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EX/4-1Ra

Active Control of Neoclassical Tearing Modes toward Stationary High-Beta Plasmas in JT-60U

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EX/4-1Rb

Control of MHD instabilities by ECCD: ASDEX Upgrade results and implications for ITER

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Introduction

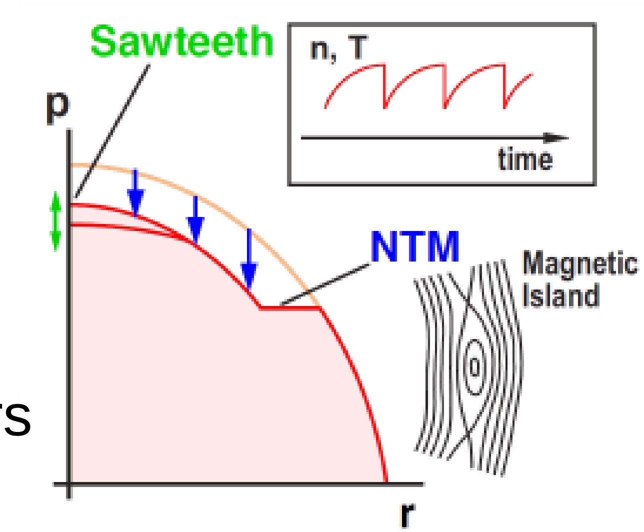
• In tokamaks, many kinds MHD instabilities are observed, and they can affect the plasma performance.

=> Control of MHD instabilities is a key issue to obtain a high-performance plasma

MHD instabilities in the core regime

• **Neoclassical Tearing Modes (NTMs)**
  - appear in a high beta plasma
  - limit the achievable beta at $\beta_N < \beta_N^{ideal}$

• **Sawtooth Oscillations**
  - have smaller effects on global parameters
  - sometimes trigger an NTM



⇨ **Active control is important**

Control tool: **Electron Cyclotron Current Drive (ECCD)**
  - highly localized current drive
  - flexible ECCD location with steerable mirror

Contents

This talk:
Control of NTM and sawteeth with ECCD in ASDEX-U & JT-60U

- Sawtooth tailoring with ECCD

Sawteeth

- Stabilization of an m/n=**3/2** NTM
  by **modulated ECCD** and
  by **narrow deposition**

3/2 NTM

- Control of growth of a **3/2** NTM
  by **central co-ECCD**

2/1 NTM

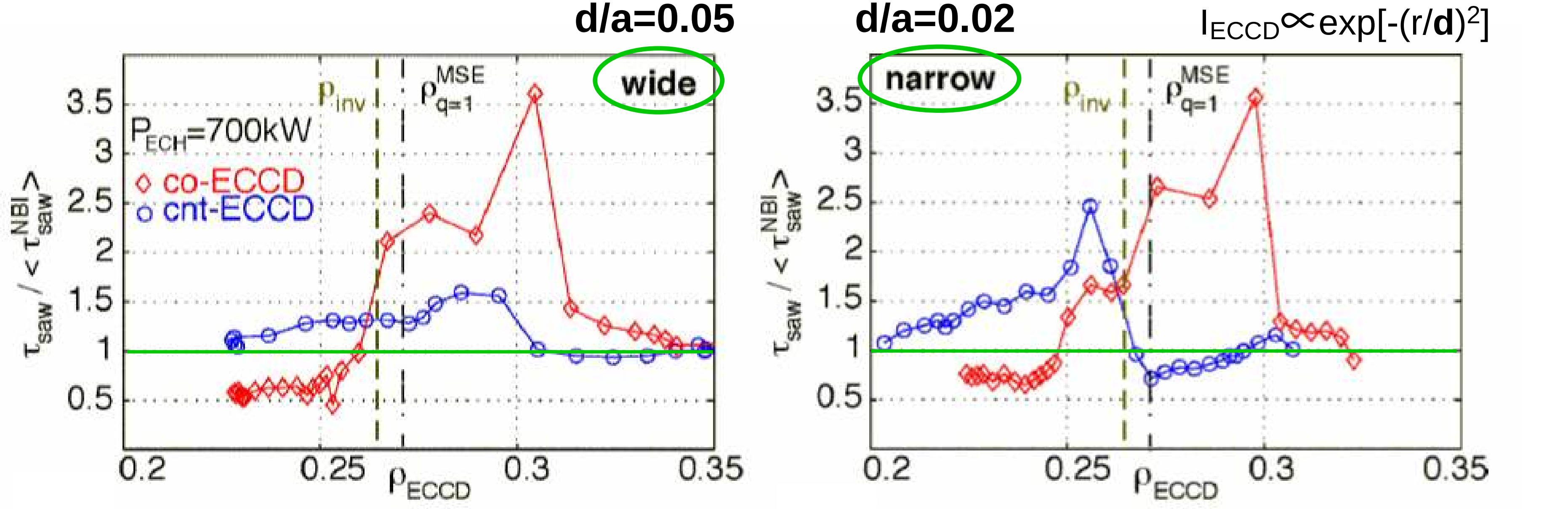
- Stabilization of a **2/1** NTM
- TOPICS code simulation of **2/1** NTM stabilization

- Summary

Sawtooth tailoring with narrow ECCD deposition

d: ECCD width

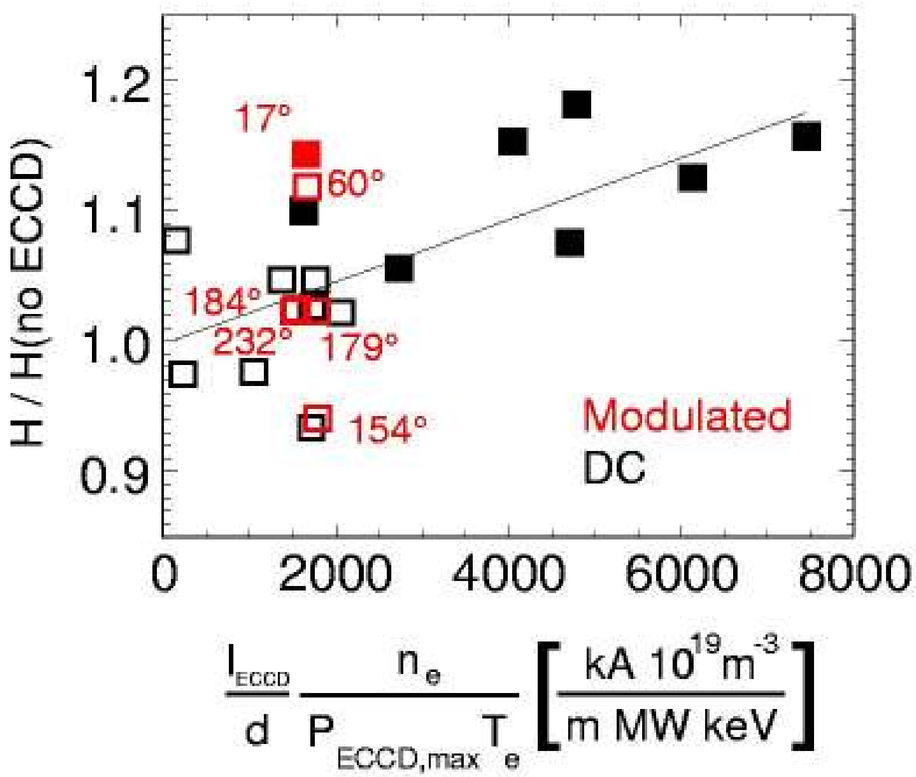
$I_{ECCD} \propto \exp[-(r/\mathbf{d})^2]$



