Max-Planck-Institut für Plasmaphysik

Modulated ECCD control of NTMs in ASDEX Upgrade

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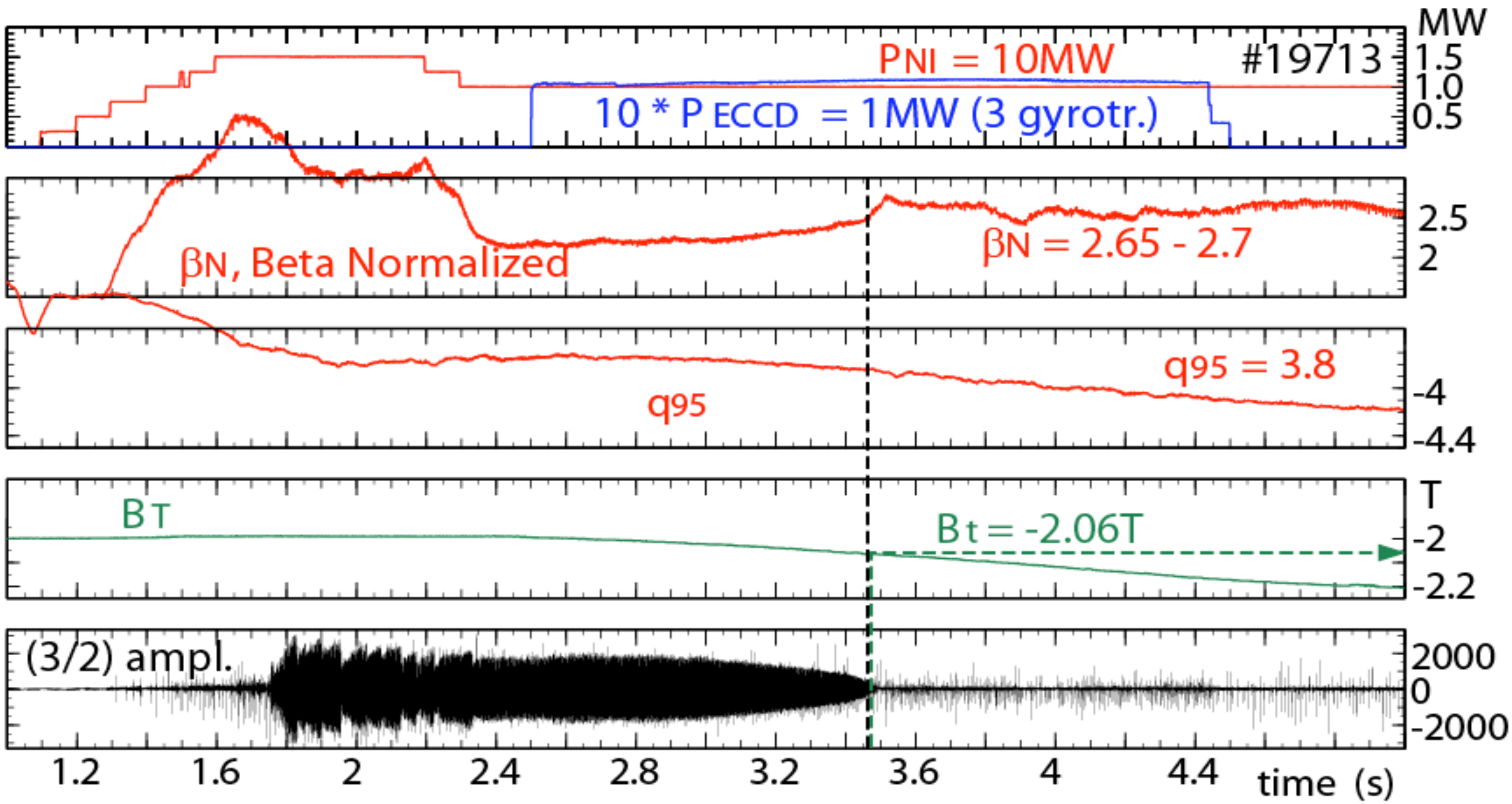
- introduction
- role of deposition width
- modulated broad ECCD
- power requirements
- persepctive and requirements for ITER
- summary

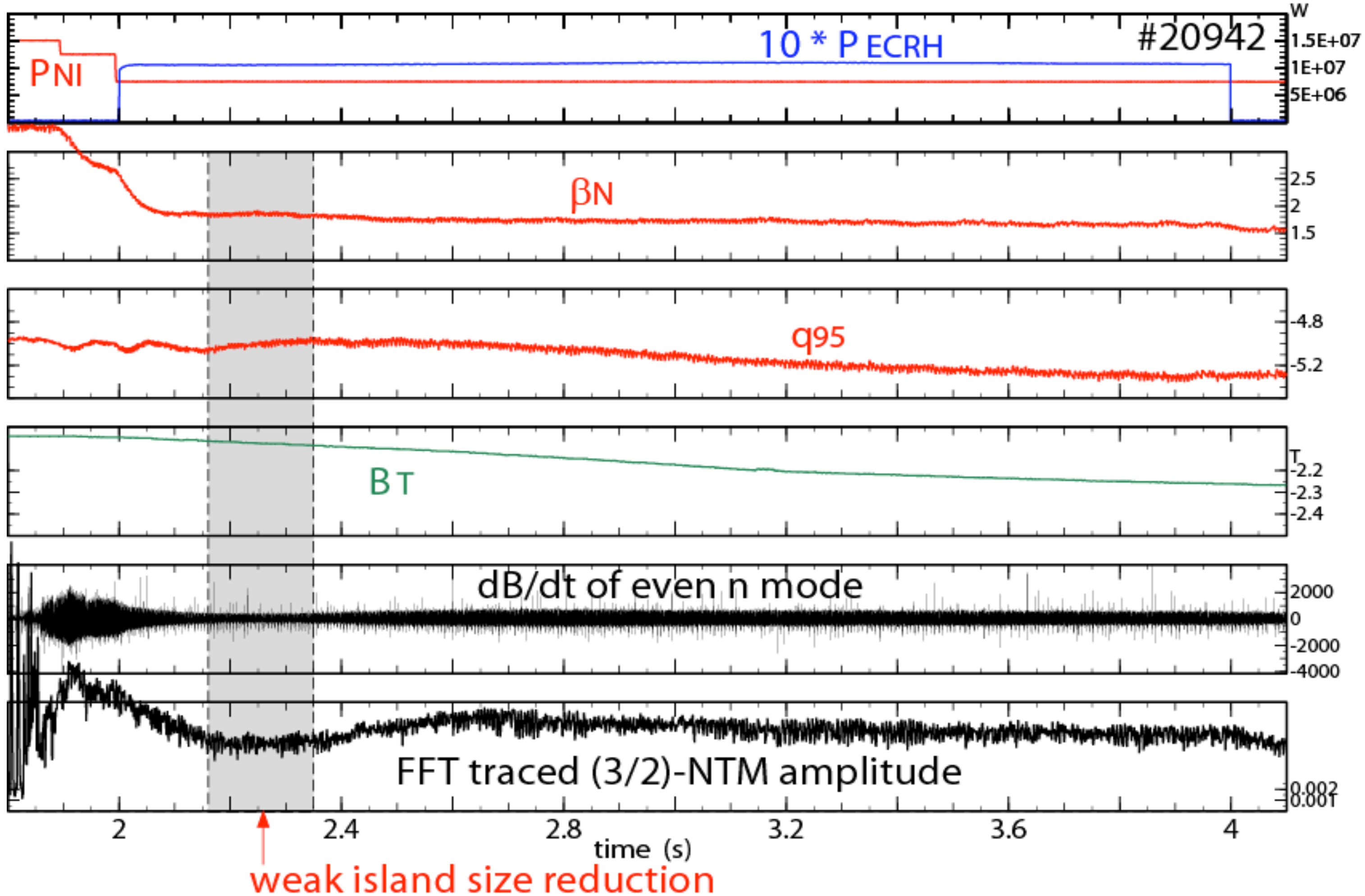
MHD-Workshop 2006: Active MHD control in ITER, Princeton (PA) , 08.11.2006

(3/2)-NTM stabilisation with narrow ECCD at low q_{95}



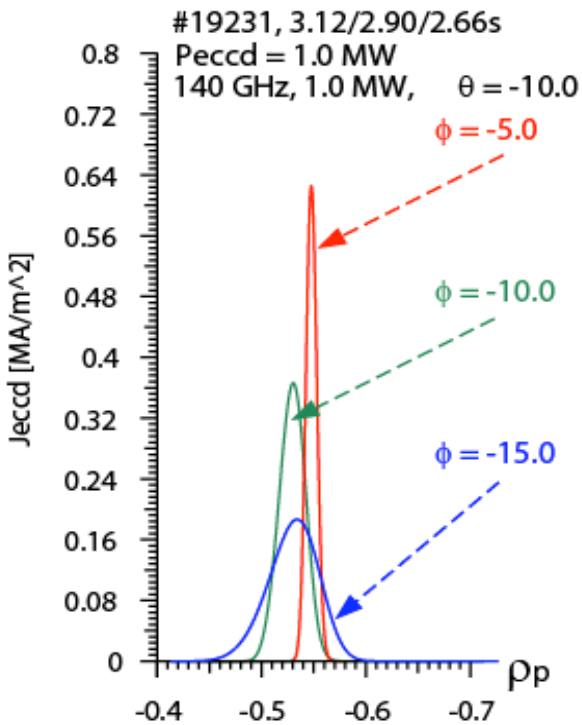
- complete stabilisation of smooth NTM at β_N=2.7 near ITER q_{95}=3.8 with only 1MW P_{ECCD}, $\beta_N/(P_{ECCD}/P_{NBI})$ = 27
- β_N increase with more PNBI possible (reexcitation, Shafranov shift)

