ASDEX Upgrade

IAEA-CN-116 / EX / 7-2

Max-Planck-Institut
für Plasmaphysik

IPP

Active Control of MHD Instabilities by ECCD in ASDEX Upgrade

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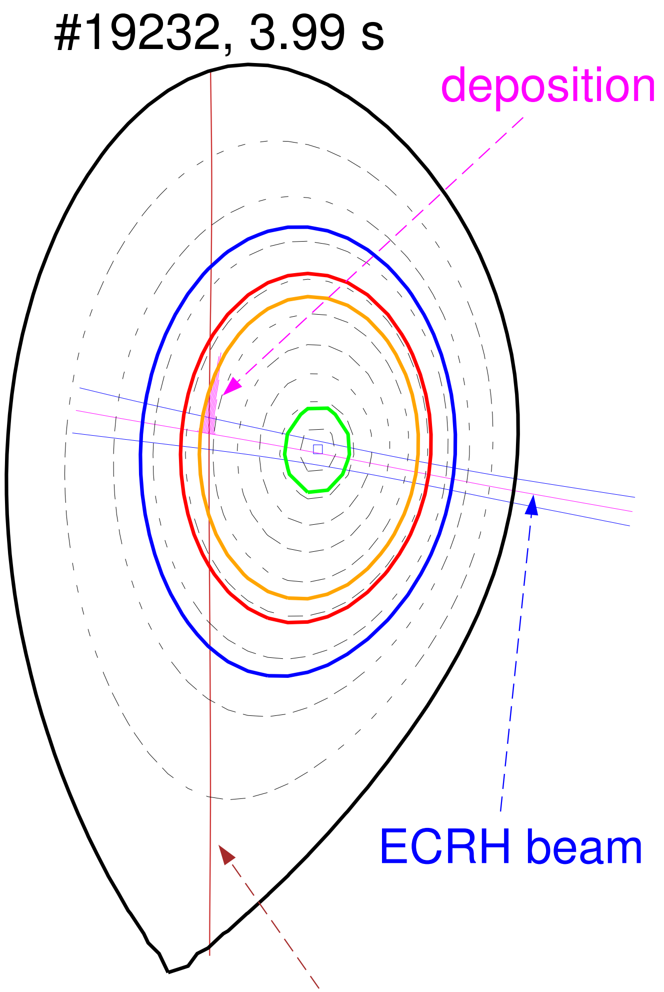
- Introduction and motivation
- Sawtooth tailoring with co / counter ECCD
- NTM stabilization with co-ECCD
- FIR-NTMs and their triggering with ECCD
- Summary and future plans

Resonant surfaces and MHD modified with ECRH / ECCD



- q=1, (flat or reversed in the centre in adv. scen.): sawteeth, fast particle driven fishbones, (1/1)-modes
  ⇒ sawtooth tailoring, avoidance of NTM trigger

- q=4/3:
  (4/3) NTM, ideal (4/3) modes during FIR-NTM
  ⇒ artificially trigger / avoid (4/3) ⇒ FIR-NTM transition

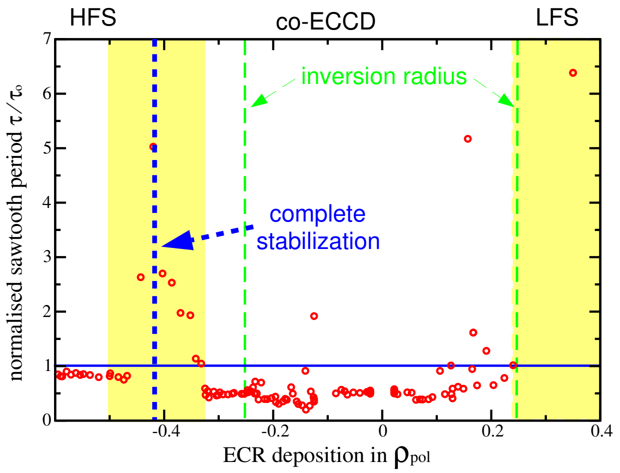
- q=3/2:
  (3/2) NTM
  ⇒ stabilisation and suppression of (3/2)-NTM

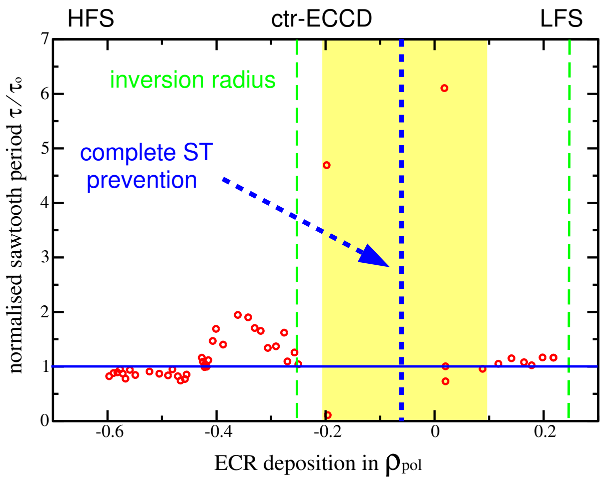
- q=2:
  (2/1) NTM, (2/1) classical current driven tearing modes
  ⇒ stabilisation and suppression of (2/1)-NTM

- control of current drive and depostion by B_t and toroidal and poloidal launching angle

Sawtooth tailoring with ECRH / ECCD

collaboration with T.P.Goodman, O.Sauter (CRPP)





- co-ECCD:
  - stabilisation / full suppression outside inversion radius
  - destabilisation for on-axis
    → explainable with critical shear criterium:
    $dq/dr\ r/q > (dq/dr\ r/q)_{crit}$
- pure heating (= 50% co and counter-ECCD):
  - similar behaviour as for co-ECCD, but less pronounced
- counter-ECCD:
  - stabilisation for on-axis
  - effect on (1/1) mode plays an additional role

$P_{NBI} = 5MW$, $P_{ECCD} \leq 1.4MW$

A.Mück, EPS2003, St.Petersburg
A.Mück, PPCF, to be subm.

High power NBI experiments: NTM avoidance at high β_N = 2.8

collaboration with T.P.Goodman, O.Sauter (CRPP)

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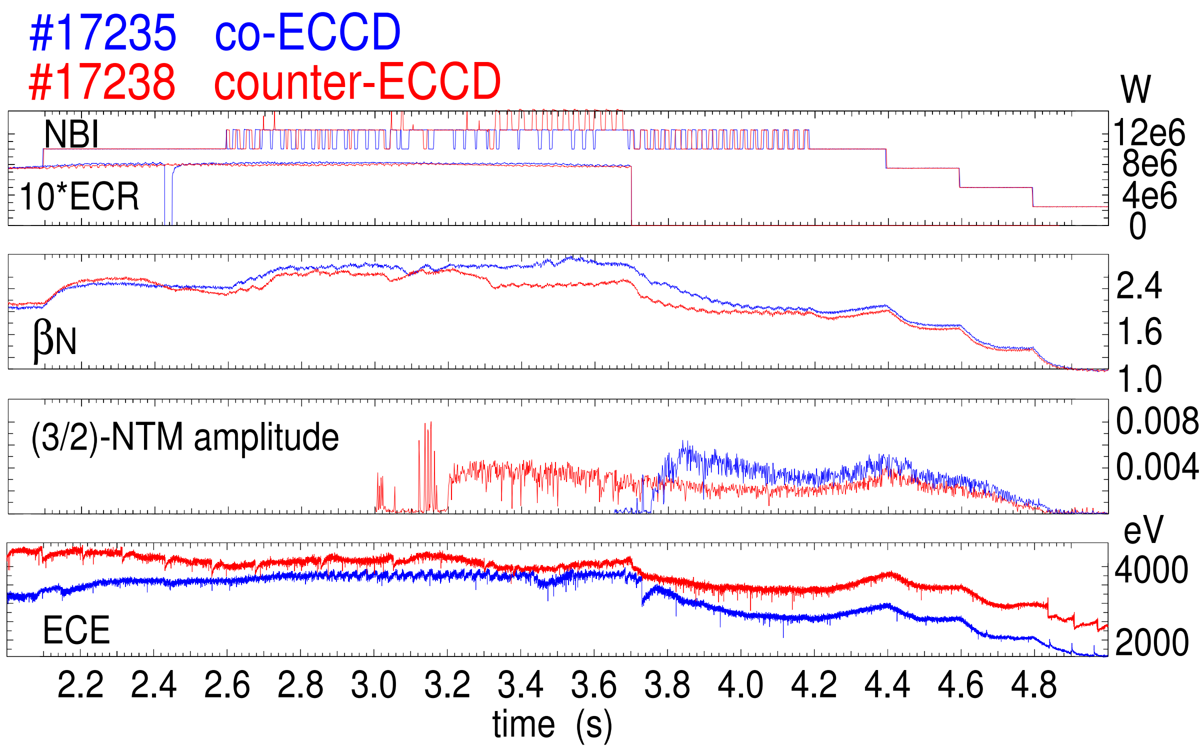

higher P_{NBI} = 10MW to reach NTM-threshold

$\beta_N \approx 2.8$ fixed by β_p feedback

- sawtooth tailoring less clear with higher $P_{NBI} \geq$ 10MW
- off-axis co-ECCD → no NTM during ECCD
  no sawteeth, first large sawtooth triggers
- on-axis counter-ECCD → fishbone triggered NTM during ECCD
  (1/1) mode further outside, no big seed-island

