ELM control

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14TH WORKSHOP ON MHD STABILITY CONTROL
Content:

• Introduction
  Edge Localized Modes
  Approaches to ELM control

• ELM mitigation with resonant magnetic perturbations

• Magnetic field stochastization

• Particle transport modification with RMP

• Heat conduction paradox

• Conclusions
Edge Localized Modes of Type I in H-mode

- Improved confinement in H-mode in tokamaks is quasi-periodically destroyed by MHD activity called Edge Localized Modes (ELM)

- Type I ELMs are seen as large spikes of radiation from neutrals produced by losses of hot charged particles from plasma
Collisionality dependences of particle and energy losses per ELM crash

Total particle loss per ELM normalized to pedestal particle content (JET):

![Graph showing particle loss per ELM vs. collisionality parameter.]

Total energy loss per ELM normalized to pedestal energy content:

![Graph showing energy loss per ELM vs. collisionality parameter.]

\[ \nu^* = \frac{qR}{\lambda} \left( \frac{R}{r} \right)^{3/2} \]

ITER tolerance level
Approaches to mitigate ELMs:

• ELM triggering by fast vertical movement of the plasma column (“vertical kicks“)

• ELM pacing using pellet injection in order to split a few strong ones into many sufficiently small ones

• ELM mitigation by noble gas injection by decreasing heat loads on divertor target plates through impurity radiation

• ELM control with resonant magnetic perturbations
Suppression of ELMs in DIII-D plasmas of low collisionality

I-coils in DIII-D
T. E. Evans et al

Mitigation and full suppression of D$_{\alpha}$-spikes due to ELMs in DIII-D
T. E. Evans et al
Mitigation of ELMs in JET

Error Field Correction Coils (EFCC) on JET:

Reduction of ELM amplitude and increase of ELM frequency:

Y Liang et al
Plasma Phys. Control. Fusion
49 (2007) B581
Triggers of type I ELMs: Ideal MHD instabilities

Ballooning instability:

Instability threshold:

\[ \left| \nabla_r P \right| > \frac{B_T^2}{2\mu_0 q^2 R} \alpha_{cr} \]

Localized high n kink “peeling,” instability:

Instability threshold:

\[ \frac{j_{||}(a)}{\langle j_{||} \rangle} > \gamma \left| \nabla_r P(a) \right| \]

Dominant mechanism of ELM suppression in DIII-D: reduction of edge pressure below instability threshold.

Heat transport is even reduced with RMP.
Mitigation of ELMs in JET

ELM are not suppress but amplitude strongly reduced probably due to evolution of working point to peeling stability boundary

S Saarelma, et al
Plasma Phys. Control. Fusion
51 (2009) 035001

Y Liang et al
Plasma Phys. Control. Fusion
49 (2007) B581
Effect of RMP on magnetic configuration

Radial magnetic field produced by coil:

\[ B_r = \sum_{\text{integer } M,N} B^M_N(r) \cdot \cos(M \vartheta - N \varphi) \]

Resonance magnetic surface (RMS):

\[ q = M/N \]

(M,N)-harmonic phase is constant \( \Rightarrow \) very small field perturbation can lead to large radial deviation of field lines

Chain of magnetic islands with width \( w \) increasing with perturbation amplitude

By strong enough perturbation \( \sigma_{Ch} = w/\Delta > 1 \) and adjacent island chains are overlapped

\( \Rightarrow \) Stochastization of magnetic field lines
Behavior of stochastic field lines

Divergence of neighbouring field lines:

\[ l \ll L_K \Rightarrow \delta = \delta_0 \exp\left(\frac{l}{L_K}\right) \]
\[ l \gg L_K \Rightarrow \delta = \sqrt{2D_{Fl}l} \]

- Kolmogorov length

\[ L_K \approx \pi qR \sigma_{Ch}^{-4/3} \]

Field line diffusivity

More exact characterization: solution of field line equations

Intersection points of field lines with poloidal plane, \( \varphi = \text{const} \), provide Poincaré plots:

by diverse approaches: field line tracing, mapping

S. S. Abdullaev, PoP, 16 (2009) 030701
RMP amplitude in plasma:

\[ B_{r}^{M,N}(r) \propto I_{\text{coil}} \times \left( \frac{r}{a} \right)^{M-1} \times f_{\text{scr}} \]

