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Motivation: H-mode pedestal height (=> global confinement) is limited by MHD instabilities => ELM crash. Quasi-periodic $f_{\text{ELM}} \sim 150$ Hz, $\Delta t_{\text{ELM}} \sim 250 \mu$s. Large heat&particle loads on divertor.

Safe ELMs for divertor $W_{\text{ELM}} < 1$ MJ, but predictions for ITER: $W_{\text{ELM,ITER}} \sim 20$ MJ => Droplets, melting of tungsten ITER divertor.

Tungsten sample after ELM–like power load (produced by electron gun).
Total ELM suppression by Resonant Magnetic Perturbations (RMPs): DIII-D (US)-first experiments, ASDEX Upgrade (Germany), KSTAR (Korea).


**AUG (Germany):** W. Suttrop PRL2011, IAEA 2012, n=1,2

**KSTAR (Korea):** Si-Woo-Yoon, IAEA 2012, n=1
**Idea:** “ergodisation” increases edge transport ($\sigma_{Chir}>1$ for $\psi>0.8$) => $\nabla P<\nabla P_{crit}$ => no ELMs? But very different response on RMPs! In ITER?

\[ \sigma_{Chirikov} = \frac{\delta_m + \delta_{m+1}}{\Delta m,m+1} > 1 \]

RMPs are foreseen in ITER (90kAt, n=4,3) will it work???

JET: ELM “mitigation”

NSTX: ELM “triggering”.

Y Liang PRL2007

RMP n=1-2

A. Kirk PPCF2013

MAST: small mitigated ELMs (n=3,4,6)
Many open questions in physics of ELMs+RMPs still remain.
Aim: progress in understanding of RMPs, give reliable predictions for ITER.

- Idea: RMP coils => magnetic perturbation => edge ergodic region => control of edge transport, MHD. However, at the same edge ergodisation in “vacuum” => different reaction of ELMs to RMPs in experiment: suppression, mitigation, triggering?

- RMPs are different from “vacuum” RMPs in plasma! Rotating plasma response: current perturbations on $q=m/n$ => screening of RMPs. [Fitzpatrick PoP 1998], [Waelbroeck NF2012], [Izzo NF 2008], [Becoulet NF 2009, 2012], [Strauss NF 2009], [Orain EPS2012], [Ferraro APS 2011] etc…

- RMPs /ELMs at high $\nu^*$? (Type II ELMs-like events, density, magnetic field fluctuations, no changes in profiles)

- Density pump-out (at low $\nu^*$)? (here not addressed yet)

- Rotation braking/acceleration? (here not addressed yet)

- Why ELMs are suppressed? (not addressed yet)
RMPs and flows in non-linear resistive MHD code JOREK (model development):
- RMPs at the computational boundary (SOL, X-point, divertor geometry)
- 2 fluid diamagnetic effects (large in pedestal!),
- Neoclassical poloidal viscosity (\(V_\theta \sim V_{\theta \text{neo}}\) in pedestal),
- \(V_\parallel\) : toroidal rotation source, SOL flows.
- Equilibrium radial electric field (large \(\text{ExB in pedestal!}\)).

RMPs in JET-like case. (n=2).
Three regimes depending on resistivity and rotation.

RMPs in MAST (n=3)

RMPs in ITER (n=3).
Non-linear reduced resistive MHD in torus (X-point, divertor, SOL) with 2 fluid diamagnetic and neoclassical effects (important in large pedestal gradients region!). JOREK. [Huysmans PPCF2009]

\[
\vec{B} = F_0 \nabla \varphi + \nabla \psi \times \nabla \varphi \\
\vec{V} = -R^2 \nabla u \times \nabla \varphi - \tau_{ic} \frac{R^2}{\rho} \nabla p \times \nabla \varphi + V \| \vec{B} \\
E \times \vec{B}
\]

\[
\text{diamagnetic}
\]

Poloidal flux:
\[
\frac{1}{R^2} \frac{d \psi}{dt} = \eta \nabla \cdot \left( \frac{1}{R^2} \nabla \psi \right) - \frac{1}{R} \left[ u, \psi \right] - \frac{F_0}{R^2} \frac{\partial \varphi}{\partial t} + \frac{\tau_{ic}}{\rho} \frac{F_0}{B^2} \left( \frac{F_0}{R^2} \frac{\partial p}{\partial \varphi} + \frac{1}{R} \left[ p, \psi \right] \right)
\]