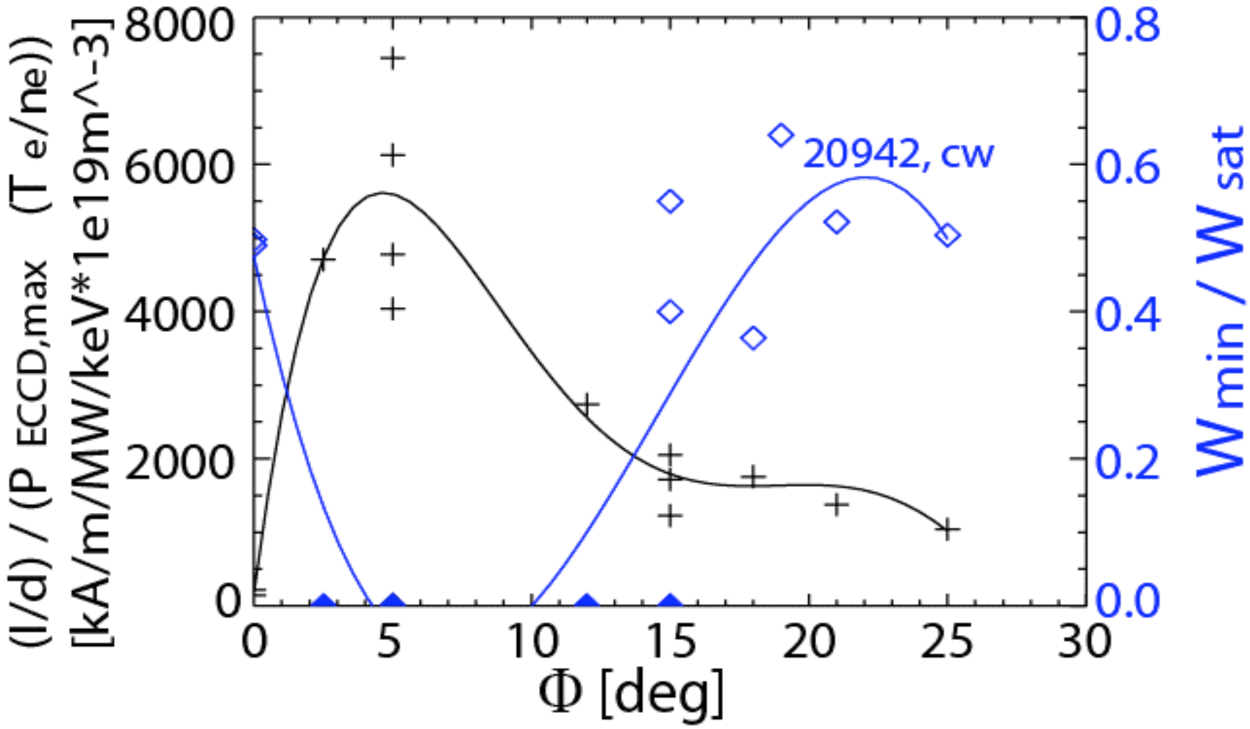
No stabilisation possible for broad ECCD deposition



- even with reduced NBI power :
- full ECCD (1.1MW) can no longer stabilise the (3/2)-NTM

Results on deposition width scan





NTM stabilisation predicted to be most efficient at high I_{ECCD}/d

- mode stabilised by helical current within island
  → *d* should be smaller than *W*
- possible to stabilise NTMs with half the total current, if better localised and narrow

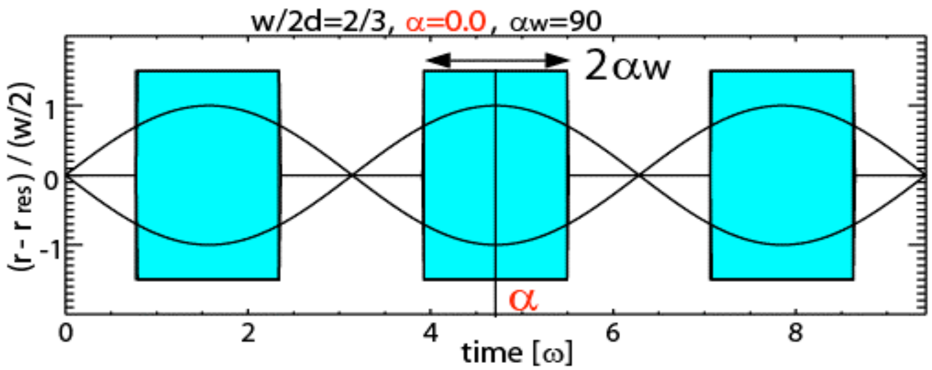
Physics of the NTM stabilisation

$$\frac{\tau_{res}}{r_s}\frac{dW}{dt} = a_{bs} r_s \beta_p \frac{1}{W} - r_s \Delta'_{stab} - c_j \frac{L_q r_s}{d^2} \frac{I_{ECCD}}{I_p(r_s)} \left(a_{mn} \eta_{mn} \left(W/d \right) \frac{d^2}{W^2} + a_{00} \right)$$

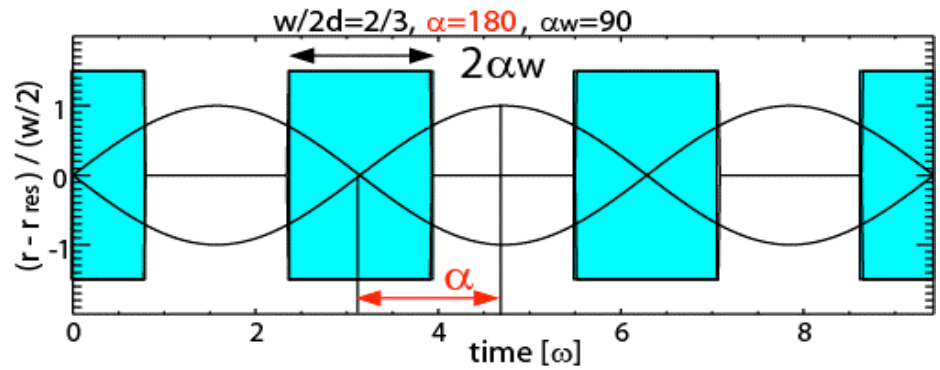
- helical (m,n) current in the island, a_{mn} – works on nonlinear stability (suppression of existing mode)
- modification of equilibrium (0,0) current profile, a_{00} – also linear stability (prevention of mode)

- $\eta_{mn} = j_{ECCD} / j_{bs}$, efficiency with which a helical component is created by island flux surface averaging
- c_j accounts for derivation from cylindrical large aspect ratio calculations
- misalignment of ECCD deposition not included

Phase locked modulated ECCD



O-point alligned co-ECCD

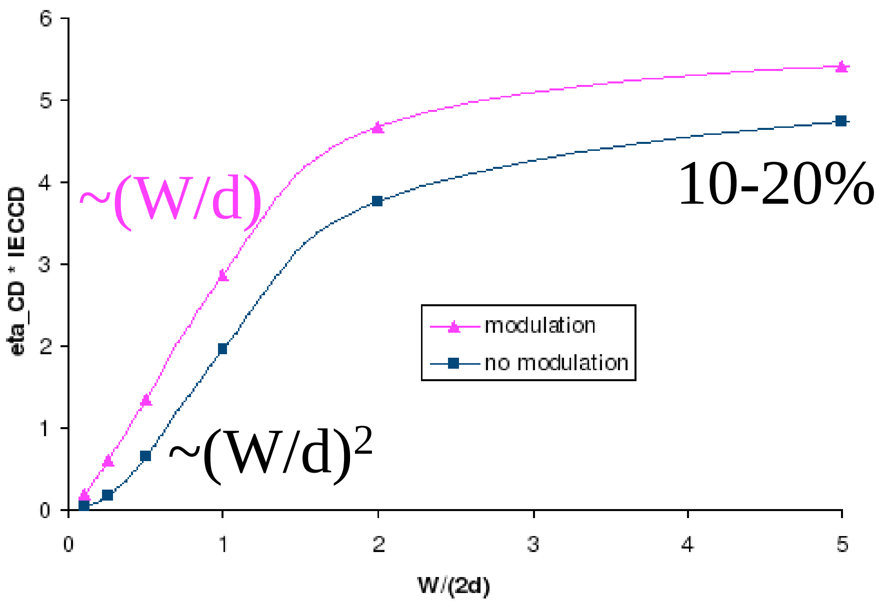


X-point alligned co-ECCD

- O-point alligned modulated ECCD :
  the current is driven helically within the island , high η_{mn}
- X-point alligned modulated ECCD should give destabilising effect (wrong phase !) + more sensitive Δ'- effect

Efficiency for driving a helical current

$$\frac{\tau_{res}}{r_s}\frac{dW}{dt} = a_{bs} r_s \beta_p \frac{1}{W} - r_s \Delta'_{stab} - c_j \frac{L_q r_s}{d^2}\frac{I_{ECCD}}{I_p(r_s)}\left(a_{mn}\eta_{mn}\left(W/d\right)\frac{d^2}{W^2} + a_{00}\right)$$



numerical calculation of η_{mn}

η_{mn}	W > 2d	W < 2d
unmod.	const	~ $(W/d)^2$
mod.	const, 10-20%	~ W/d

Predictions for the limits

$$\frac{\tau_{res}}{r_s}\frac{dW}{dt} = a_{bs} r_s \beta_p \frac{1}{W} - r_s \Delta'_{stab} - c_j \frac{L_q r_s}{d^2}\frac{I_{ECCD}}{I_p(r_s)}\left(a_{mn}\eta_{mn}\left(W/d\right)\frac{d^2}{W^2} + a_{00}\right)$$