Effect of flows in plasma close to RMS

Cylindrical geometry

Screening effect in collisional plasma edge (TEXTOR) D. Reiser et al, PoP 16 (2009) 042317

Vacuum RMP

Screened RMP

Edge Transport Barrier (ETB): diamagnetic electron rotation is of most importance

Kinetic description of RMP penetration in plasma of low collisionality
Effect of stochastization on particle transport (II): ion perpendicular transport

• Escape of light electrons along field lines is retarded by radial electric field:

\[ \Gamma_{\parallel,r}^e = -nV_{th,e}D_{FL} \left( \frac{\nabla_r n}{n} + \frac{1}{2} \frac{\nabla_r T_e}{T_e} + \frac{eE_r}{T_e} \right) \]

• \( E_r \) has to be positive for normally peaked plasma parameter profiles with \( \nabla_r n, \nabla_r T_{e,i} > 0 \)

• Contradicts to negative \( E_r \) necessary to maintain balance of radial forces for ions:

\[ enE_r = \nabla_r (nT_i) - en \left( V_\varphi B_\varphi - V_\varphi B_\varphi \right) \]

• New equilibrium with \( E_r > 0 \) is achieved if ion rotation velocity is significantly changed
Effect of stochastization on particle transport (II): ion perpendicular transport

• Deviation of $V_\vartheta$ from neoclassical value results in poloidal viscous force leading to enhanced radial drift of ions

• Ambipolarity of total radial fluxes $\Rightarrow$ Stochastic diffusivity:

$\Gamma_{\perp,r}^i = \Gamma_{\perp,r}^e + \frac{q\rho_i}{R} n (V_\vartheta - V_{neo})$

Rozhanski V and Tendler M, 1991
Reviews of Plasma Physics Vol.19 147

$D_{st} = \frac{D_i^{\perp} D_e^{\parallel}}{D_i^{\perp} + D_e^{\parallel}} \frac{T_e + T_i}{T_e}$, $D_i^{\perp} = \frac{T_e}{eB} \frac{q\rho_i}{R}$, $D_e^{\parallel} = D_{FL} V_{the}$

• In ETB with $T_e \sim 1$ keV:

$D_i^{\perp} \approx 1 m^2/s \Rightarrow D_{st} \approx D_e \Rightarrow \Gamma_{\perp,r}^i \gg \Gamma_{\parallel,r}^i$

• Total particle transport is comparable to free stream of electrons along field lines but ions go perpendicular!
Radial density profile

Measured

DIII-D

Calculated with measured temperatures and RMP screening

$I_c = 0 \text{kA}$

$I_c = 2 \text{kA}$

$I_c = 3 \text{kA}$

$\psi_N = \left( \frac{r}{a} \right)^2$

Effect of stochastization on particle transport (III): increased plasma fluctuations

- Amplitude of density fluctuations in pedestal is increased with RMP by factor of 2
- Modelling: Necessary pump out could be achieved due to enhanced $D_\perp$ only if is increased by a factor of 40-100 over neoclassical level
- Negative consequences to heat transport have to be also seen

R.A. Moyer et al, 21st IAEA Fusion Energy Conference, Chengdu, 2006, EX/9-3
Effect of stochastization on particle transport (IV): convective cells

**JOREK-code:** perturbation in plasma induced by RMP

Effect is reducing with decreasing collisionality, opposite to observations

- Electric potential
- Plasma density


Amplitude of electric potential vs. plasma resistivity
Heat conduction paradox

Heat flux densities:

\[ q^e_{r,i} = \alpha \Gamma_{r} T_{e,i} - \kappa^e_{r,i} \nabla_{r} T_{e,i} \]

- Increased at very edge with RMP
- Defined by particle sources – RMP indep.
- Defined by heat sources – RMP indep.?