Change of sawtooth period by ECCD under otherwise constant conditions

- **wide deposition**: ctr-ECCD ineffective (heating effect has opposite sign)
- **narrow deposition**: I_{ECCD}/d^2 enhanced w.r.t. heating; ctr-ECCD effective
- note: due to B_t ramp, complete stabilisation could not be studied

NTM stabilisation with narrow deposition



Open symbols: partial stabilisation

Full symbols: complete stabilisation

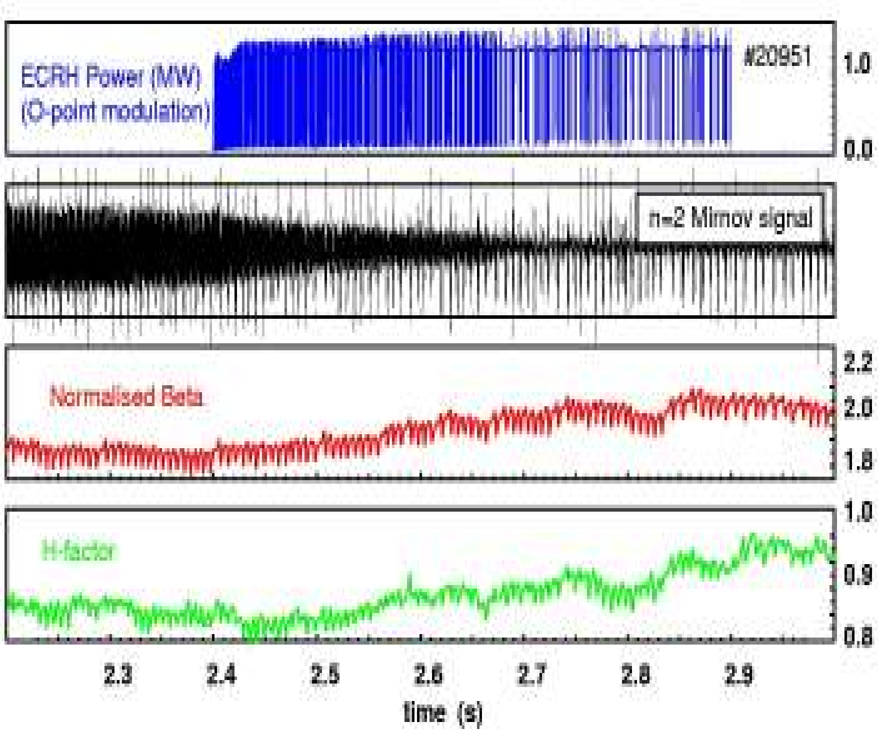
~ ECCD current density peaking

The NTM stabilisation efficiency increases with narrow deposition

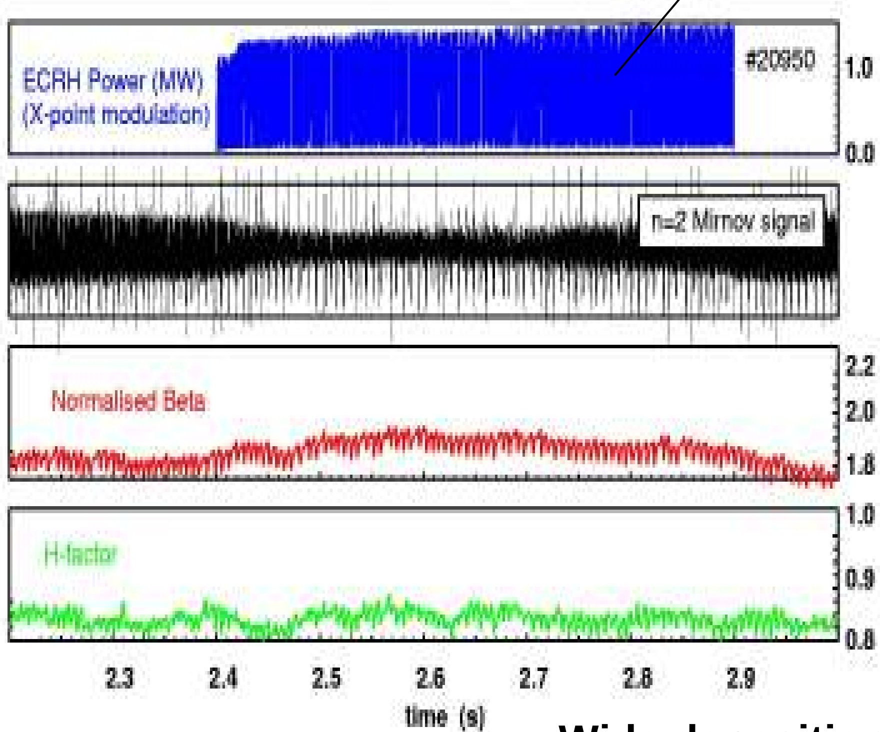
- with wide deposition (ITER case), DC ECCD results in partial stabilisation
- modulation in phase with the island leads to full stabilisation
- note that this is done with same peak P_{ECCD}, but half average P_{ECCD}

