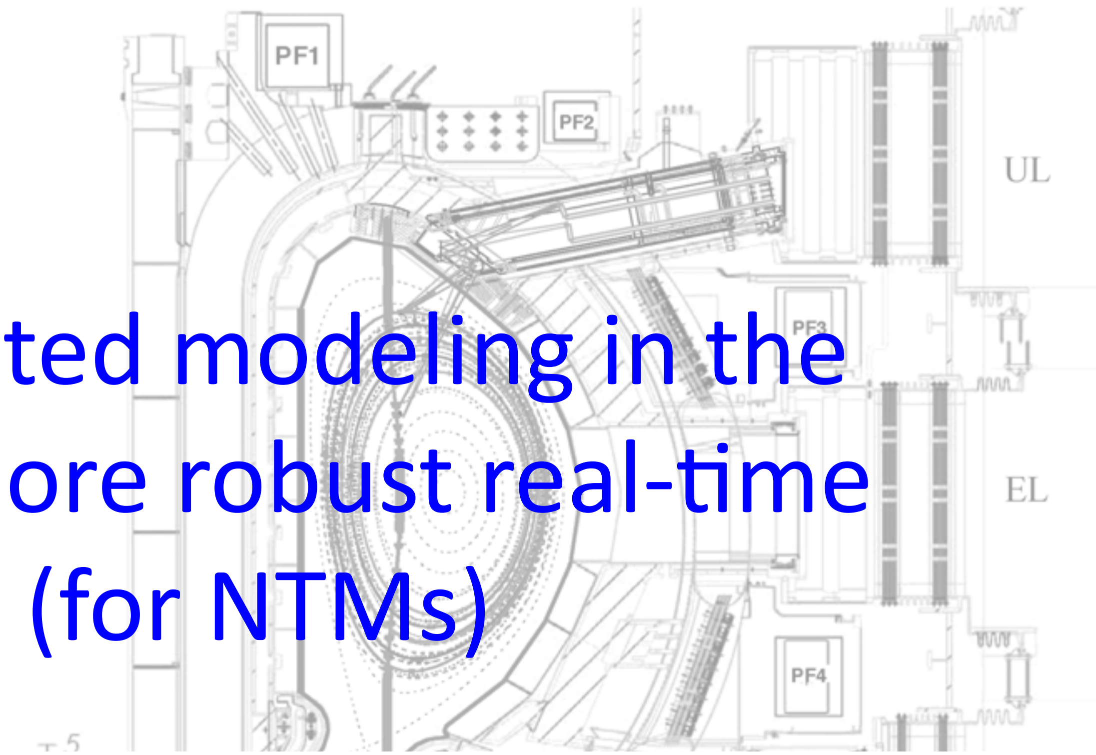

The role of integrated modeling in the development of more robust real-time control algorithms (for NTMs)

Francesca Poli and Eric Fredrickson

Acknowledgments:
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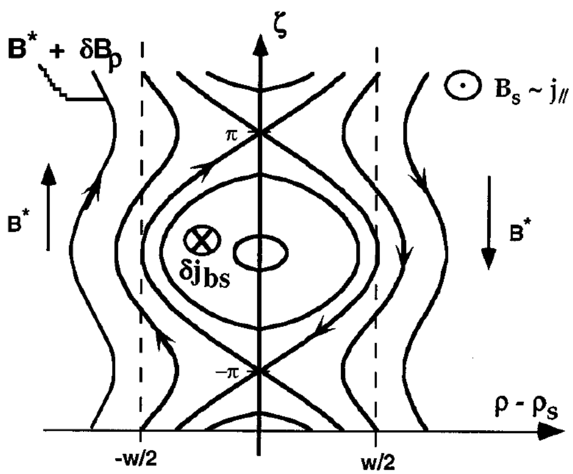
Work supported by ITER under IO/RFQ/13/9550/JTR and by DOE under DE-AC02-09CH11466.
The view and opinions expressed herein do not necessarily reflect those of the ITER Organization.

Real-time control algorithms use reduced models, but they can benefit from high fidelity physics models

- Neoclassical Tearing Modes, why we care
- NTMs on ITER: where the standard approaches fail
- What does TRANSP add to NTM control?
- NTM control on ITER: what we have learnt

NTMs can lead to significant confinement degradation



- No hard limit on β_N but confinement degradation
  $\Delta\tau_E/\tau_E \sim 4\rho_s^3 w_{sat}/a$
- $\Delta\tau_E/\tau_E \sim 20\%$ observed for (3,2)-NTM
- higher for (2,1)-NTM at low q_{95}
- NTMs can lock and lead to disruptions
  - one of the principal causes of disruption on JET

=> NTM control critical for the success of ITER

NTM control with ECCD widely used:

- replaces J_{BS} with J_{ECCD}
- highly localized ECCD deposition
- EC power modulation for alignment with O-point
- sweeping over ρ_s to compensate for lack of tracking
- high flexibility in complex control schemes
  - pre-emptive: sawtooth + NTMs
  - active detection and suppression

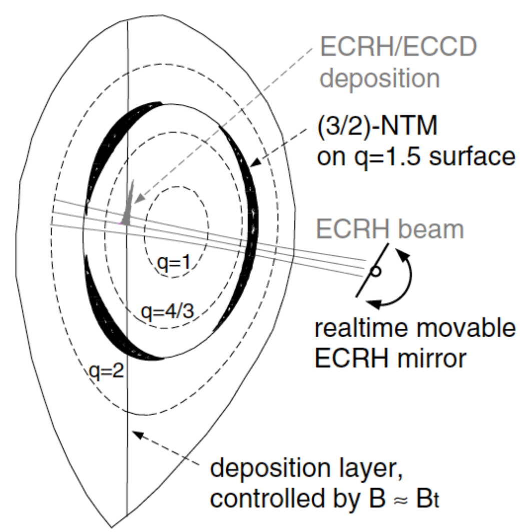
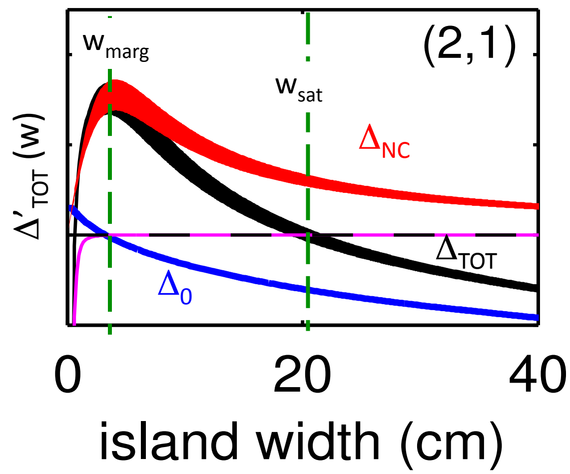


Fig.2 in Maraschek, NF 52 (2012)

Will the same techniques work on ITER?