η_{mn}	W > 2d	W < 2d
unmod.	const	~ $(W/d)^2$
mod.	const, 10-20%	~ W/d

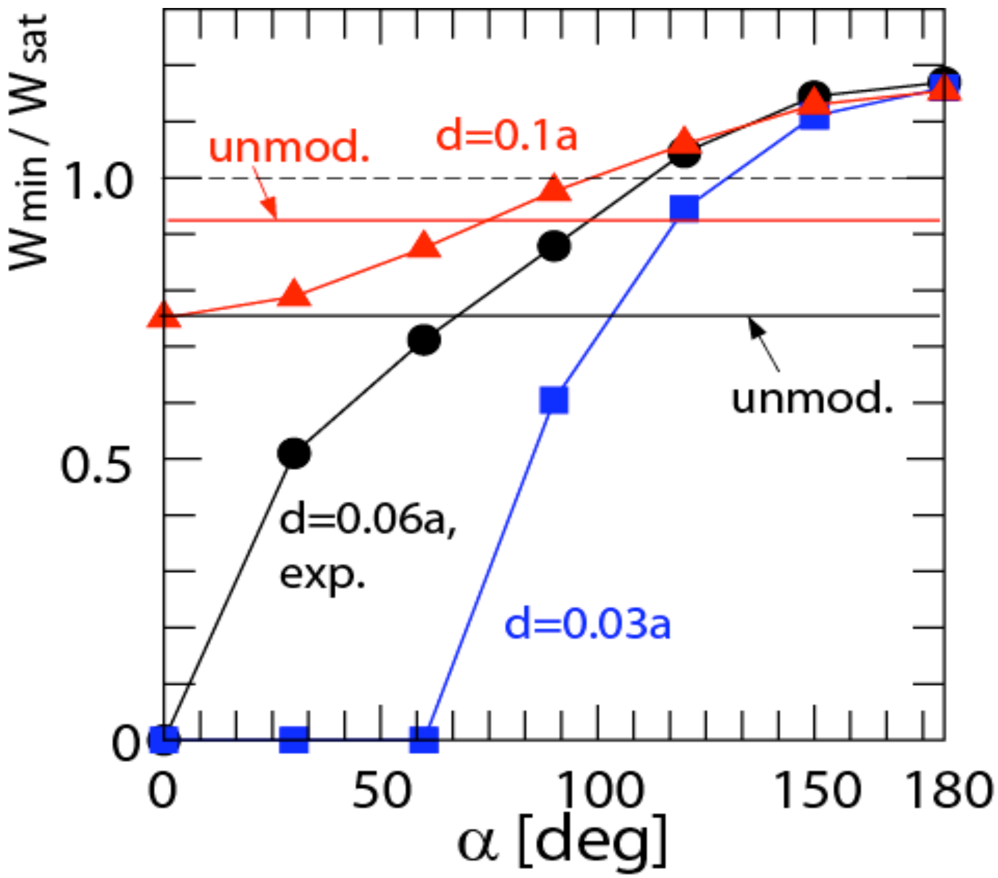
a_{mn}-term	W > 2d	W < 2d
unmod.	~ I / W^2	~ I / d^2
mod.	~ I / W^2	~ I / (d W)

a_{00} – term always ~ I / d^2

- W > d : η_{mn} ~ const. and I_{ECCD} counts; modulation has little advantage
- W < d : η_{mn} ~ $(W/d)^2$ without modulation and efficiency is small
- W < d : η_{mn} ~ W/d with modulation and efficiency is better than with cw-ECCD

⇒ **deposition should be well localized and modulated for W < d**

Prediction of stabilisation for modulated ECCD



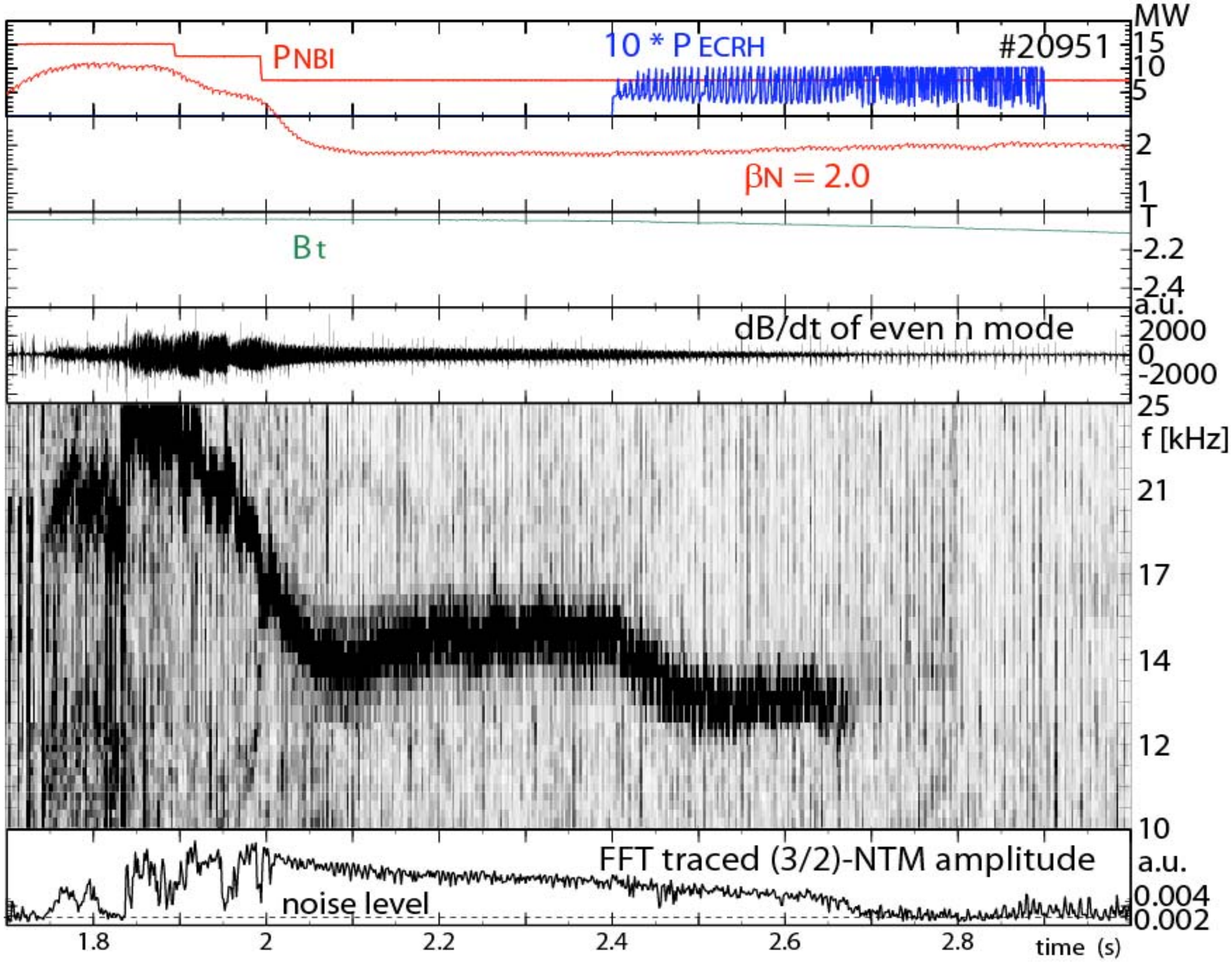
nonlinear MHD code
with 2D transport:

- equil. current profile taken
- 50% duty cycle

(Q.Yu, IAEA 2006
M.Maraschek, subm.
to PRL)

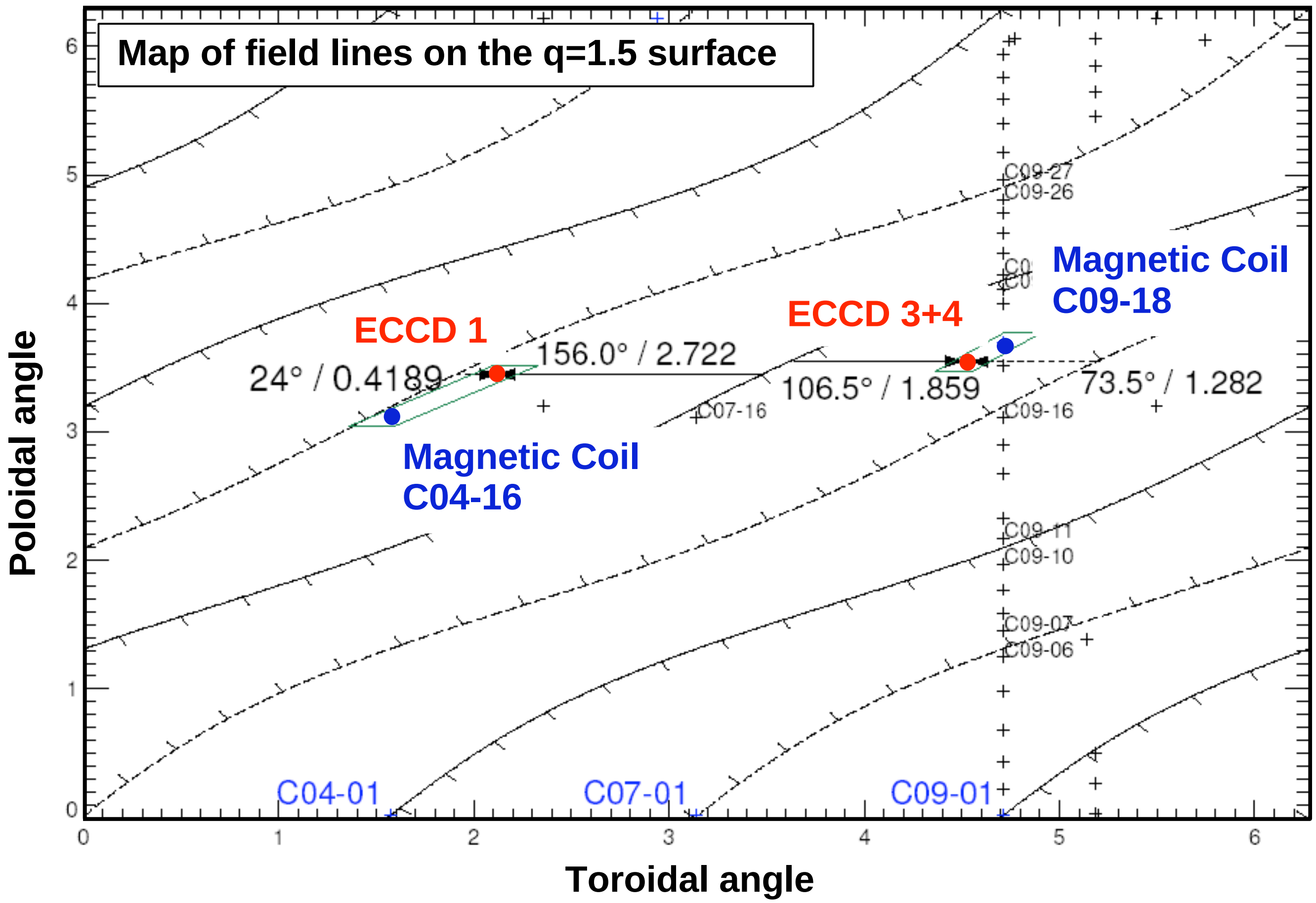
- very broad deposition → no stabilisation possible at all
- intermediate width → stabilisation can be regained for O-point modulation
- X-point modulation is predicted to be destabilising

