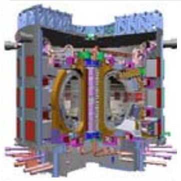


Max-Planck-Institut für Plasmaphysik

NTM control in ITER

M. Maraschek for H. Zohm

MPI für Plasmaphysik, D-85748 Garching, Germany, EURATOM Association

- ECRH in ITER
- physics of the NTM stabilisation
- efficiency of the stabilisation
- gain in plasma performance with suppressed NTM
- application to present day scenarios
- avoidance: sawtooth avoidance, early ECCD
- summary and conclusions

Physics Objectives of ECRH in ITER

Central heating and current drive

- heating to ignition – one of 3 systems (P_{AUX}=40-50 MW at Q=10)
- needs full central absorption with good CD efficiency

H&CD in steady state / long pulse scenarios (reversed shear / hybrid)

- present scenario does not foresee ECRH for off-axis CD
- ECCD at $0.5<\rho<0.7$ could play a role in reversed shear scenario

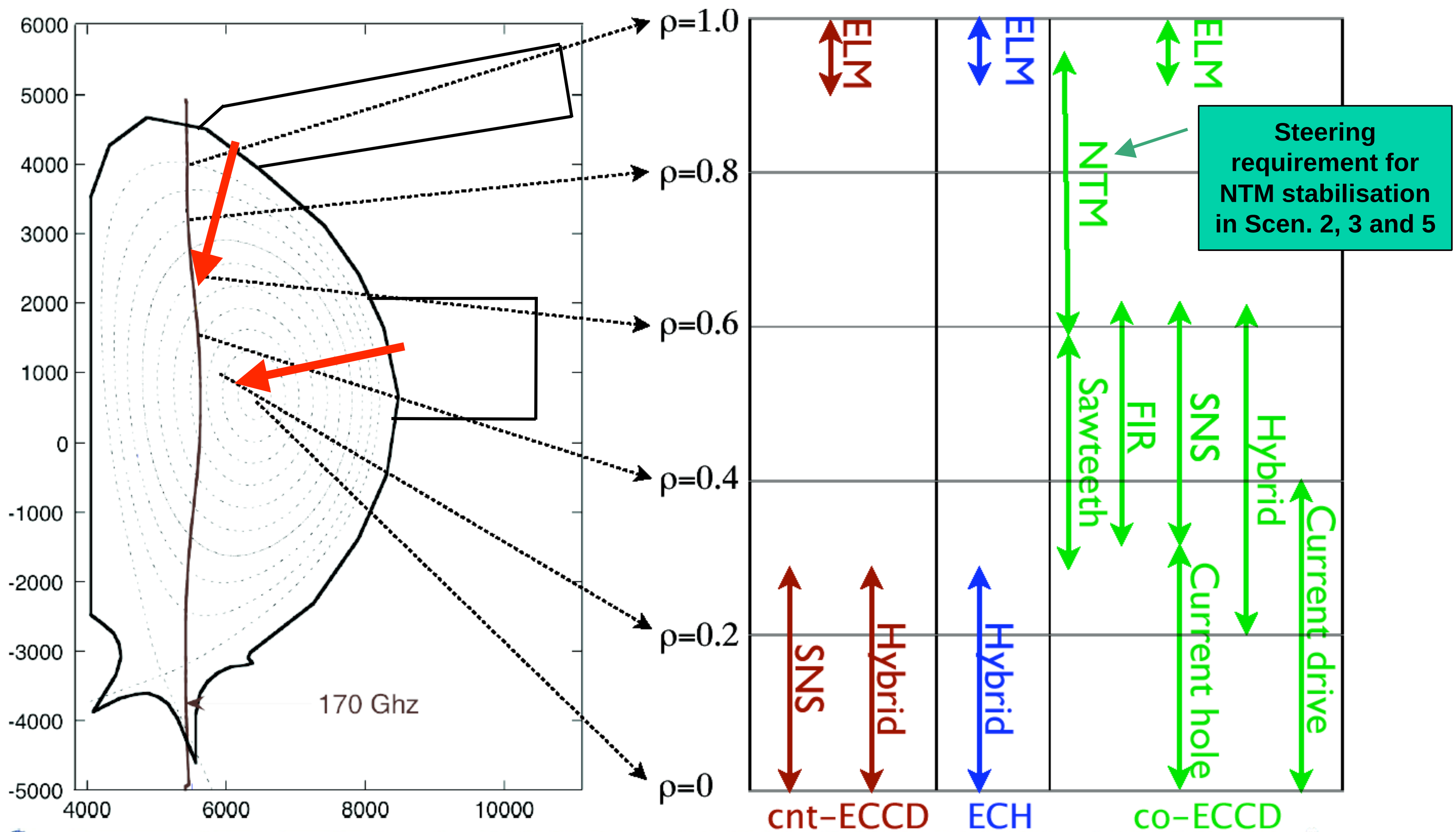
Control of MHD modes