NTM stabilisation with modulated ECCD

O-point modulation

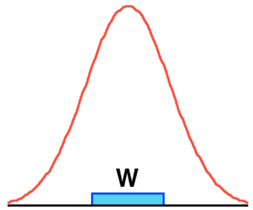


X-point modulation

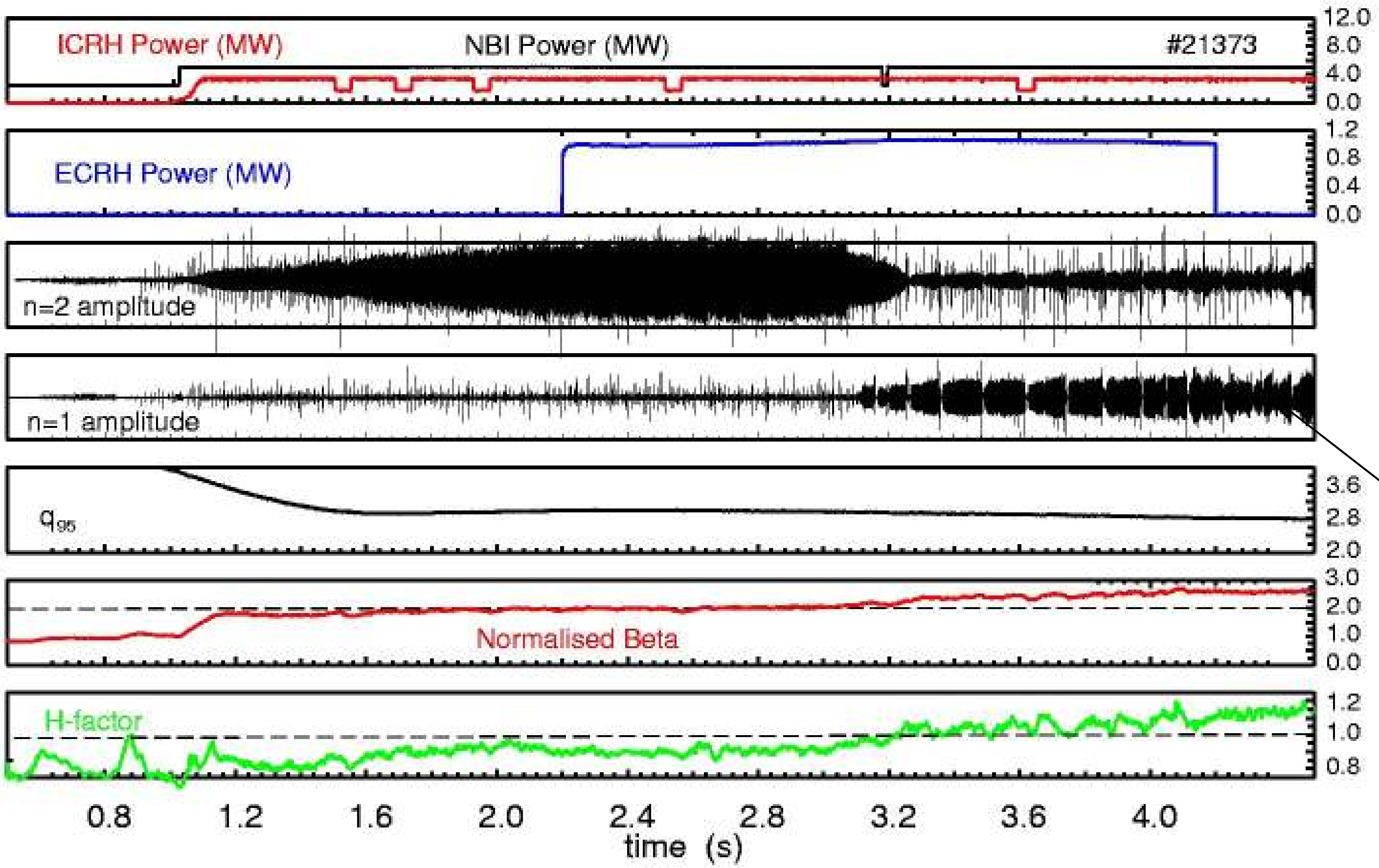


- Without modulation complete stabilisation was not achieved
- Scan of the phase of ECCD w.r.t. island O-point shows expected behaviour
  - full stabilisation with O-point modulation
  - only partial stabilisation with X-point modulation

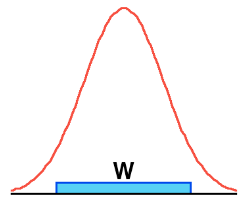
Wide deposition (W/(2d)=0.6)



NTM stabilisation under ITER relevant conditions



Narrow Deposition
W/(2d)=1.2
(without modulation)



Fishbones

β_N~2.6

H_H=1.15

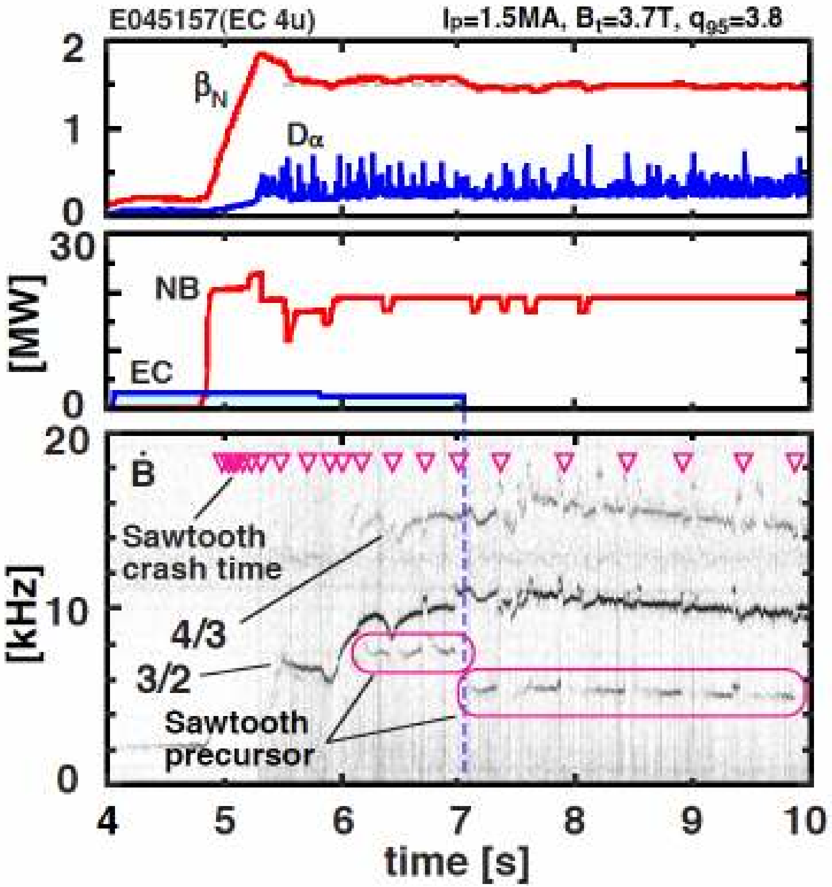
- (3,2) NTM stabilisation in improved H-mode at low q_{95} = 2.9
- After stabilisation, good improved H-mode conditions are recovered

