Control of core MHD Instabilities by ECCD in ASDEX Upgrade

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- Introduction and motivation
- Sawtooth tailoring / avoidance with co / counter ECCD
- NTM stabilisation with co-ECCD
  - Deposition width scan
  - Modulated ECCD
  - Early application of ECCD
- FIR-NTMs and their triggering with ECCD
- Summary and future plans
• $q=1$, (flat or reversed in the centre in adv. scen.):
  sawteeth, fast particle driven fishbones, $(1/1)$-modes
  ⇒ sawtooth tailoring → avoidance of NTM trigger
  → burn control

• $q=4/3$:
  $(4/3)$ 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 deposition by $B_t$
  and toroidal and poloidal launching angle
typical "natural" time-development of an NTM

1: onset at $\beta_p, \text{onset} > \beta_p, \text{crit}$, + a seed-island, such as sawteeth
2: growth to saturated size, proportional to $\beta_p, \text{sat}$
   $\rightarrow$ FIR-NTM phases at $\beta_N > 2.3$
   $\rightarrow$ stabilisation experiments with ECCD
3: reduction of $\beta_p$ by heating until $\beta_p, \text{crit}$ is reached
4: $\beta_p = \beta_p, \text{crit}$, mode decouples from $\beta_p$
5: $\beta_p < \beta_p, \text{crit}$ for all times $\Rightarrow$ mode decays away again

$W_{\text{sat}} \sim \beta_p$
$W_{\text{sat}}(\text{FIR, ECCD}) < \beta_p$

2005, M. Maraschek, IPP-Garching
Sawtooth tailoring with ECRH / ECCD

- co-ECCD:
  - stabilisation / full suppression outside inversion radius
  - destabilisation for on-axis
    → explainable with critical shear criterium: \( \frac{dq}{dr} \frac{r}{q} > (\frac{dq}{dr} \frac{r}{q})_{crit} \)

- pure heating (= 50% co and counter-ECCD):
  - similar behaviour as for co-ECCD, but less pronounced

- counter-ECCD:
  - stabilisation for on-axis
  - inverse behaviour
  - effect on (1/1) mode plays an additional role

→ impurity and He removal
→ burn control in the core

A.Mück, EPS2003, St.Petersburg
A.Mück, PPCF, 2005

\( P_{NBI} = 5\text{MW} \)
\( P_{ECCD} \leq 1.4\text{MW} \)
Optimization of sawtooth tailoring by varying the deposition width

• critical shear criterion can explain general behaviour

• clearest impact on $\tau_{st}$ for narrow deposition, especially for counter-ECCD
  ⇒ heating effect similar to co-ECCD
  ⇒ heating always present and stronger for broad deposition (> counter-ECCD)
  ⇒ $j_{ECCD}$ or $I_{ECCD}/d$ more important than total $I_{ECCD}$

• co-ECCD more efficient for sawtooth tailoring

A. Mück, PPCF, 2005
A. Manini, 32nd EPS2005, Tarragona

2005, M. Maraschek, IPP-Garching
High power NBI experiments: NTM avoidance at high $\beta_N = 2.8$

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

#17238, counter-ECCD

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

$\Rightarrow$ NTM avoidance achieved

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

$\beta_N \approx 2.8$ fixed by $\beta_p$ feedback

A.Mück, EPS2003, St.Petersburg

2005, M.Maraschek, IPP-Garching
(3/2)-NTM stabilisation with narrow co-ECCD at reduced q95 at $\beta_N = 2.7$

- complete stabilisation at $\beta_N = 2.7$ with PECCD = 1MW and P$_{NBI}$ = 10MW, ITER relev. $q_{95} = 3.8$
  $\Rightarrow \beta_N / \text{PECCD} = 2.7/\text{MW}$

- $\beta_N$ increase with more P$_{NBI}$ $\Rightarrow$ even higher $\beta_N$ achievable (re-excitation, Shafranov-shift)

2005, M.Maraschek, IPP-Garching
Influence of the deposition width on the (3/2)-NTM stabilisation

- **narrow deposition**: \( I / d = \text{current density maximal for} \ -5^\circ \ \text{(TORBEAM)} \)
  - full stabilisation with reduced \( \text{PECCD} / \text{PNBI} \) possible
  - higher \( \beta_N \) achievable at stabilisation (\( \beta_N / \text{PECCD}, \beta_N / (\text{PECCD/PNBI}) \) )

- \( W < d \) reduces the stabilisation efficiency
  - \( \text{ECCD modulated by mode} \) (only O-point) might be required for ITER
    (further modulation experiments will be performed in 2006)

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2005, M. Maraschek, IPP-Garching
Stabilisation efficiency as function of deposition width and driven current

