formation resembles a kink-like impurity density perturbation ($\delta\varepsilon \sim n_e \delta n_{Mo}$).
High-resolution AXUV and ECE measurements suggest the presence of $n_Z$ and $T_e$ fluctuations during snake formation.

\[ \delta T_e \text{ from snake phase #2} \]
(kink: before sawtooth onset)
High-resolution AXUV arrays enable $P_{\text{rad}}$ estimates before and during snake formation.

AXUV-$P_{\text{rad}}$ observations show the $n_{\text{Mo}}$ “without” contamination by $T_e$. 
High-resolution AXUV arrays enable $P_{rad}$ estimates before and during snake formation.

Snake after impurity accumulation

$\Delta P_{rad} \sim n_e n_{Mo} L_{Mo}$

$L_{Mo} \sim 7 \times 10^{-32} \text{ W} \cdot \text{m}^3$

$n_{e,0} \sim 2.2 \times 10^{20} \text{ m}^{-3}$

$\Delta P_{rad,0} \sim 2.1 \text{ MW/m}^3$

$\Rightarrow n_{Mo} \sim 1.4 \times 10^{17} \text{ m}^{-3}$

$(c_{Mo} \sim 6 \times 10^{-4})$

Do $\delta P_{rad}, \delta n_Z,$ & $\delta Z_{eff}$ have an effect on the formation and stability of the mode?

$\Rightarrow n_{Mo} \sim 2.2 \times 10^{17} \text{ m}^{-3}$

$(c_{Mo} \sim 13 \times 10^{-4})$
But, the last stage resembles that of a magnetic island produced by a resistive 1/1 internal kink.
Later snake: SXR tomographic reconstruction shows 1/1 crescent shape.

① Perturbation travels in the electron diamagnetic drift direction.

② From the transit time $\tau \sim 185-200 \, \mu s$ we calculate $v_\phi \sim 21-23 \, \text{km/s}$, which agrees with the $v_\phi$ measured from the x-ray line Doppler shifts.
High-Z impurity snakes are surprisingly resilient to sawtooth crashes.

1. $\tau_{\text{snake}} \approx 185-200 \, \mu s$ while $\tau_{\text{sawtooth}} \approx 3.66 \, \text{ms}$

$\Rightarrow \approx 20$ snake periods.

2. Crashes may cause a transient reduction of $r_{q=1}$ ($\delta r_1 \lesssim 1 \, \text{cm}$).
Circular core moves radially outwards during sawtooth crash

① During the crash the small core moves rapidly outwards to the edge of the crescent radius.

② Snake density is nearly “untouched” by thermal crash + heat pulse.

③ The location of the peak emission shrinks inward by 1-2 cm at the crash.

④ The snake toroidal transit frequency slows by ~ 25%.
AXUV reconstructions during later snake show stronger localization of impurity concentration.

① Peaked concentration moves radially outwards.

② Snake density decays steadily in time.
Dynamic MHD snake with density and temperature resembles experimental results

① MHD simulations with separate temperature and density evolution find a new nonlinear \( m/n=1/1 \) kink-like mode compatible with C-Mod early snake.

② Toroidal rotation needed.

③ Quasi-steady-state \( 1/1 \) helical density perturbation peaks near \( q=1 \) and extends outside \( q \gtrsim 1 \).

④ The helical temperature tends to minimize the perturbed pressure gradient (and free energy).

⑤ No magnetic island!

⑥ Kink motion perpendicular to density.


The density snake at $q \sim 1$ would not be affected by the sawtooth crash.

Nonlinear MHD simulation with toroidal rotation shows a slowly growing 1/1 kink over $q \lesssim 1$ with an external helical density peaked at or just outside the $q = 1$. 

M3D

Nonlinear MHD simulation with toroidal rotation shows a slowly growing 1/1 kink over $q \lesssim 1$ with an external helical density peaked at or just outside the $q = 1$. 

M3D
Snakes (a helical ion density concentration) can form without a magnetic island. C-Mod heavy impurity snakes appear to form without a magnetic island, sometimes for very long intervals, or with an island on the opposite side from the snake. Formation starts when \( q_0 \gtrsim 1 \), unlike JET pellet snakes.

Model ignores basic 1/1 instability dynamics, which require consideration of the entire region inside \( q \leq 1 \): the MRE model, based on \( m \geq 2 \) tearing mode reconnection, considers only conditions at the rational surface that affect the local current density layer, but the \( m = 1 \) snake comprises the entire volume inside \( q < 1 \).

Localized cooling around \( q=1 \) is unlikely to explain snake formation, even for snakes formed with islands.

The \( \text{dw/dt} \) model tends to greatly over-predict instability for high-Z snakes due to increased \( Z_{\text{eff}} \) and \( P_{\text{rad}} \) (Pecquet NF 97).

Theoretical implications I: cannot use a standard (Wesson-like) MRE model (cont.)

Most snakes have periodic sawtooth crashes that do not destroy the snake density. Wesson’s model does not address sawteeth!