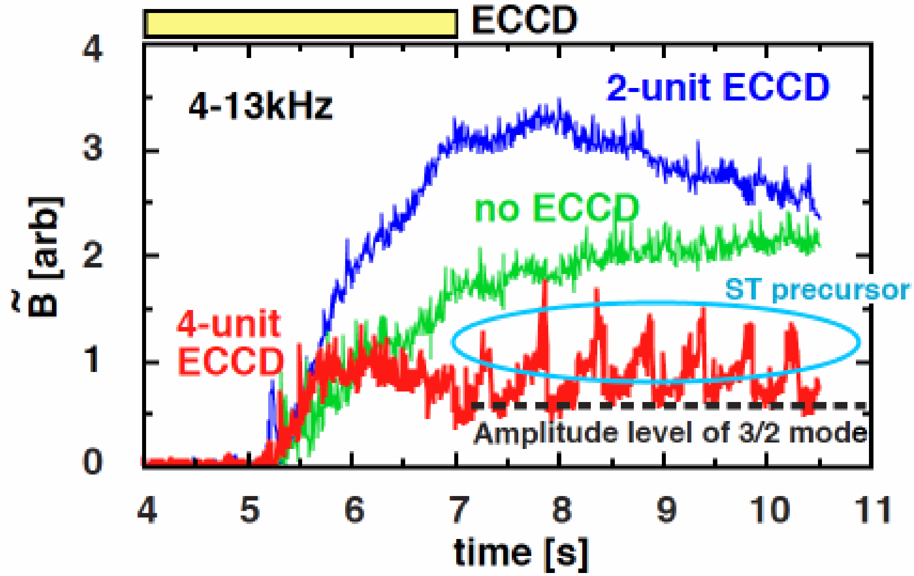
Evolution of a 3/2 NTM has been suppressed by central co-ECCD with I_{ECCD}/I_p~0.1

- Central co-ECCD can modify j(r) locally and also enhance sawteeth

=> These changes will also affect the onset & evolution of 3/2 NTM

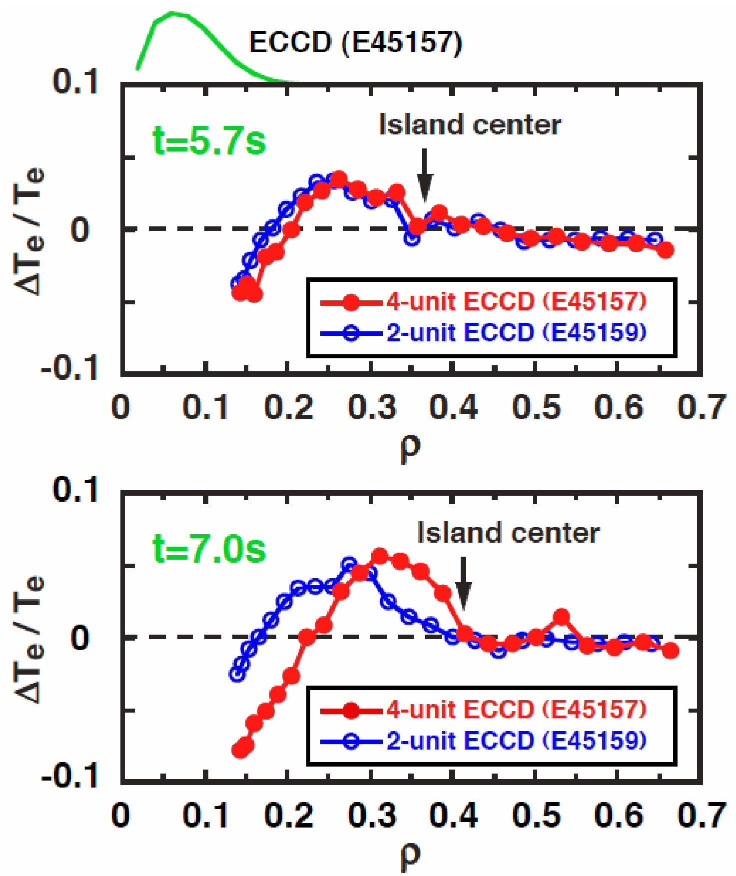
=> New scheme for active control of 3/2 NTM

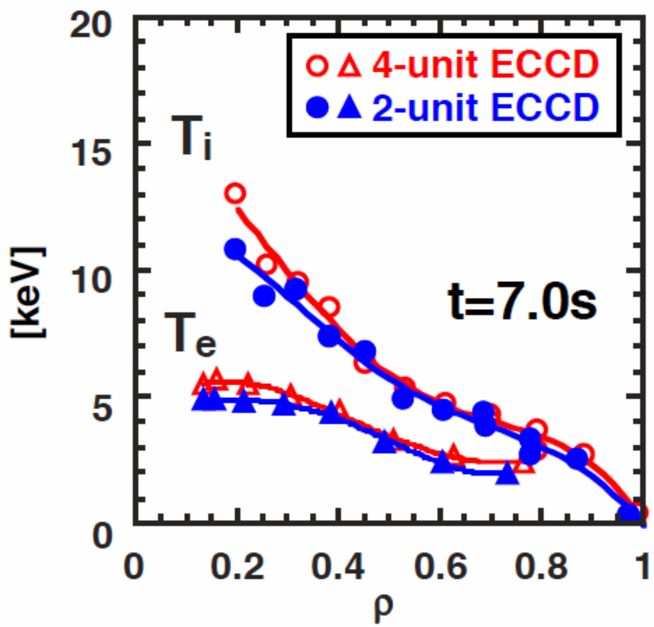




- Central co-ECCD before NB
- I_{ECCD}=130kA(calculation)~0.1I_p
- Low amplitude for 4-unit ECCD even after turn-off of ECCD
- β_N is high for 4-unit ECCD

Change in current profile and/or sawtooth behavior is the candidate for NTM suppression.





