Nonlinear ELM Simulations with M3D

H. Strauss
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Outline

• Overview of M3D
  – Simulation model

• ITER / DIII-D nonlinear ELM simulations
  – DIII-D: Crash cycle
  – ITER: outflow to divertor

• 2 fluid effects
  – Gyroviscous stabilization of high n
  – Stabilization of resistive modes
  – Nonlinear

• Pedestal model
  – EFIT, XGC

• Summary and future plans
M3D

- **Extended MHD**
  - Resistive MHD
  - 2 fluid
  - Neoclassical model
  - Coupling to neoclassical kinetic code XGC

- **Algorithmics**
  - Partially implicit
  - Parallel (mpi and omp implementations)
  - Unstructured poloidal mesh – includes magnetic separatrix
  - 1st – 3rd order FEL
  - Toroidal pseudospectral or FD

- **Vacuum modeled as 3D resistivity**
  - varies as $T^{-3/2}$
  - $S = 10^6$ at core boundary
  - $S = 10^2$ to simulate vacuum as cold plasma
ELM in ITER
ITER example

Circ \( f = 0.000 \)

\[
\text{max} \quad 0.44E+00 \\
\text{min} \quad -0.57E+00 \\
t = 0.00
\]

zoom \( f = 0.000 \)
ITER ELM: pressure

\[
\begin{align*}
\text{p max} & \quad 0.29E+00 \\
\text{min} & \quad 0.00E+00 \quad t = \quad 0.00 \\
\text{p max} & \quad 0.34E+00 \\
\text{min} & \quad -0.16E-02 \quad t = \quad 53.15 \\
\text{p max} & \quad 0.29E+00 \\
\text{min} & \quad -0.19E-02 \quad t = \quad 67.64
\end{align*}
\]
ELM pressure: initial, mode growth, outflow
ITER – pressure profiles
initial, ELM crash, relaxation
Mesh for DIII-D

- Radial mesh packing to resolve gradients at the separatrix
- Angular packing to resolve ballooning modes
- Example
  - 35x200
  - n = 0, 5, 10, ... 25
Poloidal magnetic flux
nonlinear ELM DIII-D 086166

Equilibrium flux

perturbed flux-unstable mode
nonlinear ELM: pressure

Shows pressure initially and near ELM saturation
time development of ELM after saturation pressure smooths out

$t = 27$
Initial $p$

$t = 67$
ELM

$t = 106$
relaxation
Time development: \( p(R) \) profiles:
pressure pedestal expands across separatrix, then relaxes
and moves inwards

Drop off to the right of the plots is an artifact
2 Fluid: linear dispersion relation

• ELMs are caused by MHD instabilities
  – Edge kinks (peeling) n < 10
  – Ballooning n > 10

• WKB dispersion relation with gyroviscosity
  – Have verified stabilization in M3D simulations
  – n > 20 – 30 stable in DIII-D
  – H = 0.02 - 0.03

• Resistive modes: stable or slowed

\[ \gamma = -\frac{i}{2} \omega_{*i} + (\gamma_{MHD}^2 - \frac{\omega_{*i}^2}{4})^{1/2} \]

\[ H = \frac{c}{\omega_{pi} R} \quad \omega_{*i} \sim nH \]
H = 0.06 is stability boundary, n = 10
Linear perturbed poloidal magnetic flux

MHD, $n = 10$

$2F, H = 0.1, n = 10$
Nonlinear effect of $H$

$H$ has little effect on low $n$ modes

\[ H = \frac{c}{\omega_{pi}R} \]

\[ \omega_\ast \sim nH\beta' \]
Pedestal model

• **ELM instability**
  – Edge kinks: driven by bootstrap current
  – Ballooning modes: driven by pedestal pressure gradient

• **Previous simulations used EFIT equilibrium**
  – Bootstrap current model might not be valid at edge

• **XGC – neoclassical kinetic code**
  – In reasonable agreement with experiments
  – Calculates pedestal buildup
  – Calculates bootstrap current

• **M3D / XGC**
  – Profiles of p, n, … given to M3D code
  – If unstable, calculate ELM crash
Initial XGC pressure profile

Initial EQDSK is not consistent with XGC p profile
need bootstrap current from XGC (or model)
add XGC + existing EQDSK equilibrium
Summary and future plans

• ITER / DIII-D nonlinear ELM simulations
  – Crash and outflow to divertor
  – Quantify loss to wall / divertor
  – Higher resolution
  – Better computational mesh

• 2 fluid effects
  – Study drift resistive modes
  – Include electron diamagnetic drift

• Pedestal model
  – Improve coupling with XGC code