- sawtooth control – localised CD at q=1 surface (ρ = 0.5)
- NTM control - needs far off-axis (ρ>0.7) CD with good localisation
- ELM control potentially interesting, needs very peripheral (ρ > 0.9) CD

Plasma Startup

- 3 MW for breakdown assist and voltsecond saving in current ramp-up

Physics Objectives of ECRH in ITER



M.A. Henderson et al.

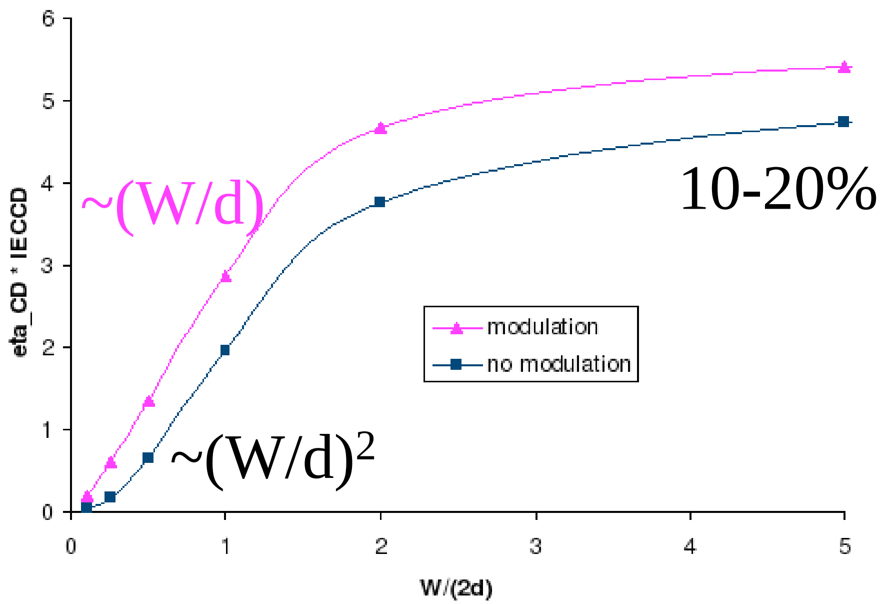
Physics of the NTM stabilisation

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

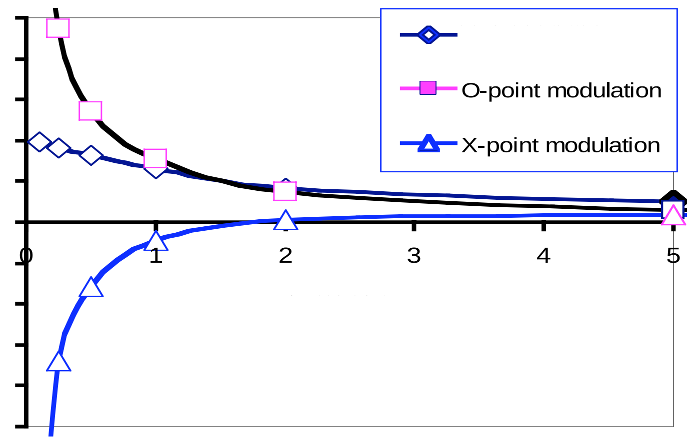
- helical (m,n) current in the island, a_{mn} – works on nonlinear stability (suppression of existing mode)
- modification of equilibrium (0,0) current profile, a_{00} – also linear stability (prevention of mode)

- $\eta_{mn} = j_{ECCD} / j_{bs}$, 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

Efficiency of stabilisation



helical current only



helical current + Δ'

