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

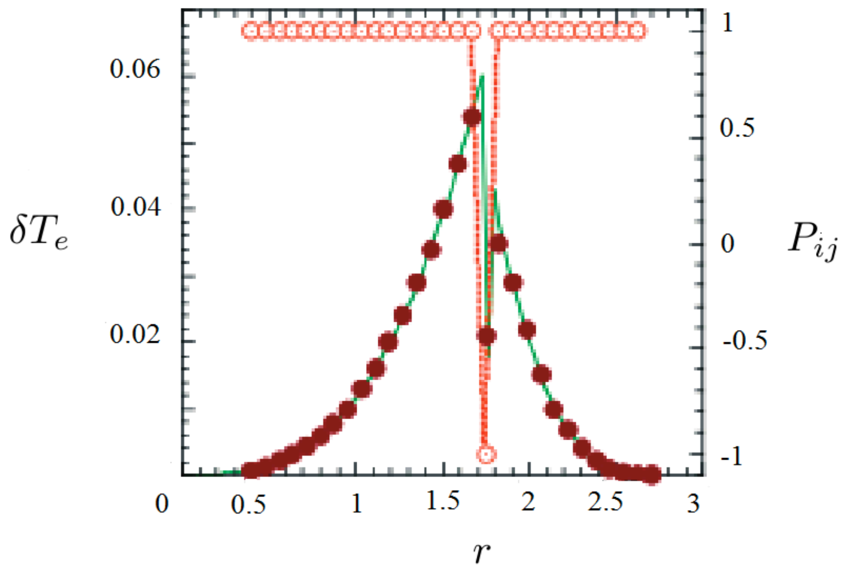
E.Lazzaro,D.Brunetti,L.Comisso

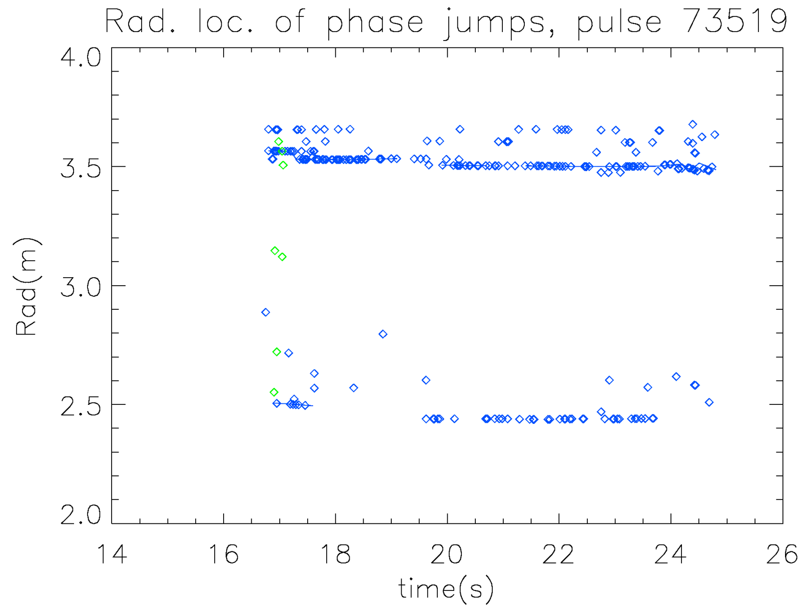
IFP “P.Caldirola”, Euratom-ENEA-CNR Association, Milano, Italy

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 δTe(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 $P_N(x) \approx \cos\delta\phi_{x,1}$ 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

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 $\Phi(\Psi) \equiv \frac{1}{2}\sum_i^N \left\|\delta T(\Psi(R_i),\mathbf{c}) - \delta T_{ECE}(R_i)\right\|^2$ under the constraint

of fulfilling the tearing mode equation in curvilinear geometry (toroidicity & shape)