NTM - stabilisation with modulated broad ECCD



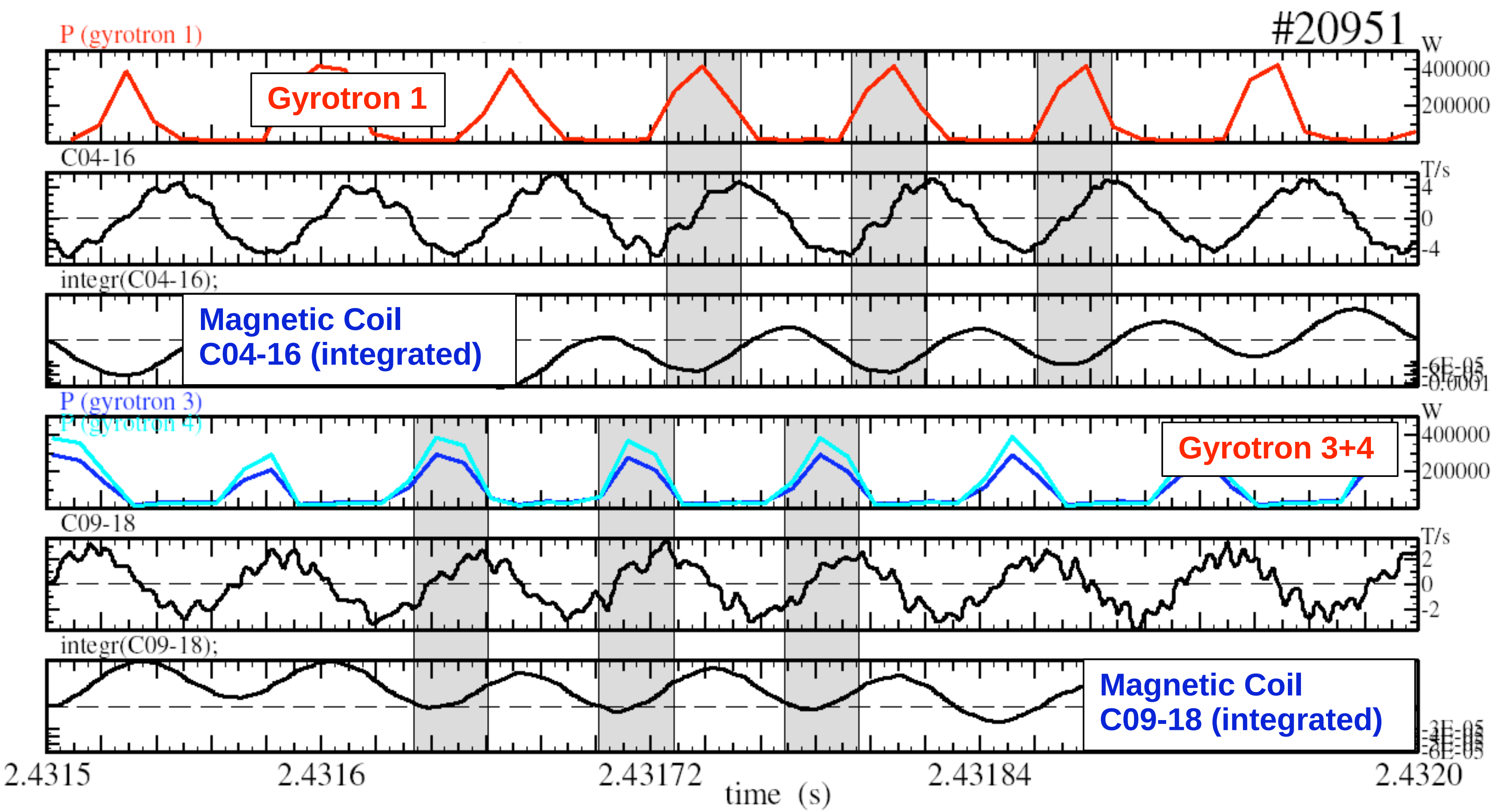
- O-point phasing can again stabilise (3/2)-NTM
- possible for smooth (3/2)-NTM with installed P_{ECCD}

Mapping of the magnetic field lines required



- need to synchronise three gyrotrons at different positions with island
- requires mapping along field lines (magnetic coil as sensor for island)

Control of the phase with nearby control coils



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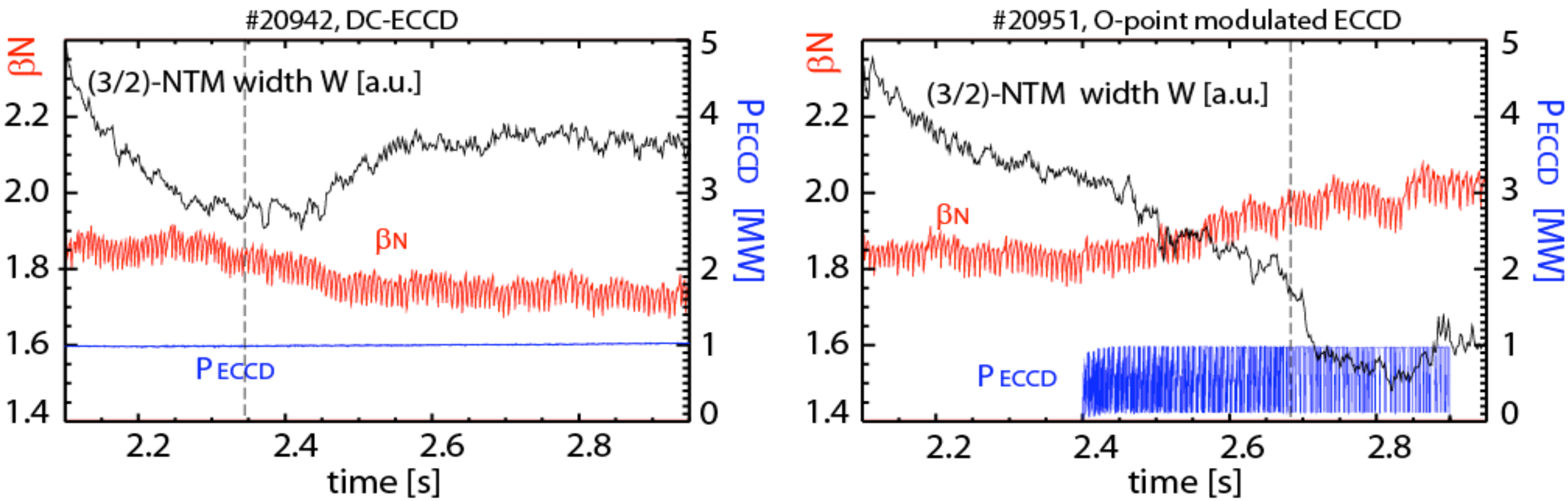
Comparison between cw-ECCD and modulated ECCD

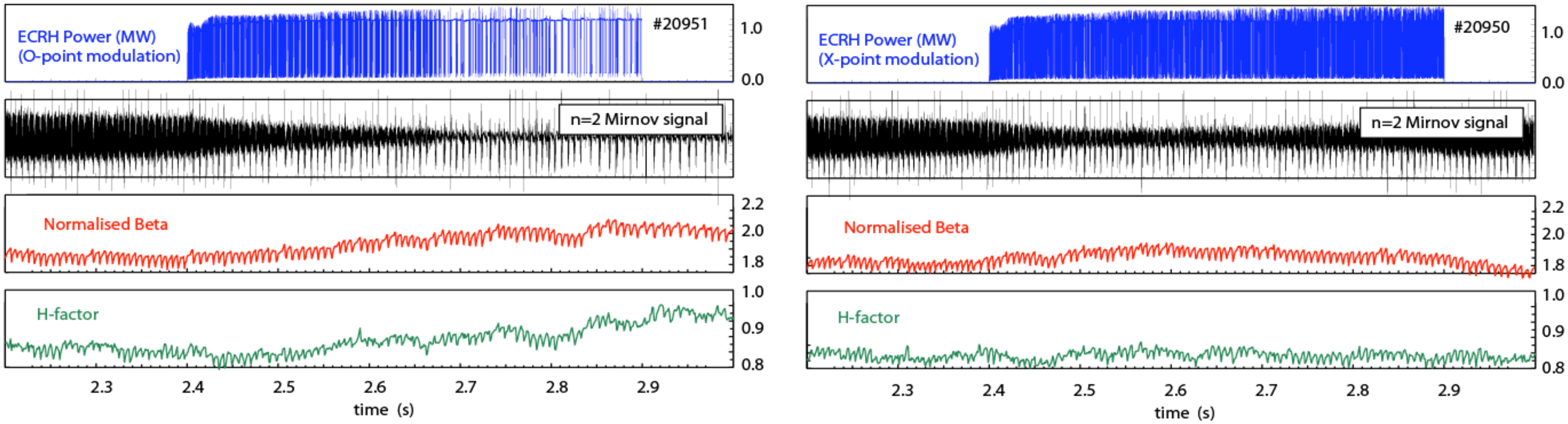


ASDEX Upgrade: NTMs rotate past ECCD antennae (plasma rotation)

- need to modulate gyrotron with island frequency of 30kHz
- 30 kHz modulation problematic, but ITER has lower rotation (2-3kHz)
  ⇒ however, narrow deposition highly desirable

