From Fingers to Blobs: Late Nonlinear Stage of Interchange

Preliminary Studies

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1. Problem

- (How) Do ELM filaments develop into blobs?
  - Late nonlinear ELMs develop prominent filaments ("fingers")
    (MAST, NIMROD/M3D ELM milestone studies, etc)
  - Under what conditions, do those filaments break into blobs?
  - Are current extended MHD codes capable of simulating such a process?
- Late nonlinear stage of ballooning/peeling.
- Prototype problem: interchange (g-mode) in a 2D slab

2. Approaches

- Reduced MHD modeling: Aydemir, Krasheninnikov, et al.
- Direct/Full/Extended MHD modeling: NIMROD
Reduced MHD model has been used for (2D slab) scrape-off layer (SOL) [Aydemir, Phys. Plasmas 12, 062503 (2005) and Refs. therein]:

\[
\begin{align*}
\partial_t U + [\phi, U] &= \frac{2\rho_s}{qR} \phi - \frac{2\rho_s}{R} [x, \ln n] + \mu \nabla_\perp^2 U, \\
\partial_t n + [\phi, n] &= -\frac{2\rho_s}{qR} n + D \nabla_\perp^2 n,
\end{align*}
\]

where \( U = \nabla^2 \phi, \ [\phi, U] = \hat{z} \cdot \nabla_\perp \phi \times \nabla_\perp U, \rho_s = \sqrt{\frac{T_e}{m_i}}/\Omega_i.\)

Full MHD model used in NIMROD for (2D slab) pedestal in this study:

\[
\begin{align*}
\partial_t n + u \cdot \nabla n &= -n \nabla \cdot u + D \nabla^2 n, \\
\rho(\partial_t u + u \cdot \nabla u) &= J \times B - \nabla p + \rho g + \mu \nabla (\cdot \rho w),
\end{align*}
\]

where \( w = \nabla u + (\nabla u)^T - \frac{2}{3} I \nabla \cdot u, \mu \) is the isotropic viscosity.
■ Local dispersion showing linear effects of dissipation [Aydemir, 2005].

■ Similar dispersion and effects of dissipation obtained from NIMROD simulations will be shown later.
Blob formation due to interchange instability [Aydemir, 2005].

Will compare with NIMROD simulations of blob formation due to interchange in rest of this talk.
■ 2D simulation in $(R, Z)$ plane; no variations in $\phi$ (purely interchange).

■ 1D equilibrium $(R)$: $g = g\hat{R}$, $B = B(R)\hat{\phi}$; perturbation propagates in $Z$ (periodic B.C.), advects in $R$ (conducting wall B.C.).

■ Density $\rho(R) = \rho_h \tanh \left( -\frac{R-R_0}{L_\rho} \right) + \rho_c$; pressure $p = \rho^\gamma$
- Linear growth from simulation $\Gamma \sim 0.26081/2 = 0.13041 \text{s}^{-1}$

- Marginal interchange instability growth $\Gamma_{\text{max}} \sim \sqrt{\frac{g}{L_\rho} + \frac{g^2}{u_\text{A}^2 + c_s^2}} = 0.14$

- $D = \mu = 0.014$ used for blob simulations shown here.
The wavenumber at peak linear growth point $k_Z = 0.2\pi$ is used for initial velocity perturbation $u_R|_{t=0} \sim \sin(k_ZZ)$.

Discrete structures appear as filaments extend radially.
Localized Outward Initial Perturbation in Tanh Shaped Pedestal

\[ u_R|_{t=0} = u_0 e^{-\left(\frac{R-R_1}{\Delta R}\right)^2 - \left(\frac{Z-Z_1}{\Delta Z}\right)^2}, \text{ where } u_0 = 0.001 \text{ (outward flow).} \]

■ Isolated blob/bubble form out of filament cap in late stage.
Localized Gaussian initial perturbation, but with $u_0 = -0.001$ flowing inward.

Transient behavior different from outward case; blob eventually forms.
Localized Inward Initial Perturbation in Tanh Shaped Pedestal (Animation)
1D equilibrium variation and $g$ vector in $R$ direction, $B$ vector in $\phi$ direction, perturbation propagates in $Z$ direction.

Density $\rho(R) = \rho_0 e^{-\frac{R-R_0}{L_\rho}} + \rho_\infty$; pressure $p = \rho^\gamma$

Less symmetric in $R$ direction; used earlier by Aydemir (2005) for SOL.
\( u_R|_{t=0} \sim \sin(k_Z Z) \), where \( k_Z = 0.2\pi \).

Final blob structures are more detached from the base than in hypertangential shaped pedestal case (less symmetric in \( R \)).
Unlike Aydemir’s results, single/isolated blob forms and more localized in $Z$ (poloidal) direction.

Notice the secondary blob formation trailing the major blob.
Localized Inward Initial Perturbation in Exponentially Shaped Pedestal

Similar to tanh shaped pedestal case, blob formation slower than in outward initial flow case.

Notice the shredding-off of small blobs from major traveling blob.
Lower dissipation case terminates before entering late nonlinear phase; optimal numerical settings are yet to be found to carry the simulation further.

Previous studies suggest it is more difficult for blobs to maintain coherent structure with low dissipation.
Blob formation in late nonlinear stage of interchange has been demonstrated in NIMROD simulations.

Dissipation mechanism appear to control the geometry and dynamics of blob formation and transport.

Future work:

- Realistic parameter regime.
- 2-fluid, extend MHD version of NIMROD.
- Ballooning instability toroidal geometry.
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