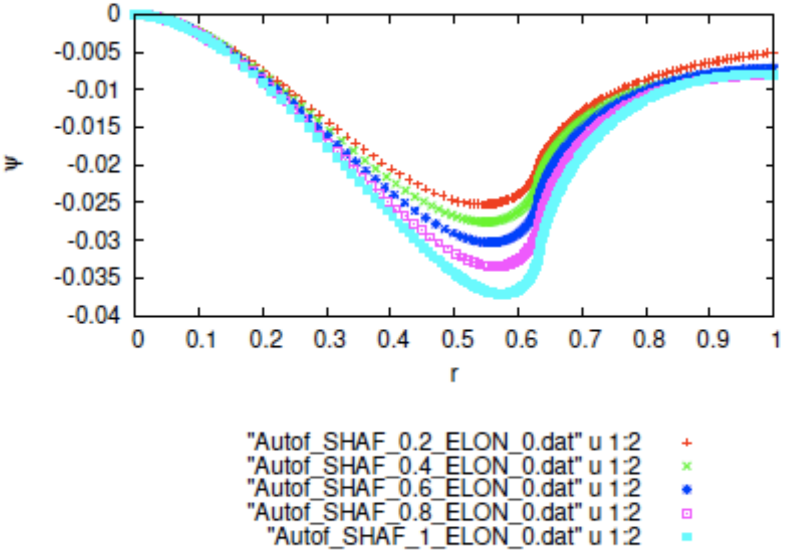
$$(m-nq)\left\{\left(\frac{g_{\vartheta\vartheta}}{g}\right)_{0,0}\Psi''_{m,n} + \left(\frac{1}{\sqrt{g}}\left(\frac{g_{\vartheta\vartheta}}{\sqrt{g}}\right)'\right)_{0,0}\Psi'_{m,n} - \left(\frac{1}{\sqrt{g}}\left(\frac{\dot{g}_{r\vartheta}}{\sqrt{g}}\right)\right)_{0.0}\Psi'_{m,n} - \left(\frac{g_{rr}}{g}\right)_{0,0} m^2\Psi_{m,n}\right\} - mq\left(\frac{J_0^{\varphi\prime}}{F_0'}\right)_{0,0}\Psi_{m,n}$$

Geometric effects on tearing eigenfunction

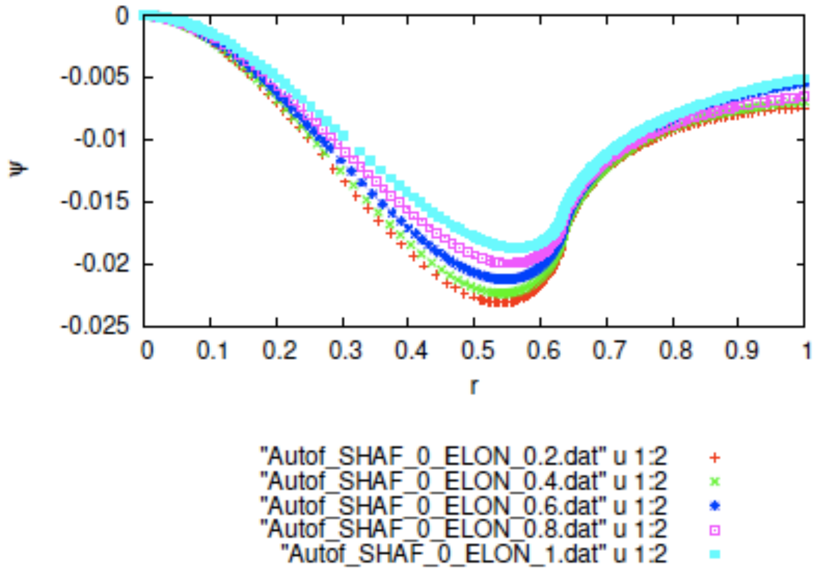
- Toroidal, shaped, equilibrium configuration described by:

$$R = R_0 + r\cos\vartheta + \Delta + r\lambda\sin\vartheta - E\cos\vartheta + O(\varepsilon^2)$$
$$Z = r\sin\vartheta - r\lambda\cos\vartheta + E\sin\vartheta + O(\varepsilon^2)$$