For 4-unit ECCD, sawtooth amplitude & ρ_{inv} increase in time

Similar temperature profile

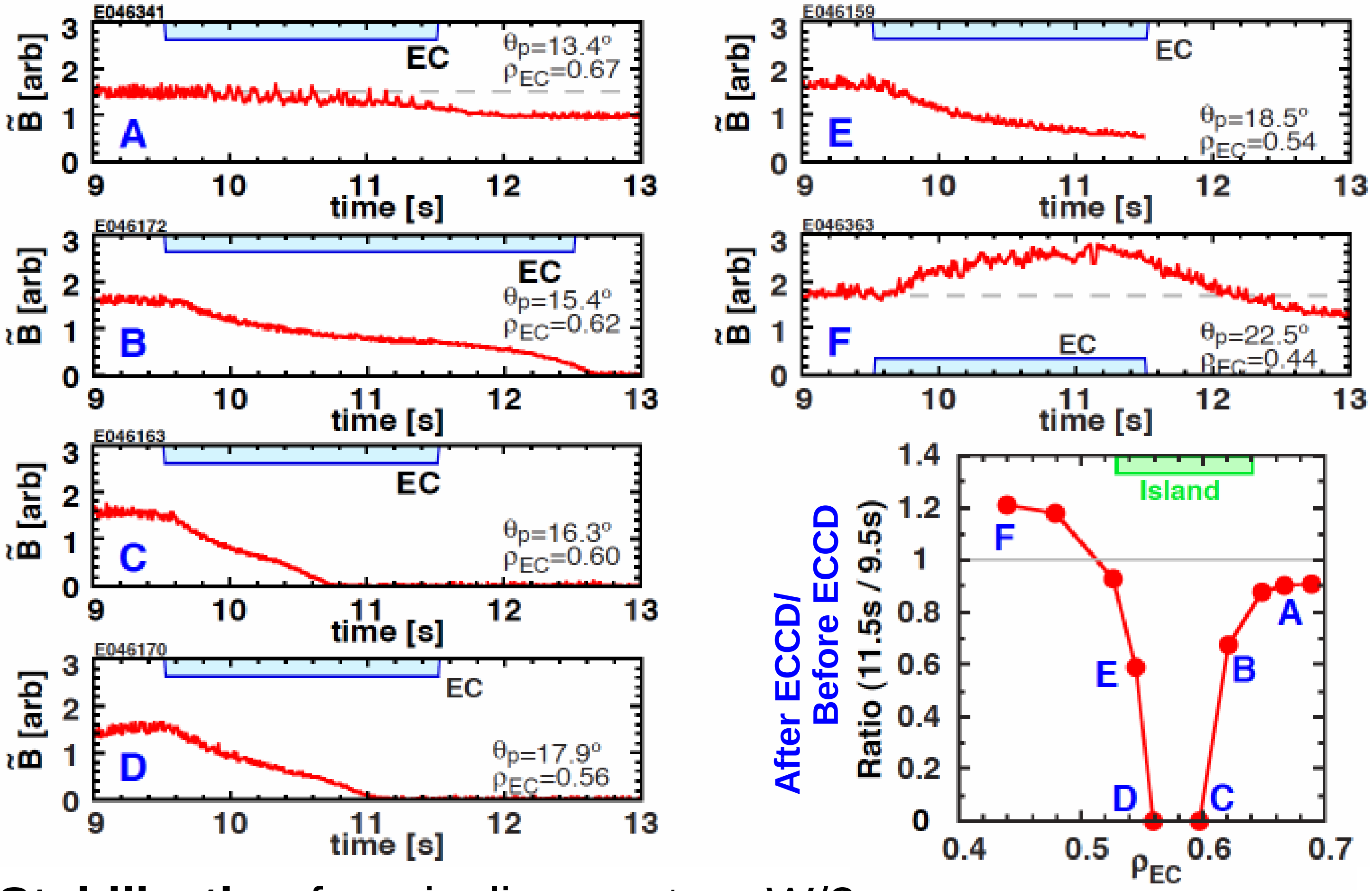
Electron density is also almost the same

⇒Change in pressure is not likely to be the candidate

Sawteeth and a small-amplitude 3/2 NTM can coexist without large confinement degradation by central co-ECCD

An m/n=2/1 NTM has been completely stabilized by ECCD at q=2 (ρ~0.6)

m/n=2/1 NTM: Larger confinement degradation or disruption
=> Active stabilization is essential

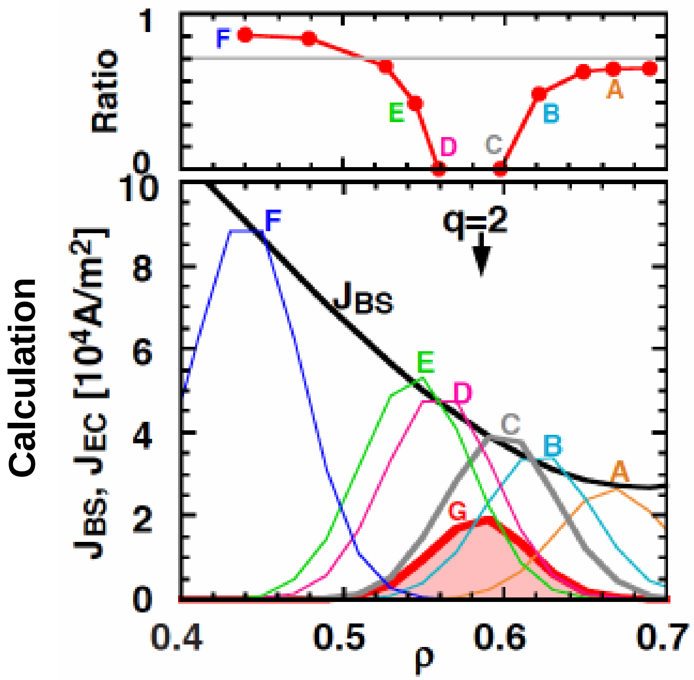


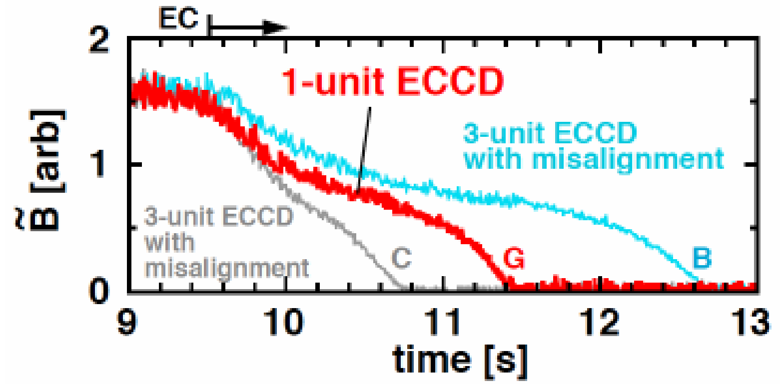
- **Stabilization** for misalignment <~W/2
- **Destabilization** for misalignment ~W

"Precise injection is important"

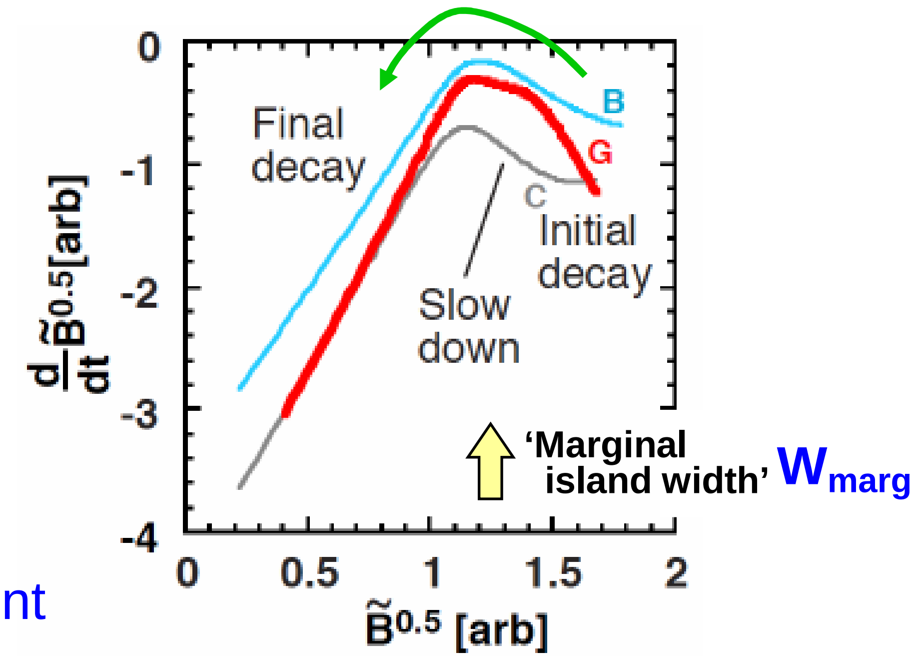
Further optimization of ECCD location has enabled complete stabilization with J_{EC}/J_{BS}~0.5