ITER extrapolations are based on asymptotic solutions

$$\frac{dw}{dt} = 1.22\frac{\eta}{\mu_0}\left[\Delta'(w) + \Delta'_{NC} + \Delta'_{pol} + \Delta'_{GGJ} + \Delta'_{ECCD} + \Delta'_{ECH}\right]$$ Modified Rutherford Equation



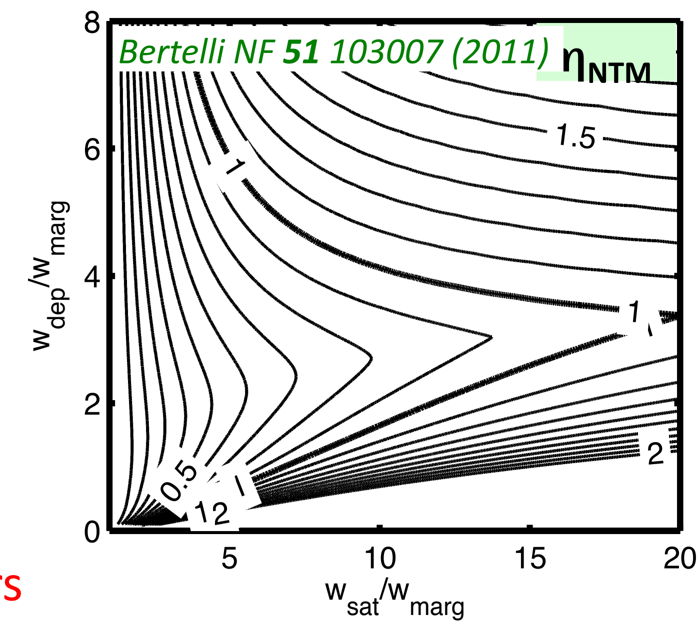
- find dw/dt=0 for given equilibrium and kinetic profiles

Zohm: $\eta_{NTM}>1.2$

Sauter: $\eta_{NTM} w_{dep}>5cm$ $w_{dep}<5cm$

- scan island parameters and EC deposition to find
- figure of merit η_{NTM}: $P_{NTM}=\eta_{NTM}P_{EC}J_{BS}/J_{CD}$

- η_{NTM} useful for real-time control applications



Stabilization criteria depend on plasma parameters and EC deposition width, which change in time

Asymptotic solutions do not account for dynamic response of the system

– effects of misalignment (systematic or transient)
– threshold effects on the detection of the island
– (changing in time) broadening of EC deposition
– time-scales of NTM growth, as compared to hardware constraints

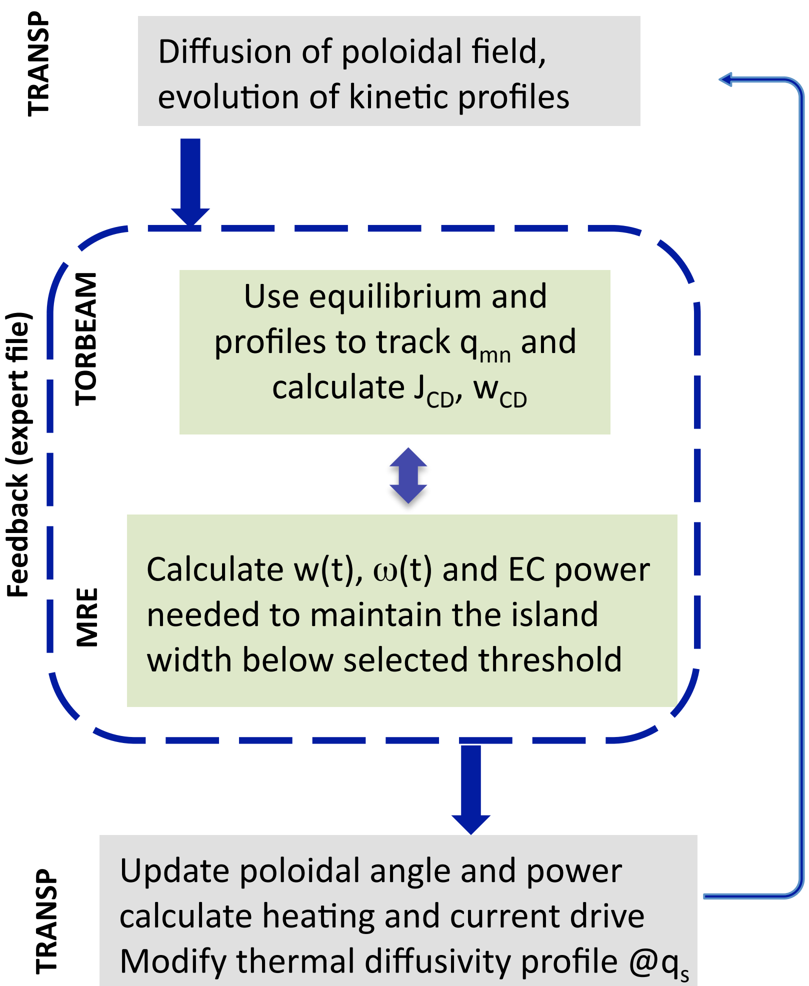
$\leq$3 s => how fast the power can be switched between mirrors (switch design)
=> affects combined applications with EL/UL (core heating+MHD)

1 s => how fast the Upper Launcher can sweep over the full poloidal range
=> affects combined applications with UL (sawteeth+NTM)

– the plasma response to ECCD and ECRH.

