3-D self-organization in RFPs with connections to stellarator MHD

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Self-organization to helical state is rather general trend in the RFPs in certain operational regimes.

A dominant tearing mode grows spontaneously, then transition to QSH occurs with reduction of amplitudes of the secondary modes.

Optimum regime for self-organization lies in shallow-reversal regime.

Higher plasma current $I_p$ or higher values of $S$ may be favorable to longer and purer QSH (or SH) state.

Growth time of the single dominant mode may have machine (or some other parameter(s) ) dependence – fast growth in RFX-mod and slow growth in MST.

The self-organized helical RFP is accompanied by formation of the internal (electron) transport barrier.
Helically deformed RFP is also realized in our low-aspect-ratio machine RELAX.

Current dynamics of self-organization in RFPs is dominated by current driven tearing modes.

What would be the role of pressure driven modes in high beta RFP plasmas?

Studies on pressure driven modes have been carried out in LHD.
Outline

A brief review of 3-D self-organization in RFPs

Operational regimes in low-aspect-ratio RFP plasmas in RELAX

Comparison of QSH in $A=2$ RFP with 3-D MHD computation results

Internal structure of pressure driven MHD instability and its role in profile change in LHD
Conventional self-organization theory for RFP
- Taylor relaxation -

In low-beta plasmas, minimum energy state for a specified value of magnetic helicity $K$ can be described by the force-free equilibrium.

$$ \nabla \times \mathbf{B} = \mu \mathbf{B} $$

In a cylindrical approximation, the minimum energy solution to the force-free equilibrium bifurcates to symmetric and (symmetric + m=1 helical) states when the magnetic helicity is increased.
For $K$ larger than a critical value, the minimum energy state is a mixture of symmetric and m=1 helical state, where helix of the m=1 component coincides with that of the external field – externally nonresonant helical structure.

There exists the major difference between m=1 Taylor state and the present experimental helical RFP state – externally nonresonant helix (Taylor relaxation) or internally resonant helix (experimental self-organized state).
Concept of self-organization in the RFP

- formation and sustainment of the configuration through nonlinear MHD
- of general interest as a control problem of highly nonlinear system
REversed field pinch of Low-Aspect-ratio eXperiment

\[ R/a = A = 2 \]

(51 cm/25 cm)

- \( I_p < 100 \text{ kA} \)
- \( n_e = 10^{18} \sim 2 \times 10^{19} \text{ m}^{-3} \)
- \( T_e < 100 \text{ eV} \)
- \( \tau_D \sim 2 \text{ ms} \)

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Lower $A$ means lower $n$ for dominant $m = 1$ modes

more space in the core region
Motivation to explore the low-aspect-ratio RFP

- With an adequate choice of $q_0$, more space would be available in the core region without major resonant surface
  - easy growth of magnetic island associated with core resonant dominant mode
  - Good confinement with QSH for achieving high beta would be expected
- The bootstrap current would become sizable if very high beta could be achievable
  (target parameters: $T_e \sim 300\text{eV}$, $n_e \sim 4 \times 10^{19} \text{m}^{-3}$ at $I_p \sim 100\text{kA}$)
RFP plasmas in RELAX

- Low-aspect-ratio RFP plasmas:
  \[ I_p < 100 \text{ kA}, \quad n_e = 10^{18} \sim 2 \times 10^{19} \text{ m}^{-3}, \quad T_e < 100 \text{ eV}, \quad \tau_D \sim 2 \text{ ms} \]

- MHD properties have been studied in discharges with 40kA < \( I_p < 100 \text{kA} \) during flat-topped phase longer than 0.5ms
$F$ and $\Theta$ keep some relation over wide range of parameters

In shallow reversal region,

- Periodic QSH or Helical Ohmic RFP state tends to be realized

In deep reversal, high-$\Theta$ region,

- Amplitudes of resonant modes are suppressed significantly
- SXR emission increases, indicating good plasma performance
Quasi-single helicity state in RELAX

\( m=1/n=4 \) mode behavior:

- Longer QSH period for slower rotation
- Shorter QSH period with higher spectral index \( N_s \) for faster rotation