Effective radial heat conduction are most probably reduced with RMP

Rough estimate for heat conduction in stochastic field

\[ \kappa^e_{r,i} \approx \frac{q^e_{r,i} - \alpha \Gamma_{r} T_{e,i}}{-\nabla_{r} T_{e,i}} \]

\[ \kappa^e_{r,i} \approx \kappa_{\perp} + \kappa_{st}^{e}, \quad \kappa_{st}^{e} \approx \kappa_{\parallel} B_{r}^2 / B^2 \]

- \( \kappa_{\perp} \): in ETB ion neoclassical and electron anomalous perpendicular heat conductions decrease with dropping plasma density
- \( \kappa_{st}^{e} \): contribution of 50 m²/s is expected
  A.B.Rechester and M.N.Rosenbluth, PRL 40 (1978) 833

Heat flux limit concept: conductive heat flow along perturbed field lines is strongly reduced compared to free stream flow

\[ \kappa_{st}^{e} \approx nD_{FL} V_{the} \]

\[ q_{\parallel}^{e} \approx \beta nV_{the} T \]

0.03 \( \leq \beta \leq 0.1 \)
Parallel heat flux in collisionless plasma

Electric field $E_x$:

\[ \Gamma_x \left( \partial_x n, \partial_x T_e, E_x \right) = 0 \]

Moreover: in collisionless plasma distribution at $x=0$ is a mixture of particles from different positions with different temperatures $\Rightarrow$ any expansion $f = f_M + f_1 + f_2$ is questionable $\Rightarrow$ particle modeling, e.g., with XGC0 code $\Rightarrow \beta << 1$


Simple estimate: plasma decay in layer $- \Delta \leq x \leq 0$ with initial linear profiles of $n(x)$ and $T(x)$

Without $E_x$:

$\bar{q}_x = 0.32 \, n_{\text{max}} \, T_{\text{max}} \, \sqrt{T_{\text{max}}} / m_e$

With $E_x$:

$\bar{q}_x = 0.034 \, n_{\text{max}} \, T_{\text{max}} \, \sqrt{T_{\text{max}}} / m_e$
Modification of temperatures with RMP

- Ion neoclassical and electron anomalous perpendicular heat conductions in ETB decrease with dropping plasma density
- Electron parallel heat conduction is restrained by heat flux limit

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### Calculated Data

- \( T_i(keV) \) (left)
- \( T_e(keV) \) (right)

- Normalized flux \( \psi_N \)

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**DIII-D(exp)**

\( \psi_N \) vs. \( T_i(keV) \) and \( T_e(keV) \) with experimental data and calculated curves for different plasma current levels.
Electric field and rotation

Radial ion flow in stochastic field provides Lorenz force:

\[ F_L^T = e\Gamma_{\perp,r}^i B_P \]

which affects plasma rotation

W/o RMP: \( D_e^\parallel = 0 \Rightarrow E_r = E_r^{\text{neo}} < 0 \)

With RMP: \( D_e^\parallel > 0 \Rightarrow E_r^{\text{amb}} > 0 \)

\[
E_r = E_r^{\text{neo}} \cdot \frac{D_i^\perp}{D_i^\perp + D_e^\parallel} + E_r^{\text{amb}} \cdot \frac{D_e^\parallel}{D_i^\perp + D_e^\parallel}
\]
Conclusions

• External resonant magnetic perturbations (RMP) are efficient tool for mitigation and even complete suppression of edge localized modes (ELM)

• Magnetic field stochastization produced by RMP modifies essentially transport properties in the edge transport barrier, reducing the pressure gradient below the threshold of MHD instabilities

• This happens mostly because of pump out effect leading to plasma density reduction and several mechanisms for increased particle transport have been identified: flows along perturbed field lines, perpendicular ion transport due to deviation from neoclassical equilibrium, enhancement of plasma fluctuations, convective cells

• Reduction of perpendicular heat conduction with decreased density and restrain of parallel heat losses due to heat flux limit preserve good energy confinement in ETB with RMP

• Complexity of RMP impacts on processes both in the edge and in the central plasma regions necessitates an adequate and coherent approach for understanding the physics and making predictions for ITER, as, e.g., in the CPES, EMC3-EIRENE projects