- Sensitivity of tearing eigenfunction to Δ_{shaf}, E



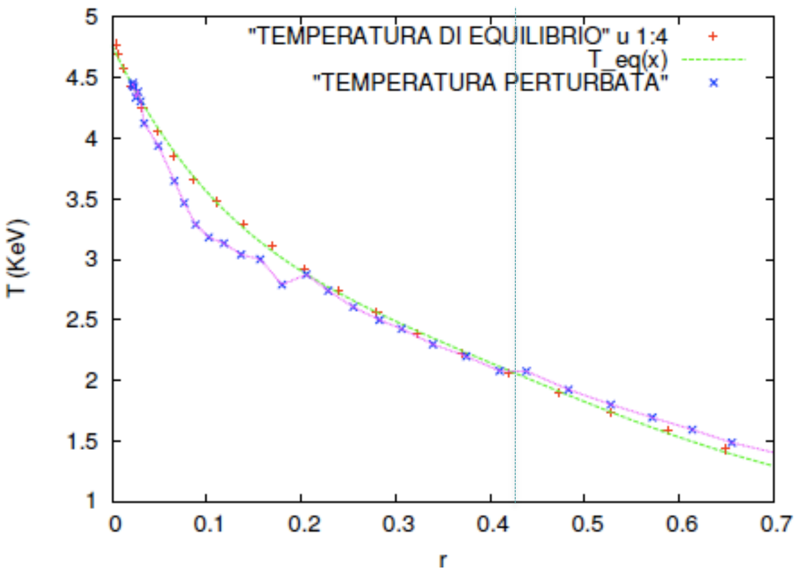
Sensitivity to Δ_{shaf}



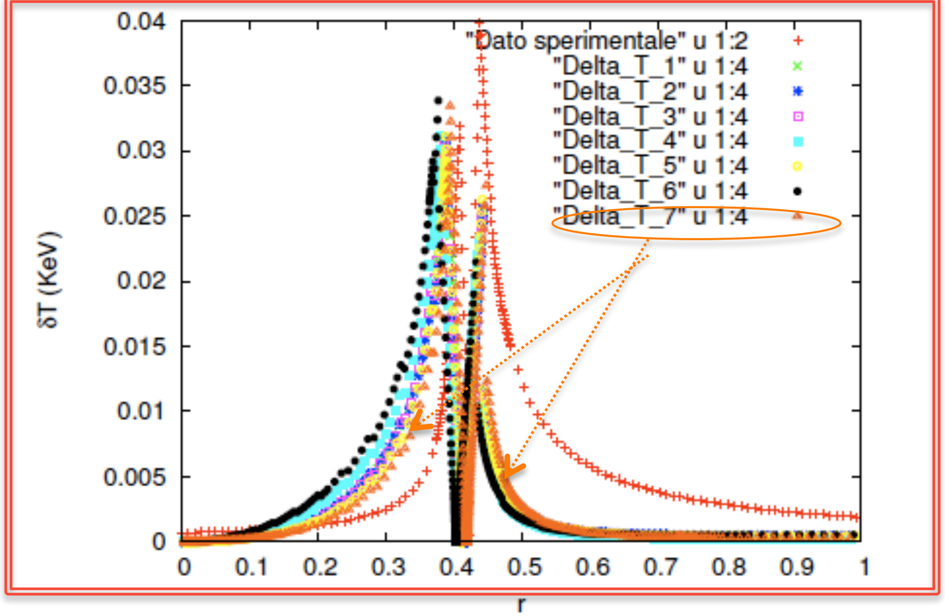
Sensitivity to E

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), Δ_{Shaf}, *E*



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



(b) Il funzionale minimizzato è ...
alla curva Delta_T_7 (triangoli ...

Automatic optimization

E	Δ_s	q_0	Φ	Δ'
1	1	1.0912	3.8454	-2.8175
1	1	1.09749	3.77903	-2.6243
1	1	1.04312	4.14636	-3.567
1	1	1.24197	5.3007	-0,7313
1	1	0.929192	3.75385	-4.741
1	1	1.35433	6.21886	2.0911
1	1	0.826206	2.81569	−5.84774

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
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$$\frac{\tau_R}{r_s}\frac{dW}{dt} = r_s\Delta'_0 + \beta_p\left(\frac{\varepsilon^{1/2}}{s}\frac{r_s}{W_c}\frac{W/W_c}{1+(W/W_c)^2} - r_s g\frac{\varpi(\varpi-\omega_{*i})}{\omega_{*e}^2}\left(\frac{L_s}{L_n}\right)^2\frac{\rho_{i\theta}^2}{W^3}\right) + \frac{8 r_s\delta_{EC} q}{\pi W^2}\eta_h\left(\frac{W}{\delta_{EC}}\right)\left(\frac{J_{EC}(t)}{J_{boot}}\right)$$

Neoclasssical bootstrap effect

ECCD control tern

- If the (helical) ECCD current is driven within a depth δ_{EC}<W, **important 2D nonlinear** effects are missed by the Rutherford models

Study of 2D effects in a Neoclassical 4-Field Model*

Faraday-Ohm

$$\frac{\partial \psi}{\partial t} + \vec{v}_E \cdot \vec{\nabla}\psi = -\vec{v}_{pe} \cdot \vec{\nabla}\psi - \eta_{NC}\left(J_{\|} - J_{bs} - J_{EC}\right)$$

Shear-Alfvén

$$\frac{\partial U}{\partial t} + \vec{v}_E \cdot \vec{\nabla} U = \frac{1}{m_i n} B_0 \nabla_{\|} J_{\|} - \frac{\mu_0 (1+\tau_T)}{m_i n B_0}\left(J_{\|}\nabla_{\|} p_{e\Delta} + p_{e\Delta}\nabla_{\|} J_{\|}\right)$$

Parallel ion velocity

$$\frac{\partial v_{i\|}}{\partial t} + \vec{v}_E \cdot \vec{\nabla} v_{i\|} = -\frac{(1+\tau_T)}{m_i n}\left(\nabla_{\|} p_e + \frac{2}{3}\nabla_{\|} p_{e\Delta}\right)$$

