TH/2-1Ra:
Physics of Resonant Magnetic Perturbations Used for Type I Edge Localized Modes Suppression in Tokamaks.

M. Bécoulet¹, G. Huysmans¹, X. Garbet¹, E. Nardon², M. Schaffer³, A. Garofalo³, K. Shaing⁴-5, A. Cole⁴, J-K. Park⁶, P. Cahyna⁷.

¹Association Euratom-CEA, IRFM, Cadarache, 13108, St-Paul-lez-Durance, France.
²Euratom/UKAEA Fusion Association, Culham Science Centre, Abingdon, OX143DB, U.K.
³General Atomics, P.O. Box 85608, San Diego, CA 92186-5688, USA.
⁴University of Wisconsin, Madison, WI53706-1609, USA.
⁵Plasma and Space Science Center and Physics Department, National Cheng Kung University, Tainan, Taiwan 70101, Republic of China.
⁶Princeton Plasma Physics Laboratory, Princeton, NJ 08543, USA.
⁷Association EURATOM/IPP.CR, Prague, Czech Republic.

TH/2-1Rb:
MHD Simulation of Resonant Magnetic Perturbations

H.R. Strauss¹ L. Sugiyama², G.Y. Park¹, C. S. Chang¹, S. Ku¹ I. Joseph³

¹New York University, New York, New York, USA 10012
²MIT, Cambridge, MA, USA 02139
³University of California, San Diego, CA, USA 92186
Type I ELMs are not tolerable in ITER => RMPs in ITER.

Motivated by experiments:

DIII-D, I-coils
Evans NF2007, EX/4-1, IAEA2008


9 (3 row) in-vessel RMP coils:
ELM suppression: ~60kAt, n=4, vacuum ergodic magnetic field for $\psi_{1/2} > 0.9$.
+Vertical stabilisation,
+Resistive Wall Modes control (25Hz)

JET, EFCC,
Liang PRL2007, EX/4-2, IAEA2008
Motivation: understanding of plasma response on RMPs

1) Why ELMs are suppressed?
   At present we think: $\nabla P < P_{\text{crit, ELM}}$?

2) Is vacuum criterion (ergodic zone for $r > 0.9$) enough for ELM suppression?
   Yes: DIII-D, ~JET, not on NSTX, MAST?

3) Resonant window in $q_{95}$?
   Narrow on DIII-D, but it should work for $q_{95} = 3-5$ in ITER!

4) Mechanism for density “pump-out”? Can MHD ExB + // transport explain?
   Turbulence with RMPs?

5) Why $T_e$ flattening in ergodic region is not seen in experiment?
   Screening RMPs by rotation? Flux limit in $\chi//$?

6) Mechanism for plasma braking/acceleration?
   Neoclassical Toroidal Viscosity? Or +….? 

---

$DIII-D$ Osborn EPS2005, EvansEX/4-1, similar on JET(Liang EX/4-2)
Outline:

Many common results in two papers (M.Becoulet TH/2-1Ra =“MB”, H. Strauss TH/2-1Rb =“HS”)=> they are presented in comparison.

-Resonant and non-resonant harmonics penetration time (MB)
-Screening of RMPs by plasma rotation (MB+ HS)
-Density transport due to RMPs (MB+HS)
-Heat transport due to RMPs (HS)
-Neoclassical Toroidal Viscosity with RMPs: plasma braking or acceleration? (MB)

Numerical tools:

M.Becoulet et al TH/2-1Ra : Non-linear reduced resistive MHD, toroidal rotation , resonant (jxB) braking and Neoclassical Toroidal Viscosity (NTV). DIII-D,ITER.

Codes: -RMHD-cylinder (up to $\eta$$\sim$10-9) Huysmans PRL2001;
-JOREK- 3D in torus, X-point , SOL, $\eta$$\sim$10-6) HuysmansNF2007
-NTV vacuum in torus=> input to RMHD (not self –consistent)

H. Strauss et al TH/2-1Rb: Non-linear resistive full MHD with ne and Te transport (convective and conductive), toroidal rotation. DIII-D, NSTX.

Code: -M3D- 3D in torus, X-point, SOL, $\eta$$\sim$10-6)
$V_{tor}=0$. Resonant harmonic penetration time: $\tau_{RMP}/\tau_A \sim S \sim 1/\eta$

Non-resonant: Alfvén-like time.

Characteristic time of island formation on the pedestal top ($r \sim 0.9$, $q_{res} = m/n = 3$)

$\sim 60\text{ms} \ (\text{DIII-D}); \sim 600\text{ms} \ (\text{ITER})$

M. Becoulet et al TH/2-1Ra

Edge islands on $q = m/n$ are formed first since: $\eta \sim T_e^{-3/2}$

$n=3, m=9, \eta = \text{const}$

$\sim \text{ITER}$

$\sim \text{DIII-D}$

$t=4000\tau_A$

$n=3, m=5-11$

$t=84000\tau_A$
Screening of RMPs by toroidal rotation.

H. Strauss et al  TH/2-1Rb: DIII-D #126006, I-coils, n=3, parabolic profile of $V_{\text{tor}}$

Zero rotation, amplification of RMP

Rotation screens RMP

M3D

Perturbed poloidal n=3 flux along a ray
More screening at stronger rotation and lower resistivity

DIII-D and ITER–like resistivity and rotation: central islands are screened, edge is ergodic.

Non-resonant harmonics: no islands, no screening!