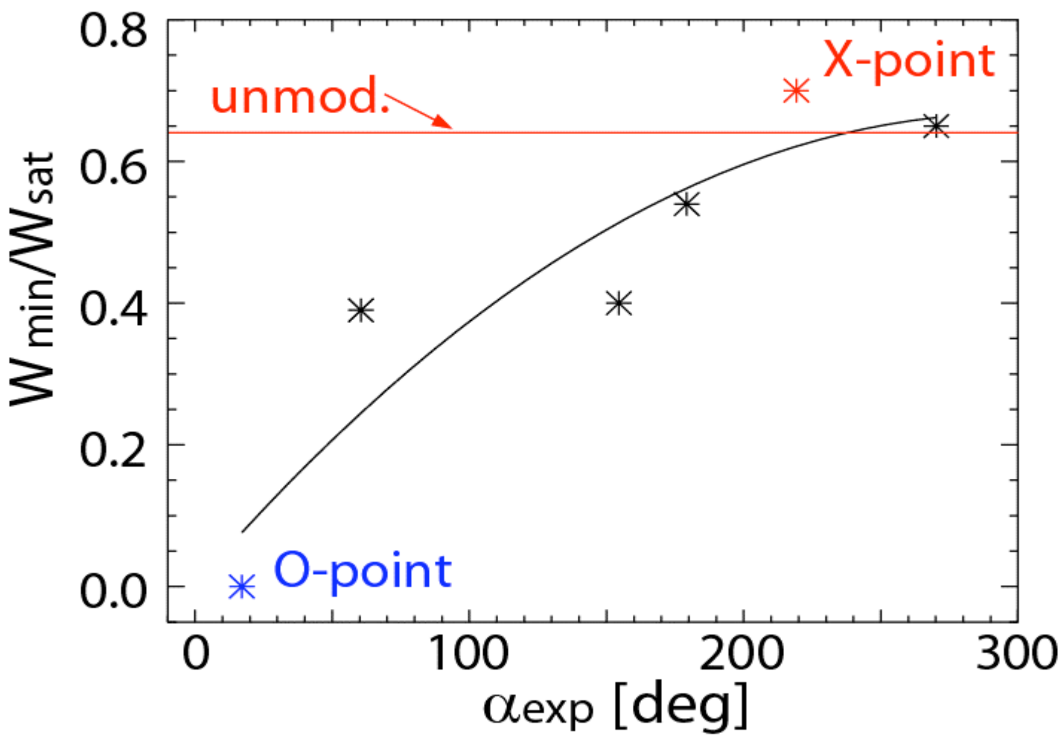
- regain of stabilisation with O-point modulation compared to cw-ECCD

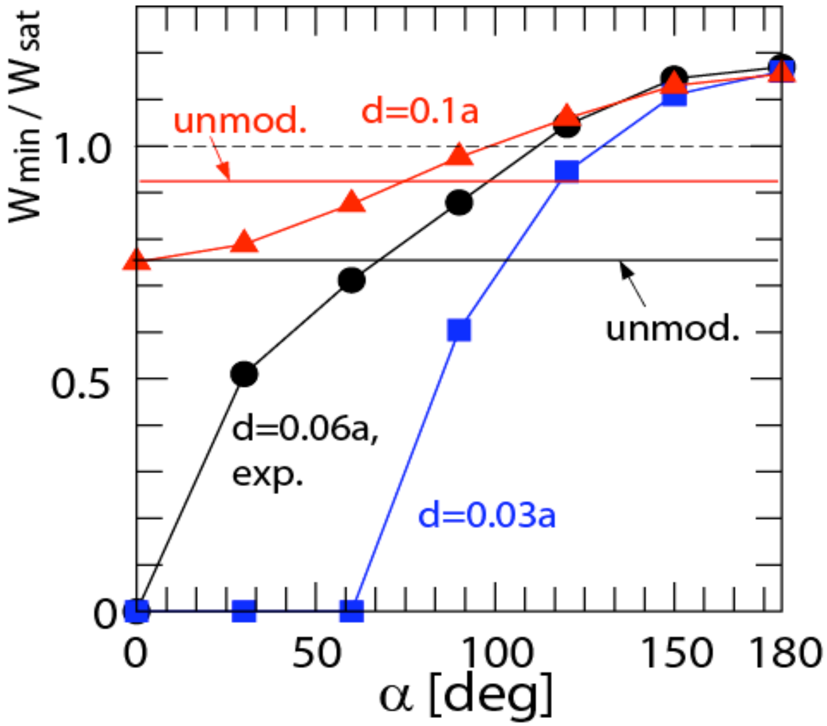
Comparison between O and X-point modulated ECCD



- weak, but still stabilising effect of ECCD in X-point
- clearly increased β_N and H-factor for O-point case compared to X-point case

Experimental ECCD phase dependence of island size

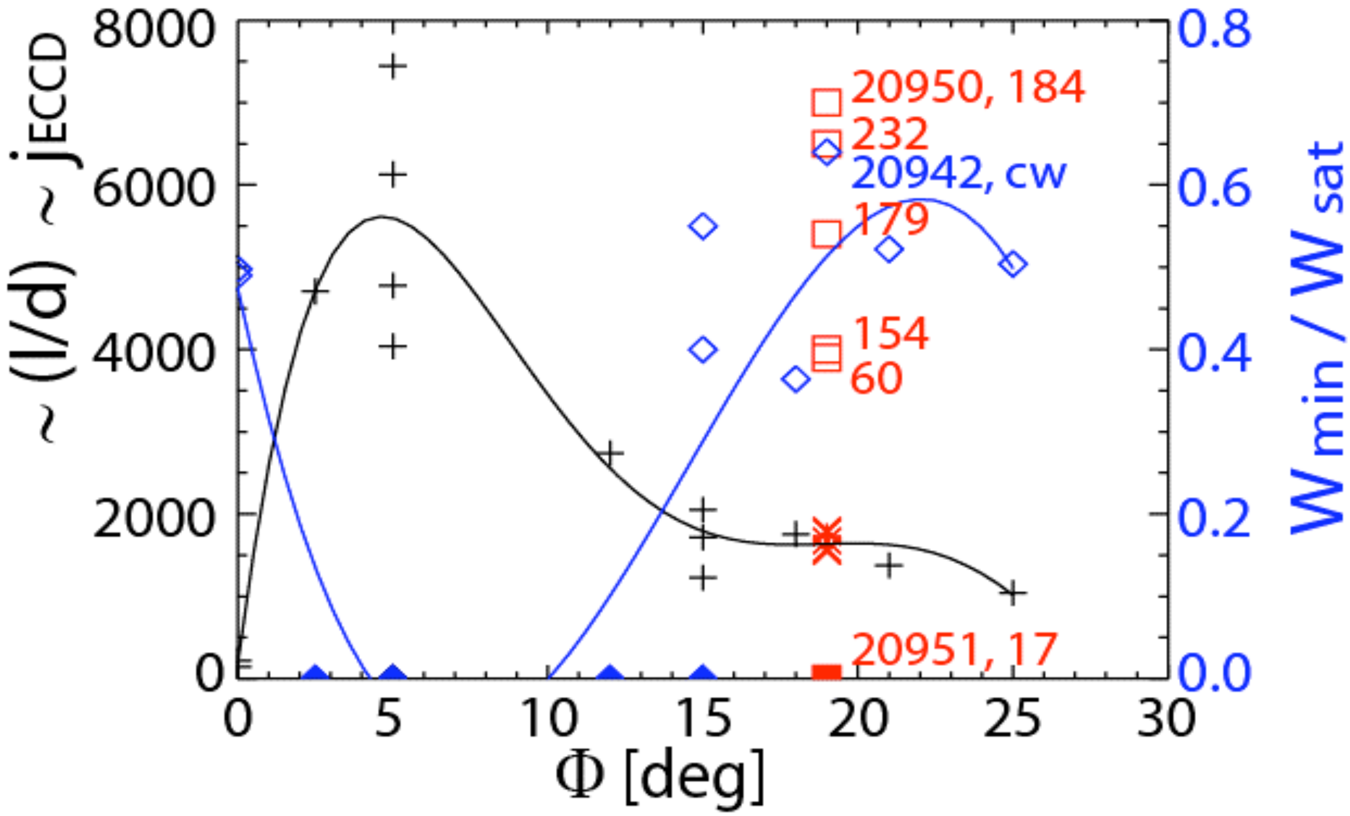




- dependence of island size reduction could be perfectly reproduced
- X-point phasing worse than non-modulated, remaing Δ’ effect,
- current profile not adjusted to experiment

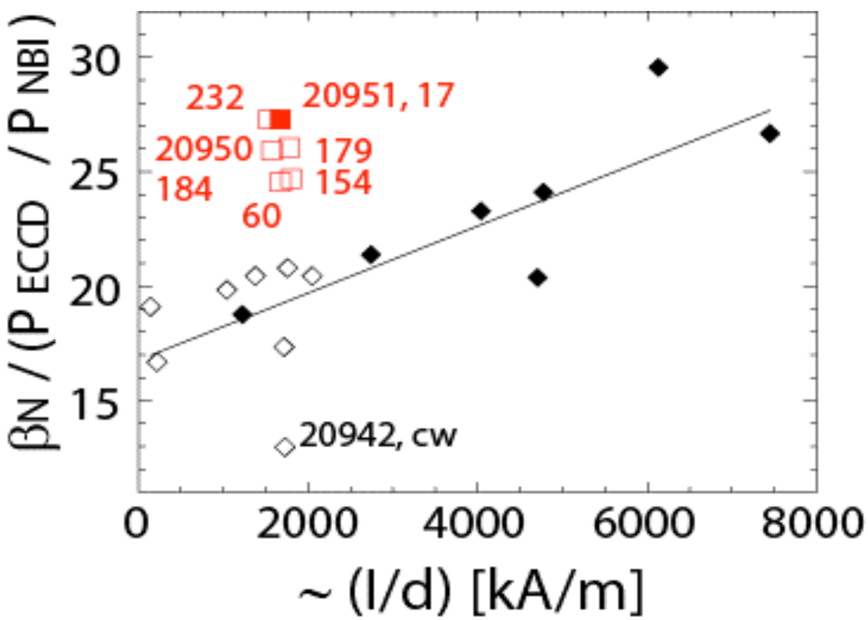
(M.Maraschek, subm. to PRL)