Spectral index:

\[
N_s = \left[ \sum_{n=n_{\text{min}}}^{n_{\text{max}}} \left( \frac{b_{1,n}^2}{\sum_n b_{1,n}^2} \right) \right]^{-1}
\]

Helical hot core is suggested from SXR pin-hole camera
q profiles and toroidal mode spectrum of m=1 modes

- Shallow reversal region: Dominant modes are core resonant m=1/n=4,5,6.
- Deep reversal region: Amplitudes of m=1 modes are reduced to ~1/4. Broader spectrum
- Increased magnetic shear may contribute to the lower fluctuation amplitudes in deep reversal case.
- No evidence of externally resonant mode?

q profiles from equilibrium reconstruction code RELAXFit
Field line trace using ORBIT suggests recovery of flux surfaces

Deep reversal case

$F \sim 0$

Helical Ohmic state

1-D equilibrium, linear eigenfunction in cylindrical geometry in ORBIT

3-D equilibrium and 3-D eigenfunctions are needed
3-D MHD computation results for A=2 RFP

Linear growth of each mode up to $t \sim 60 \tau_A$, followed by rapid self-organization to helical equilibrium in $\sim 20 \tau_A$.

$F \sim 0$

QSH for shallow $F$

$\Rightarrow$ in agreement with experiments
Time evolution of equi-pressure surface to QSH
Possible formation of helical magnetic axis for this particular equilibrium
Connections to stellarator MHD

Self-organized RFP has a simple structure in real coordinate space
➢ Is it still simple in magnetic coordinate?
➢ How does the field spectrum look like in magnetic coordinate space?
➢ Is it favorable to particle orbits?

The plasma boundary may be influential on 3-D equilibrium
➢ RFP edge region may be stochastic due to the externally resonant modes
➢ Can we define clear outermost flux surface or shape of the plasma boundary?
➢ Is there possible means to determine or define the outermost flux surface in stochastic region?

Is the self-organization concept applicable to stellarator with strong external helical field? The role of pressure-driven modes?
Rotating low-order MHD instabilities are often observed in high-beta LHD discharges.
Fine structures or local flattening appear in density or temperature profiles in such high-$\beta$ plasmas with possible degradation of confinement performance.

Volume average beta, $<\beta>$% 
m/n=1/1 magnetic fluctuation level in ($\beta$, $S$) space
Objectives of internal structural studies of low-order MHD mode in LHD

✓ to make quantitative evaluation of the effect of the low-order global MHD instabilities on the confinement performance
✓ to find out appropriate parameter(s) characterizing the mode in expressing the relationship between the mode and its effect on confinement performance

In identifying the direct effect of the m/n=1/1 mode, we have selected discharges which are marginally stable or unstable to the mode.
Example of a discharge marginally stable to m/n=1/1 mode

Edge magnetic fluctuation level: ~0.03%

Coherent m/n=1/1 magnetic fluctuation disappears at t=1.9s, with improved $\langle \beta \rangle$ from ISS04 scaling prediction.
Internal mode structure at $t=1.8s$ estimated from multi-chord SXR diagnostic

SXR fluctuation peaks at the $m/n=1/1$ resonant surface

No phase inversion across the resonant surface (No magnetic island?)

$\Rightarrow$

Similarity to linear theory prediction of resistive interchange mode
Parameters characterizing the m/n=1/1 mode and confinement performance

- **Local mode width $\Delta$:**
  FWHM from $\xi_r$ profile

- **Line-integrated mode width $\Delta_{1/2}$:**
  FWHM from normalized $\delta I_{SX}$

- **(Relative) mode amplitude:**
  Normalized maximum $\delta I_{SX}$
Parameters characterizing the m/n=1/1 mode and confinement performance

\( b_{11} \): RMS amplitude at the resonant surface based on the sheet current model where a sheet current is assumed on the resonant surface having the amplitude to reproduce experimental \( b \) on the inner wall surface.