- J_{EC}/J_{BS} : measure of 'efficiency' in NTM stabilization
- Complete stabilization with small J_{EC}/J_{BS} is desirable



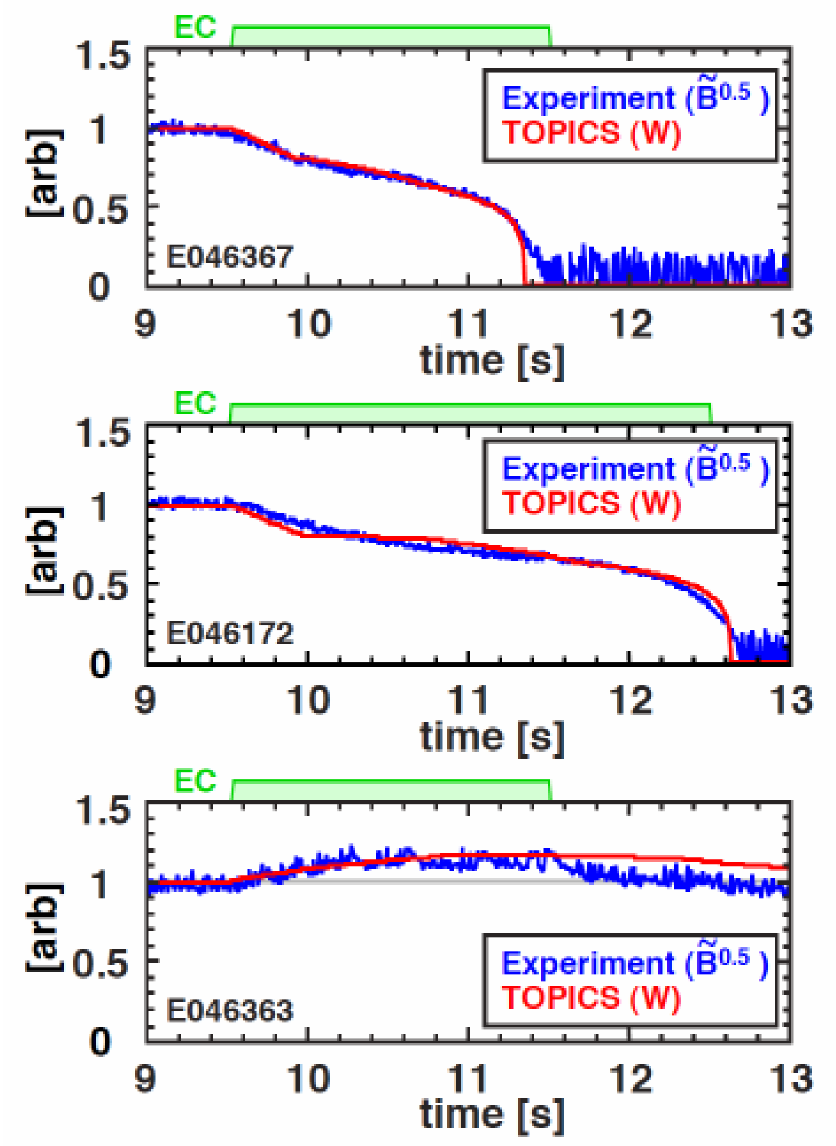


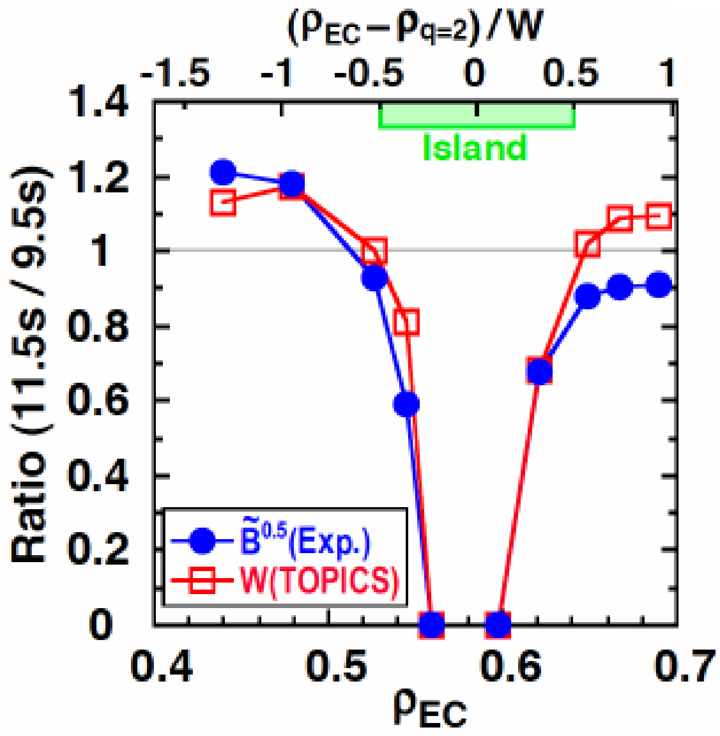
- 2/1 NTM was completely stabilized with 1-unit ECCD
  (0.6MW, ~5kA)



- Temporal evolution: 3 phases
- Similar W_{marg} even for different ECCD location & EC-driven current

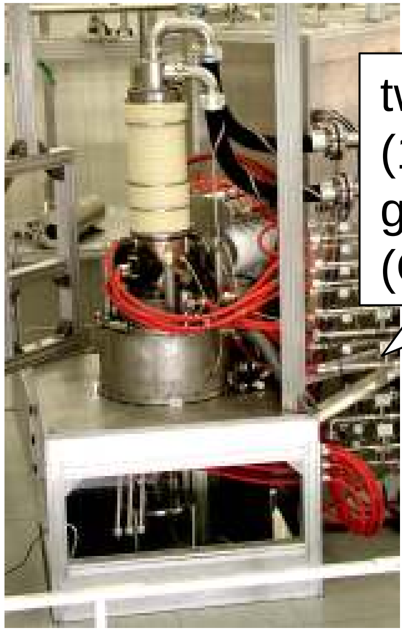
TOPICS simulation with modified Rutherford equation well reproduces experimental results.