Electron pressure

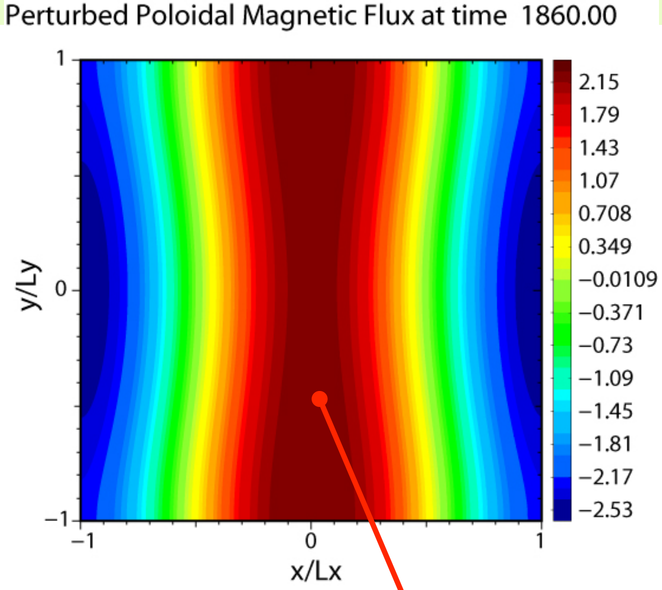
$$\frac{\partial p_e}{\partial t} + \vec{v}_E \cdot \vec{\nabla} p_e = -\left(\frac{5}{3} p_e + \frac{4}{9} p_{e\Delta}\right)\nabla_{\|}\left(v_{i\|} - \frac{J_{\|}}{en}\right)$$

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

Closure relation for anisotropy

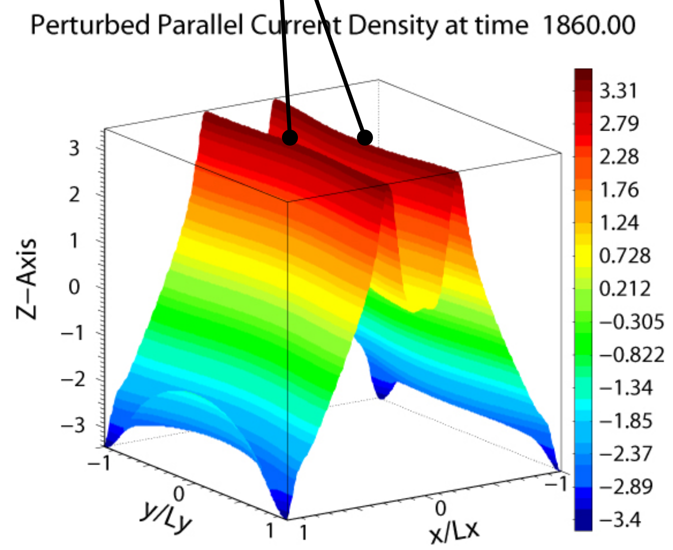
[*] Lazzaro, Comisso, Valdettaro, Phys. Plasmas **17**, 052509 (2010)

ECCD centered on the *O*-point

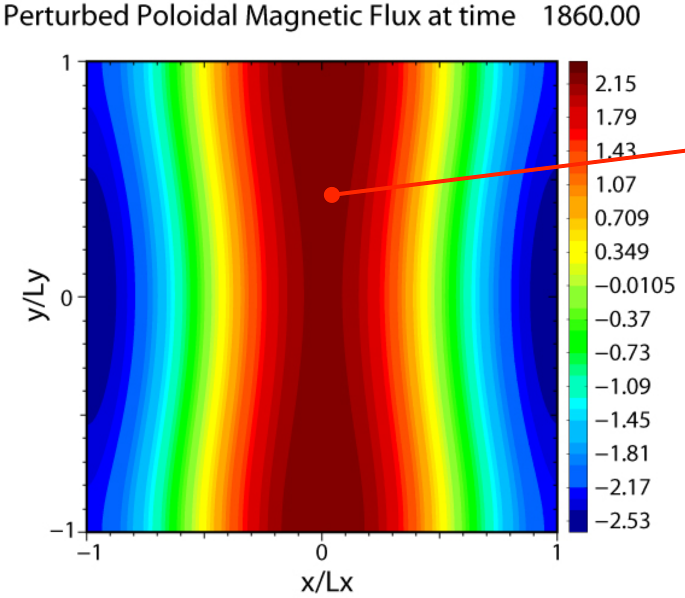


ECCD deposition has led (promptly) to a *new equilibrium state* without singular points!