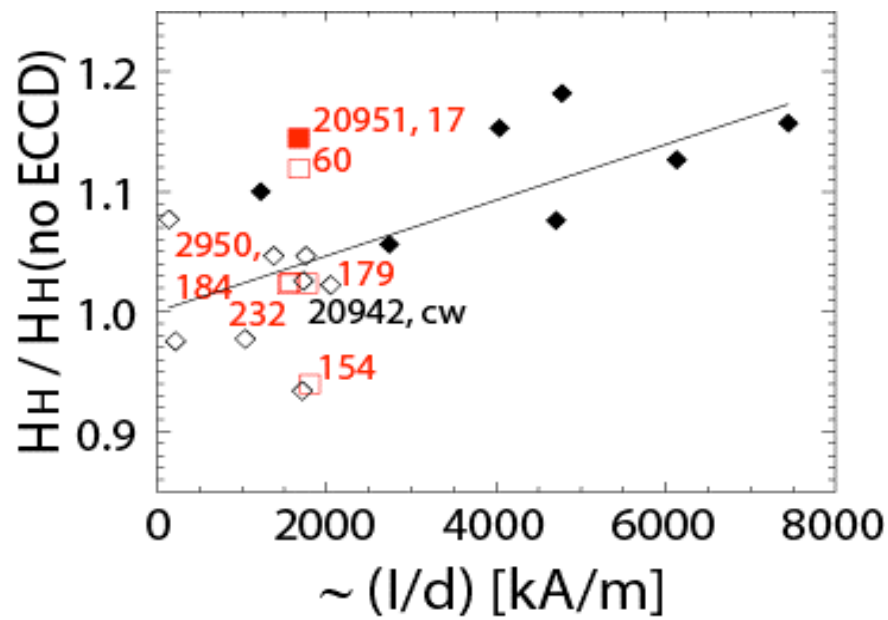
Stabilisation capability with modulated ECCD



- Variation of stabilisation as function of phase angle and resulting current peaking $I_{ECCD}/d \sim j_{ECCD}$
- O-point: regain of stabilisation
- X-point: worse than DC ECCD

What do we gain in performance ?





- increase in β_N and H_H / H_H (no ECCD) with increased current peaking $I_{ECCD}/d \sim j_{ECCD}$ for unmodulated cases
- additional improvement for O-point modulated cases for both figures of merit for given current peaking

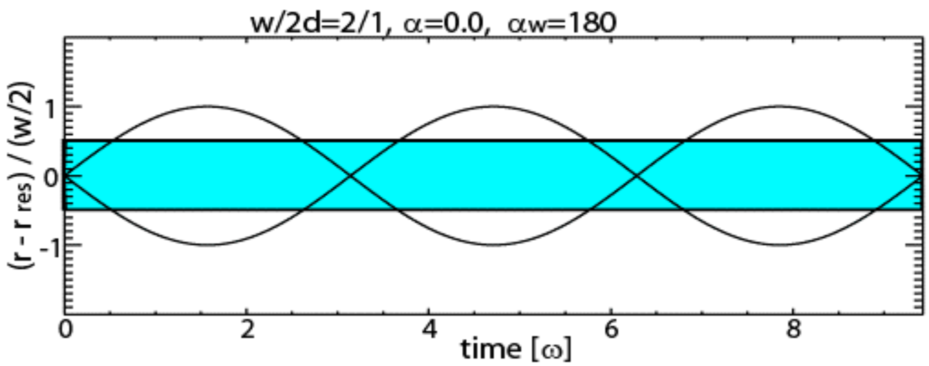
Summary and conclusions

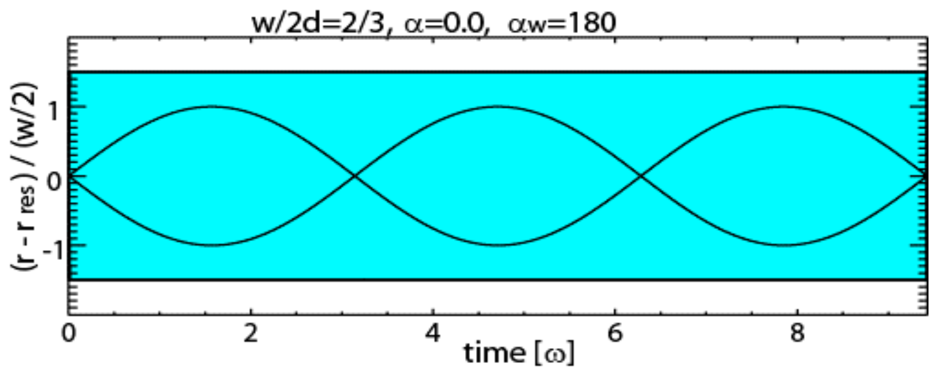
- extended depostion width scan verifies previous results
- O-point modulation of ECCD regains stabilisation
- X-point modulation worse than cw-ECCD
- phase scan consistent with theory
- improvement in achievable pressure and confinement

- modulation highly desirable for ITER ECRH in addition to optimisation of the deposition width

END

Status and perspective of constant ECCD





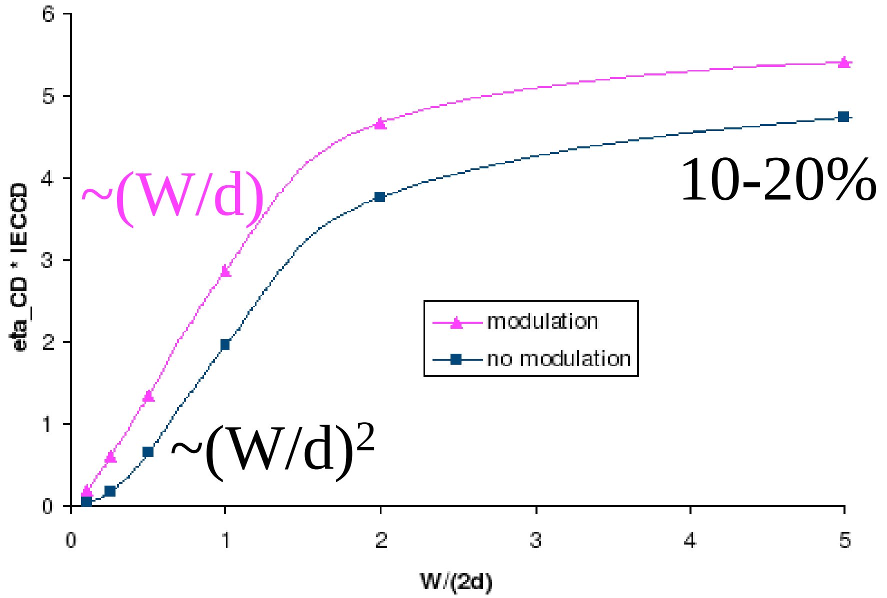
present experiments: $2d < W_{marg}$

ITER, large exp. due to Lamor radius: $2d > W_{marg}$

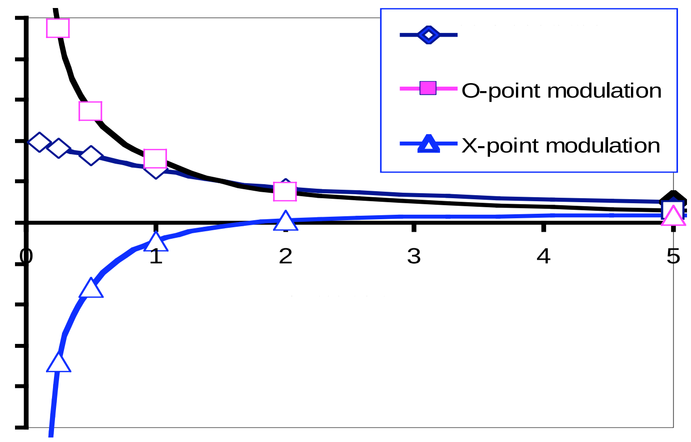
- in ITER / any larger experiment $2d > W_{marg}$ is likely:
  - launcher geometry (technics),
  - device independent marginal island size ~ ρ_{pi} (physics)

- driving helical current within the island is relevant
  $\Rightarrow$ O-point modulation of co-ECCD

Efficiency of the overall stabilisation



helical current only



helical current + Δ’

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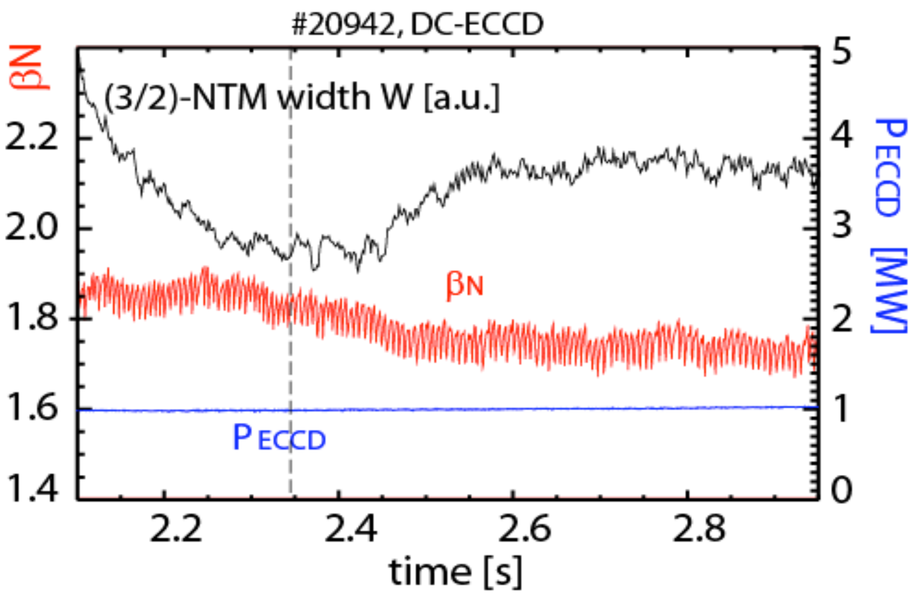