- The saturation of the mode, needed to create a sustained snake, would also require that the equilibrium jump in the magnetic flux $\frac{d}{dt}$, measured by $\frac{d}{dt}$, be large and negative (stabilizing) to counterbalance the strong destabilizing terms. It must remain so during the snake lifetime, which seems to rule out the possibility of sawtooth oscillations.
- Applicable to all snakes, not just impurity.
- A strongly stabilizing $\frac{d}{dt}$’ appears unrealistic.
- C-Mod impurity snake concentrates into the late stage crescent island by a mechanism that differs from snake formation (observations suggest a role for first few sawteeth)

Model is based essentially on pressure, not density and temperature separately. Sawtooth instability cannot be separated from snake “island”.

Theoretical implications II: snake models based on pressure solely are inadequate

• Models of the snake based solely on pressure have a fundamental difficulty in explaining its stable co-existence with sawtooth crashes.

• The linearized internal kink mode is driven by the axisymmetric pressure gradient over the $q < 1$ region. Non-linearly, the mode eventually displaces and destroys the high pressure central core.

• Previous MHD studies of snakes generally equate the higher snake density with higher pressure. This puts the impurity snake on the same side of the kink structure as the hot sawtoothing core. Additional heating of the core would then destabilize the kink (e.g. sawtooth temperature rise) and the resulting crash would destroy both the higher pressure core and the snake density. On the other hand, higher pressure on the island side would tend to stabilize the sawtooth.

• In the C-Mod snakes the high density and temperature fall on opposite sides; in that sense the higher pressure of the high $Te$ core drives the sawtooth, but not the snake!
Theoretical implications III: snakes are dynamic phenomena, not static ideal equilibria

• The likely explanation for the persistence of the snake is that it embodies a quasi-steady-state magnetic structure. Its $1/1$ helical configuration and close association with the $q = 1$ surface and ongoing sawtooth crashes suggest that it is related to the $1/1$ internal kink mode with magnetic reconnection.

• Static ideal MHD equilibria with a 3D helical core based on pressure balance reproduce some of the features of the original pellet snakes observed at JET (Cooper, PRL’10, NF’11, PPCF’11).

• However, the C-Mod observations of the snake’s gradual formation from zero amplitude, its smooth transition from a broadly kinked core to a crescent shape with no evidence of a phase shift, and the details of the periodic sawtooth crashes rule out a steady state force balance.

Tokamak equilibria that have helical pressure distributions resembles sawtooth-free kink snake (?).

Static ideal MHD equilibria with reversed q-profiles can have non-axisymmetric pressure profiles without islands.

① Bifurcated helical equilibrium states resemble saturated internal ideal kink mode structures like early C-Mod snake formation.

② Static model is inconsistent with the presence of sawtooth crashes.

③ Simulation results do not resemble the later stage of the C-Mod snake.
A suite of novel imaging diagnostics enables estimates of the $n = 1$ helical structure of $P_{\text{rad}}$, $n_z$, $n_e$, $T_e$, $Z_{\text{eff}}$, and $\eta$ inside the $q \leq 1$ region with adequate temporal and spatial resolution.

Observations of C-Mod heavy-impurity snakes (e.g. Mo, Ar) suggest important differences between the density and temperature dynamics that cannot be explained by a pressure-only model.

C-Mod heavy impurity snakes appear to form through a new type of internal kink-like mode, without an initial magnetic island.

Nonlinear MHD simulations with density and temperature evolution (M3D code) show a new 1/1 mode inside $q<1$, with a sustained 1/1 helical density concentration centered around $q=1$.

Snake formation and evolution do not fit Wesson's model based on a modified Rutherford equation (MRE).
EXTRA
Outline

① Background and motivation

① Typical SXR observations and full diagnostic suite

② Snake formation and theoretical implications.

③ Summary
Almost all the ionized Mo in the core of Alcator C-Mod is Ne-like Mo (Mo32+)

1. Mo is the main high-Z intrinsic impurity at C-Mod (PFCs).

2. The average Mo ion charge for core electron temperature of interest is \( \langle Z \rangle \sim 32 \).

3. Data from XTOMO and AXUV arrays - with known cooling factors - can be used as a proxy for \( n_{Mo}/n_e \):

\[
L_{Mo} \sim 7 \times 10^{-32} \text{ W} \cdot \text{m}^3
\]
High resolution x-ray imaging spectrometer monitors He-like and H-like Ar, as well as Ne-like molybdenum (Mo^{32+})
Can we conceive obtaining a $\Delta'$ for the (1,1)?

$R_0 \sim 67-68 \text{ cm}$

$\omega_{\text{sat}} \sim 1-1.5 \text{ cm}$

$r_s \sim 5 \text{ cm}$

$P_{\text{rad,BOLO}} (\theta \sim 0, t=0.340 \text{ s})$
Both sawtooth crashes & background transport contribute in flushing impurities from snake

① SXR emissivity decreased \( \sim 1.0 \text{ MW/m}^3 \) in 50 ms.

② Circular core displaced in time back to the original magnetic axis.

③ \( r_{q=1} \) might also broadens in time due to current density penetration.