⇒ NTM avoidance achieved

A.Mück, EPS2003, St.Petersburg

(3/2)-NTM stabilisation with co-ECCD at β_N = 2.6

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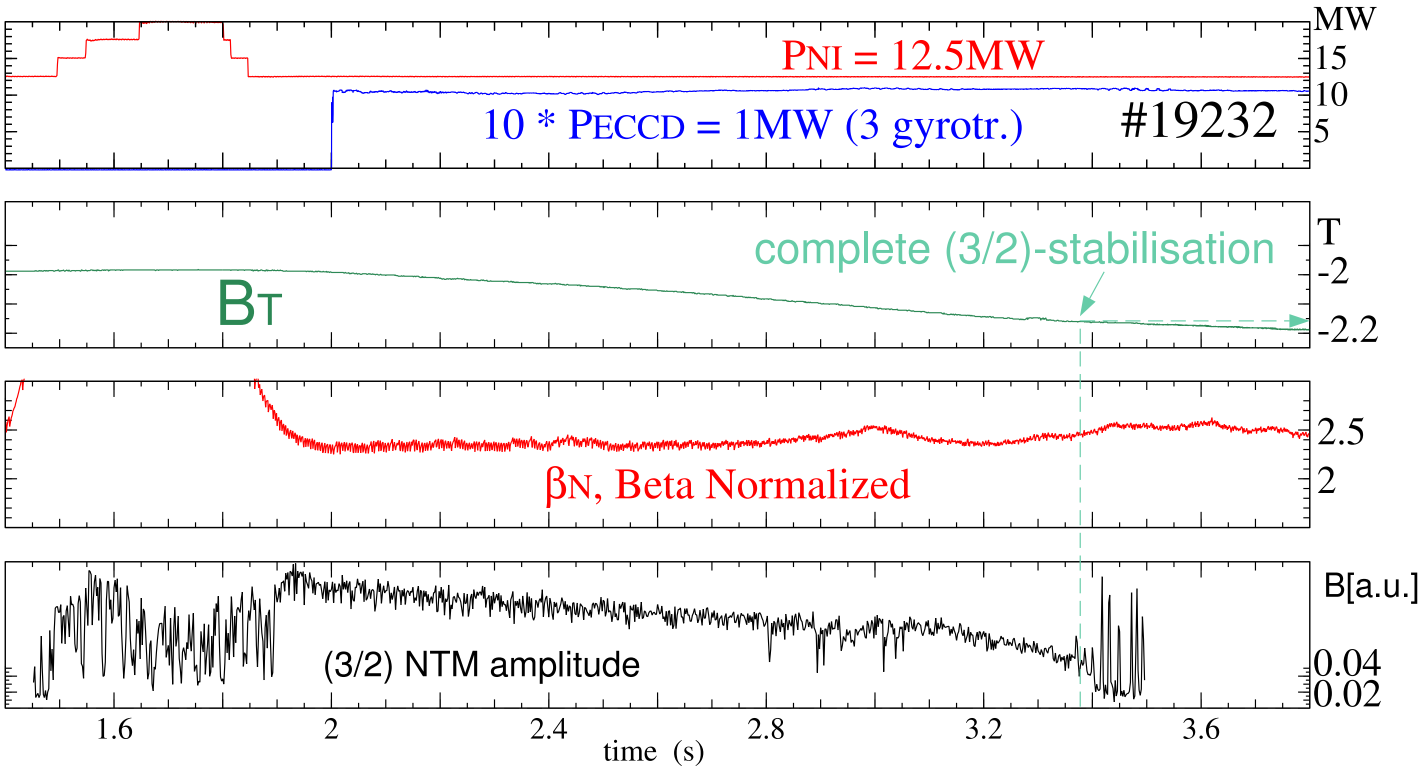
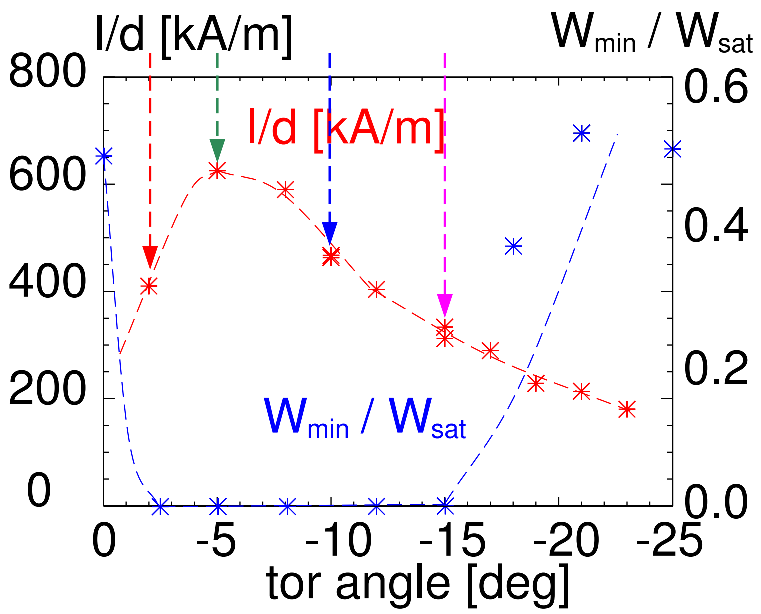
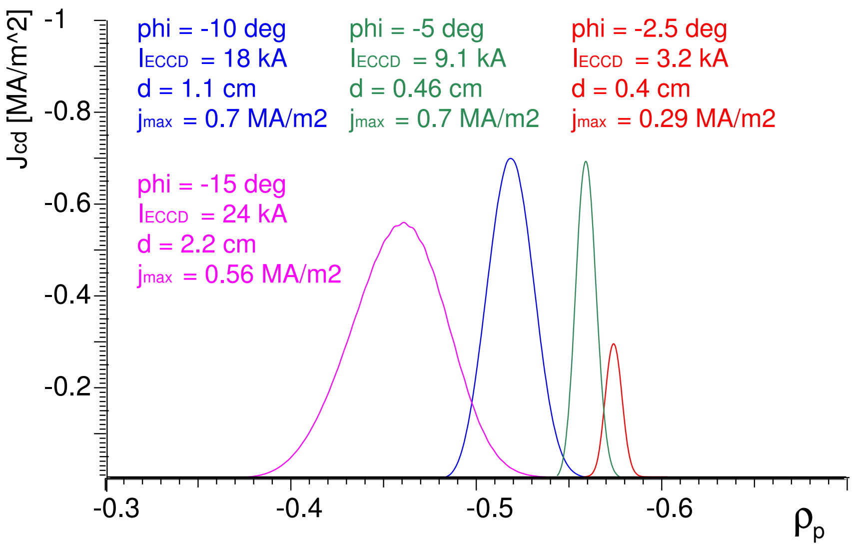


- complete stabilisation at β_N = 2.6 with P_{ECCD} = 1MW and P_{NBI} = 12.5MW
  ⇒ β_N / P_{ECCD} = 2.6/MW

- β_N increase with more P_{NBI} not considered ⇒ even higher β_N achievable (re-excitation)

Influence of the deposition width on the (3/2)-NTM stabilisation





(Bt = const, ρ_{dep} not corrected)

- narrow depostion: I / d = current density maximal for -5° (TORBEAM)
  - ⇒ full stabilisation with reduced P_{ECCD} / P_{NBI} possible
  - ⇒ higher β_N achievable at stabilisation (β_N / P_{ECCD}, β_N / (P_{ECCD}/P_{NBI}))

- W > d reduces the stabilisation efficiency
  - ⇒ ECCD modulated by mode (only O-point) might be required for ITER (modulation experiments will be performed in 2005)