Current sheets appear on both sides of singular surface, as *alternative* to the equilibrium with magnetic islands

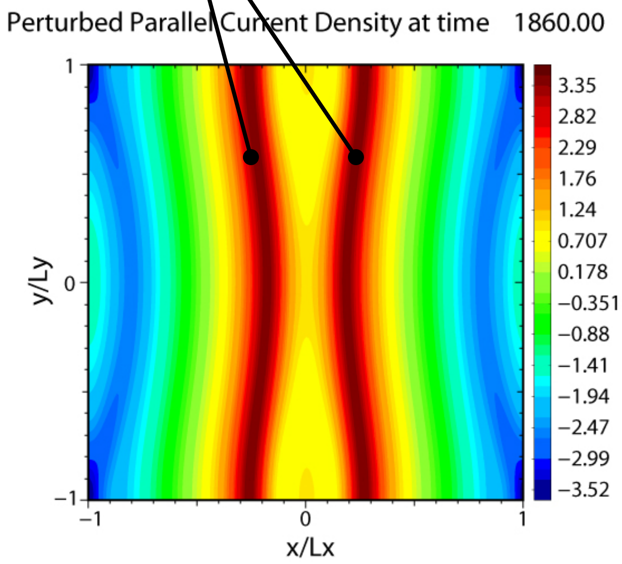


ECCD with angular offset



Notwithstanding the phase offset, reconnection is frozen!

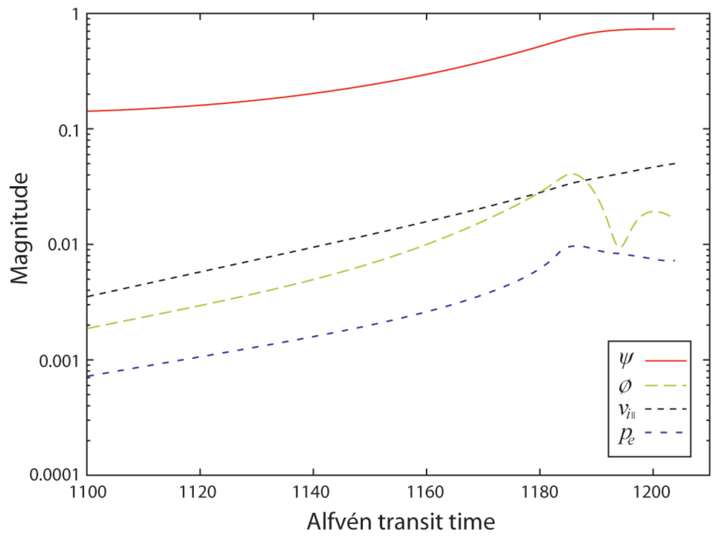
Current sheets



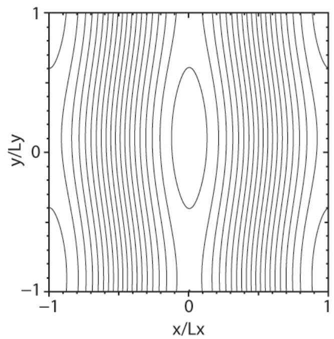
A (moderate) angular offset of ECCD produces a behavior very much like that of an exact deposition on the *O*-point

Response to a train of *narrow* ECCD pulses

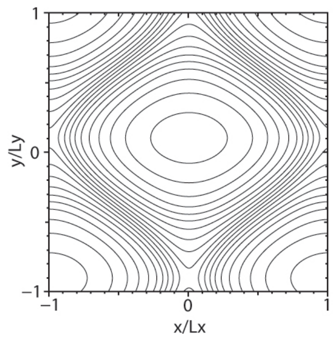
Free system evolution



(a)