Assessment of NTM control should account for all these effects for optimization of available resources

Self-consistent evolution of NTMs and plasma profiles can help designing stable discharges and more robust control schemes

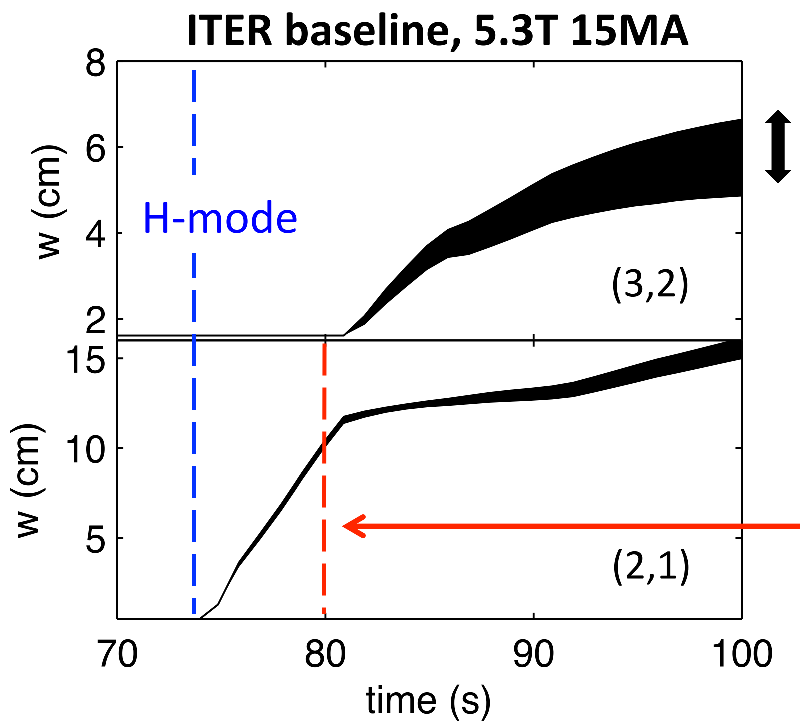


- Interface TRANSP with MRE for self-consistent calculation of plasma equilibrium, HCD and NTM evolution, with EC feedback control.
- Advantages: evaluate plasma response to EC feedback for control schemes assessment

CAVEATS:

- validation against experiments (ASDEX-U, JET, DIII-D, NSTX) in progress.
- NTM onset conditions might require additional stability calculations

(2,1)-NTM grows and locks faster than power switch



Uncertainty due to choice of k_1:

$$\Delta'_{NC} = k_1 \frac{16 J_{BS}}{s \langle J \rangle} \frac{w}{w^2 + w_d^2}$$

(2,1)-NTM onset soon after H-mode

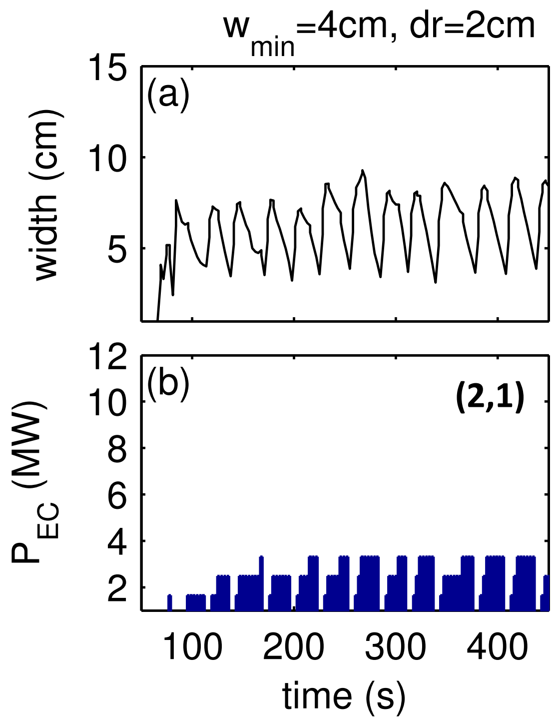
(2,1)-NTM **locks after~5s**

ECE threshold ≥ 2cm → <3s between detection and locking

Equilibrium reconstruction ≥ 2cm

Not enough time to search for (2,1)-NTM and suppress it.
It has to be prevented from growing above threshold

Switching power between applications not a viable solution



EC feedback control

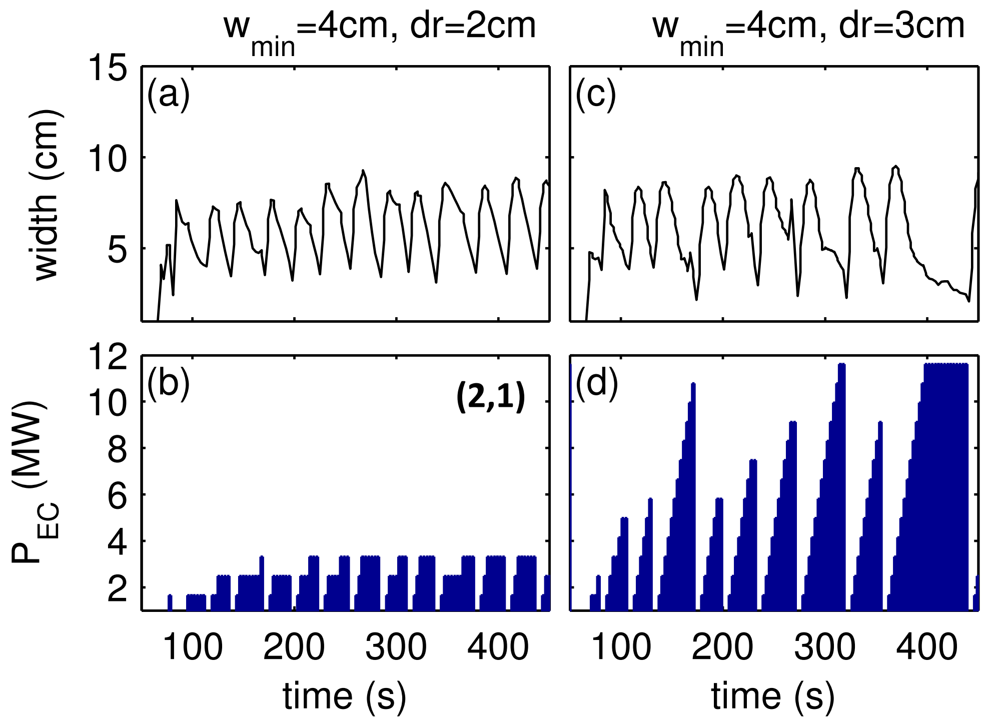
- Assume EC is used for anything than NTM control
- Wait until island size exceeds w_{min}
- calculate EC power needed to drop Δ'_{max}=0
- move EC power to the Upper Launcher (it takes 3s)
- when island w<w_{min} => drop power to 0

$\Rightarrow$ NTM grows back as EC removed from (m,n)

Implication #1: Power needs to be reserved for control of (2,1)

In 3s the island has time to grow back (high β_{pol} in ITER)
But it takes <100ms to turn on/off a gyrotron

