Locked-mode avoidance and recovery without external momentum input using ICRH

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26th IAEA Fusion Energy Conference
Kyoto, Japan, 17-22 October 2016
Motivation

① Locked-mode avoidance in low-density Ohmic discharges is highly desirable, if not crucial, for reliable tokamak operation.

② Locked-mode threshold studies have considered only engineering macroscopic parameters resulting in a scaling law of the form:

\[ \frac{B_{r}^{\text{lock}}}{B_T} \propto \bar{n}_e^{\alpha_n} B_T^{\alpha_B} q_9^{\alpha_q} R_0^{\alpha_R} \]

C-Mod: \( \alpha_n \approx 1, \alpha_B \approx -0.7, \alpha_q \approx -0.57 \) (S. Wolfe, PoP’05)

③ The influence of drift-MHD as well as collisional and neoclassical flow-damping effects dependent on local kinetic profiles can alter the predicted engineering scaling & have not yet been considered.

④ Goal #1: study the evolution of the plasma profiles (\( T_e, i & \nu_\phi \)) during the formation of error-field-induced locked-modes without external sources of fueling and momentum input.

⑤ Goal #2: Attempt locked-mode avoidance and recovery using available RF techniques (e.g. ICRH and LHCD).
Locked-modes are studied in C-Mod at ITER-$B_\phi$ & without NBI fueling & momentum input

① LMs are easily obtained in low-density plasmas which may impair the heating phase proposed for accessing H-modes.

② LM excitation and suppression can be achieved by using the A-coils.

③ In C-Mod: $I_p \sim 0.8$ MA, ITER-$B_\phi$, $q_{95} \sim 4$.

④ Sawteeth are present. No long-lived modes, e-fishbones, ELMs, or MARFEs.

⑤ External fueling or momentum sources (e.g. NBI) are absent!

⑥ Non-perturbative Ar puffs needed for XCIS: $n_Z$, $v_{Z,\phi}$, and $T_Z$. 
A decrease of the plasma density (pump-out) is observed in error-field induced locked-modes

① Density pump-out at the edge is ~30% while at the core is ~50%, at nearly constant $T_e$.

① Density pump-out can also cause a reduction in mode-locking thresholds.

② Density pump-out is the main cause for decrease in:
   a) Stored energy: $W_{\text{MHD}}$
   b) $\tau_E$
   c) $\beta_N$
   d) Neutrons

④ Core density is reduced by $\times 2$ but the $P_{\text{rad}}(R)$ is nearly constant (core impurity transport changed ?).
Strong reduction of density fluctuations and change of sawtooth cycle are characteristic signatures of locked-mode onset

① Strong reduction of density fluctuations measured by reflectometer (as reflection layer moves out).

① Apparently no other MHD during locked-mode?

① Change of sawtooth cycle nature is significant:

Before: $\Delta T_{e,0} \sim 200-250$ eV
$\Delta t \sim 5$ ms, $f = 200$ Hz

After: $\Delta T_{e,0} \sim 100-150$ eV
$\Delta t \sim 0.15$ ms, $f = 6.6$ kHz

④ Sawteeth remains even when $n_e$ and $p_e$ were reduced by a factor of 2.
Fast & high-resolution $T_e$ profiles show flattening just inside the nominal $q=2$ radius

① The flattened region appears to be located @ $q=2$ surface.

② The width of the flattened region, (≈1-2 cm), places only a lower bound on the actual island width.

③ FRC-ECE diagnostic view is not aligned well with the O-point.

Note: Sampling of the magnetic island across the same FRC-ECE channels was made using a ‘waggle’ in the toroidal-field during a locked-mode experiment (see inset).
40-70 kHz (possibly high-\(m\)) magnetic signatures appear during error field penetration and last for the entire locked-mode.

1. Mode observable only with magnetic probes. Is not core-localized since cannot be “observed” with SXR-XTOMO, ECE or TCI.

2. Mode amplitude appear large for high-\(n\), which should be falling-off fast with radius.
GPI fluctuations at the **edge** show strong changes before and after central plasma locks (including edge ~60 kHz mode!)

