Non-linear MHD modelling of ELMs dynamics and their control by RMPs

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IPP Prague (Czech Rep)
IPP Garching (Germany), DIFFER (Netherland)

New:
KSTAR(Korea)
EAST (China)
IPR(India)

Motivation:
control of MHD in ITER
JOREK. Non-linear resistive MHD in realistic tokamak geometry, wall, coils. High space resolution (mm to m), time scales (Alfven time 10^{-7} s to sec). perp/parallel heat conductivity $\gg 1$

$$\vec{B} = F_0 \vec{\nabla} \phi + \vec{\nabla} \psi \times \vec{\nabla} \phi$$

$$\vec{V}_i = \frac{-R^2 \vec{\nabla} u \times \vec{\nabla} \phi - \tau_{IC} \frac{R^2}{\rho} \vec{\nabla} p \times \vec{\nabla} \phi + \vec{V} \vec{B}}{\vec{E} \times \vec{B}}$$

$$\tau_{IC} = \frac{m_i}{(2\cdot e \cdot F_0 \sqrt{\mu_0 \rho_0})}$$

diamagnetic parameter

Total pressure (here $T_i = T_e = T/2$)

$$p = \rho T$$

Poloidal flux:

$$\frac{1}{R^2} \frac{\partial \psi}{\partial t} = \eta \vec{\nabla} \cdot \left( \frac{1}{R^2} \vec{\nabla} \psi \right) - \frac{1}{R} [u, \psi] - \frac{F_0}{R^2} \frac{\partial}{\partial \rho} u + \frac{\tau_{IC}}{2 \rho B^2} \frac{F_0}{R^2} \left( \frac{F_0}{R^2} \frac{\partial}{\partial \rho} p + \frac{1}{R} [p, \psi] \right)$$

Parallel momentum:

$$\vec{B} \cdot \left( \rho \frac{\vec{\nabla}}{\partial t} \right) = -\rho \left( \vec{V} \cdot \vec{\nabla} \right) \vec{V} - \vec{\nabla} (\rho T) + \vec{J} \times \vec{B} + \vec{S}_V - \vec{V} \vec{S}_\rho + \nu \left( \nabla \nabla \right) \vec{V} - \nabla \cdot \Pi_n$$

Poloidal momentum:

$$\vec{V} \cdot \left( \rho \frac{\vec{\nabla}}{\partial t} \right) = -\rho \left( \vec{V} \cdot \vec{\nabla} \right) \vec{V} - \vec{\nabla} (\rho T) + \vec{J} \times \vec{B} + \vec{S}_V - \vec{V} \vec{S}_\rho + \nu \left( \nabla \nabla \right) \vec{V} - \nabla \cdot \Pi_n$$

Temperature:

$$\frac{\partial (\rho T)}{\partial t} = -\vec{\nabla} \cdot (\rho \vec{V}) - \gamma \rho T \vec{\nabla} \cdot \vec{V} + \vec{\nabla} \cdot \left( K_{\perp} \nabla_{\perp} T + K_{||} \nabla || T \right) + (1-\gamma) S_T + \frac{1}{2} V^2 S_{\rho}$$

Mass density:

$$\frac{\partial \rho}{\partial t} = -\nabla \cdot (\rho \vec{V}) + \nabla \cdot \left( D_{\perp} \nabla_{\perp} \rho \right) + S_{\rho}$$

Temperature dependent viscosity, resistivity:

$$\eta \sim \eta_0 (T / T_0)^{-3/2}$$

Neoclassical poloidal viscosity

$$\nabla \cdot \Pi_{i,neo} \approx \mu_{i,neo} \rho (B^2 / B_{\theta}^2) (V_{\theta,i} - V_{\theta,neo}) \vec{e}_{\theta} \cdot \vec{e}_{\theta} = (R / |\nabla \psi|) \nabla \psi \times \nabla \phi$$

Ion poloidal velocity $\Rightarrow$ neoclassical

$$V_{\theta,i} \rightarrow V_{\theta,neo} = -\kappa_{i,neo} \tau_{IC} (\nabla_{\perp} \psi \cdot \nabla_{\perp} T) / B_{\theta}$$

$$B_{\theta} = |\nabla \psi| / R$$
Magnetic field aligned grid \((R, Z, \phi)\), X-points, SOL, wall and divertor. 2D cubic Bezier elements (C1) in poloidal plane, Fourier in toroidal. Non-linear, fully implicit, large sparse matrix.

Finite elements in poloidal plane: 2D cubic Bezier (16 control points), C1.

Toroidal direction: Fourier decomposition.

Fully implicit Crank-Nicholson or Gears scheme

Large sparse matrix solver (PastiX) using iterative method (GMRES).

HPC: MPI/OpenMP, typical run: 50,000-200,000 cpuh >20Mcpuh/year
JOREK code was designed to study & understand MHD instabilities in fusion plasma and propose & optimize methods of active MHD control. Strong link with experiment, predictions for ITER.

Global vertical displacement event (VDE)

Disruptions control by massive gas injection, runaways

ELMs control by pellets injection

QH-mode

Edge localized modes (ELMs)

ELMs control by Resonant Magnetic Perturbations (RMPs)

Contours of pressure perturbation during pellet triggered ELM in ITER plasma.
ELMs physics: peeling (current)-ballooning (pressure gradient) instabilities. ELM crash: magnetic reconnections in non-linear phase. Conductive (ergodisation) and convective (ExB) transport.