If this term is \(\sim 0\) at \(q=m/n\) \(\Rightarrow\) no RMP screening

Parallel momentum:
\[
\vec{B} \cdot \left( \rho \frac{\partial \vec{V}}{\partial t} \right) = -\rho \left( \vec{V} \cdot \nabla \right) \vec{V} - \nabla (\rho T) + \vec{J} \times \vec{B} + \vec{S}_\varphi - \vec{V} \| (\nabla \nabla) \vec{V} - \nabla \cdot \vec{\Pi}_{neo}
\]

Poloidal momentum:
\[
\vec{V} \varphi \cdot \nabla \times \left( \rho \frac{\partial \vec{V}}{\partial t} \right) = -\rho \left( \vec{V} \cdot \nabla \right) \vec{V} - \nabla (\rho T) + \vec{J} \times \vec{B} + \vec{S}_\varphi - \vec{V} \| (\nabla \nabla) \vec{V} - \nabla \cdot \vec{\Pi}_{neo}
\]

Temperature:
\[
\frac{d(\rho T)}{dt} = -\vec{V} \cdot \nabla (\rho T) - \gamma \rho T \nabla \cdot \vec{V} + \nabla \cdot \left( K \left( \nabla T + K \| \nabla T \| \right) \right) + (1-\gamma)S_T + \frac{1}{2}V^2 S_\rho
\]

Mass density:
\[
\frac{d \rho}{dt} = -\nabla \cdot (\rho \vec{V}) + \nabla \cdot (D \nabla \rho) + S_\rho
\]

Temperature dependent viscosity, resistivity:
\[
\eta \sim \eta_0 (T/T_0)^{-3/2}
\]

Neoclassical poloidal viscosity [Gianakon PoP2002]

Ion poloidal velocity \(\Rightarrow\) neoclassical

\[
\nabla \cdot \vec{\Pi}_{neo} = \mu_{i,neo} \left( B^2 / B_\theta^2 \right) (V_{\theta,i} - V_{\theta,neo} \vec{e}_\theta)
\]

\[
\vec{e}_\theta = (R / |\nabla \psi|) \nabla \psi \times \nabla \varphi
\]

\[
V_{\theta,i} \rightarrow V_{\theta,neo} = -k_{i,neo} \tau_{ic} (\nabla \psi \cdot \nabla T) / B_\theta
\]

\[
B_\theta = |\nabla \psi| / R
\]
JET-like case. Equilibrium flows (w/o RMPs): parallel velocity (central source, SOL-sheath conditions on divertor targets).
Poloidal velocity => neoclassical in the pedestal.

- **Parallel flow.**
  - **Central plasma**: toroidal rotation source keeps initial $V_{||}$ profile: $S_{V_{||}} = -v_{||} \Delta V_{||}, t=0$
  - **SOL**: sheath conditions on targets: $V_{||,\text{div}} = \pm C_s$

- **Poloidal flow.**
  \[ V_{\theta,i} = \left[ -\left( \nabla \psi, \nabla u \right) - \tau_{IC} \left( \nabla \psi, \nabla p \right)/\rho + V_{||} B_{\theta}^2 \right] / B_{\theta} \]
  \[ V_{\theta,e} = \left[ -\left( \nabla \psi, \nabla u \right) + \tau_{IC} \left( \nabla \psi, \nabla p \right)/\rho \right] / B_{\theta} \]

- **Pedestal:** $V_{\theta,i} \rightarrow V_{\theta,\text{neo}} \propto \nabla T_i$
- **SOL:** $V_{\theta,i} \approx V_{||} B_{\theta}$

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**JET-like:** $R=3m$, $a=1m$, $q_{95}=3$, $T_0=5keV$, $n_e=610^{19}m^{-3}$, $f_0=9kHz$.