(2/1)-NTM stabilisation with co-ECCD at β_N = 2.3

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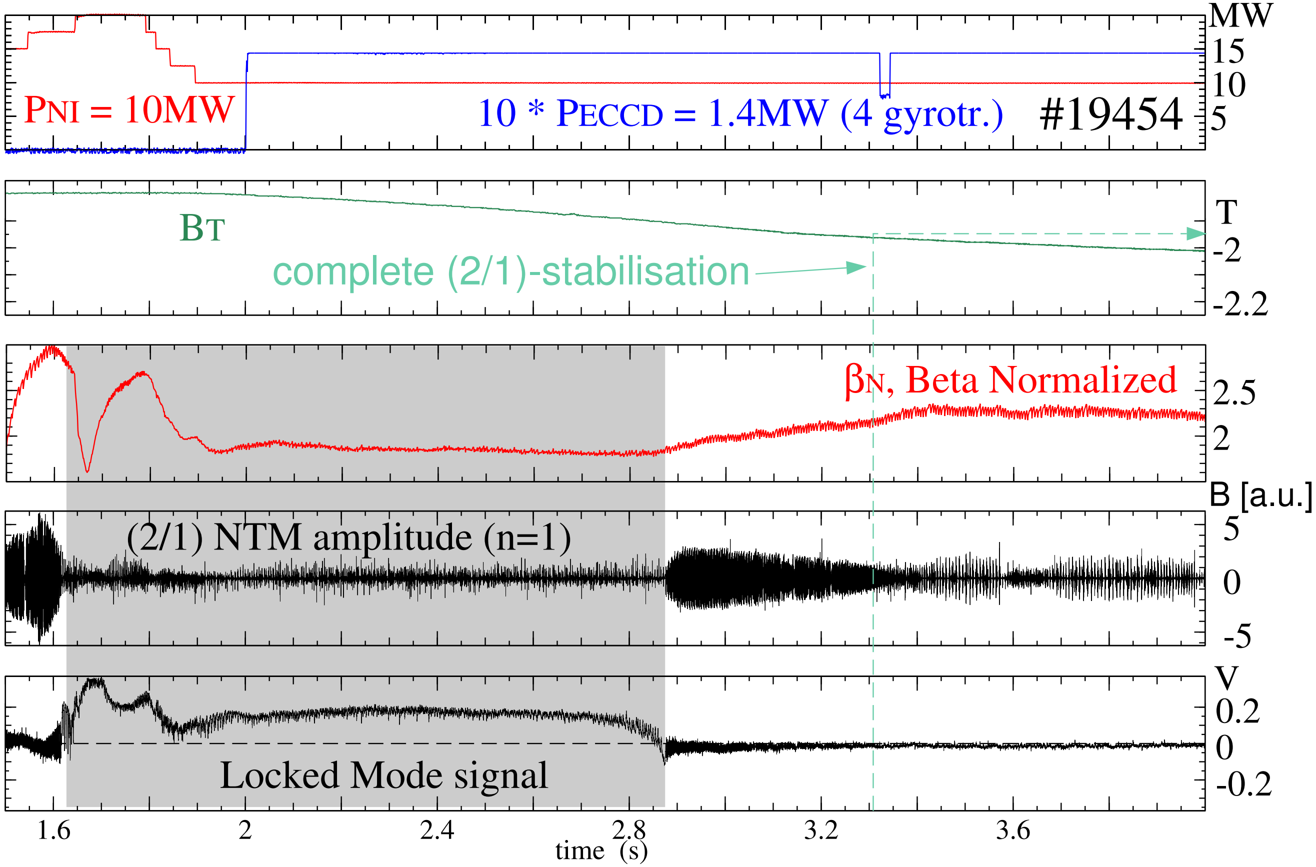

- stabilisation at β_N = 2.3 [1.9] with P_{ECCD} = 1.4MW [1.9MW], P_{NBI} = 10MW [6.25MW]
  - ⇒ β_N / P_{ECCD} = 1.64/MW [1.0/MW]
    - ⇒ stabilisation of the (2/1) NTM requires more power ($\beta_{p,marg}$, less current drive)
    - ⇒ current density I/d is the figure of merrit for both NTMs
- faster unlocking of (2/1)-NTM ⇒ injection in the O-point of the locked mode works

Nonlinear modelling allows separation of different terms

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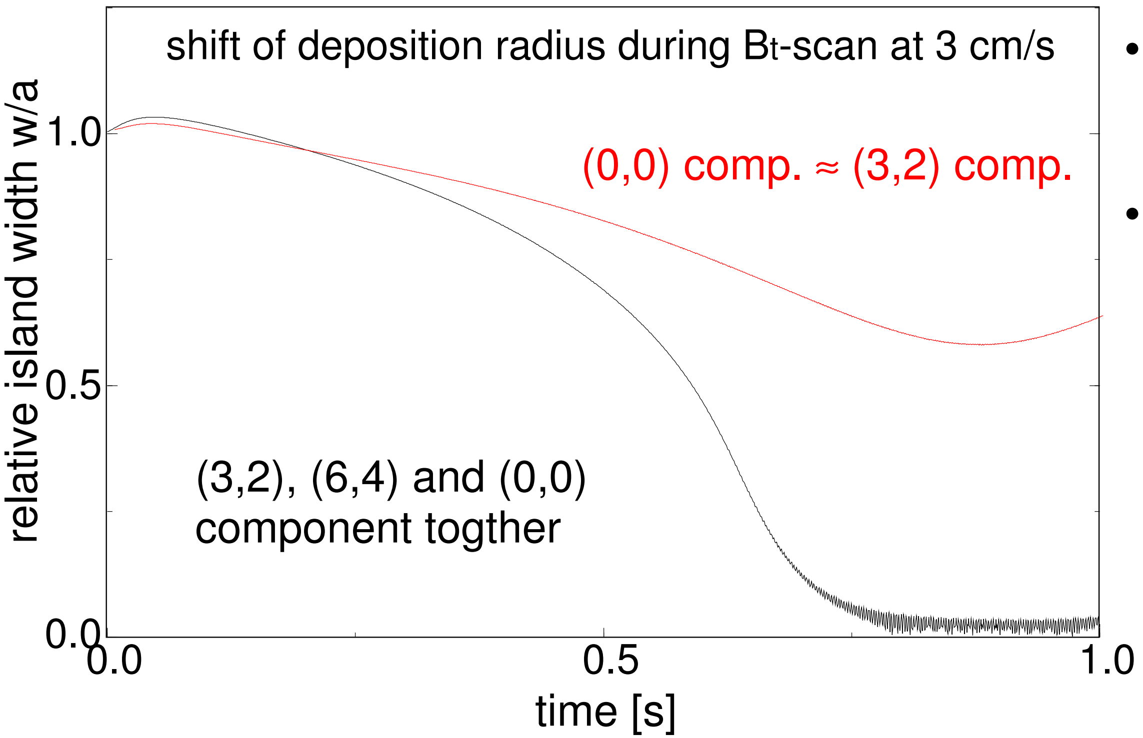

- time dependent Fokker-Planck code to calculate $j_{ECCD}(r,t)$
  [G. Giruzzi et al.,NF,39(1),107(1999)]
- nonlinear 2D-MHD (circular cylinder)
  [Q. Yu and S. Günter, POP,7,312 (2000)]

- typically 1-2% of plasma current driven at resonant surface (Fokker-Planck-Code)

- Modelling of DC co-ECCD with scan of deposition and Fourier analysis :

  → helical current ((3,2)-comp.) and Δ'-effect ((0,0)-comp.) are of similar importance

  → complete stabilisation only due to synergy of both effects

FIR-NTMs - a general NTM behaviour for $\beta_N > 2.3$

collaboration with D.F.Howell (UKAEA)

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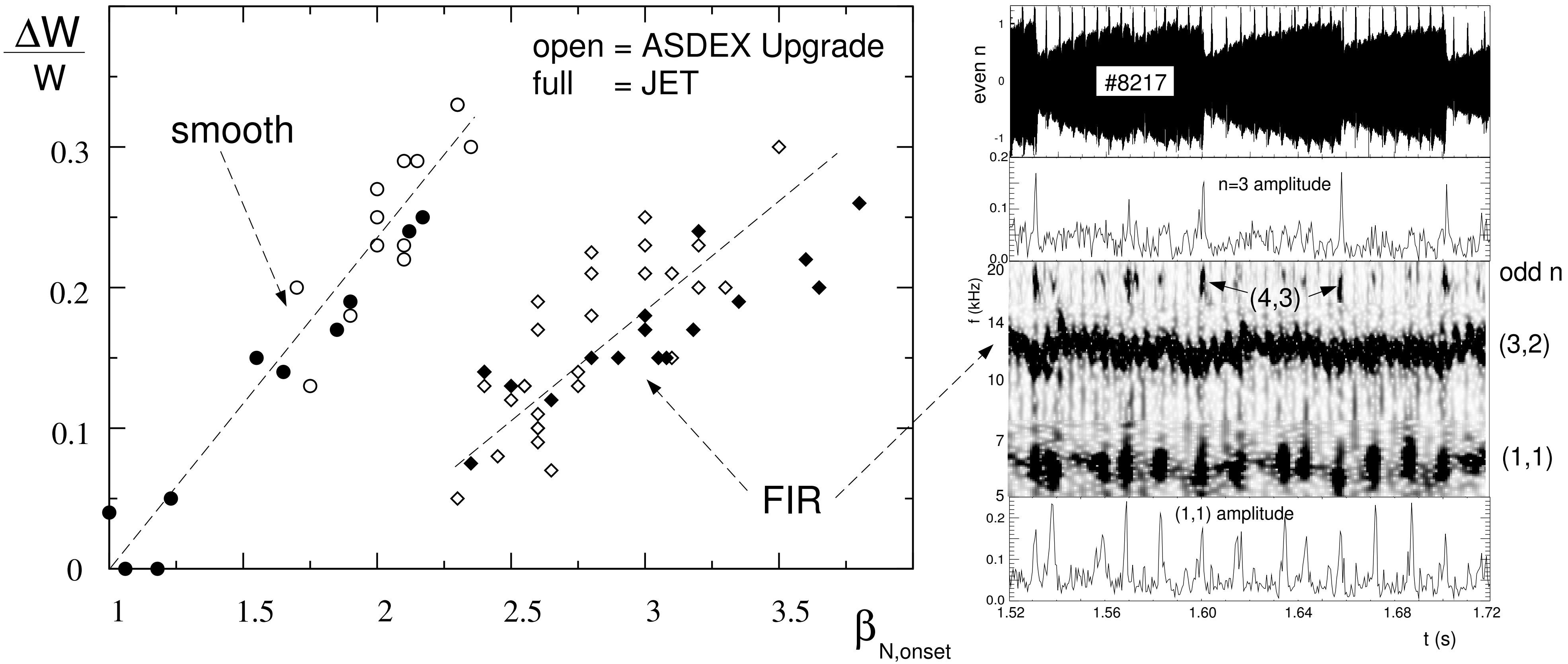

- common behaviour of FIR-NTM for $\beta_N > 2.3$ for JET and ASDEX Upgrade
  → stabilility of required coupled ideal (4/3)-mode (high ∇p, low ∇q ↔ infernal mode)