Large edge current (bootstrap): drives peeling/kink modes

[Huysmans PPCF 2005]

Large edge pressure gradient in H-mode drives ballooning modes

ITER, n=12, 7.5MA

ELM crash is due to ergodisation of edge magnetic field, reconnection with SOL. Energy conduction along field lines. Splitting of strikes

Density ExB convective transport $\Rightarrow$ ELM filaments.
ELM dynamics with flows. In experiment: rotation of precursors before ELM crash electron or ion diamagnetic direction? Why?

Filaments (and blobs) in SOL in ion diamagnetic direction.

Typically rotation in anti-clockwise (electron diamagnetic direction) . MAST, AUG, KSTAR

(KSTAR: Yun PRL, 2011)

But sometimes rotation in clockwise (ion diamagnetic direction, here on KSTAR).

Why?

(KSTAR: courtesy of M. Kim)
In the frame rotating with plasma (Er=0, V ExB=0) in ion dia direction

ideally unstable if \( \gamma_i > \omega_i^*/2 \).

frequency of the mode is: \( \omega_i^*/2 \)

in laboratory frame:

\[
V_{\text{mode}} = V_{\text{ExB}} + V_\parallel \cdot b_\theta + V_i^*/2.
\]

V ExB is in electron direction, poloidal projection of V// - in ion. Resulting velocity can be in electron (more often) or ion (~at strong Vtor).

JOREK. JET

JOREK. KSTAR (ion 3-4km/s, 5.3 km/s in experiment)
Non-linear phase. Deceleration of rotation, stochastisation, generation of strongly sheared mean $n=0,m=0$ flow. Filaments are ejected in ion dia direction. (Huysmans NF2007, Morales EPS2014, PRL sub)
Diamagnetic drifts are the most important in the model to reproduce (1) ELMy cycling regimes and (2) symmetric power deposition in inner/outer divertors. (Orain PRL, 2015, PPCF2014)

ELMy cycling regimes JOREK with diamagnetic drifts in the model

**w/o diamagnetic**

**with diamagnetic**
ELM control by Resonant Magnetic Perturbations (RMPs)

Idea of ELM control by RMPs: small radial magnetic field \( \delta B^r \sim 10^{-4} \), islands on resonant surfaces \( q = m/n \), ergodic edge \( \rightarrow \) increase transport \( \rightarrow \) decrease \( \nabla P \) below ELM triggering threshold?

[Becoulet NF2005,08,10, Orain PoP 2013]

\[ q = (m+1)/n \]

\[ q = m/n \]

\( \theta \)

\( r/a \)

\( (\sim\text{centre}) \quad r/a = 0.95 \quad \text{ergodic zone} \quad r/a = 1 \)

« Lobes » structures observed with RMPs on MAST
ELM suppression/mitigation by Resonant Magnetic Perturbations (RMPs). Edge control by externally imposed stochastic fields. RMPs in ITER.


ITER RMP In-Vessel Coils:
3 rows of 9 RMP coils are planned
Physics of RMPs penetration. Plasma response currents on rational surfaces (q=m/n). Screening of RMPs is typical response.

Response current on q=m/n with RMPs.

ITER. RMP screening by rotation
(Becoulet IAEA 2012)
Amplification of RMPs is also possible (if \( n = n_{\text{RMP mode}} \) is \( \sim \) unstable). “External kink response” amplifies RMP compared to vacuum. Experiment suggest amplification\( \Rightarrow \)ELM mitigation/suppression (?)\)

F. Orain SFP workshop 2015.
AUG, RMPs. \( N = 2 \). Scan of phase between coils. **Strongest ELM mitigation at \( \Delta \Phi = +90^\circ \)**
ELM mitigation by RMPs. Mitigated ELMs = non-linear driven modes coupled to RMPs ⇒ edge ergodisation, continued MHD turbulence prevent large ELM crash (Becoulet PRL 2014)

RMP off: ELM (most unstable n=9)

Mitigated ELMs: continued MHD, mixture of n=3,6,9
Conclusions:

1. Code JOREK is resistive non-linear fluid MHD code especially designed for modelling of transient MHD events in realistic tokamak geometry (including ITER) and their active control. Resistive wall, flows, open and closed field lines, coils, divertor geometry etc… Reduced MHD version is most developed, full MHD started. 2D finite elements (cubic 2D Bezier) C1+toroidal harmonics. 3D finite elements started.

- Disruptions & control by massive gas injection, runaway electrons;
- ELMs dynamics (precursors and filaments) on linear and non-linear stage, heat/particle fluxes in divertor.
- ELMs control by RMPs.
- ELMs control by pellets.
- QH mode (naturally small ELMs regime at low collisionality)

Etc….

Future: New physics for ELMs/RMPs: (recycling in divertor, pump-out etc), multi-harmonics, multi cycles, comparison with experiment ELMs/RMPs (KSTAR, AUG, DIII-D…). Long term: ITG turbulence, L/H transition with neoclassical flow?

Numerical improvements needed: automatic grid, memory for larger matrix inversion, stability with flows (when large diamagnetic) especially on non-linear phase of ELM crash, large ELMs….
Non-linear phase. The mean flow generation is due to Maxwell stress \( (\text{Huysmans NF2007, Morales EPS2014, PRL sub}) \)

\[
\delta_t w_E = - \int \dot{\rho} \nabla u^* \cdot \nabla_\perp (\delta_t \Phi) \, dV = \int \left( - \frac{v_E^2}{2R} [u^*, \dot{\rho}] - R \dot{\rho} w_E [u^*, \Phi] + R [u^*, P] 
- u^* \nabla \phi \cdot \nabla \times (R^2 \rho (v_i^* \cdot \nabla) v_E) \right) \, dV.
\]