- \( \beta N / \text{PECCD} \) variation reason for some scatter
- PECCD might be larger than required for stabilisation (\( \text{PECCD} > \text{PECCD, marginal} \))

- the figure of merit \( \beta N / \text{PECCD} \) gives the achievable \( \beta N \) at the stabilisation
- \( \beta N / \text{PECCD} \) "maximum" at maximal current peaking \( I/d \)

- similar improvement achieved for \((2/1)-\text{NTM}\)
(3/2)-NTM stabilisation with broad ECCD (19°) at early and late application

collaboration with A.Lazaros, E.Westerhof (FOM)

- 0.6s delay of mode onset, with identical fishbone activity
- mode amplitude comparable due to β-drop
- power requirement for subsequent stabilisation not resolved
- more peaked deposition I/d gave no clear answers

2005, M.Maraschek, IPP-Garching
Stabilisation of NTMs by non-modulated ECCD (intermediate width)

- Stabilisation also effective for non-modulated current drive for $d < W$, but:

  - for $W \leq d$ the required current increases significantly for non-modulated ECCD, compared to modulated ECCD

Q.Yu, PoP 2004
NTM stabilisation with modulated broad ECCD

- Reduction of island size, $\beta_N$ recovery $\Rightarrow$ phasing correct, but DC gives similar behaviour
- FIR-NTM phase at $\beta_N = 2.8$ $\Rightarrow$ yet no clear answer possible, PECCD too small

2005, M.Maraschek, IPP-Garching
FIR-NTMs - a general NTM behaviour for $\beta_N > 2.3$

collaboration with D.F.Howell (UKAEA)

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

- triggering of ideal pressure driven (4/3) mode by q-flattening with ECCD
  (ideal: growth time, duration; $\nabla p$, $\nabla q$ - dependence as for infernal modes)
- FIR behaviour of NTM at lower / higher $\beta_N$ can be triggered / suppressed
- control of FIR-NTM feasible $\iff$ complete stabilisation main target

2005, M. Maraschek, IPP-Garching
Present status and plans for the future

- feed-forward $B_t$ - scan $\rightarrow$ 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 $\rightarrow$ efficiency?
     - PNB increase to raise $\beta_N$ $\Rightarrow$ keep ECCD on q-surface without an NTM

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

  $\rightarrow$ seed-island avoidance (such as sawteeth and/or fishbones)
  $\rightarrow$ co-ECCD to "prevent" bootstrap hole at the resonant surface
  $\rightarrow$ global tailoring of the j-profile ($\Delta'$ effect) or
     - the $n_e$-profile (bootstrap is driving term via $\nabla n_e$)
     - to reduce drive for MHD mode
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 controlled 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
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 \( P_{\text{NBI}} \), deposition width, NTM avoidance at high \( P_{\text{NBI}} \)
  → **deposition width scan** ⇒ \( I/d, \beta \text{N}/PECCD \)
  ⇒ narrow deposition reduces required power (NTM,sawteeth)
  → **early ECCD** delays NTM onset
  → **modulation** of ECCD, no clear answer yet
  → trigger and suppress **FIR-NTM** ⇒ physical understanding

**Outlook:**

- application of **feedforward** technique:
  → **deposition width** and **modulation** experiments
  → extension for more general scenarios (ITER hybrid scenario)

- **realtime feedback control** with increased ECCD power and control capabilities will be applied in 2006 for stabilisation and avoidance
possible routes to influence NTMs by ECCD

sawtooth tailoring / avoidance of seed-island / NTM
- avoidance
- reduced size, trigger
- \( q = 1 \)
- early ECCD
- \( q = m/n \)
- [A.Mück, NF, 2005]

triggering transition to FIR-NTM
- reduce magn. shear for (4/3)-mode
- \( q = 4/3 \)
- [S.Günter, PPCF, 2004]

active stabilization of saturated island
- deposition width / island width \( \rightarrow \) modulation required for ITER?
- reduced requirements for early ECCD? \( (W < W_{\text{sat}}) \)
- \( q = m/n \)
- [G.Gantenbein, PRL, 2000]
Dependence of the sawtooth frequency on the NBI selection

- variation of tangency radius governs the fast particle distribution from NBI  
  ⇒ 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

  ⇒ correction for sawtooth frequency required!
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:
      \[\frac{dq}{dr} \frac{r}{q} > \left(\frac{dq}{dr} \frac{r}{q}\right)_{\text{crit}}\]

- **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
    → impurity and He removal
    → burn control in the core

\[
P_{\text{NBI}} = 5\text{MW} \\
P_{\text{ECCD}} \leq 1.4\text{MW}
\]

A.Mück, EPS2003, St.Petersburg
A.Mück, PPCF, 2005

2005, M.Maraschek, IPP-Garching
Modelling the effect of co-ECCD / counter-ECCD / pure ECRH on sawteeth