$\tau_{IC} \sim 2.10^{-3}$; $\mu_{i,\text{neo}} \sim 10^{-5}$; $k_{i,\text{neo}} = 1$; $\eta = 5.10^{-8}$

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M. Bécoulet, 30-31.01.2013, Meeting ANEMOS
JET-like case. Radial electric field “well” in the pedestal=>large ExB rotation=>likely to screen RMPs.

\[ E^r = -\frac{\nabla \psi \cdot \nabla}{|\nabla \psi|} \]

JET-like parameters.
Vacuum RMP (EFCC, $n=2$, $I_{coil}=40kA$) are increased in time at JOREK boundary. Poloidal magnetic flux perturbation (max) with RMPs in plasma with flows. Toroidal current perturbations on the rational surfaces ($q=m/2; m=3,4,5,6$) with RMPs.
Central islands are screened: \((m/n)=3/2; 4/2\).
Edge ergodic region: \((5/2, 6/2)\) penetrate \(\eta \sim T^{3/2}\).

JET-like case. Stronger RMP screening for lower resistivity and larger poloidal rotation. Ergodic region at the edge.

Similar results in cylinder [Becoulet NF 2012]

M. Bécoulet, 30-31.01.2013, Meeting ANEMOS
JET-like case. Three regimes depending on rotation & resistivity.

- high $\eta$, low $\tau_{IC}$: rotating oscillating islands $f^* \approx m V_\theta / (2\pi r_{res}) \sim 6\text{kHz}$
- high $\tau_{IC}$: static islands, more screening of RMPs.
- low $\eta$, low $\tau_{IC}$: intermediate-oscillating, quasi-static islands

$\Rightarrow$ fluctuations of magnetic field, density and temperature no significant transport

(Possibly related to RMPs suppression at high $\nu^*$? Rutherford regime? [Fitzpatrick PoP 1998], [IzzoNF2008])
JET-like case. $V_\parallel$ can be stabilising and destabilising. Mechanism? Change in radial electric field (ExB part in poloidal rotation)? => under investigation

$V_\parallel$ is destabilising

$V_\parallel$ is stabilising
RMPs generated by coils in 90L configuration. Limits (numerical stability):

\[ I_{\text{coil, simulation}} = I_{\text{coil, experiment}} / 10 \]

\[ \tau_{IC} = 10^{-2} \quad \text{(realistic one: } 5 \times 10^{-2} \text{)} \]

With RMPs: \( n=3 \) grows, driven by RMPs

\[ \tau_{IC} = 10^{-2} \]

\[ n=3 \text{ Fourier component of the magnetic perturbation} \]
MAST case. Current response on resonance surfaces. Density, temperature, toroidal current are not uniforme on flux surfaces (here presented surface close to separatrix)
MAST case. In both cases (w/wo dia): screening of the central harmonics (m=4-9), penetration/amplification (with dia) at the edge (m>10)

Dashed: without diamagnetic. Full line: with diamagnetic effects.
Boundary deformation in MAST. Lobes induced by RMPs: in DND configuration, only located in the LFS.
RMPs in ITER. W/o RMPs $n=3$ is stable. With RMPs $\Rightarrow n=3$ static perturbations at the edge.

ITER, IVC, max: $I_{\text{coil}}=90\text{kAt}$, $n=2,3,4$. Used here $n=3$, 54kAt.

ERGOS (vacuum) $\Rightarrow$ JOREK boundary

Magnetic energy, $n=3$, IVC, max 54kAt

RMPs on
RMP off
Equilibrium flows and radial electric field in ITER (w/o RMPs)

ITER: H-mode, 15MA/5.3T, R=6.2m, a=2m, q_{95}=3, T_0=27.8keV, n_e=810^{19}m^{-3}, f_0=1kHz

\tau_{IC} \sim 5.10^{-4}; \mu_{i,neu} \sim 10^{-5}; k_{i,neu} = 1; \eta = 10^{-8}
RMPs in ITER. With RMPs $\Rightarrow n=3$ static perturbations at the edge.

$\Psi_{n=3}$

$n_{e,n=3}$

$J_{\phi,n=3}$

$T_{e,n=3}$
With RMPs: (density, temperature, pressure, current have stationary 3D structures at the edge. They are not constant at flux surfaces as in equilibrium. Future: 3D MHD stability to study…

Pressure inside separatrix with RMPs in ITER.