Before locking:
- upward-going ($k_\theta>0$) feature at 100-200 kHz
- downward-going ($k_\theta<0$) feature at 10-20 kHz

After locking:
- 100-200 kHz ($k_\theta>0$) and 10-20 kHz ($k_\theta<0$) features disappear.
- a ~60 kHz feature appears (also seen by magnetic probes).
Propagation of edge turbulence changes direction in the lab frame during locking phase

① Before locking: data inside LCFS shows a clear structure moving in the electron diamagnetic drift direction ($v_0=3-5$ km/s).

② $S(k,f)$ changes dramatically in the process of locking which is ≠ than turbulence suppression (no decrease in fluctuation power).

③ The propagation of the local turbulence changes direction in the lab frame ⇒ consistent with a plasma spin-down during the mode locking.
CXRS enables $T_i$ and $v_{\phi,\theta}$ profiles at the edge ($0.9 < \rho < 1.0$) confirming the decrease in the toroidal velocity during plasma locking phase.

- During the plasma locking phase the $T_i$ drops $\sim 100$ eV @ $\rho = 0.9$ (~50% drop).
- $v_{\phi}$ shows a decrease from about 20 km/s to zero over $\sim 70$ ms (approx. to the time it takes for the density to pump-out as the plasma locks)
After several energy confinement times ($\tau_E$’s) the \textit{core} plasma is also assumed to be at rest.

\begin{figure}[h]
\centering
\includegraphics[width=\textwidth]{plot.png}
\caption{Graph showing plasma parameters over time.}
\end{figure}

Notes:

1. ‘+/-’ velocity indicates co-current/counter-current directed rotation.

2. LM braking drives the rotation to “zero” (has been verified by independently calibrated spectrometers).

Error-field-induced locked-mode:

a) The resonant error field is ramped.

b) When LM-threshold is reached a rapid transition to a non-rotating “state” is observed.

c) After several $\tau_E$’s (~100 ms) a stationary magnetic island develops and leads to a major confinement degradation.
Early ICRF power-scan delayed the mode onset (LM avoidance experiment)

1. $P_{\text{ICRF}}=1$ MW: no $L \rightarrow H$ transition.
   a) Need fine-tuning for $P_{\text{ICRF}}$,threshold
   b) $W_p \times 2$ to 55 kJ.

2. $P_{\text{ICRF}}=2,3$ MW: $L \rightarrow H$ transition.
   a) $W_p: 25 \rightarrow ~60-150$ kJ
   b) Density increases: $n_{eL,04} \sim 2 \times 10^{20} \text{ m}^{-3}$

3. Plasma locks later when RF turns off.

4. Locking time should be sensitive to $n_e$, $T_{e,i}$ and $V_\phi$. 
Using $P_{\text{ICRH}}>0.5$ MW successfully delayed locked mode onset

1. After ICRH power turns off, LM grows again and high-f signatures persist
2. Could provide a tool for soft-landing locked-modes and avoid disruptions.
3. Is the locked-mode threshold sensitive to evolution of $n_e$, $T_e,i$ and $V_{\phi,0}$?.
$P_{ICRH} \gtrapprox 1-2$ MW is required for H-mode accessibility and delay of locked-mode onset (but “locks” again after $P_{ICRH}$ is turned off).

Locked mode conditions are very reproducible ($n_e$, $T_{e,i}$ and $V_\phi$).
Neutron rate was not affected by error field during RF LM-avoidance experiments
Late ICRH power-scan aimed at stabilizing the locked-mode (LM recovery experiments)

1. Locking time is similar for all these cases due to nearly identical time-history of plasma density, temperature and toroidal velocity.

2. Plasma did not turn into H-mode at lower-density (~1/2 of the density before locked-mode onset) even though $P_{\text{ICRF}}=1$-$3 \, \text{MW}$.