- Modelling of the sawtooth period for pure (!) ECCD and ECRH
- Sweep of the deposition layer over the q=1 surface

- Heating effect similar to co-ECCD with comparable size and broader effect
- Small counter-ECCD (broad dep.) effect can be understood in the experiment

C. Angioni, NF 43 (2003), p.455

2005, M. Maraschek, IPP-Garching
Power dependence of the sawtooth behaviour

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

2005, M. Maraschek, IPP-Garching
(3/2)-NTM stabilisation with narrow co-ECCD at $\beta_N = 2.6$

- complete stabilisation at $\beta_N = 2.6$ with $P_{ECCD} = 1\text{MW}$ and $P_{NBI} = 12.5\text{MW}$
  \[ \Rightarrow \beta_N / P_{ECCD} = 2.6/\text{MW} \]

- $\beta_N$ increase with more $P_{NBI}$ not considered \(\Rightarrow\) even higher $\beta_N$ achievable (re-excitation)
B_t = 2.0T, I_p = 1.1MA, higher $\beta_N$ (narrow ECCD deposition) at more ITER relev. $q_{95}$, but no complete stabilisation achieved, due to lower $T_e$ and less driven current.
(2/1)-NTM stabilisation with narrow co-ECCD at $\beta_N = 2.3$

- stabilisation at $\beta_N = 2.3$ [1.9] with $PECCD = 1.4$MW [1.9MW], $P_{NBI} = 10$MW [6.25MW]  
  \[ \Rightarrow \quad \beta_N / PECCD = 1.64/MW \] [1.0/MW]  
  \[ \Rightarrow \quad \text{stabilisation of the (2/1) NTM requires more power (} \beta_{p,marg}, \text{ less current drive)} \]

- faster unlocking of (2/1)-NTM  \[ \Rightarrow \quad \text{injection in the O-point of the locked mode works} \]
stabilisation efficiency as function of deposition width, driven current, ...

- q95 variation reason for some scatter
- for complete stabilisation PECCD might be too large (PECCD > PECCD, marginal, IECCD > IECCD, marginal)
- the figure of merit
  \[ \beta_N / \text{PECCD} \]
  gives the achievable $\beta_N$ at the stabilisation
- $\beta_N / \text{PECCD}$ "maximum" at maximal $I/d$
Nonlinear modelling allows separation of different terms

- 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

2005, M. Maraschek, IPP-Garching
Stabilization of neoclassical modes by non-modulated current drive

Non-modulated co-ECCD (AUG)

Non-modulated counter-ECCD (AUG)

Numerical modelling

Stabilisation due to synergy of helical current and change in $\Delta'$

2005, M. Maraschek, IPP-Garching
Stabilisation of NTMs by non-modulated ECCD (intermediate width)

- modulated ECCD in O-point: $P_{\text{ECCD}}/P_{\text{NI}} \approx 4-8\%$, 40% $\beta_N$ recovery with mode reduction
- stabilisation also effective for non-modulated current drive for $d < W$

H. Zohm et al. NF 39 (1999)


2005, M. Maraschek, IPP-Garching
Stabilisation of NTMs by non-modulated ECCD (intermediate width)

- modulated ECCD in O-point: PECCD/PNI \( \approx \) 4-8%, 40% \( \beta_N \) recovery with mode reduction
- stabilisation also effective for non-modulated current drive for \( d < W \)

\[ \rightarrow \] clearly highest reduction rate at early modulated phase

2005, M. Maraschek, IPP-Garching
• correct phase adjustment for modulated deposition from the equilibrium

• ECCD is capable for modulation with \( f = 30 \text{ kHz} \)

• requirement for ITER for \( W > d \)?
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
Triggering / suppressing of FIR-NTMs with ECCD

- triggering of ideal pressure driven (4/3) mode by q-flattening with ECCD
- FIR behaviour of NTM at lower / higher $\beta_N$ can be triggered / suppressed
General idea of a feedback loop for NTM stabilisation

- NTM detection
  - mode numbers
  - ECCD localisation
    - mode localisation
      - localisation from calibrated / improved equilibrium
      - launch angle
        - launch angle of ECCD
      - mode phase
        - ECCD and loop on
  - first guess
    - ECCD and loop off
      - NTM amplitude = 0, \( \beta_N \text{ - max, } \omega_{MHD} \text{ = max, } \ldots \)

- \( \rho_{NTM} = \rho_{ECCD} \)
- \( \rho_{ECCD} \) and loop on
- ECCD and loop off
- ECCD and loop on
- launch angle
  - \( \leftrightarrow R_{plasma}, B_t \text{ at DIII-D} \)
- 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