NEW ASPECTS OF THE IDENTIFICATION OF MAGNETIC ISLANDS FROM ECE SIGNALS AND CONTROL BY ECCD

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Outline

- New method of reconstruction of the structure of the tearing modes from ECE signals for intershot analysis
- Response of tearing unstable plasma slab to an rf driven current in the frame of a neoclassical nonlinear slab model
- Appearance of current sheets and secondary island structure
- Open questions for control strategies
ECE $\delta T_e(r,t)$ fluctuations and rotating tearing mode islands

- Ideally, the Temperature fluctuations at the Island rotation frequency should invert their phase near to the island O-point [J. Berrino et al, Nucl. Fusion 45 2350 (2005)].
- The normalized cross-correlation $P_{ij}(x) \approx \cos \delta \phi_{x,i}$ of thermal fluctuations sensed by two adjacent ECE channels has a concavity that is extremal at the rational surface $x=0$ and can be monitored on a sequence of ECE channels.

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ECE $\delta T_e(r,t)$ fluctuations and radial tearing modes structure

- New method of reconstruction of the structure of the tearing modes from measurements of ECE $\delta T_e(r,\zeta)$ for intershot analysis

$$\delta T(r, \zeta) = T(r, \zeta) - T_0(r) = \frac{W^2}{16} T_0'(r) \frac{S_s}{r_s} \frac{q/q_s}{1 - q/q_s} \frac{\Psi(r)}{\Psi(r_s)} \cos \zeta$$

- Minimisation of functional $\Phi(\Psi) = \frac{1}{2} \sum_i \left\| \delta T(\Psi(R_i), c) - \delta T_{ECE}(R_i) \right\|^2$ under the constraint of fulfilling the tearing mode equation in curvilinear geometry (toroidicity & shape)

$$(m - nq) \left\{ \left( \frac{g \phi \theta}{g} \right)_{0,0} \psi_{m,n}'' + \left( \frac{1}{\sqrt{g}} \left( \frac{g \phi \theta}{\sqrt{g}} \right) \right)' \psi_{m,n}' - \left( \frac{1}{\sqrt{g}} \left( \frac{g \phi \theta}{\sqrt{g}} \right) \right)_{0,0} \psi_{m,n}' - \left( \frac{g \phi \theta}{g} \right)_{0,0} \psi_{m,n} - \left( \frac{g \phi \theta}{g} \right)'_{0,0} m^2 \psi_{m,n} \right\} - mq \left( \frac{J_0'}{F_0} \right)_{0,0} \psi_{m,n}$$
Geometric effects on tearing eigenfunction

- Toroidal, shaped, equilibrium configuration described by:

\[
R = R_0 + r \cos \theta + \Delta + r \lambda \sin \theta - E \cos \theta + O(\varepsilon^2)
\]
\[
Z = r \sin \theta - r \lambda \cos \theta + E \sin \theta + O(\varepsilon^2)
\]

- Sensitivity of tearing eigenfunction to \( \Delta_{\text{sha}} \), \( E \)

**Sensitivity to \( \Delta_{\text{sha}} \)**

**Sensitivity to \( E \)**

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Geometric effects on tearing eigenfunction

- Minimization of mean square discrepancy $\Phi(\Psi)$ is to be performed in terms of control parameters of equilibrium: $q(0)$, $\Delta_{Shaf}$, $E$

JET Te profile for #70677 with (3,2) NTM

Automatically optimization

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Remarks on models of NTM control by ECCD

- Much detailed work has been devoted to extension of the basic nonlinear Rutherford model to obtain **quantitative criteria** for the **power required to control a magnetic island** by rf driven current.

- The generalized Rutherford Equation for the tearing mode island width $W$ is obtained by a **nonlinear averaging of Faraday-Ohm law** over the single scale length defined by the width of the magnetic island separatrix.

$$\frac{\tau_R}{r_s} \frac{dW}{dt} = r_s A'_o + \beta_p \left( \frac{e^{1/2}}{s} \frac{r_s}{W_c} \frac{W/W_c}{1+(W/W_c)^2} \right) - r_s g \frac{\omega(\omega - \omega^*)}{\omega^2_e} \left( \frac{L_s}{L_n} \right)^2 \frac{\rho_{\theta i}^2}{W^3} + \frac{8r_s \delta_{EC}q}{\pi W^2} \eta_h \left( \frac{W}{\delta_{EC}} \right) \left( \frac{J_{EC}(t)}{J_{boot}} \right)$$

- If the (helical) ECCD current is driven within a depth $\delta_{EC} < W$, **important 2D nonlinear** effects are missed by the Rutherford models.
Study of 2D effects in a Neoclassical 4-Field Model*

Faraday-Ohm
\[
\frac{\partial \psi}{\partial t} + \vec{v}_E \cdot \vec{\nabla} \psi = -\vec{v}_{pe} \cdot \vec{\nabla} \psi - \eta_{NC}(J_\parallel - J_{bs} - J_{Ec})
\]