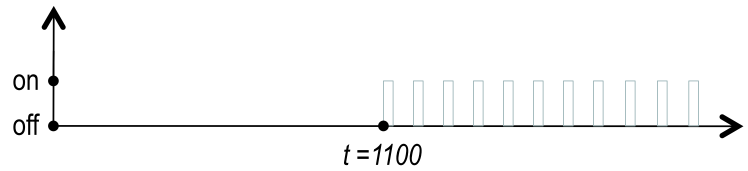


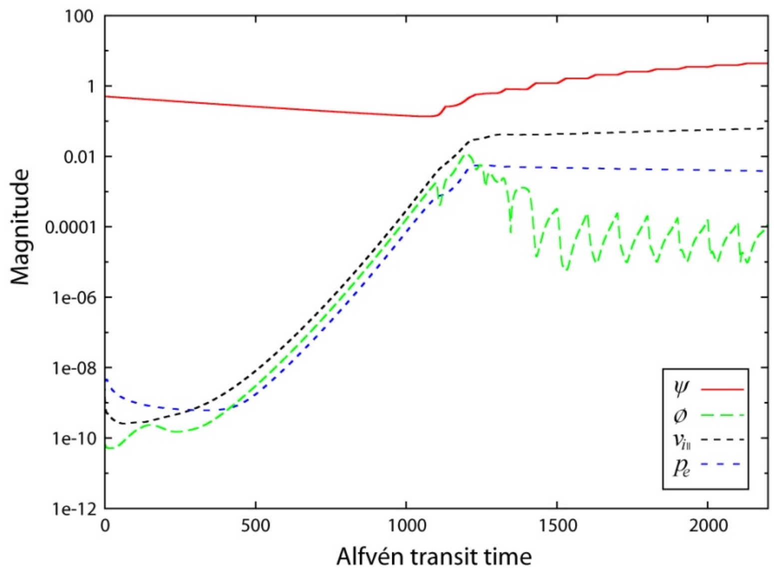
(b) $t = 1100$



(c) $t = 1180$

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

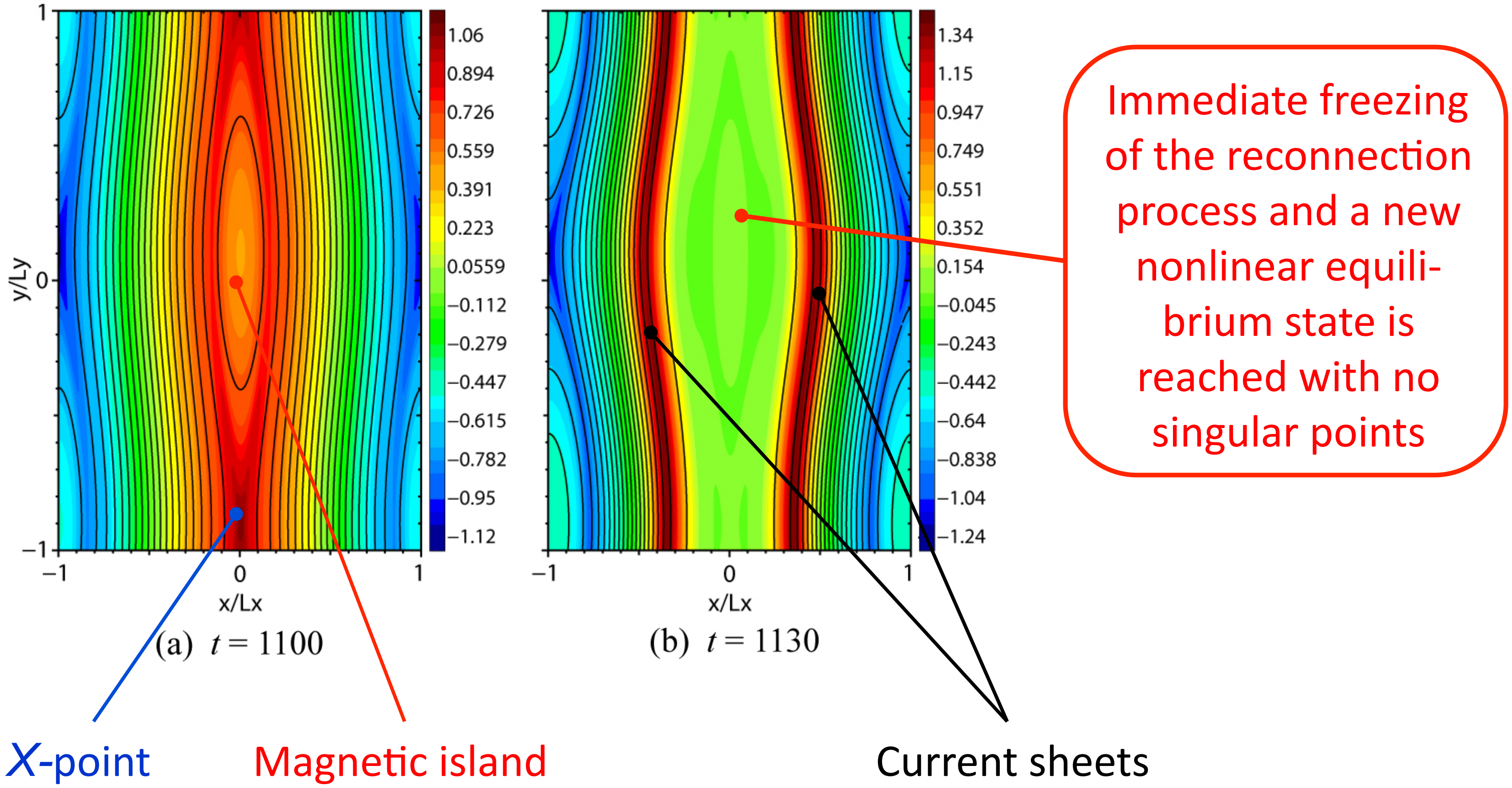