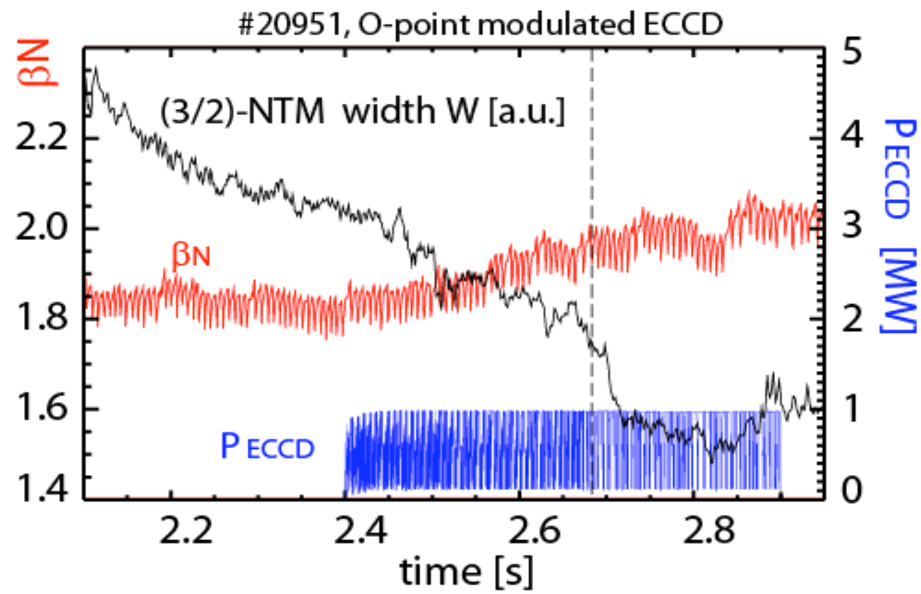

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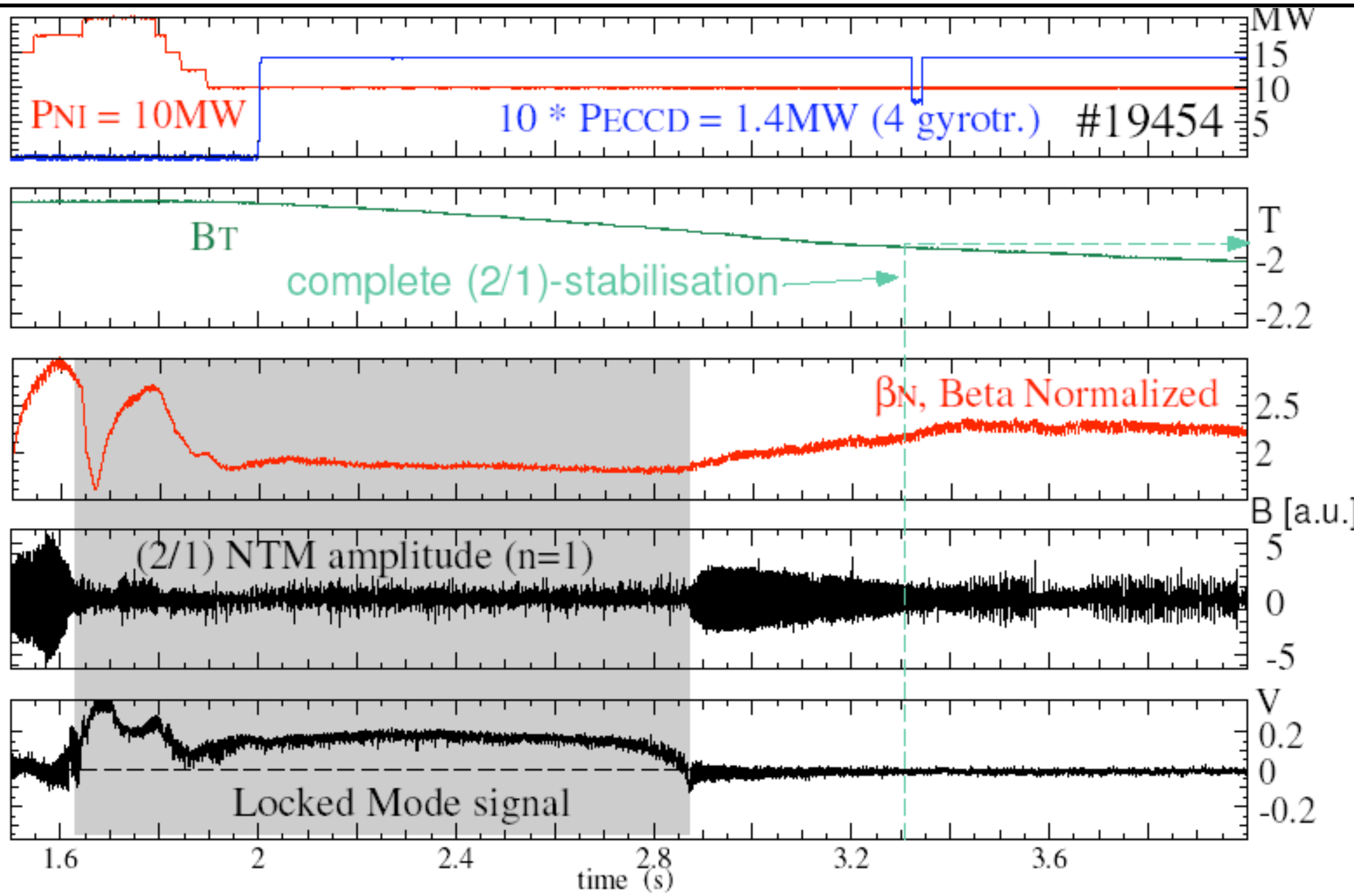
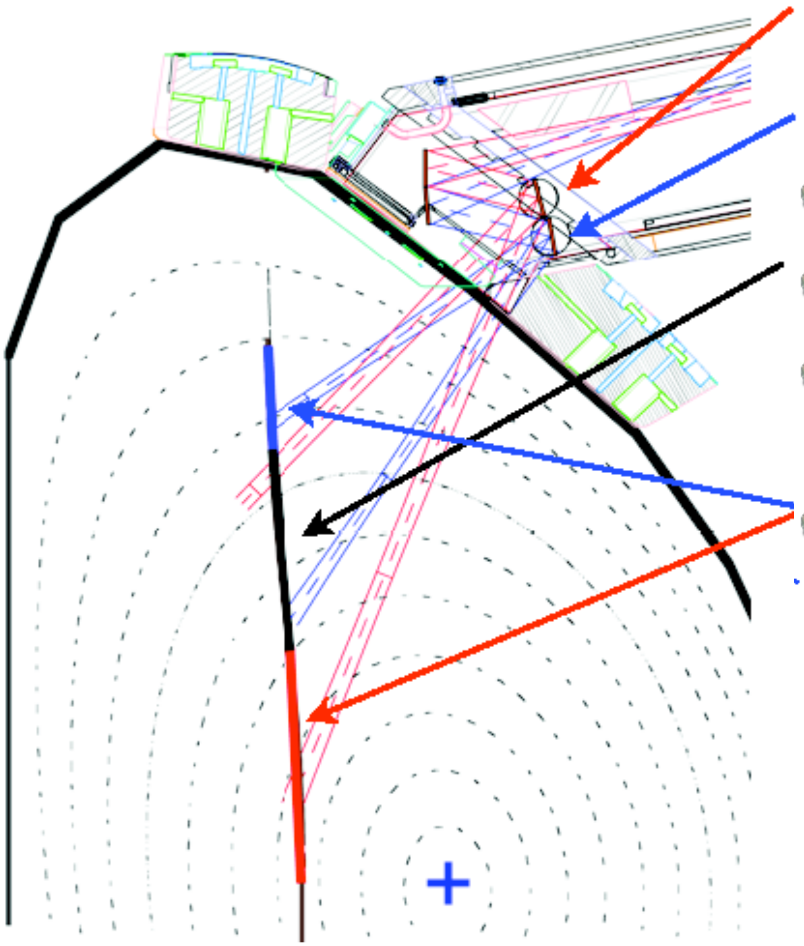
Recent progress in validating physics requirements



Narrow deposition allows (2,1) stabilisation at higher β_N than before

- full stabilisation at β_N = 2.3 with 1.4 MW (β_N = 1.9/1.9 MW for broad dep.)
- but: for (2,1) stabilisation, still power limited (should do this at β_N = 3!)

Present Lines of Optimisation: FS Upper Launcher



- Use upper steering row to access inner surfaces
- Use lower steering row to access outer surfaces
- 20MW applied over principle NTM region $0.75<\rho_\psi\leq0.88$
- 13.3MW over $0.38<\rho_\psi\leq0.75$ and $0.88<\rho_\psi\leq0.93$

Beam penetration not prependicular to flux surfaces:

- j_{ECCD} is more than sufficient, but still relatively broad deposition
- major redesign of ITER ECRH required to gain smaller $Z_{launcher}$!