Shear-Alfvén
\[
\frac{\partial U}{\partial t} + \vec{v}_E \cdot \vec{\nabla} U = \frac{1}{m_i n} B_0 \nabla_\parallel J_\parallel \frac{\mu_0 (1 + \tau_T)}{m_i n B_0} (J_\parallel \nabla_\parallel p_{e\Delta} + p_{e\Delta} \nabla_\parallel J_\parallel)
\]

Parallel ion velocity
\[
\frac{\partial v_{i\parallel}}{\partial t} + \vec{v}_E \cdot \vec{\nabla} v_{i\parallel} = -\frac{(1 + \tau_T)}{m_i n} \left( \nabla_\parallel p_e + \frac{2}{3} \nabla_\parallel p_{e\Delta} \right)
\]

Electron pressure
\[
\frac{\partial p_e}{\partial t} + \vec{v}_E \cdot \vec{\nabla} p_e = -\left( \frac{5}{3} p_e + \frac{4}{9} p_{e\Delta} \right) \nabla_\parallel \left( v_{i\parallel} - \frac{J_\parallel}{en} \right)
\]

\[
p_{e\Delta} = -\frac{m_e n q \mu^e}{\tau_{ee} \varepsilon} \frac{\nabla_\parallel B}{\left( \nabla_\parallel B \right)^2} \left( \frac{\partial \phi}{\partial r} - \frac{1}{en} \frac{\partial p_e}{\partial r} + \frac{1}{3en} \frac{\partial p_{e\Delta}}{\partial r} \right)
\]

Closure relation for anisotropy


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ECCD centered on the O-point

ECCD deposition has led (promptly) to a new equilibrium state without singular points!

Current sheets appear on both sides of singular surface, as alternative to the equilibrium with magnetic islands.
A (moderate) angular offset of ECCD produces a behavior very much like that of an exact deposition on the O-point.

Notwithstanding the phase offset, reconnection is frozen!

ECCD with angular offset

Perturbed Poloidal Magnetic Flux at time 1860.00

Current sheets

Perturbed Parallel Current Density at time 1860.00
Response to a train of narrow ECCD pulses

Free system evolution

Pulsed (ECCD centered on the O-point) system evolution

[Comisso and Lazzaro, to appear on Nucl. Fusion]

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Immediate freezing of the reconnection process and a new nonlinear equilibrium state is reached with no singular points.
Magnetic Island behavior under ECCD pulses

The rf current profile clings on the secondary small scale flux tubes enhancing the filamentation!

The injected current causes a reduction of the primary magnetic island width

New X-points

A secondary magnetic island is growing

New O-point

Conclusions

• An automatic method developed for identification of the structure of tearing modes, capable of estimating the linear D’ appears promising.
• The study of two dimensional time dependent response of a tearing mode magnetic island to an RF driven current shows the possibility of strong nonlinear effects.
• Application of Extended Magnetohydrodynamics (ExMHD)* model shows:
  • first the prompt appearance of current sheets tending to shield the rf current effect
  • subsequently a nonlinear filamentation of the island structure that eventually proceeds towards formation of secondary islands
  • The rf J profile spreads on ψ surfaces, clinging also onto the small scale nonlinear structures and enhancing them.

• ECCD control of NTM based on painstaking tracking of island “phase” is probably unnecessary.
• Successful NTM control experiments are not at odds with this interpretation.

[*] J.D. Callen, C.C. Hegna, C.R. Sovinec, LP1.00062 at DPP-APS Meeting, Denver, CO, 24-28 October 2005
THE END
Further discussion
with contribution of E. Tassi
Discussion of NTM metastability and control issues

Early control of seed island: less power

Frequency-phase tracking necessary

\[ \frac{\tau_R}{r_s} \frac{dW}{dt} = r_s \Delta'_0 + \beta_p \left( \frac{\varepsilon^{1/2}}{s} \frac{r_s}{W/W_c} \frac{W}{W_c} \frac{1}{1 + (W/W_c)^2} \right) - r_s \Delta'_\text{pol} + r_s \Delta'_E \]

\[ \Delta'_\text{pol} \approx g \frac{\sigma}{\omega} \left( \frac{\varepsilon - \omega_*}{\omega_*^2} \right) \left( \frac{L_s}{L_n} \right)^2 \frac{\rho_{i\theta}}{W^3} \]

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\[ \beta_{cr} \text{ NTM excitation suppression} \]

Hysteresis!

Squeezing a saturated island: maximum RF power required

RF power deposition on \( q=m/n \) surface required
Dissipationless limit & Hamiltonian form

Faraday-Ohm

Shear-Alfvén

Parallel ion velocity

Electron pressure

With:

Hamiltonian

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