Maintaining good alignment is critical



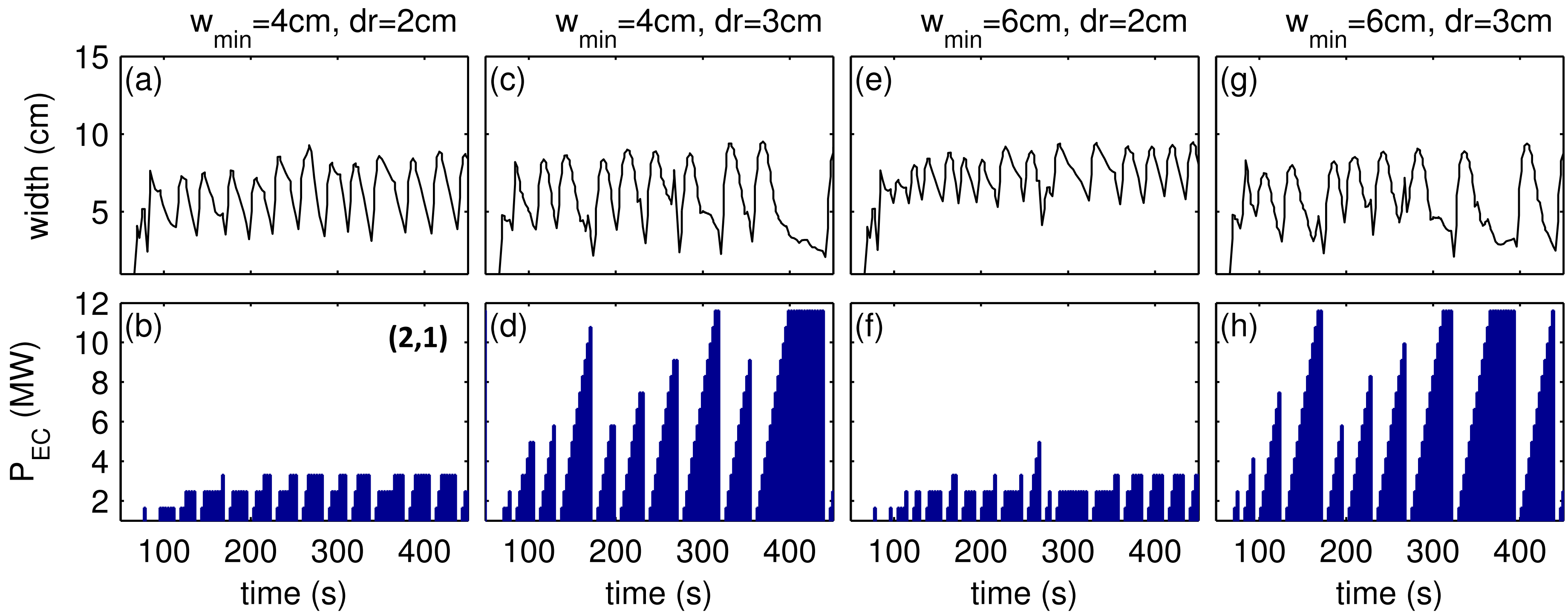
Lower power needed if EC is better aligned.

⇒ even 1cm does matter

Implication #1: Power needs to be reserved for control of (2,1)

In 3s the island has time to grow back (high β_{pol} in ITER)
But it takes <100ms to turn on/off a gyrotron

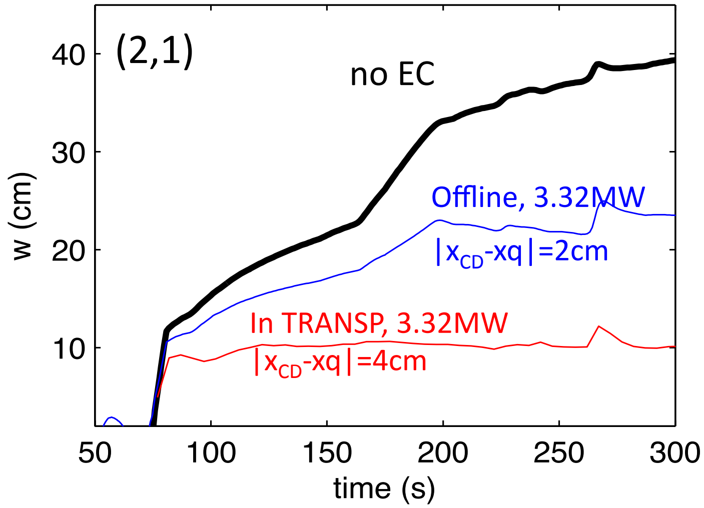
Good alignment more important than S/N detection



Implication #1: Power needs to be reserved for control of (2,1)

Implication #2: pre-emptive control preferable for stabilization of (2,1)

Self-consistent calculation of NTM evolution and plasma profiles set lower limits on EC power needs

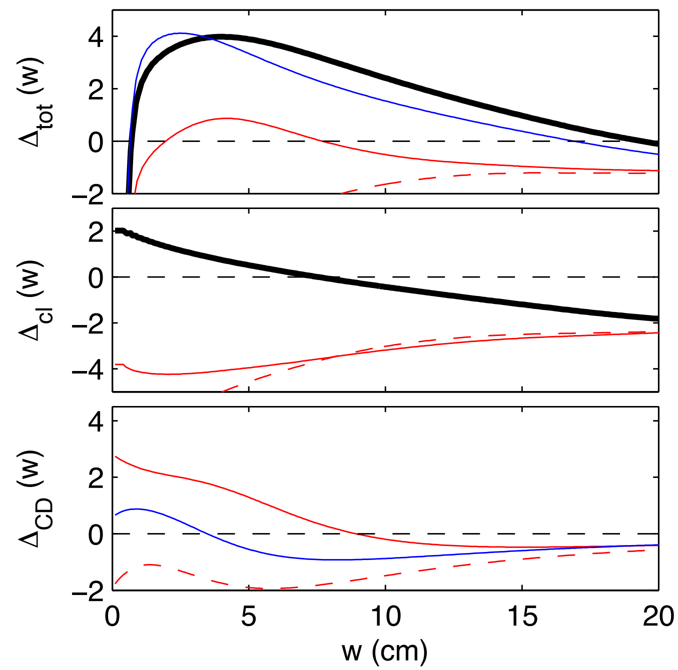


- Δ'_{CL} responds to local modification of current profile
- Δ'_{ECCD} responds to time variations of $|x_{CD}-x_q|$ and w_{CD}

if $|x_{CD}-x_q|$ =2cm => full suppression in TRANSP, unstable offline.