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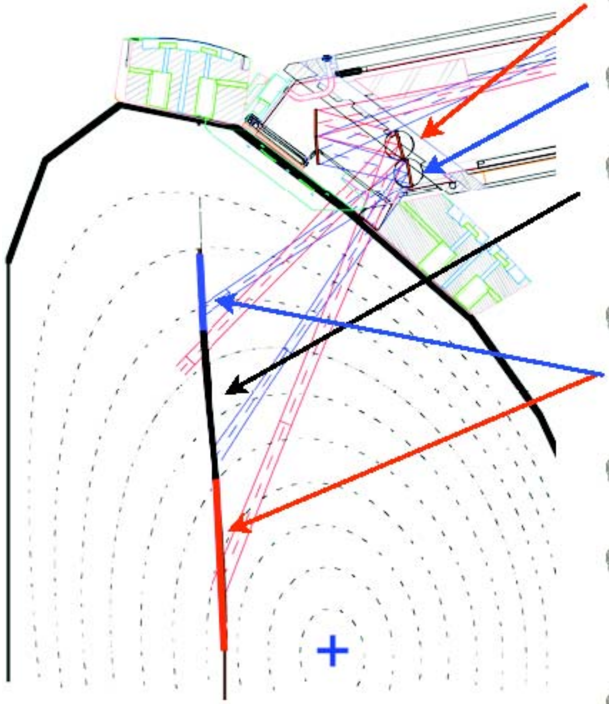

- 4 Ports or 32 entries for 24 gyrotrons
- Use upper steering row to access inner surfaces
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- Decreases opening in first wall
- Decreases overall rotation (fatigue) of steering mechanism
- Maintains $\eta_{NTM}=1.2$ (with $\leq$13MW)

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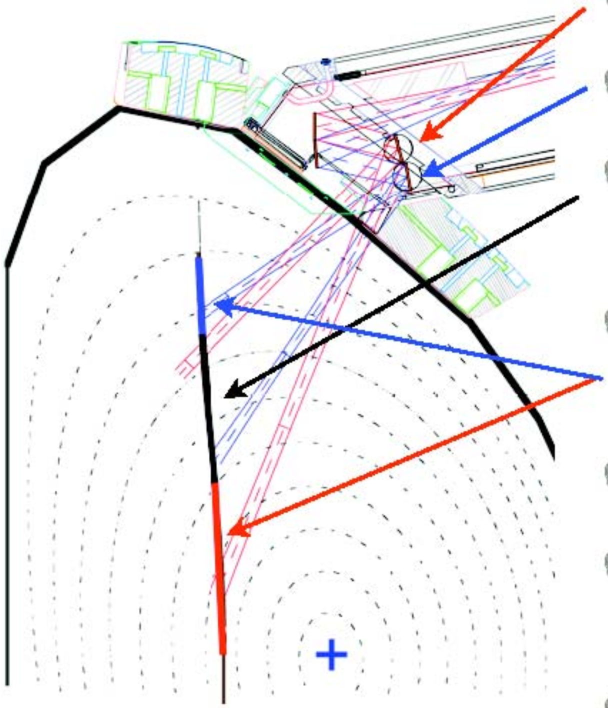

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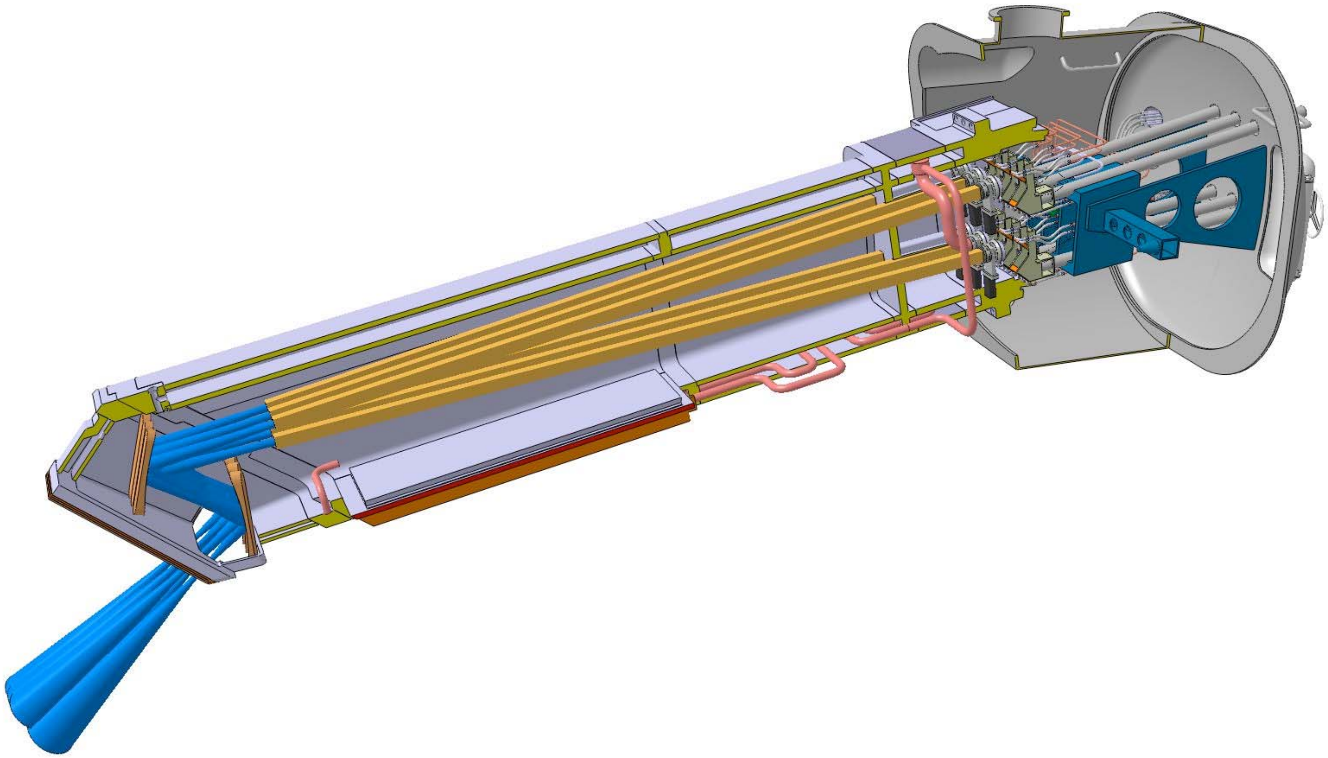
Possibilities to enhance FS Upper Launcher performance:

- since j_{ECCD} is more than sufficient, steering range can be expanded
- partitioning of power in the different rows can enhance flexibility

The present system design: Upper Launcher



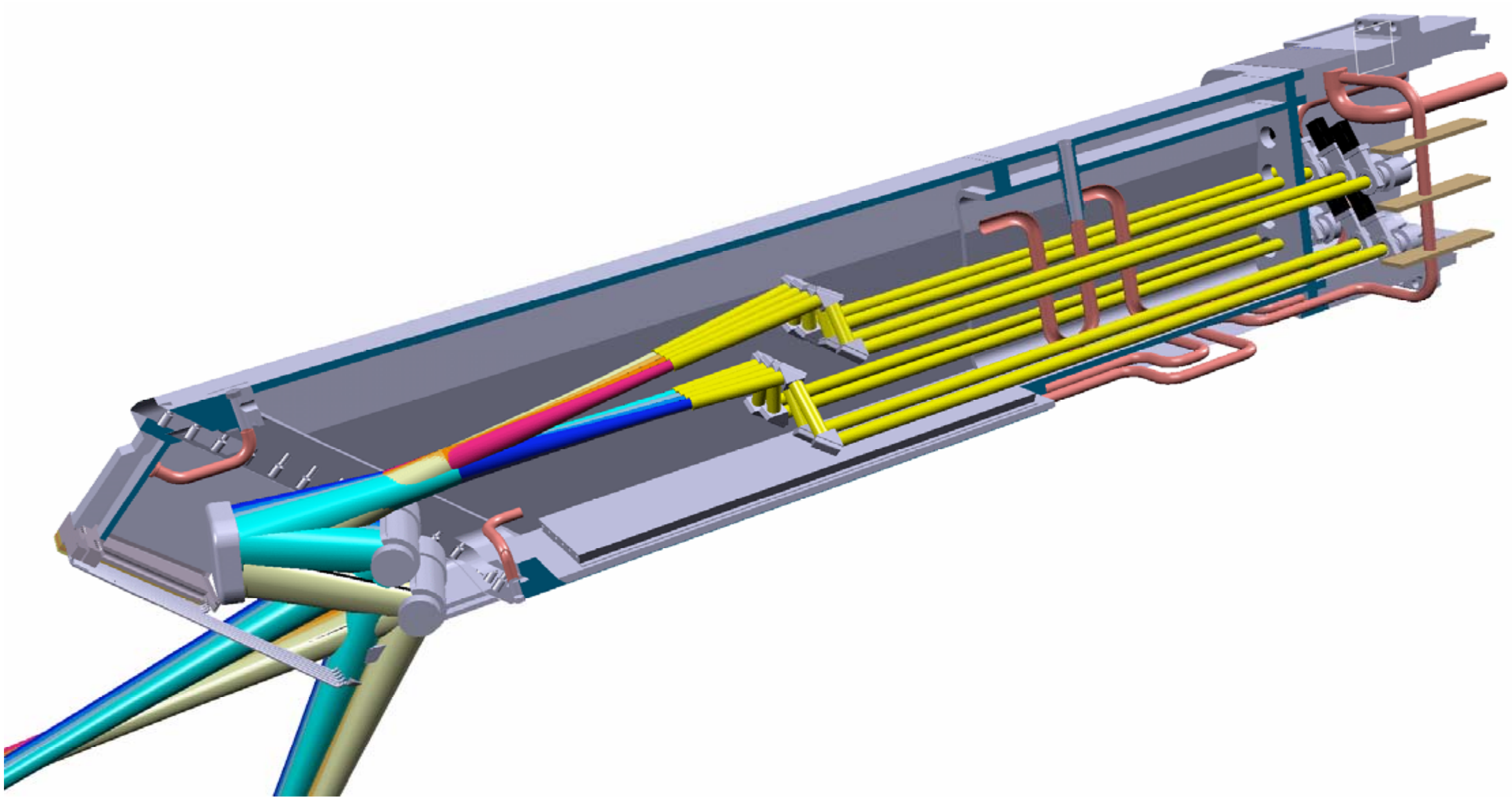
Alternative design based on remote steering

• no moving parts close to plasma

but: spot size in plasma much bigger than for front steering

⇒ physics perfromance reduced w.r.t. that of front steering solution

The present system design: Upper Launcher



Reference design(s) based on front steering

- upper launcher: poloidal (remote) steering range ±8-10º at front mirror

  launched from 3 ports in 2 rows of 4 beams per row

  biggest challenge: engineering of moving parts at front end