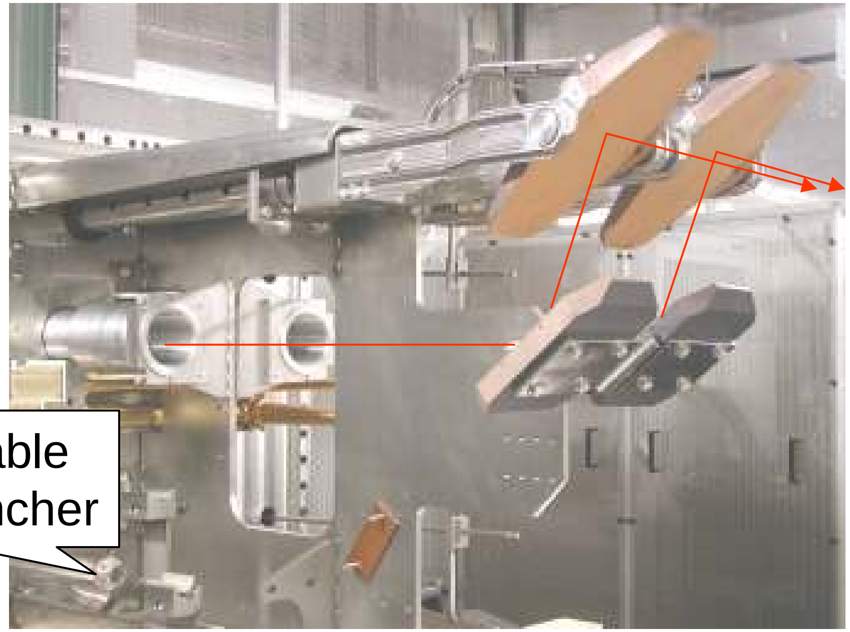




- Simulation with the same set of coefficients in the modified Rutherford equation
- Stabilization and destabilization are well reproduced

ASDEX Upgrade enhances its capabilities in this area





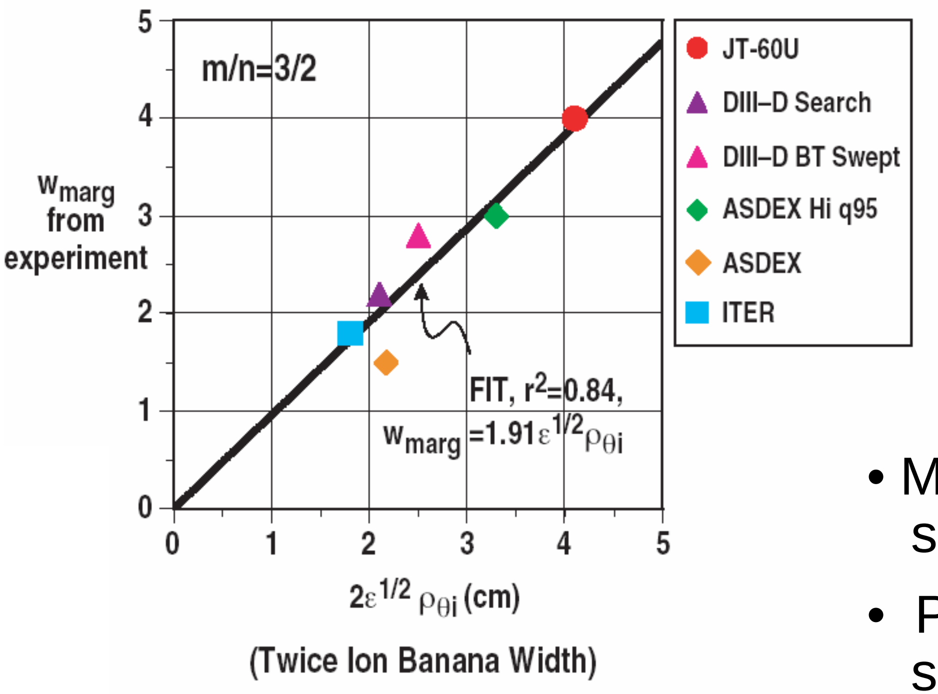
- Extension of ECRH system to multi-frequency, 10 s, 4 MW under way
- Feedback system for deposition control is being set up:

sensors:	ECE correlation
	ECE with same sightline as ECRH mirror
	on-line q-profile reconstruction
actuators:	radial shift of plasma position
	fast (50 ms) steering of poloidal launch angle

Another presentation of NTM stabilization

Results from cross-machine comparison of NTM stabilization and extrapolation to ITER

R.J. La Haye, R.J. Buttery, N. Hayashi, A. Isayama, M. Maraschek, R. Prater, L. Urso, H. Zohm, **EX/P8-12 (Poster on Saturday morning)**



2/1 NTM stabilization in ITER

ΔR (cm)	$\Delta R/d$	J_{EC}/J_{BS}
0	0.00	0.89
1	0.13	1.04
2	0.27	1.27
3	0.40	1.63

- Multi-machine database of NTM stabilization has been made
- Prediction analysis on 2/1 NTM stabilization in ITER shows that
  J_{EC}/J_{BS}=0.9 for perfect alignment
  J_{EC}/J_{BS} >1 for misaligned ECCD