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

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

Launcher requirements: power / focusing

Modelling using the Rutherford equation has led to the definition for η_{mn}

- $j_{ECCD}/j_{bs} < 1$: insufficient
- $1 < j_{ECCD}/j_{bs} < 1.2$: marginal
- $j_{ECCD}/j_{bs} > 1.2$: sufficient (try to take into account uncertainty of ~20%)

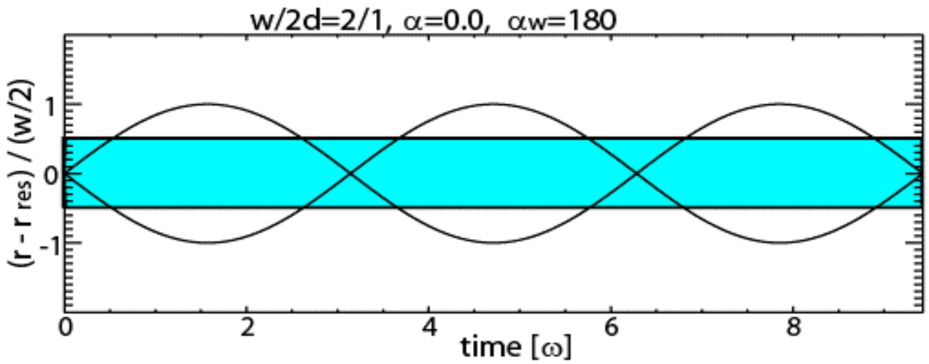
Figures of merit for NTM stabilisation by ECCD

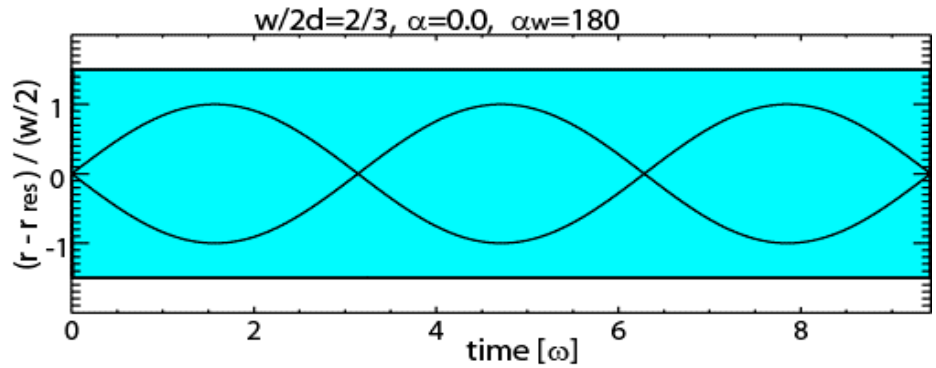
- equilibrium current profile: change in Δ' is determined by dj/dr: I_{ECCD}/d^2
- helical component: current within island counts : I_{ECCD} for $d < W$

  I_{ECCD}/d for $d > W$

$\Rightarrow$ no unique criterion, but *localised current profile* (small d) is favourable