- ELMs have a similar effect at JET for $\beta_N > 1.9$ for low B_t, low q_{95}
- presence of q=1 surface modifies behaviour in improved H-mode

Triggering / suppressing of FIR-NTMs with ECCD

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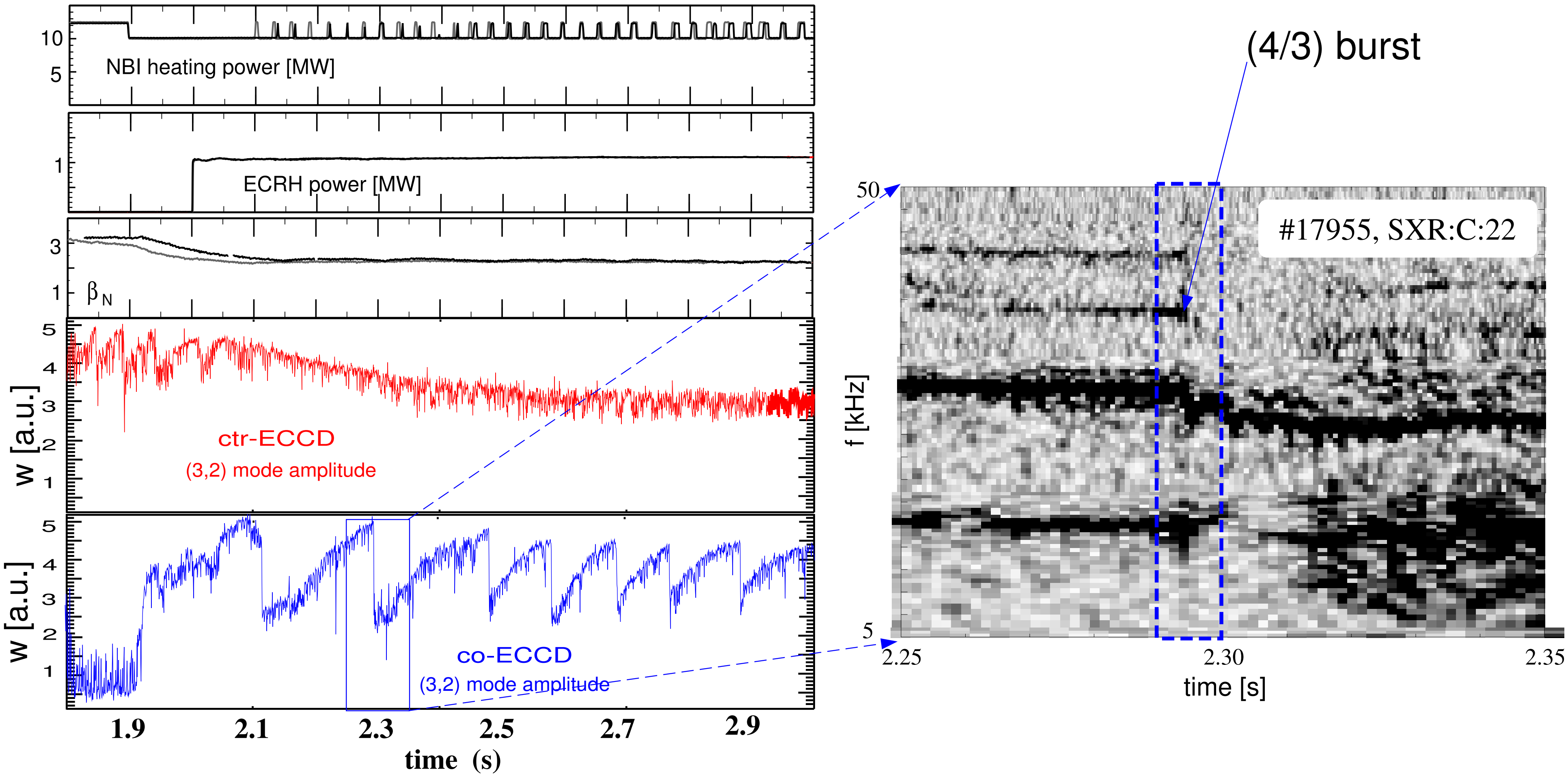

- triggering of ideal pressure driven (4/3) mode by q-flattening with ECCD
  (ideal: growth time, duration; ∇p, ∇q - dependence as for infernal modes)
- FIR behaviour of NTM at lower / higher β_N can be triggered / suppressed

Present status and plans for the future

- feed-forward B_t - scan ⟶ feedback stabilisation:
  (1) realtime detection of (m/n) mode, its localisation and deposition of the ECCD
  (2) feedback loop for the resonant surface ($\rho_{ECCD} = \rho_{NTM}$)
  (3) steerable ECCD launchers and tunable gyrotrons
  → immediate reaction at still small island → efficiency ?
  → P_{NBI} increase to raise β_N ⇒ keep ECCD on q-surface without an NTM

- ultimate goal is not only removal, but avoidance of NTM
  ⇒ feedback loop on $\rho_{ECCD} = \rho(q)$ with equilibrium q-profile

  → seed-island avoidance (such as sawteeth and/or fishbones)
  → co-ECCD to "prevent" bootstrap hole at the resonant surface
  → global tailoring of the j-profile (Δ' effect) or
  the n_e-profile (bootstrap is driving term via ∇n_e)
  to reduce drive for MHD mode

Summary and outlook

- local co / counter-ECCD has been shown to be a powerful tool to control core MHD
  - → narrow deposition layer, well controlable deposition and width

→ sawtooth tailoring at intermediate P_{NBI}, NTM avoidance at higher P_{NBI}
→ NTM stabilisation with narrow deposition reduces power requirements (β_N/P_{ECCD})
→ trigger and suppress FIR-NTM phases ⇒ physical understanding

Outlook:

- application of feedforward technique:
  - → deposition width and modulation experiments with broad deposition, extension towards more general scenarios

- realtime feedback control with increased ECCD power and control capabilities will be addressed in 2005 for stabilisation and avoidance

Dependence of the sawtooth frequency on the NBI selesction

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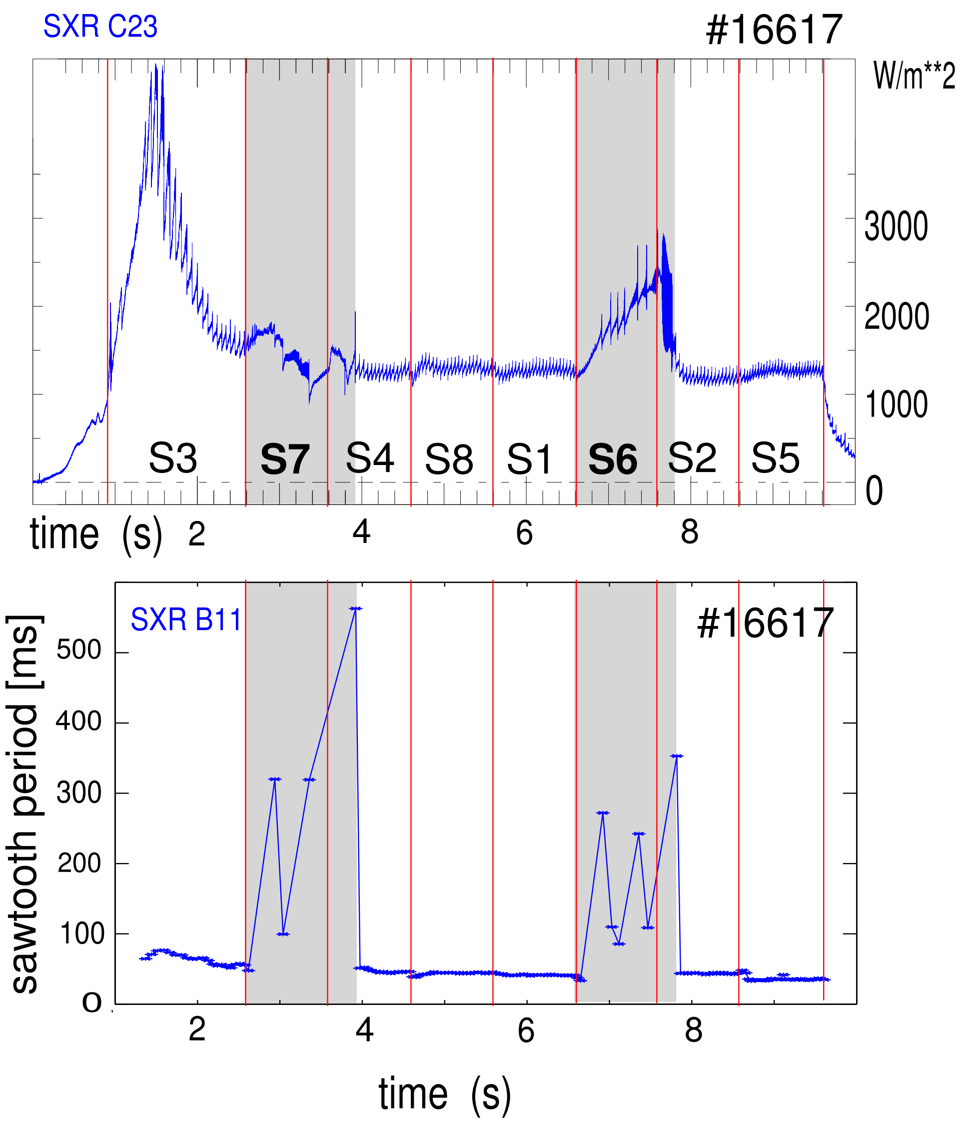
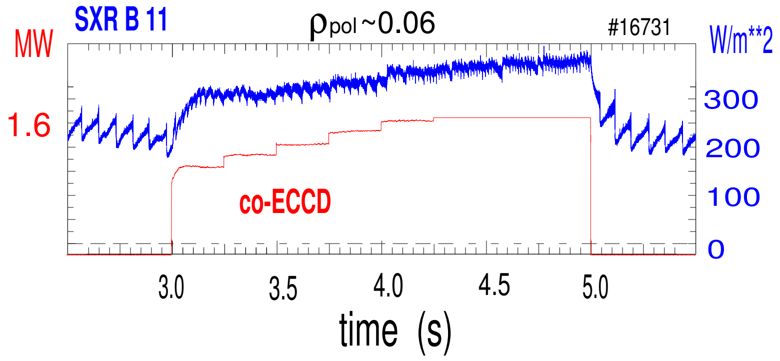
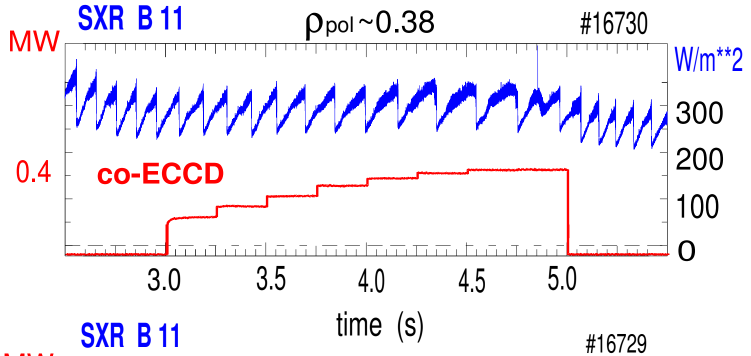