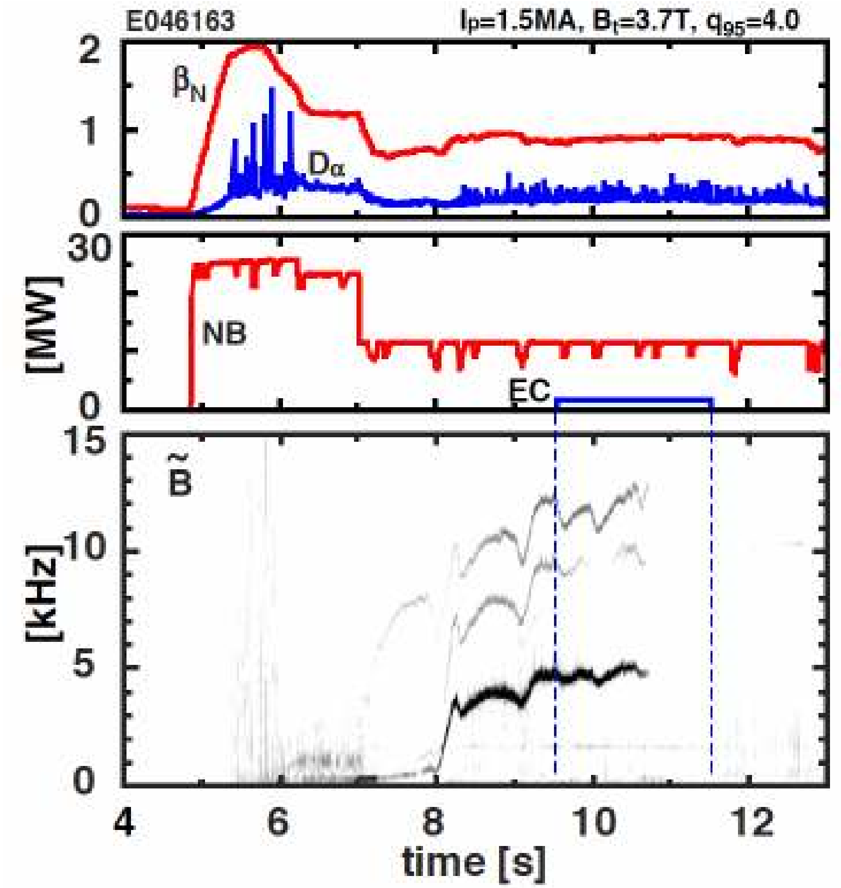
Summary

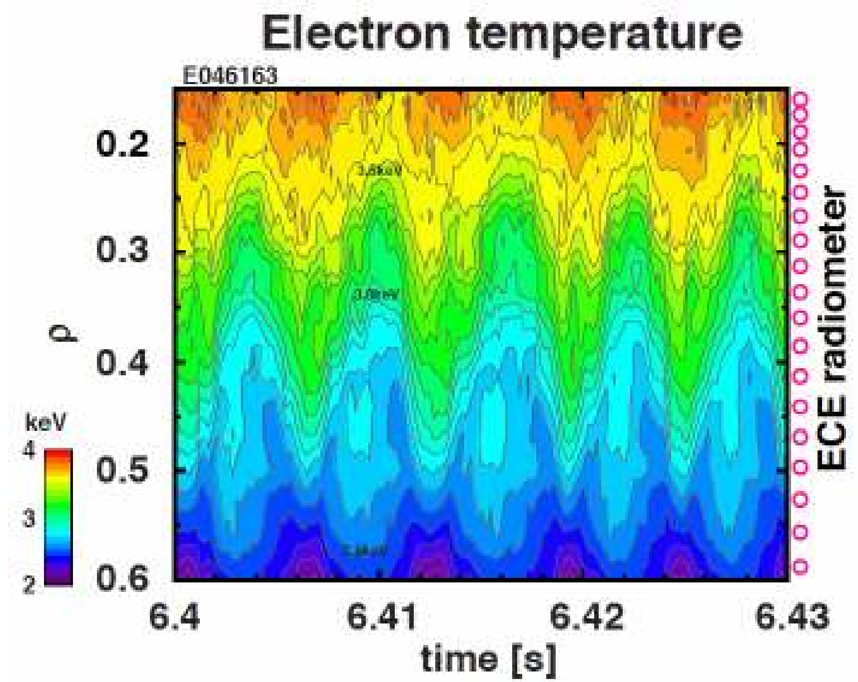
Active control of NTM and sawteeth with ECCD has been extensively performed in ASDEX-U & JT-60U

- Narrow ECCD deposition is very effective in
  - sawtooth tailoring
  - 3/2 NTM stabilization in an Improved H-mode
- Effectiveness of modulated ECCD in 3/2 NTM stabilization was demonstrated
- Appropriate central co-ECCD can suppress the growth of a 3/2 NTM
- A 2/1 NTM was completely stabilized with J_{EC}/J_{BS}~0.5
- TOPICS simulation well reproduces island evolution in experiments

More detailed results of this talk will be presented at the poster session on Saturday morning!

Typical discharge of 2/1 NTM stabilization





- Mode onset at t~5.8s, β_N~2 (β_p~1.2)
- Step down of NB power with unidirectional NB at t=7s
  => Mode rotation from t~8s
- Unmodulated EC wave injection from t=9.5s.
  => Complete stabilization at t=10.7s

Evolution of NTM is described by the modified Rutherford equation

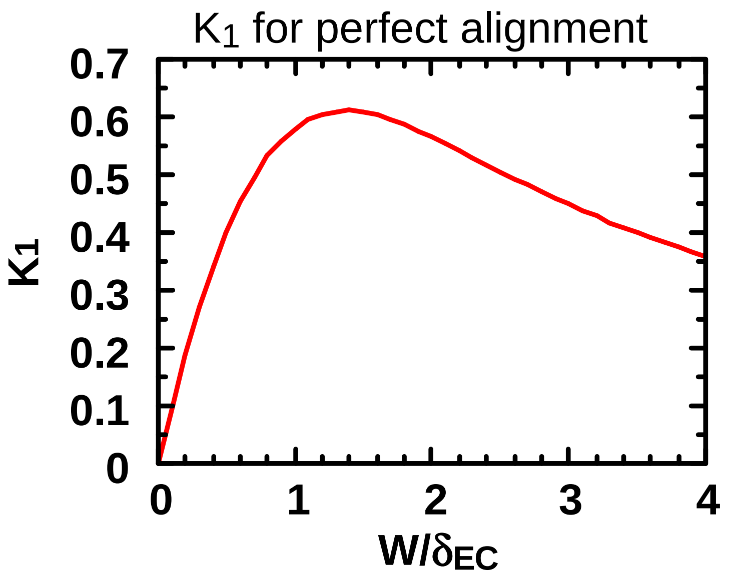
W: Island width

$$\frac{\tau_R}{r_s}\frac{dW}{dt} = r_s\Delta'_0 + r_s\delta\Delta' + a\frac{J_{BS}}{J_{//}}\frac{L_q}{W}\left(1-\frac{W_{pol}^2}{3W^2} - K_1\frac{J_{EC}}{J_{BS}}\right)$$

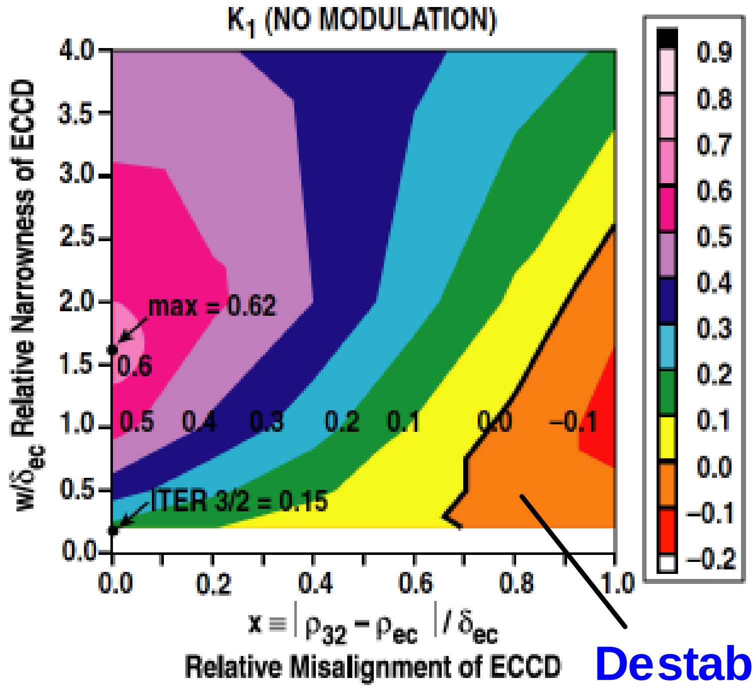
ECCD effect on Δ'

Classical stability

ECCD term



F.W. Perkins et al, Proc. 24th EPS (1997), vol. 21A, p.1017



Destabilization

R.J. La Haye et al., Nucl. Fusion **46** (2006) 451