Status and perspective of constant ECCD





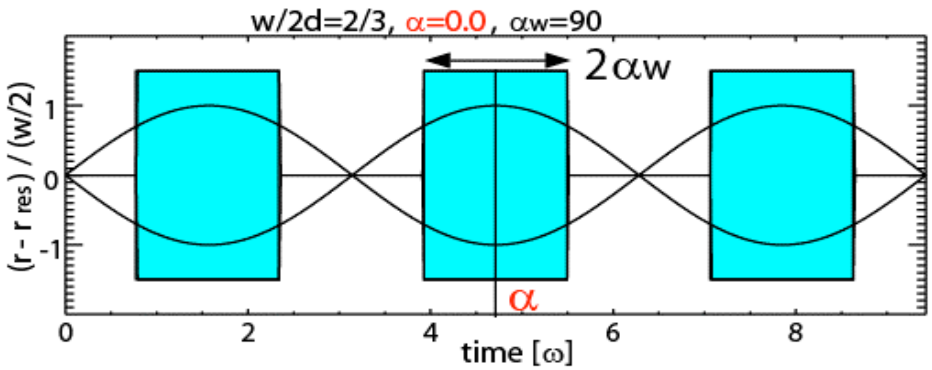
present experiments: $2d < W_{marg}$

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

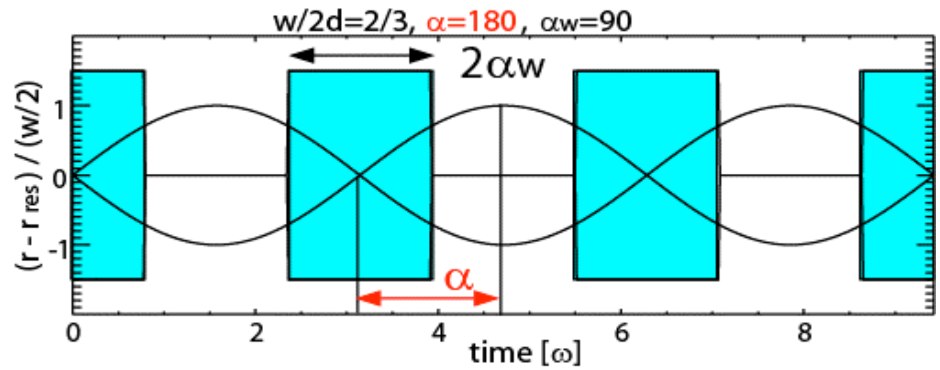
- in ITER / any larger experiment $2d > W_{marg}$ is likely:
  - launcher geometry (technics),
  - device independent marginal island size ~ ρ_{pi} (physics)