Current inside separatrix with RMPs in ITER.

Pressure on separatrix with RMPs in ITER.

Current on separatrix with RMPs in ITER.
Boundary deformation. Lobes near X-point (smaller with rotation). Splitting of strike points (> on outer target).

ITER wall

~6cm

w/o flows

with all flows - screening

~22cm

ITER

Inner target

Outer target

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Small changes in edge $T_e$, $n_e$ profiles. Modulations of $T_e$,$n_e$: max $\sim$ near X-point.

ITER

$RMP$ on

$RMP$ off

$RMP$ on

$RMP$ off

Edge $n_e,T_e$ profiles at $Z=-0.6m$

- $T_e$keV
- $n_e$20m^{-3}
- $T_e$keV
- $n_e$20m^{-3}

Edge pressure profile at $Z=-0.6m$

- $P$(kPa)

- $P$(kPa)
Non-linear resistive MHD code JOREK development for RMPs with flows: 
- RMPs - at the boundary, 2 fluid diamagnetic effects, neoclassical poloidal viscosity, toroidal rotation source, SOL flows.

JET-like(n=2).Three regimes:
- high $\eta$, small (poloidal) rotation (high $\nu^*$?) => oscillating and rotating islands, fluctuations $\delta n_e, \delta T_e, \delta \psi(t)$ (~kHz).
- low $\eta$, higher rotation => static islands, more screening of RMPs.
- Intermediate => oscillating, quasi-static islands.

MAST case (still limited in coil current amplitude /10 ,dia parameter /5) : RMP penetration, screening/amplification with dia. 3D boundary deformation.

RMPs (n=3) in ITER. Screening of central islands, static screened edge islands, ergodic edge, splitting of strike points (>outer), flattening of averaged $n_e,T_e$ profiles, 3D edge temperature, density, current structures, boundary deformation: lobes near X-point.

Future: RMPs interaction with ELMs (multi-harmonics modelling). Modelling of realistic shots MAST, JET, AUG. Continue ITER RMPs with ELMs.
Comparison JOREK&ERGOS(vacuum)&RMHD(cylinder).

- JOREK (torus, rotating plasma): RMPs screening on \( q=m/n \) (stronger for central islands). Amplification \( r<r_{\text{res}} \) in JOREK.

- Compared to vacuum (ERGOS).
  RMPs screening by rotating plasma (JOEK), smaller screening for edge RMP harmonics \( (\eta \sim T^{-3/2}) \).

- Compared to cylinder (RMHD, \( q=q_{\text{tor}} \)): Stronger RMPs screening in JOREK. Amplification for \( r<r_{\text{res}} \).

\[
\psi_{mn} \text{ for } (n=3, m=8:11)
\]

\[
\times 10^{-3}
\]

ITER

\[\psi_{\text{norm}}\]

ITER

\[\psi_{\text{norm}}\]

Screening factor: \( n=3, m=8:11, q=q_{\text{tor}} \)

\[\text{RMHD: Becoulet NF 2012}\]
Island is not screened if at $q \sim (m/n)$ electron poloidal velocity $\rightarrow$ zero. For ITER parameters: $V_{e,\theta} \neq 0$

Ohm’s law $\rightarrow$ if electron poloidal velocity $\rightarrow$ zero: $V_{e,\theta} \mid_{q \sim m/n} = V_{E,\theta} + V_{\text{dia}} \approx 0$

current perturbation $J \varphi, mn \mid_{q \sim m/n} \rightarrow 0$

no RMP screening $\Rightarrow$ vacuum-like island.

For ITER parameters used here electron poloidal velocity is not zero: $\Rightarrow$ screening

$V_{\theta,e} = \left[ -(\nabla \psi, \nabla u) + \tau_{\text{IC}} (\nabla \psi, \nabla p) / \rho \right] / B_{\theta}$
Peak heat fluxes on divertor targets are ~25% reduced (spreading due to ergodisation) with RMPs on.

Heat flux on inner and outer divertor targets.

NB! No divertor physics (radiation, ionisation, sources, detachment...) in the model.
Pressure gradient is 3D, locally could be even steeper with RMP.