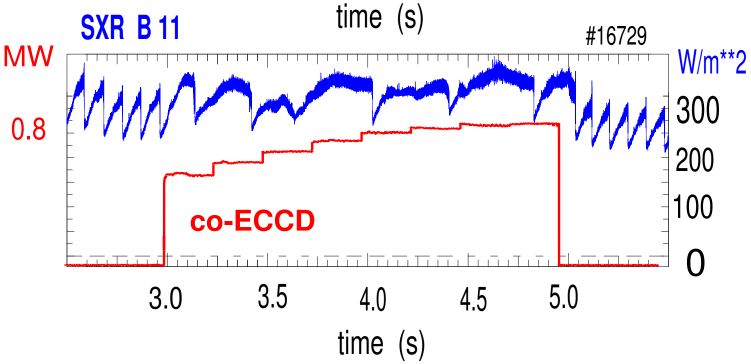
- variation of tangency radius governs the fast particle distribution from NBI
  $\Rightarrow$ fast particle stabilisation
- variation in the particle energy between 100 keV and 60 keV has an additional impact
- significantly different deposition profiles for different sources

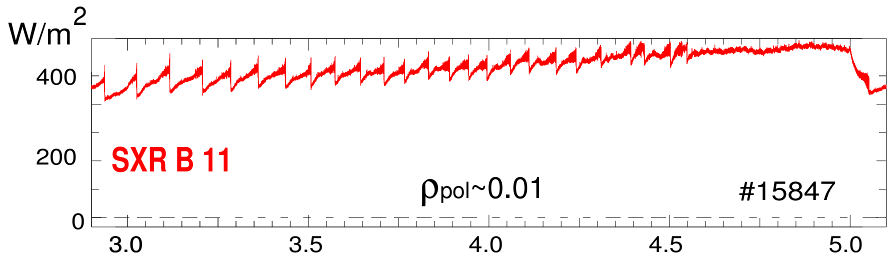
$\Rightarrow$ correction for sawtooth frequency required !

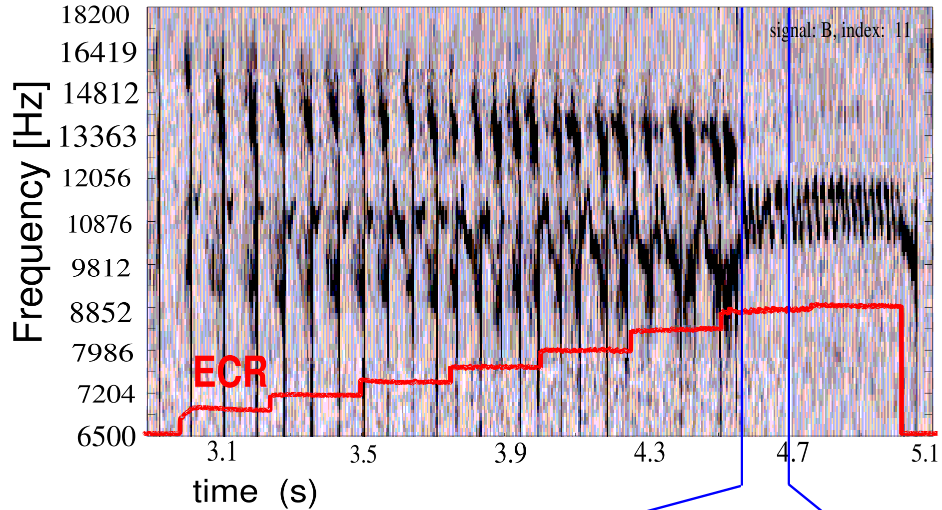
Power dependence of the sawtooth behaviour