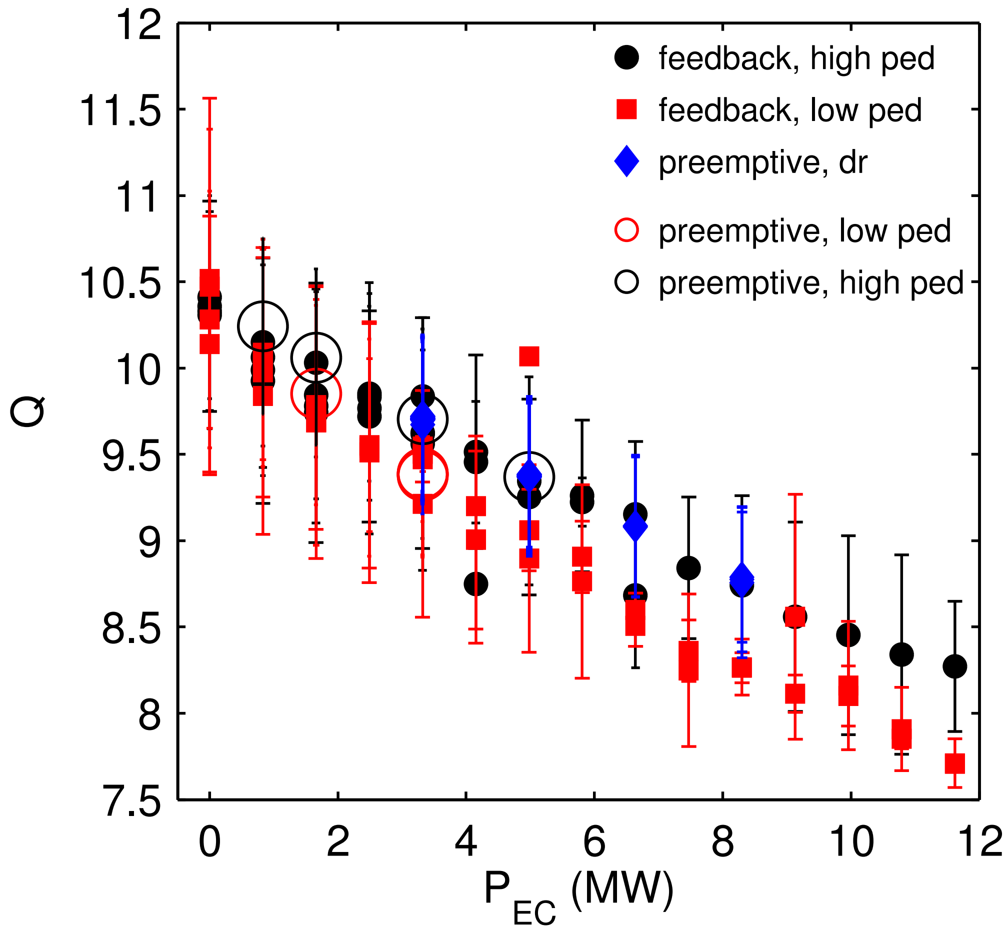
$$\Delta'_{CD} = 32\pi^{1/2}\frac{J_{CD,max}}{\langle J_\phi\rangle s}F(\tilde{w})M(\tilde{w},D)G(\tilde{w},x_{dep})$$

Deposition profile — Modulation — Alignment



⇒ 5-8 MW need to be reserved for NTM control
(instead of 20MW as previously assessed with offline calculations)

Pre-emptive control is a good compromise between NTM control and minimum reduction of Q



Active search for NTM =>
Q~ 7.5 – 10
P_{EC} up to 12 MW

Pre-emptive control =>
Q~9
P_{EC} up to 5 MW

In both cases w~6-10cm @q=2
$\Delta\tau_E/\tau_E$ ~ 10-15%

Self-consistent calculations set lower limits on EC power requirements on ITER, but more constraints on control

- NTM control techniques used on present-day experiments might not be directly applicable to ITER
- When plasma response is taken into account in the assessment, upper limit on EC power is reduced to 5-8MW.
- Fast growth rate raises question on active search and combined sawtooth-NTM control on ITER
- Need to pre-emptively stabilize the (2,1)-NTM
- Pre-emptive control minimizes power usage
- Broadening deposition profile up to 6-7cm required on q=2
- EC alignment within $0.5w_{CD}$ required
- Alignment more important than S/N of detection diagnostic

PPPL

Recycle an old code for TFTR and include EC

*E. Fredrickson PoP **7** 4112 (2000)*

$$\frac{\partial w}{\partial t} = 1.22\frac{\eta}{\mu}\left[\Delta'(w) + \Delta'_{nc} + \Delta'_{pol} + \Delta'_{GGJ} + \Delta'_{CD}\right]$$

$$\Delta'_{NC} \approx k_1 \frac{16 J_{BS}}{sw\langle J\rangle} \approx \frac{16 J_{BS}}{s\langle J\rangle}\frac{w}{w^2 + w_d^2}$$

$$w_d \approx 5.1 k_d \frac{r_s}{\epsilon s n}\left(\frac{\chi_\perp}{\chi_\parallel}\right)^{1/4}$$

Threshold condition

$$\Delta'_{pol} \approx -k_2 \frac{\rho_{\theta i}^2 \beta_{pol} g(\epsilon^{3/2}, v_i/\omega_{\star e})}{w^3}\left(\frac{L_q}{L_p}\right)^2$$

NOTE: island rotation frequency not included yet in TRANSP

$$\Delta'_{GGJ} \approx -5.4 k_4 \frac{\beta_{pol}\epsilon^2 L_q^2}{r_s w |L_p|}\frac{q^2 - 1}{q^2}$$