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

Phase locked modulated ECCD



O-point alligned co-ECCD



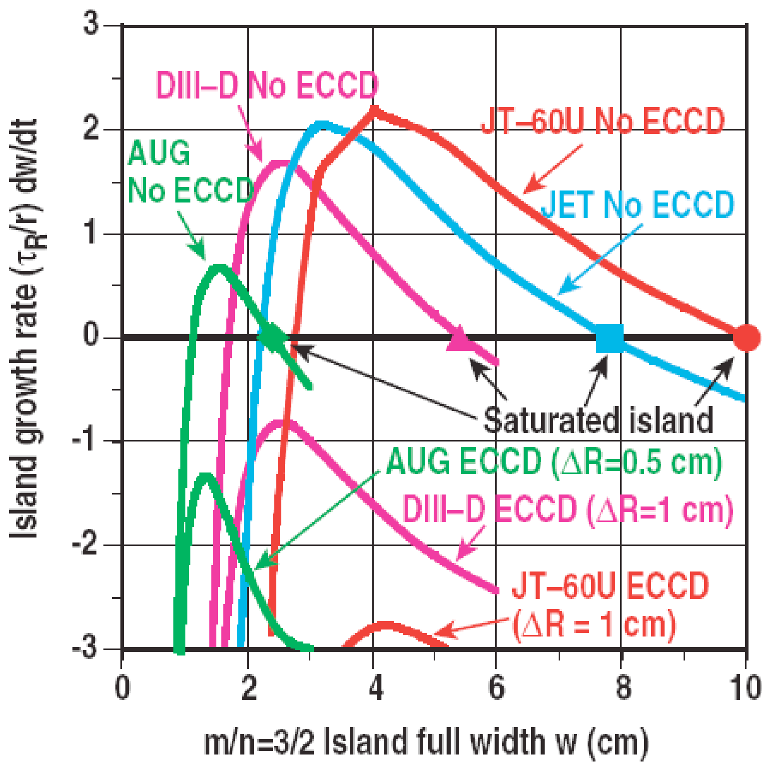
X-point alligned co-ECCD

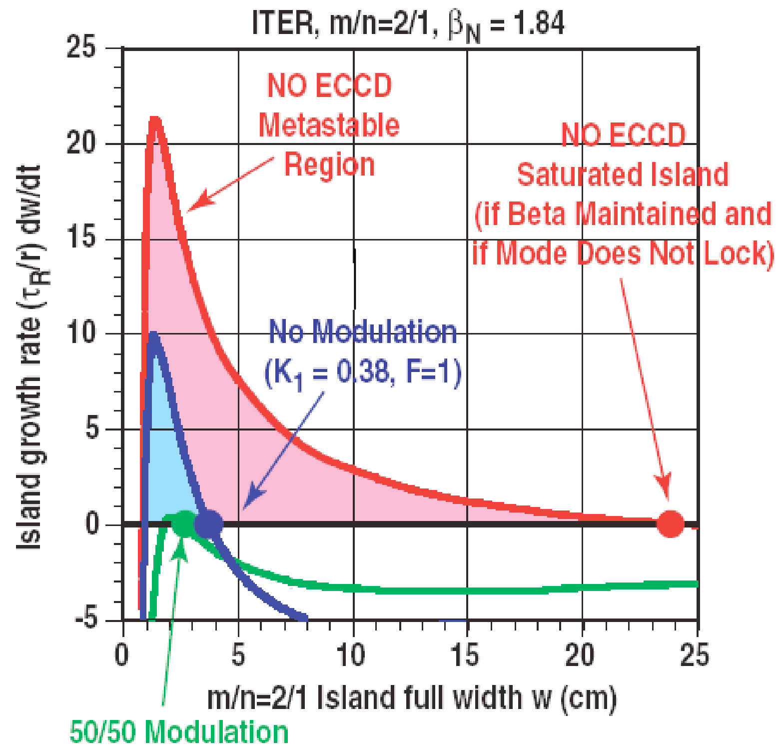
- O-point alligned modulated ECCD :
  the current is driven helically within the island , high η_{mn}
- X-point alligned modulated ECCD should give destabilising effect (wrong phase !) + more sensitive Δ'- effect

→ discussed in detail in the next talk

Possible misalignement ΔR of ECCD

Device	Shot #	β_N	q_{95}	j_{ec}/j_{bs}	j_{bs}/j_{II}
AUG	19713	2.7	3.85	3.1	0.21
DIII–D	122507	1.9	3.5	0.9	0.15
JET	47276	1.9	3.4	——	0.14
JT-60U	E41666	1.5	3.8	1.2	0.19





c_j=1, misalignment $\Delta R/\delta_{ec}$ for ITER:

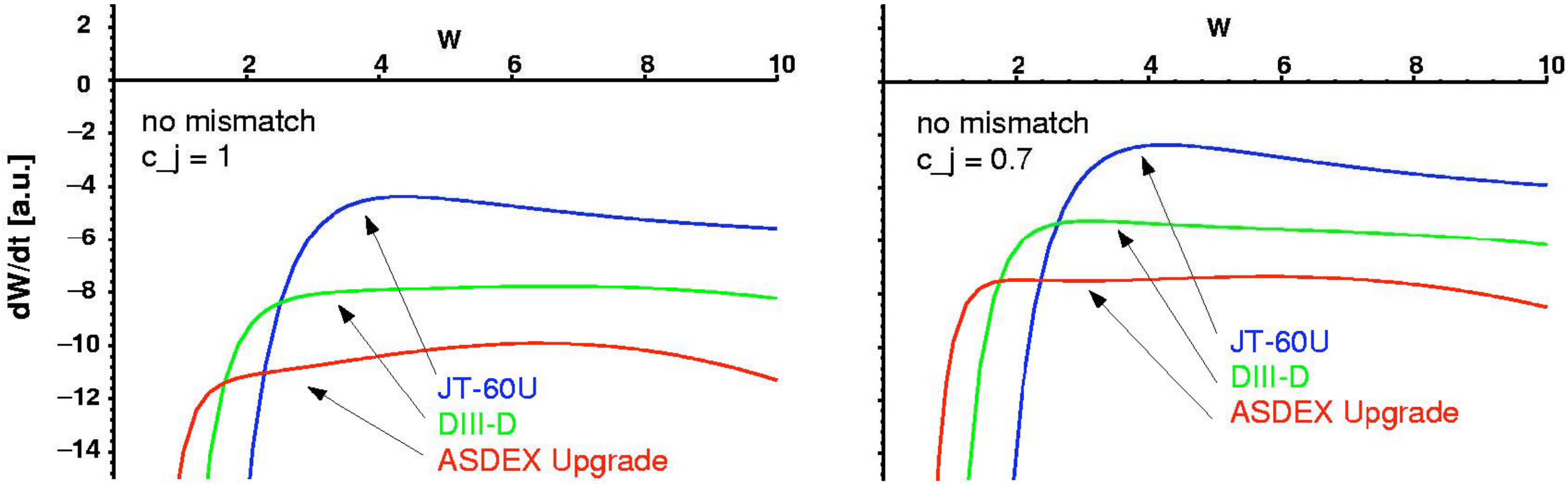
η_{32} = 0.75 .. 1.10, $\Delta R/\delta_{ec}$= 0 .. 0.27