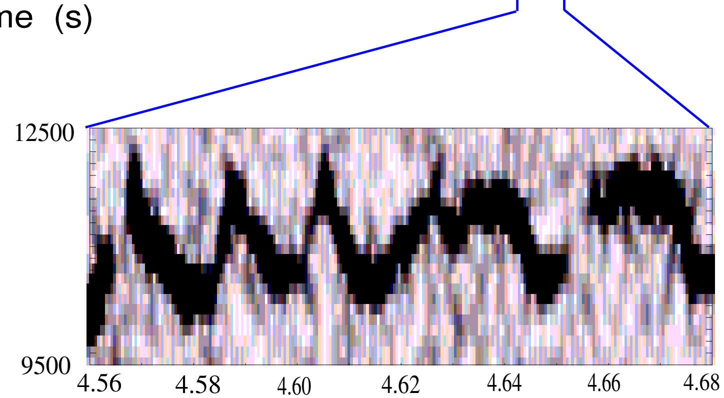




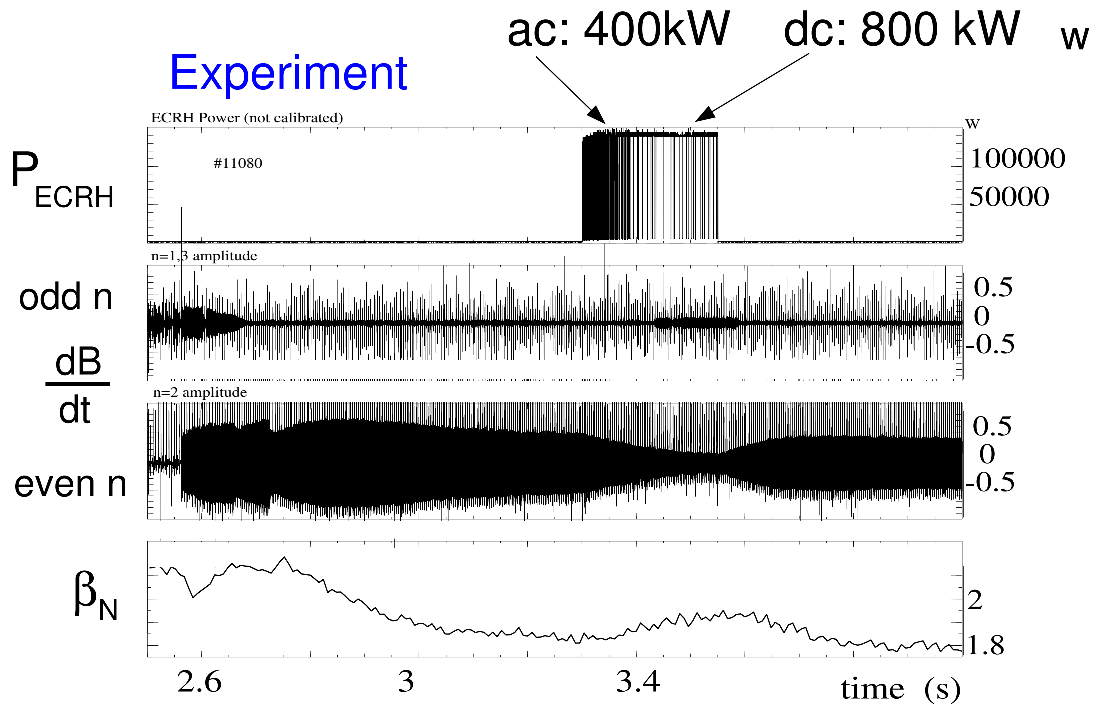




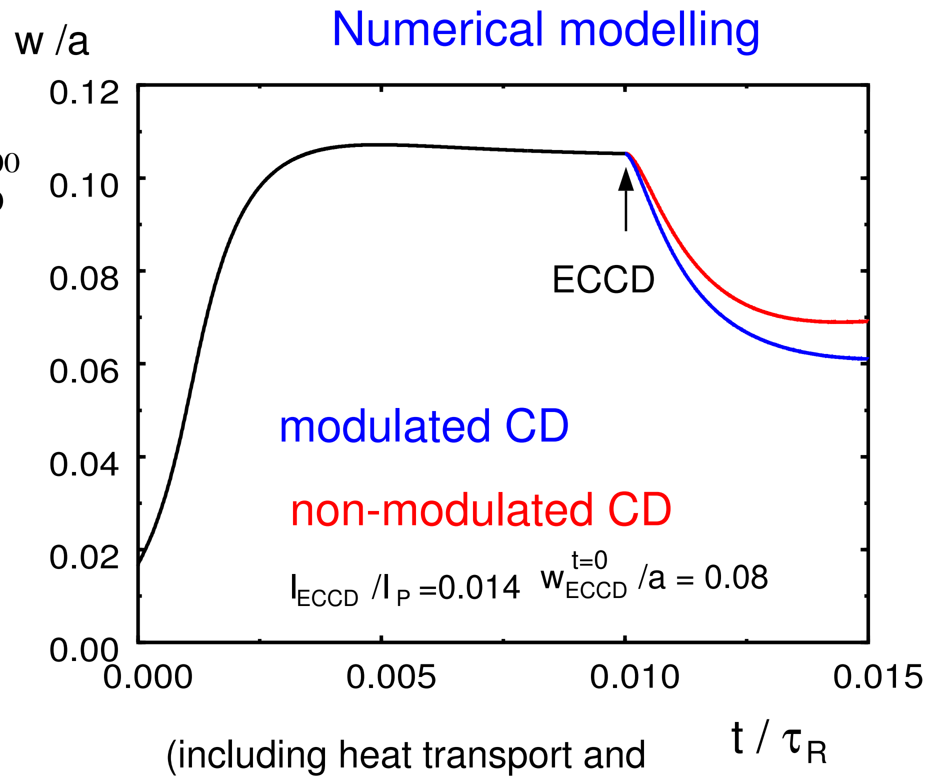
- variation of (1/1) ampl. with constant sawteeth
- (1/1) mode survives
- role of the (1/1) mode



Stabilisation of neoclassical modes by external current drive in the O-point of the islands



H. Zohm et al. NF 39 (1999)



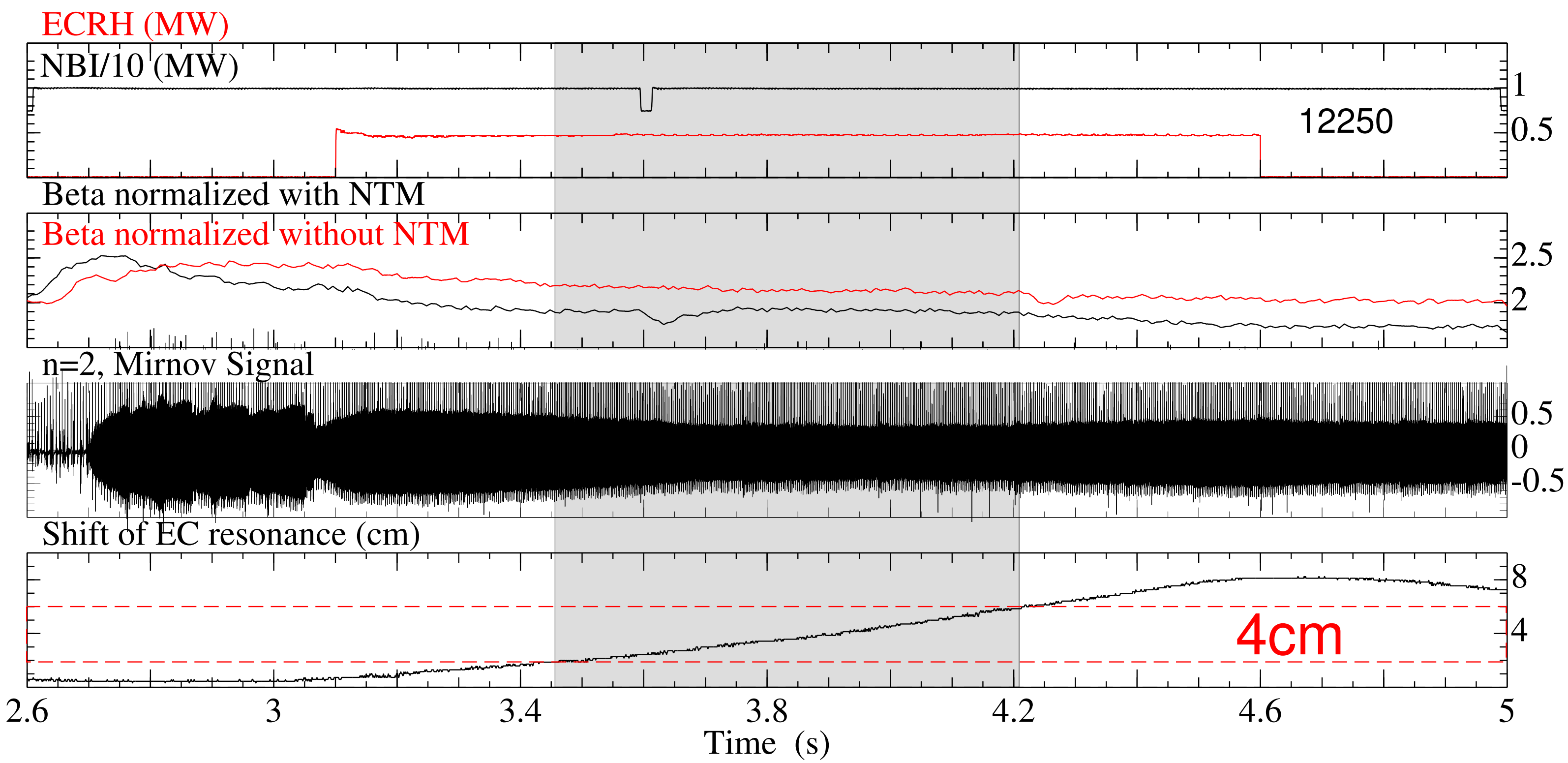
(including heat transport and current diffusion)

Q. Yu, S. Günter, PPCF 40 (1998) 1977

modulated ECCD in O-point: $P_{ECCD}/P_{NI} \approx$ 4-8%, 40% β_N recovery with mode reduction

Stabilisation is also effective for non-modulated current drive

B_t - scan for resonance



- resonance scanned with 400 kW co - ECCD (+heating)
  - shift of deposition of ECCD: ≈ 8 cm
  - shift of mode during scan: ≈ 2 cm
  - shot to shot variation of mode location ≈ 2 cm

⇒ resonant intervall ≈ 4cm
same order as island half width and deposition width

Co / Counter current drive and heating alone

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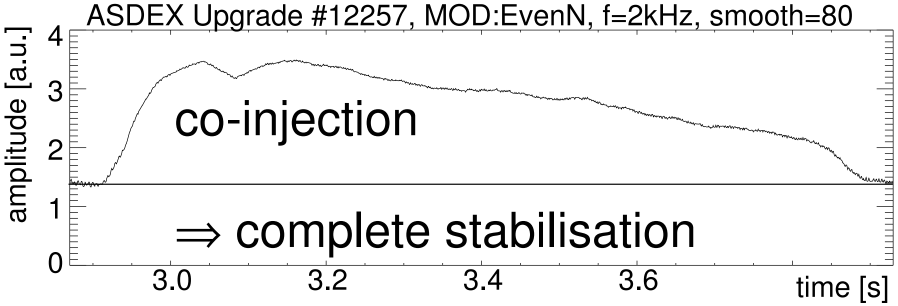
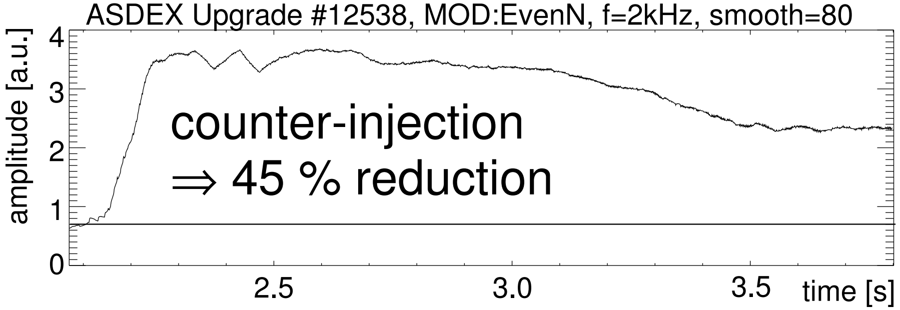
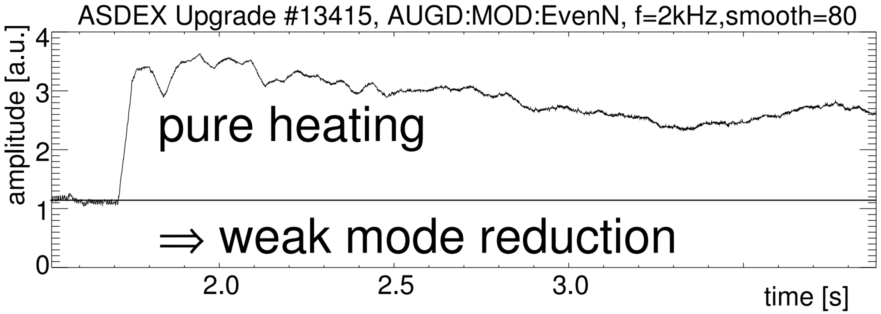
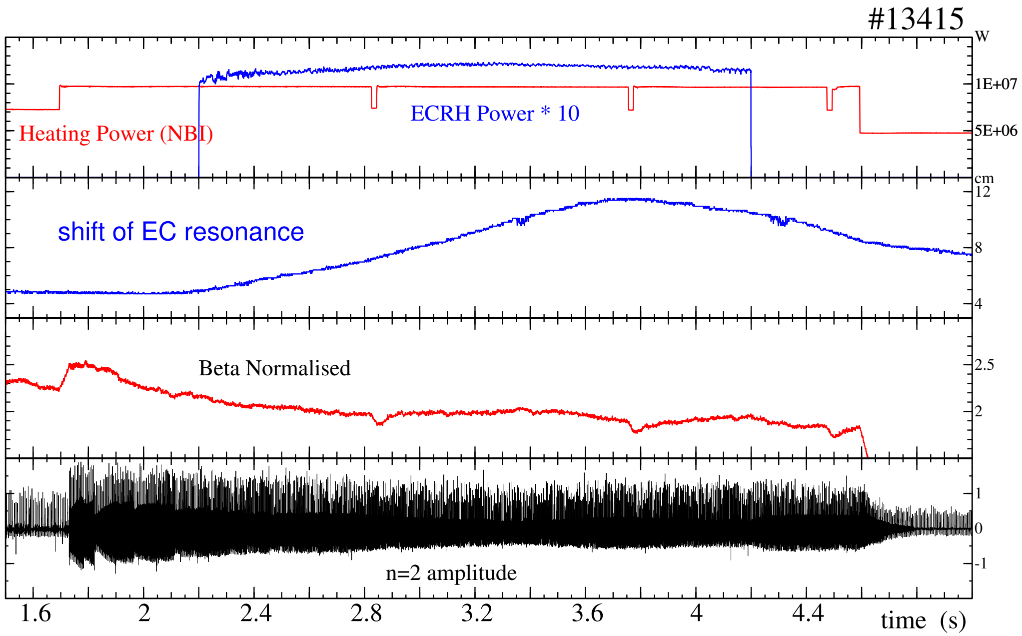