*W. Houlberg PoP **4** 3230 (1997)*

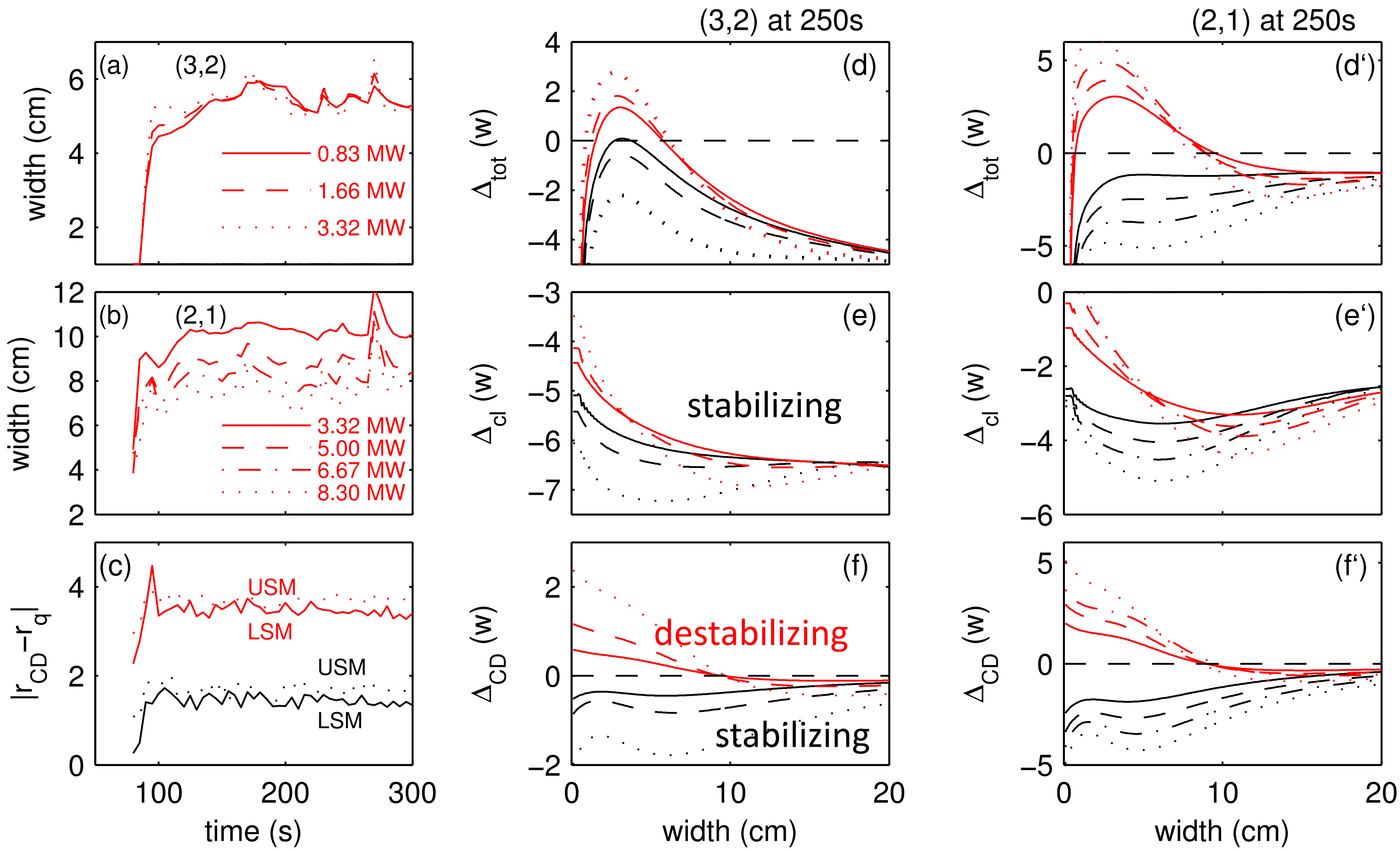
$$\Delta'_{CD} = k_6 16\pi^{1/2}\frac{\mu_0 L_q}{B_p}\frac{J_{CD,max}}{w_{CD}} F(w) M(w)$$

*N. Bertelli NF 7 **51** 103007 (2011)*

$$F(w) = 0.25\frac{1 + 0.96\widetilde{w}}{1 + \widetilde{w}\left(1.5 + \widetilde{w}\left(0.43 + 0.64\widetilde{w}\right)\right)}$$