η_{21} = 0.89 .. 1.63, $\Delta R/\delta_{ec}$= 0 .. 0.40

$\Delta R/\delta_{ec}$ sufficiently small

R. La Haye et al., NF 46 (2006), 451-461

Fit of the Rutherford equation, stabilisation efficiency

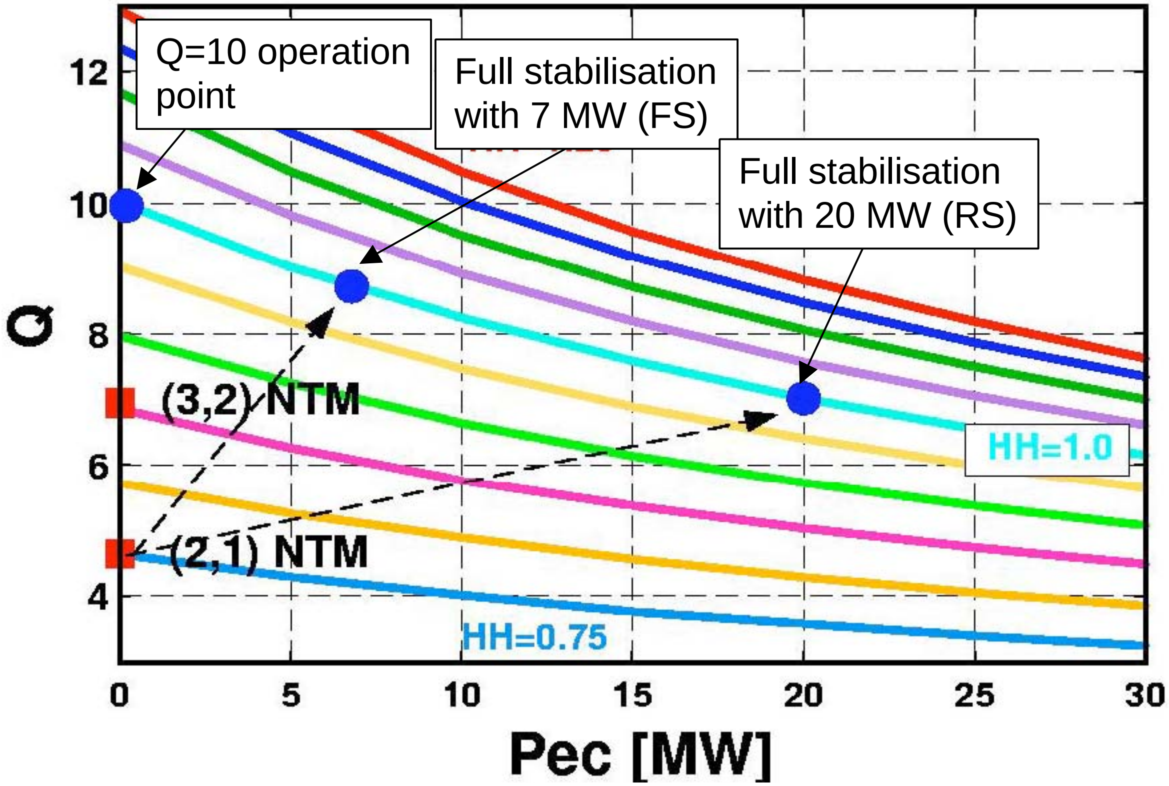


- fit to Rutherford equation gives overstabilisation, but not observed
  ⇒ introduction of c_j, no deposition mismatch
- (2/1)-NTM stabilisation in ITER:
  - no mismatch, $c_j = 0.7$ → $\eta_{21} = 1.26$
  - finite mismatch $\Delta R/\delta_{ec}=0.27$, $c_j = 1$ → $\eta_{21} = 1.26$

⇒ experimental input required to get P_{marg} (mismatch ↔ c_j)

L. Urso et al., Como meeting

Gain in performance with supressed NTM



ITER burn curves in the presence of ECCD at q=3/2 (A) and q=2 (B)