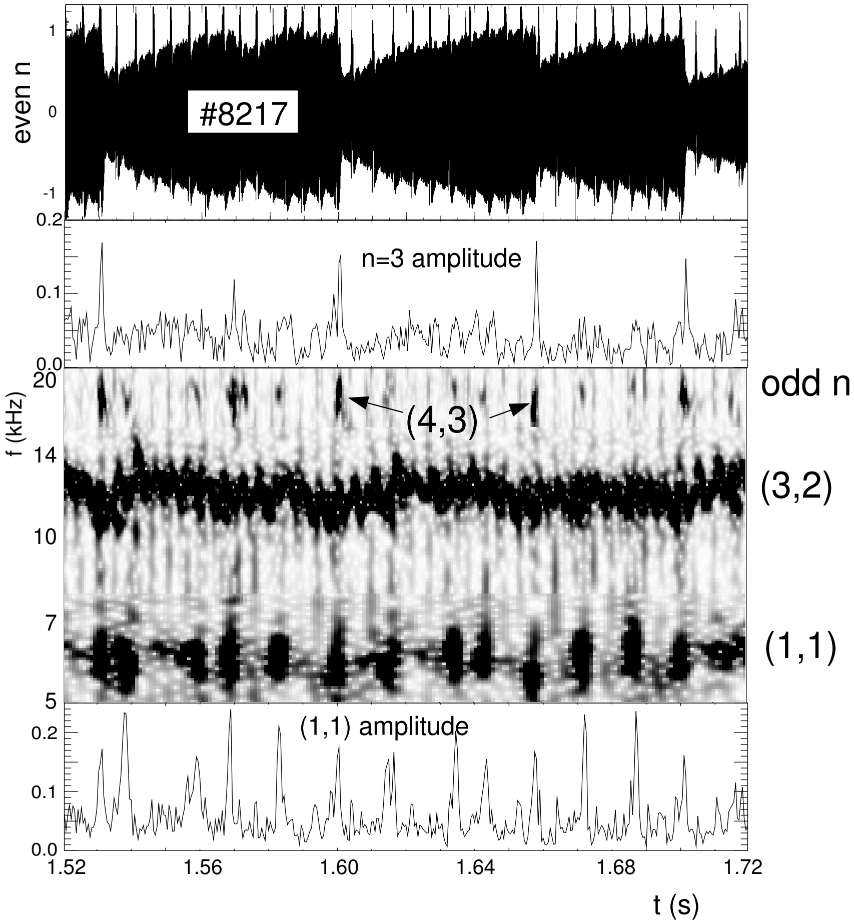
- application of magnetic field ramp
- ECRH: -15°, +15°, 0° for co-ECCD, counter-ECCD, heating

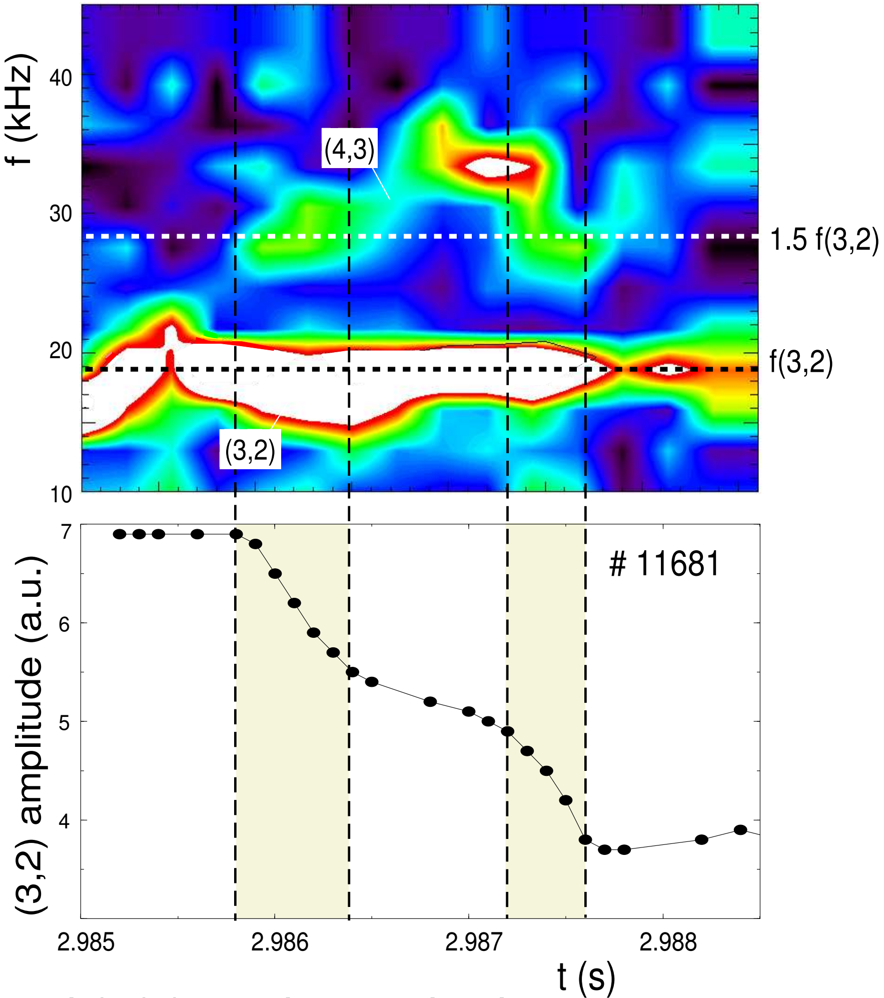
- comparison between co- and counter-ECCD

effect(co) = heating + ECCD
effect(counter) = heating − ECCD

⇒ heating and ECCD result in a comparable stabilizing and destabilizing
- heating alone not sufficient to stabilize mode at a given ECRH power