The H factor based on the ISS04 scaling as indication of confinement performance:

\[
\frac{H_{\text{ISS04}}}{H_{\text{ISS04,at**s}}} : \text{the ratio of the H factor estimated using instantaneous parameters to that in the absence of the m/n=1/1 mode at } t=** \text{ using the ISS04 scaling.}
\]
Internal structure of m/n=1/1 mode and its effect on confinement performance

SXR amplitude lower than 0.3%
  => no degradation
1.5% mode amplitude
  => ~5% degradation
3% mode amplitude
  => ~10% degradation

(a) B=1.75T, $\langle \beta \rangle \sim 1\%$
  No degradation

(b) B=1.375T, $\langle \beta \rangle \sim 0.5\%$
  Degradation of ~5%

(c) B=0.9T, $\langle \beta \rangle \sim 1\%$
  Degradation of ~10%
Decrease in $T_e$ due to the $m/n=1/1$ mode is restricted only in the peripheral region.

\[ \text{Decrease in } T_e \text{ due to the presence of the } m/n=1/1 \text{ mode is restricted to the peripheral region} \]

\[ \Rightarrow \text{decreased region corresponds to the mode width} \]

\[ \Rightarrow \text{limited influence on the core region with high fusion power} \]
Internal structure of the \( m/n=1/1 \) mode, magnetic fluctuation level and their effect on confinement performance

- strong correlation between mode amplitude and confinement performance
- Effect on confinement performance becomes evident when the line-integrated mode width normalized to minor radius exceeds 10%
Summary and future work

Summary:
- 3-D self-organization to helical RFP is a general trend.
- In shallow-reversal region in RELAX, QSH with helical hot core has been attained without external control.
- The self-organization process in low-A RFP have been reproduced in 3-D MHD computations.
- In LHD, quantitative estimate of the effect of pressure driven mode on confinement has been performed. The mode is responsible for local change in temperature profile.

Future work in RELAX:
- Feedback control of magnetic boundary – RWM stabilization
- Diagnostics – Thomson scattering for Te measurement
- Supersonic gas injection for fuelling
Magnetic boundary control system in RELAX

- toroidal $\times 16$, poloidal $\times 4$
  saddle coil array installation
  almost completed for feedback control of RWM

- Construction of the power supplies in progress

- Introduction of digital feedback controllers in progress
backup
RWM is problematic for longer pulse operation in RELAX

$\tilde{B}_r(a) / B_p(a) \approx 1 - 1.5\%$

$\Rightarrow I_p$ starts decreasing

Initial growth of $m=1/n=-4$ resonant mode, followed by growth of the non-resonant $m=1/n=2$ external kink mode with growth time of resistive wall time constant.
Characteristic phenomena in shallow-reversal regions
- SXR tangential images suggest helical hot core in QSH -

\(< m=1/n=4 \text{mode dominant case} >\)

Experimental image

Simulated image with helical core
\( (\alpha=3, w=15\text{cm}, r_{\text{m}}=14\text{cm}) \)

helical deformation and line-of-sight of SXR pin-hole camera

Vertical intensity profiles at 0.1\( \alpha \) outward from the center

Vertical intensity profiles along the central chord
Magnetic field profile in shallow-reversal regions is characterized by Helical Ohmic Equilibrium state

- **Symbols**: measured profiles with radial array of magnetic probes.
- **Solid lines**: Ohmic helical equilibrium solution (Paccagnella (2000)), details are in the next slide.
- Shafranov shift $\Delta/a \sim 0.2$.
- The helical structure rotates at a frequency of $\sim 10$ kHz.

![Diagram showing axisymmetric components and m=1 helical components.](image)
3-D MHD computation for $A=2$ RFP

Cylindrical coordinate $(R, \varphi, Z)$

$$(N_R \times N_\varphi \times N_Z) = (153 \times 128 \times 153)$$

Boundary conditions
- Perfectly conducting and no-slip wall at all boundaries of the computation region
- $B_\perp=$const. $V=0$, $j=0$ on the boundary

Initial equilibrium
Based on reconstructed equilibrium from experiments using RELAXFit code (axisymmetric equilibrium)

Initial perturbations
- Random white noise in velocity field is given at $t=0$