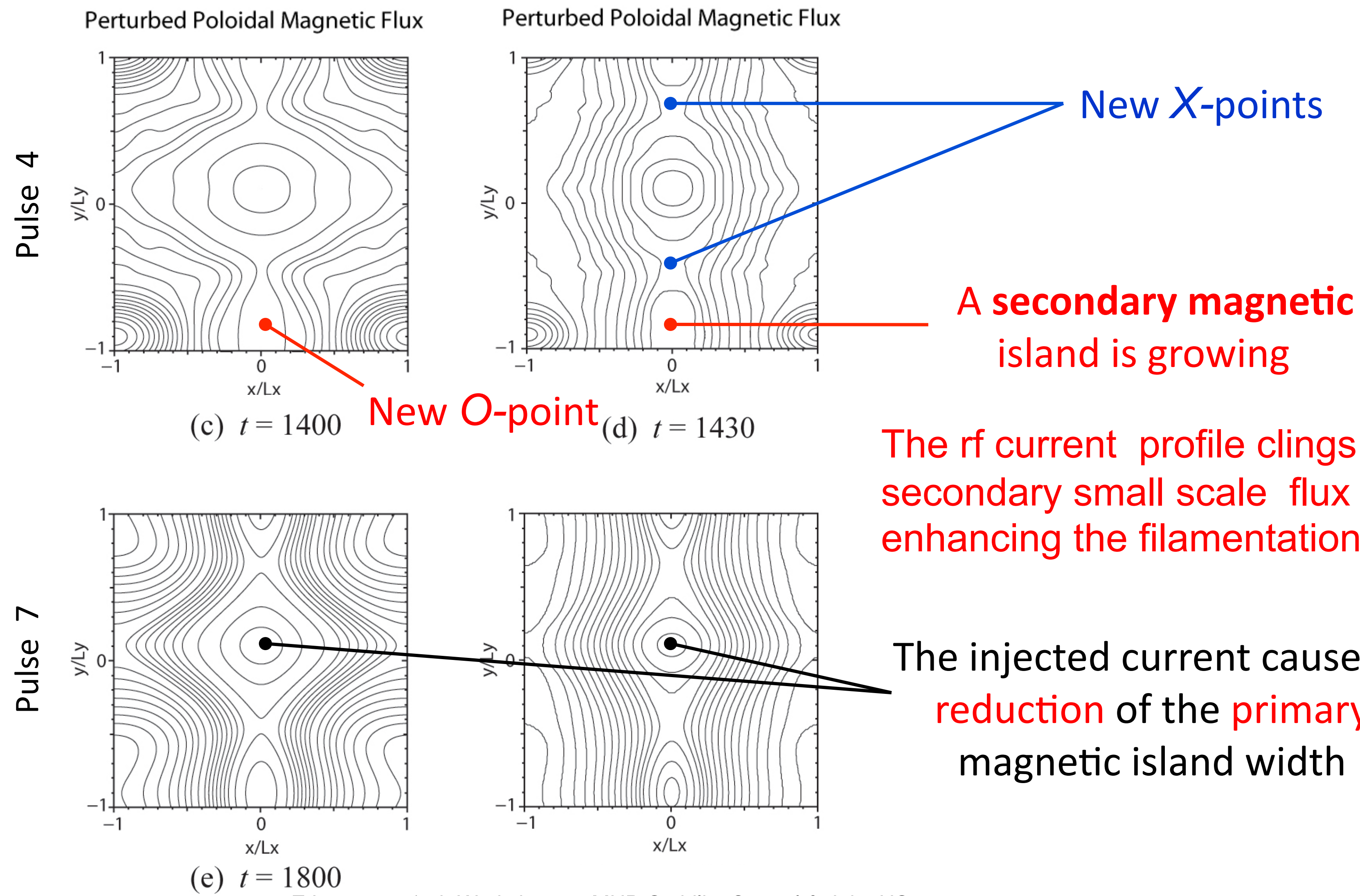
[Comisso and Lazzaro, to appear on Nucl. Fusion]

Effect of the *first* narrow ECCD pulse

Poloidal magnetic flux (black lines) and out-of-plane current density (color)