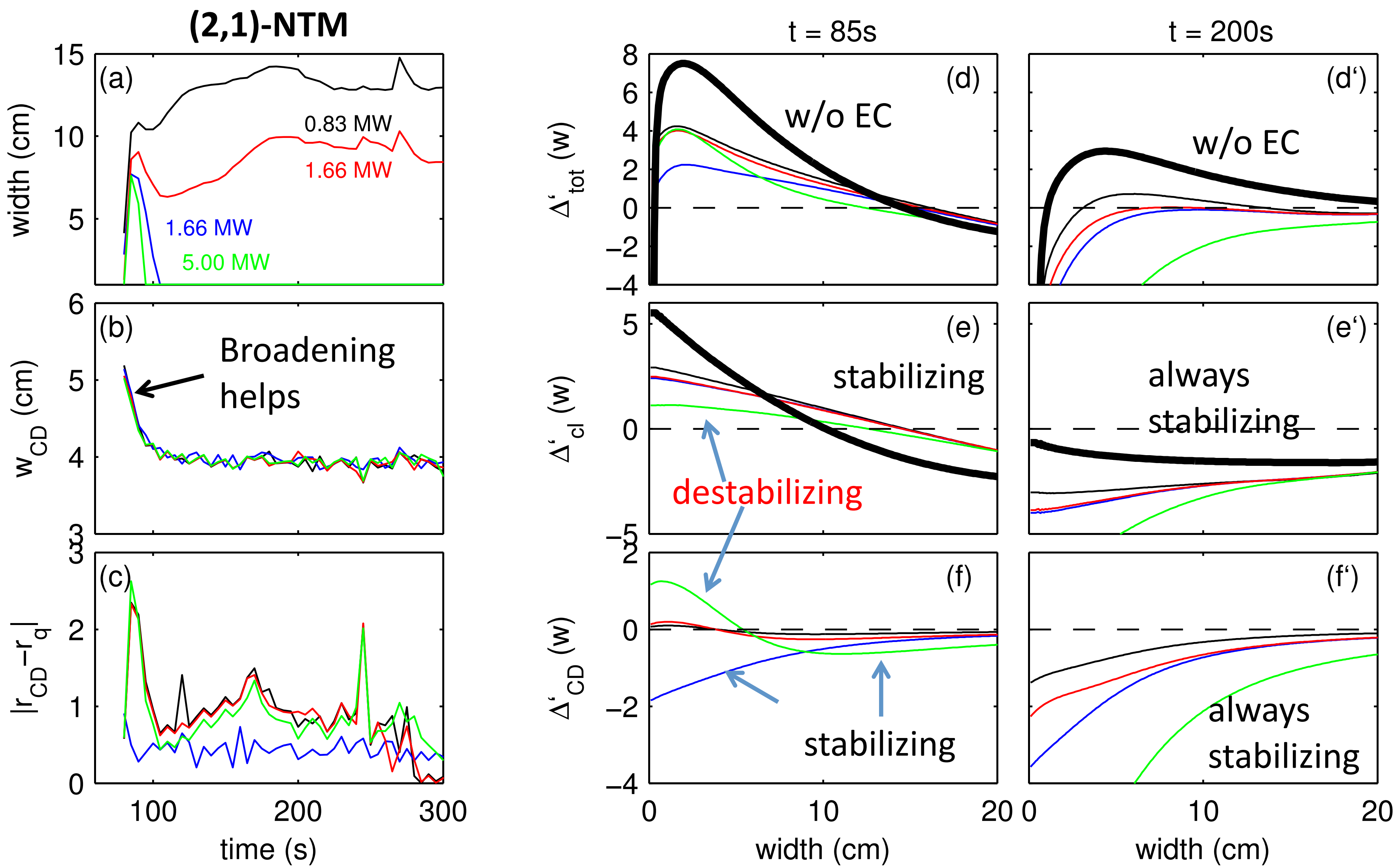
$$\widetilde{w} = w/w_{CD}$$

Full suppression obtained only if $dr<0.5w_{CD}$

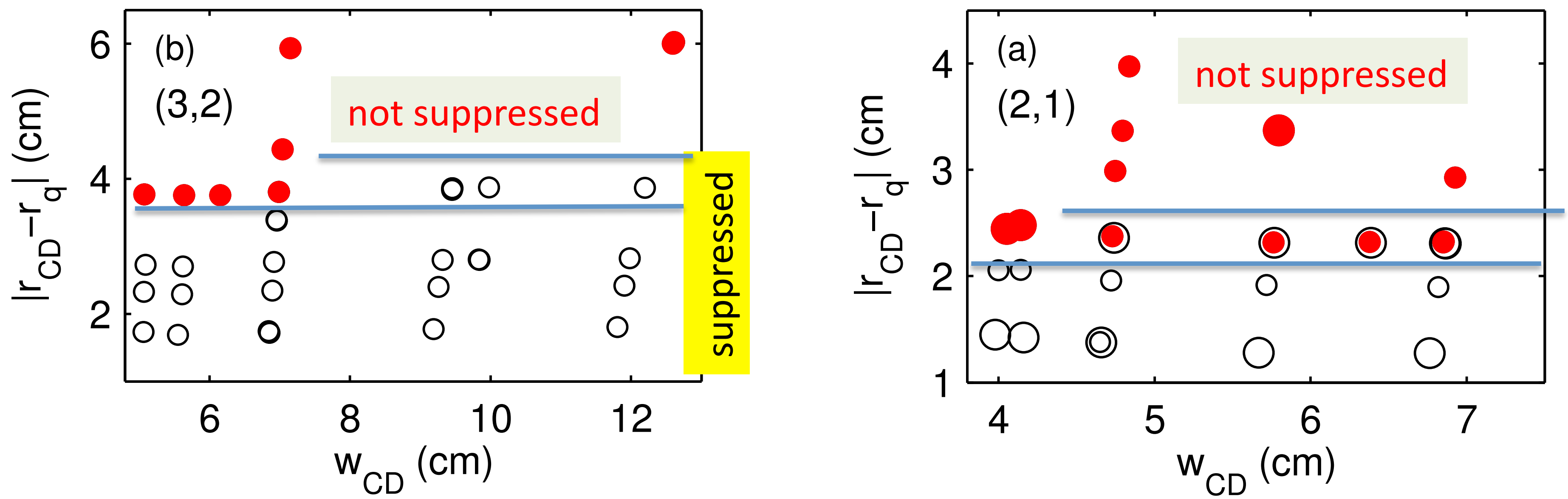


Not much benefit in increasing EC power if $dr=|r_{CD}-r_q|\sim w_{CD}$

Loss of alignment at NTM onset affects stabilization at later times



Broadening of w_{CD} is a good boost for early stabilization



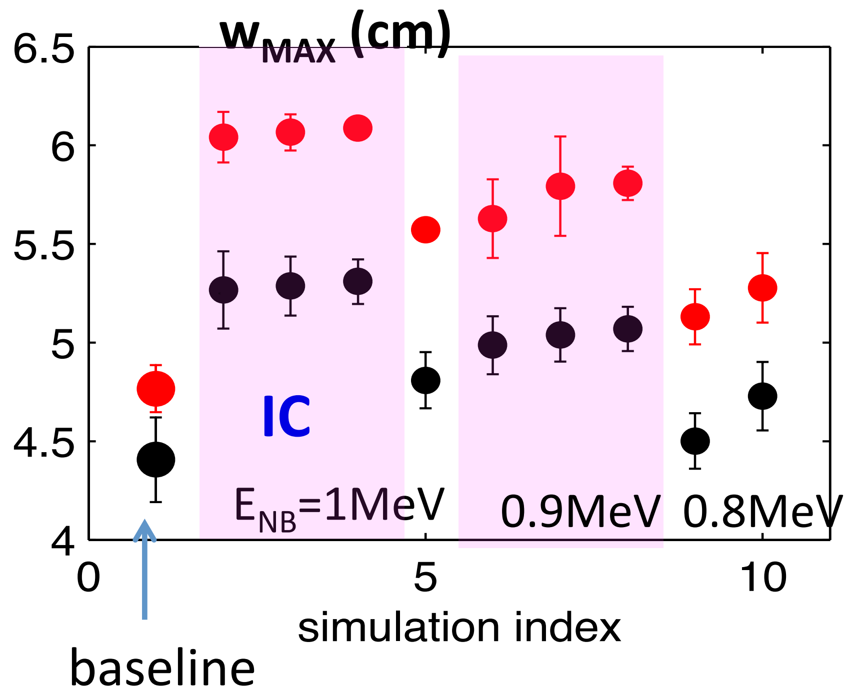
(3,2) suppressed always with dr<~ 0.5w_{CD}

suppressed with >50% broadening and dr~w_{CD}

(2,1) suppressed always with dr< 0.5w_{CD}

with 50% broadening and larger power if dr~ 0.5w_{CD}

Discharge design becomes critical at half-field



w_{CD} => 2.6 cm @ q=1.5 (5 cm at full field)
1.5 cm @ q=2.0 (4 cm at full field)

J_{max} comparable (total driven current is half)

$\Rightarrow$ Alignment is most important

Trend observed with NBI energy and with IC heating scheme:

- w_{max} size decreases with NBI energy
- at constant E_{NB}, w_{max} increases with H minority fraction
- at constant E_{NB}, w_{max} drops w/o IC.