Screening factor for resonant $q=m/n$ harmonic:

$$\frac{\psi_{pl}}{\psi_{vac}} \bigg|_{\text{res}} \sim \eta \frac{5}{6} \frac{1}{V_{\text{tor}}}$$

visco-resistive linear regime
(FitzpatrickPoP1998)

DIII-D–like
($\sim 10\text{kHz} \ \eta_0=10^{-8}$)

ITER–like
($\sim 1\text{kHz}, \ \eta_0=10^{-9}$)
MHD density pump-out with RMPs seen in modelling.

Open question; is modelled MHD pump-out a mechanism observed in exp.? In

(Nardon PoP 2007)
M. Becoulet et al TH/2-1Ra

Remote H. Strauss et al TH/2-1Rb

Radial ExB velocity with RMPs

with rotation, // transport and RMPs

Radial ExB ~30% diff

\[ V_{r,max} \sim 7 \text{m/s} \]

\[ \eta \sim 10^{-6} \]

\[ \eta \sim 10^{-9} \text{ (but in ITER:)} \]

\[ \eta \sim 10^{-8} \text{ (DIII-D:)} \]
M3D: $T_e$ flattens in ergodic layer (not seen in exp.), no change in the core $T_e$: profile steeping (seen in exp.)

$T_e$ w/o RMPs  
$T_e$ with RMPs

M3D, H. Strauss et al TH/2-1Rb
Similarity ELM-RMP: magnetic perturbations => transport

RMP~ stationary mag. flux perturbation due to external coils

\( \delta \psi_{RMP} \)

\( \delta \psi_{ELM} \)

Nardon PoP 2007

H. Strauss et al TH/2-1Rb

Large density transport

Huysmans EPS 2008

ELM - mag. flux perturbation during \( \tau_{ELM} \sim 200 \mu s \), ballooning /peeling mode

\( \delta \psi_{ELM} \)

Density

Smaller in temperature

Density profile
Toroidal rotation+RMPs: Neoclassical Toroidal Viscosity?

Radial drift of trapped particles in helical magnetic perturbations. Plasma flow “feels” helical perturbation as an additional viscose force in toroidal direction.

Drift - kinetic equation, bounce-averaging 
=> flux surface averaged force: 

\[ F_{NTV} = -\left\langle 1/\rho_m \cdot \tilde{e}_{\psi} \cdot \nabla \hat{\psi} \right\rangle = -\nu_{eff} b^2 (V_{\psi} - V_{\psi*}) \]

M.Bécoulet et al TH/2-1Ra, 

DIII-D, ITER –”\nu” is expected, but “1/\nu” is closer to experiment?

Coefficients depend on regimes:

“\nu_{eff} \sim 1/\nu_i” : 

\[ q\omega_E < \nu_i / \varepsilon < \sqrt{\varepsilon} \omega_i \]

drift collisions transit

“\nu_{eff} \sim \nu_i” : 

\[ \nu_i / \varepsilon < q\omega_E \]

Still very controversial : depend on plasma response : JKPark EX/5-3Rb, 2008 IAEA –ideal, 3D equilibrium
RMHD modelling with RMP in ITER: large NTV (if $1/\nu$) + slow intrinsic rotation => counter toroidal rotation.

If “$\nu$” - no changes in rotation.

$$F_{NTV} \sim -\alpha_{NTV}(V_{tor} - V_{neo}) \quad V_{neo} \sim \frac{1}{r} T < 0$$

- counter to $l_p$

Coefficient $\alpha_{NTV}$ in modelling.

For comparison: “natural” viscosity:

$$\sim 3 \times 10^{-7} \text{ (1m}^2/\text{s)}$$

M. Bécoulet et al TH/2-1Ra
Both co and counter rotation screen core islands.

ITER, n=4, central islands are screened if $V_{tor} \neq 0$ ("+" or "-").

Notice: for locally if $V_{tor} \approx 0$ => islands re-appear

M. Becoulet et al TH/2-1Ra
Counter acceleration observed on DIII-D with RMPs

A. Garofalo et al accepted PRL 2008

DIII-D exp: co-counter NBI + RMPs
Co-rotation: braking with RMPs;
Zero or weak counter: acceleration(!)
Strong counter rotation: braking

Modelling for DIII D#127744 with NTV(1/ν)+co/counter NBI: the same trend as in experiment.

\[
\frac{\partial \nu}{\partial t} = \delta_{\text{co-counter}} S_{\nu} + 2 \nu \nabla - a_{NTV,1/\nu} (\nu - \nu_{\text{neo}})
\]

M. Bécoulet et al TH/2-1Ra

---

22nd IAEA FEC, 15.10.2008, Geneva, Switzerland, TH/2-Ra-b, presented by M. Bécoulet
Conclusions from non-linear MHD modelling of RMPs:

1) Resonant harmonics ($q=m/n$) penetrate on local resistive time scale. Non-resonant ~ Alfven-like time ($MB$)
2) Plasma rotation screens the RMP from the plasma: shrinks islands and reduces overlap to thin edge layer. ($HS+MB$)
3) Screening is larger for low resistivity and stronger rotation. DIII-D, ITER: central islands are screened, edge $r>0.9$ is ergodic ($MB$)\[ \psi_{mn}^{pl}/\psi_{mn}^{vac} \bigg|_{res} \sim \eta^{5/6}/V_0 \]
4) Non-resonant harmonics: no islands, no screening ($MB$).
5) RMP cause some density “pump out” ($HS+MB$). Experimental?
6) Temperature cools in stochastic layer (not seen in experiment, model for $\chi/\psi$), no changes in the core ($HS$).
7) Slow intrinsic rotation + strong NTV (here in vacuum and “1/$\nu$”!) => counter rotation. If “$\nu$” –no changes in rotation ($MB$) => More benchmarking between codes and experiment is needed!

And much more on tomorrow morning poster session!