3. H-mode power threshold increases significantly at lower density

4. Recovery is not as successful as LM-avoidance:
   a) $T_{e,0}$ increases only 400, 600, 1000 eV while the $n_{e,0}$ augments are small.
   b) $P_{\text{ICRF}}=1, 2, 3 \, \text{MW} \Rightarrow \Delta W_p=20, 35, 55 \, \text{kJ}$. 
When $P_{\text{ICRH}} > 1$ MW the magnetic signatures disappear

① Successfully suppressed also the magnetic signatures “associated” to the locked-mode.

② Could provide recipe for avoiding locked-mode and disruptions.

③ Confirms strong $n_e$-dependence of mode-locking thresholds; what about $T_{e,i}$ and $V_{\phi,0}$?
$P_{ICRH}$ successfully “unlocks” the core plasma “recovering” conditions before mode onset (...but will lock again after $P_{ICRH}$ is turned off)

Is anomalous momentum transport ($\propto \nabla T$) responsible for the spin-up? And if so, why in the counter-current direction?
During the ICRH-LM recovery experiments:

a) edge spins in the co-current direction …

b) core spins in the COUNTER-current direction
(conserving momentum without external torque ?)
Neutron rate did not recover H-mode values due to error-field density pump-out

Factor of 10 smaller than H-mode LM-avoidance experiments

C-Mod’s LM-recovery experiments

[x10^{12} n/s]

Ohmic (P_{ICRH}=0)

Recovery expts:

P_{ICRH}=1 MW

P_{ICRH}=2 MW

P_{ICRH}=3 MW

Neutron rate: S_n

Time (s)
P_{ICRH} might be changing the temperature and density gradients at mid-radius.

1. $T_{e,0}$ and $n_{e,0}$ increased by ~50%. $n_e(R)$ is nearly flat in the core.

2. $\nabla T_e$ changes ~ 50% from -16 to -23 keV/m.

3. Anomalous momentum transport ($\propto \nabla T_{e,i}$) responsible for unlocking?

4. $V_\phi$ is a very attractive parameter for scaling, by its direct relation with the viscous torque.
High-resolution ECE diagnostic shows heating also at the edge during ICRH recovery phase

① During mode-locking the plasma temperature decreased in the vicinity of the \((m/n)=(2/1)\) rational surface by \(~100\) eV

② In the ICRH recovery phase the plasma edge and core re-heats, at least restoring the initial profiles and even increasing gradients.
Acceleration in the ion-diamagnetic-drift direction is observed at the **edge** with GPI diagnostic during LM recovery experiments.

1. S(k,f) shows an increase after RF hits the plasma but with no feature in the EDD.

2. Instead, the growth of fluctuation power in the HF components (if compared with unheated LM) is due to an acceleration in the IDD.

3. Acceleration increases with $P_{\text{ICRH}}$.
   - 1MW: $v_{\text{slow}}=0.63\text{km/s}$, $v_{\text{fast}}=2.27\text{km/s}$
   - 2MW: $v_{\text{slow}}=0.80\text{km/s}$, $v_{\text{fast}}=2.50\text{km/s}$
   - 3MW: $v_{\text{slow}}=0.85\text{km/s}$, $v_{\text{fast}}=2.97\text{km/s}$
Summary

① Locked-modes can be studied in C-Mod at ITER-Bt, without NBI fueling and momentum input.

② The use of ICRH heating *in-sync* with the error-field ramp-up resulted in a successful delayed of the mode-onset when $P_{\text{ICRH}} \geq 1$ MW.

③ Once $P_{\text{ICRH}}$ is turned off, the core plasma “locks” at later times depending on the evolution of $n_e$ and $V_t$.

① For the recovery experiments the "induced" edge/core $V_\phi$ spun in the co/counter-current direction recuperating the direction and magnitude before the mode onset.

② Turbulent-induced momentum transport can not be ruled out.

③ ICRH waves heats the edge as well as induce $v_{\phi,\theta}$ flows.

④ ICRH could be an important actuator to circumvent error-field LM disruptions in tokamak. Proposal to test in large tokamaks (e.g. JET).