Generalized NTM stabilization criteria

*N. Bertelli et al, NF **51** (2011) 103007*

$$0.82\frac{\tau_r}{r_s}\frac{dw}{dt} = r_s\Delta'_0 + r_s\delta\Delta'_0(w) + r_s\Delta'_{BS}(w) + r_s\Delta'_{CD}(w) + r_s\Delta'_H(w)$$

Stabilization criteria obtained from GRE, assuming dw/dt=0

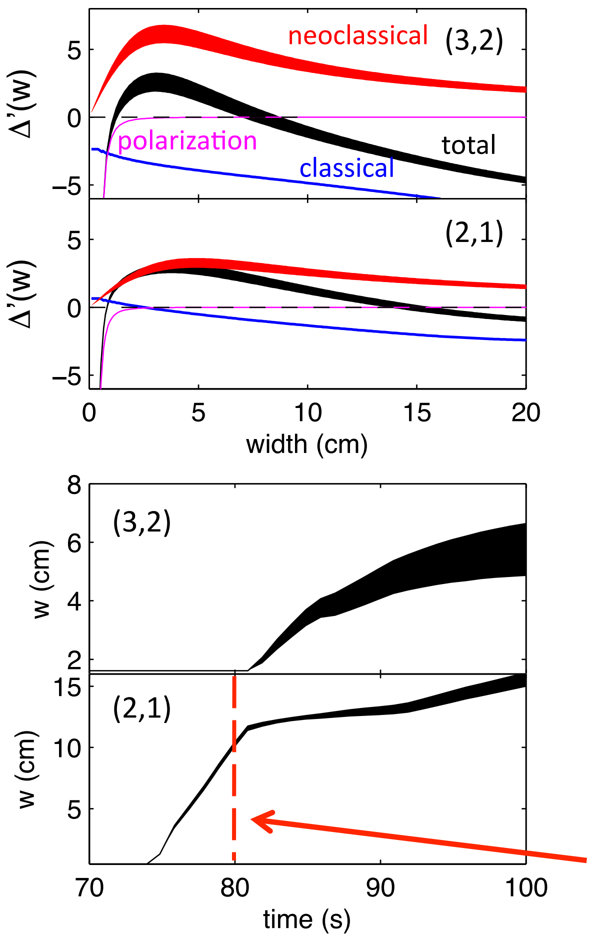
$$\eta_{NTM} = Max\left[\frac{4w_{dep}}{3\pi^{3/2}}\left(\frac{w^{-1}f(w,w_{marg}) - w_{sat}^{-1}f(w_{sat},w_{marg})}{F_{CD} + \frac{w_{dep}^2}{w_{marg}^2}\overline{\eta}_H F_H + 0.25D_{\mathrm{mod}}erfc\left(\frac{w}{w_{dep}}\right)}\right); \quad 0 \le w \le w_{sat}\right]$$

General form: includes heating term (it changes the trend for narrow deposition width) => want to be as general as possible

ECCD term calculated under the hypothesis of:

- EC deposition perfectly aligned with (m,n)

(2,1)-NTM grows faster than mirror switching time



w_{SAT} => uncertainty depending on assumptions and pressure profiles

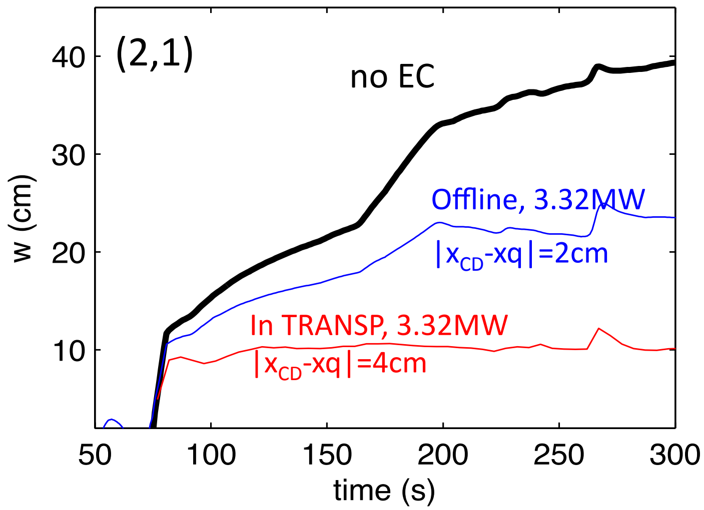
Calculation of D'cl makes a difference
Allows for effects on modified current profile

(2,1) w_{seed} ~1 cm
⇒ difficult to detect (ECE threshold > 2 cm)
⇒ Difficult to track (equilibrium > 2 cm)

(2,1)-NTM grows to 10cm and LOCKS in~5s

(3,2) w_{ECCD} >> $w_{seed,}$ w_{ECCD} >~ w_{max} as in present-day experiments
(2,1) w_{ECCD} >> $w_{seed,}$ w_{ECCD} <~ w_{max} not as in present-day experiments

Self-consistent calculation of NTM evolution and plasma profiles set lower limits on EC power needs



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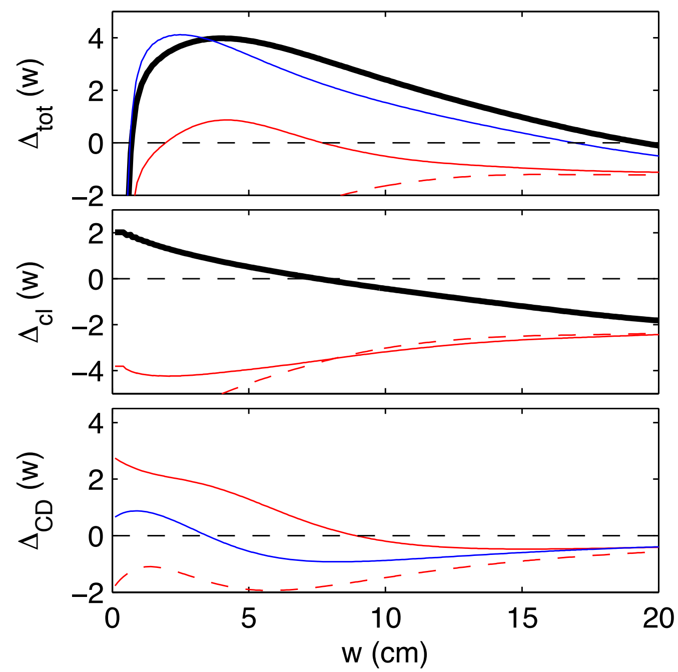
$$F(\tilde{w}) = 0.25\frac{1+0.96\tilde{w}}{1+\tilde{w}(1.5+\tilde{w}(0.43+0.64\tilde{w}))}$$

$$G(w) = 1-2\frac{x_{dep}}{g(\tilde{w})}\; e^{-\left(\frac{x_{dep}}{g(\tilde{w})}\right)^2}\int_0^{x_{dep}/g(\tilde{w})} dt\; e^{t^2}$$

$$g(\tilde{w}) = \frac{0.38\tilde{w}^2+0.26\tilde{w}+0.5}{\tilde{w}+1}$$



PPPL