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

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

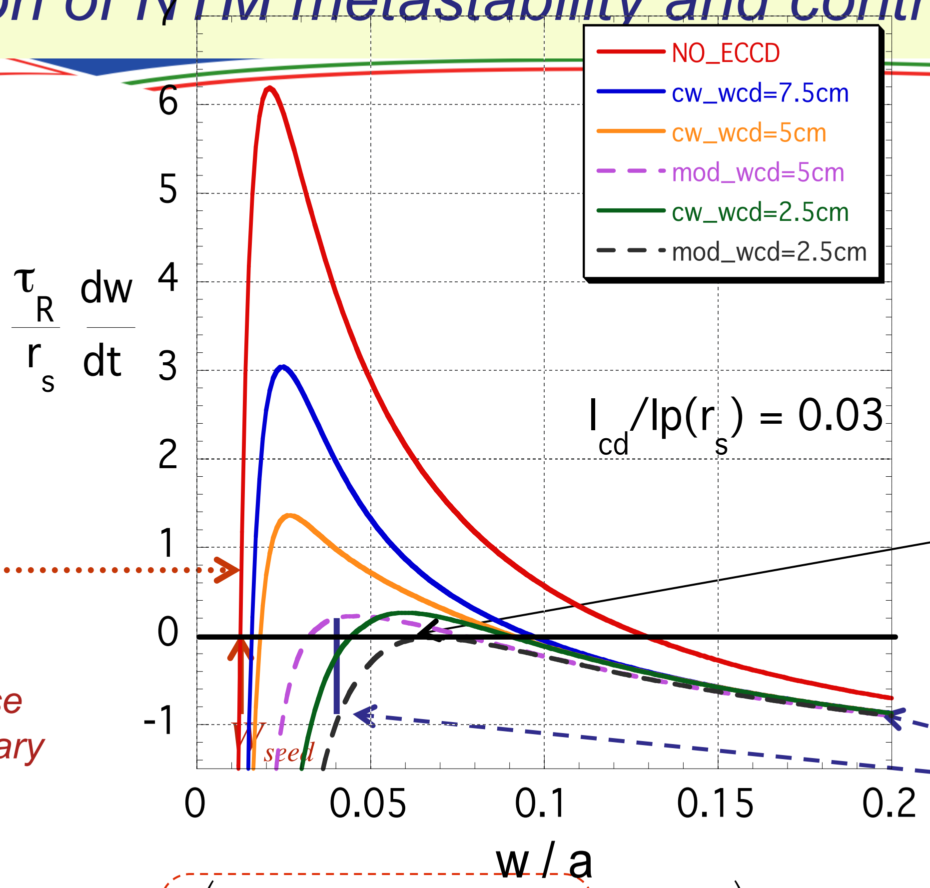
•Successful NTM control experiments are not at odds with this interpretation

[*] 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



β_{cr} NTM excitation

β_{mar} suppression

Hysteresis!

Early control of seed island:
less power

Frequency-phase tracking necessary

Squeezing a saturated island:
maximum RF power required

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

Δ'_{boot}

$$\Delta'_{EC} = \frac{8q\delta_{EC}}{\pi W^2}\eta\left(\frac{W}{\delta_{EC}}\right)\left(\frac{J_{EC}(t)}{J_{boot}}\right)$$

$$\Delta'_{pol} \approx g\frac{\varpi(\varpi-\omega_{*i})}{\omega_{*e}^2}\left(\frac{L_s}{L_n}\right)^2\frac{\rho_{i\theta}^2}{W^3}$$

*RF power deposition on **q=m/n** surface required*

Dissipationless limit & Hamiltonian form

Faraday-Ohm

$$\frac{\partial \psi}{\partial t} + [\phi, \psi] = d_i[\exp p, \psi],$$

Shear-Alfvén

$$\frac{\partial U}{\partial t} + [\phi, U] = -[\nabla^2 \psi, \psi],$$

Parallel ion velocity

$$\frac{\partial v_{i\|}}{\partial t} + [\phi, v_{i\|}] = (1+\tau_T)[\psi, \exp p],$$

Electron pressure

$$\frac{\partial p}{\partial t} + [\phi, p] = \frac{5}{3}[\psi, v_{i\|}] + \frac{5}{3} d_i [\psi, \nabla^2 \psi],$$

With:

$$\bar{t} \rightarrow \frac{v_A}{L} t, \qquad \bar{x} \rightarrow \frac{x}{L}, \qquad \bar{\psi} \rightarrow \frac{\psi}{B_0 L}, \qquad \bar{\phi} \rightarrow \frac{\phi}{v_A L B_0},$$

$$\bar{v_{i\|}} \rightarrow \frac{v_{i\|}}{v_A}, \qquad p \equiv \ln \bar{p_e} \rightarrow \ln\left(\frac{p_e}{m_i n v_A^2}\right), \qquad \bar{U} \rightarrow \frac{L}{v_A} U,$$

Hamiltonian

$$H = \int d^2x \left(\frac{|\nabla \psi|^2}{2} + \frac{|\nabla \phi|^2}{2} + \frac{v_{i\|}^2}{2(1+\tau_T)} + \frac{\exp p}{(5/3)} \right)$$