FIR-NTMs by nonlinear mode coupling with(m+1,n+1) modes and (1,1) mode

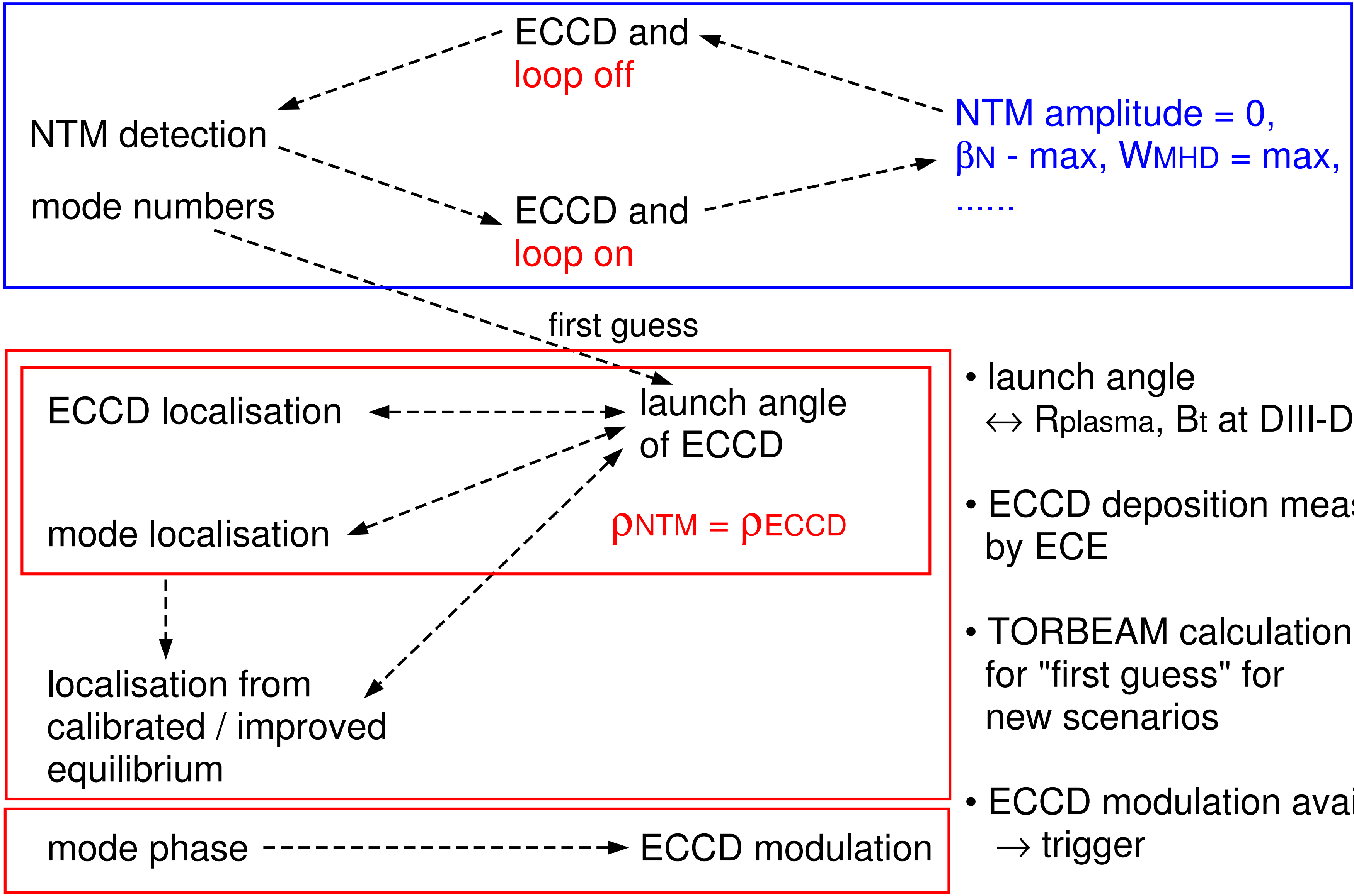




- presence of both (m+1/n+1) mode and (1/1) mode required
- phase locked resonance required

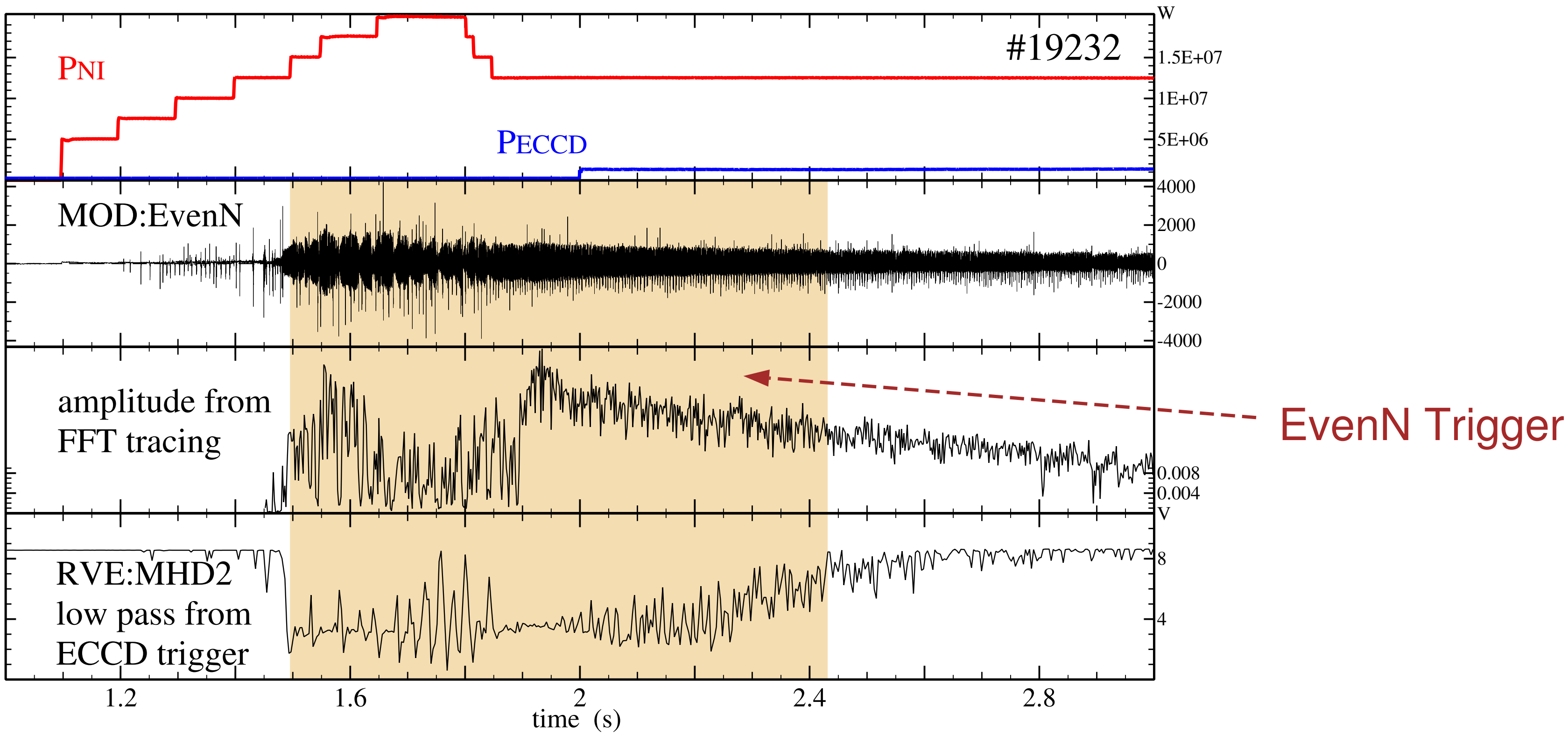
A.Gude, Nucl. Fusion 42 (2002) 833

General idea of a feedback loop for NTM stabilisation



- launch angle
  ↔ R_{plasma}, B_t at DIII-D
- ECCD deposition meas. by ECE
- TORBEAM calculations for "first guess" for new scenarios
- ECCD modulation available
  → trigger

Newly developed tools for the stabilisation (SENSOR)



- detection of odd n ((2/1)-NTM, but (1/1) also) and even n ((3/2)-NTM)
  ⇒ diagnostic upgrade provides realtime n=1, n=2, n=3 detection
- detection of localisation of the mode and ECCD via realtime ECE / SXR

Detection of mode and ECCD on ECE (SENSOR)

- NTMs can be directly measured from high time and radial resolution ECE

- ECCD modulation (90%) → mode can be detected at the same time on ECE

⇒ input quantities for NTM feedback stabilisation available

- high time resolution
- realtime capabilities

A.Keller, EPS2003, St. Petersburg

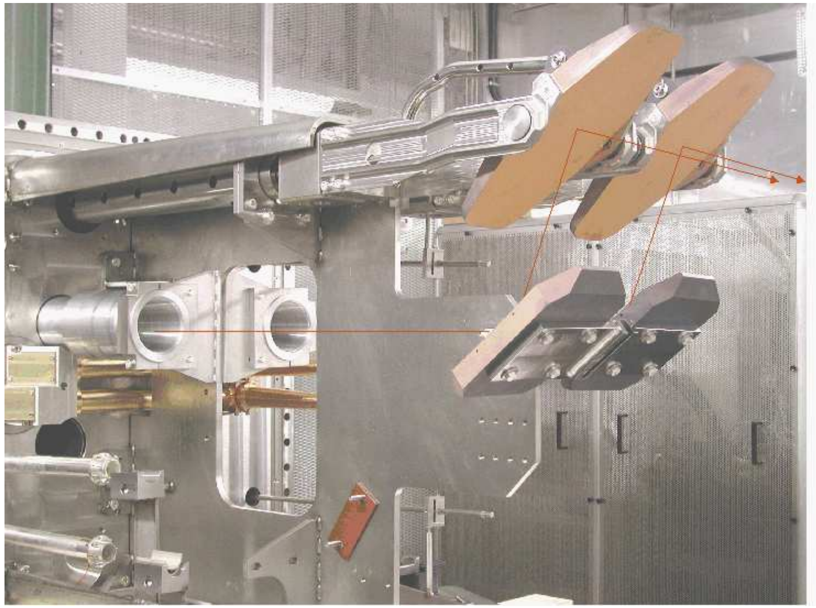
The new ECRH system on ASDEX Upgrade (ACTOR)

power: 4 MW, provided by 4 gyrotrons

pulse length: 10 sec

frequency: 105 / 140 GHz as a 2-f-gyrotron
105 / 117 / 127 / 140 GHz as a step tunable gyrotron
change of frequency between pulses

launcher: feedback controled deposition via poloidal launching angle
toroidal angle can be set between pulses



heating and current drive, in particular for advanced tokamak regime
suppression of tearing modes
control of transport and pressure profile