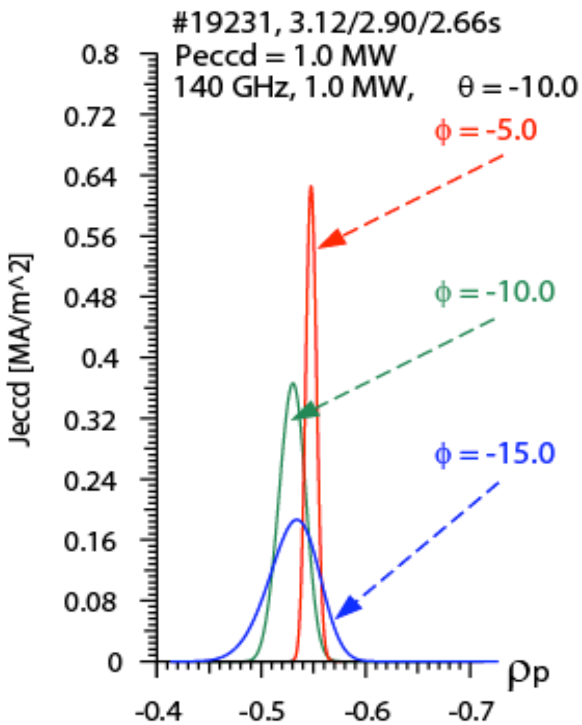
(O. Sauter and H. Zohm, EPS 2005, IAEA 2006)

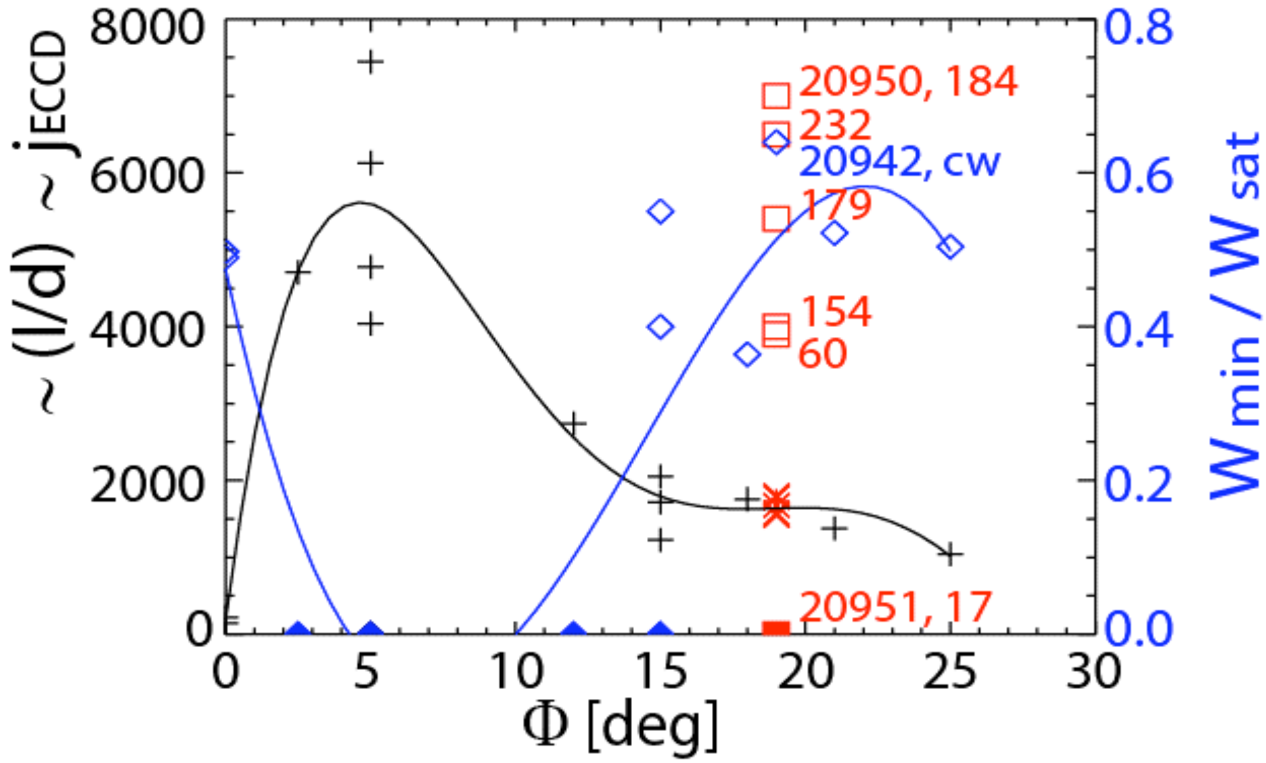
P_{ECCD} only partially included in Q (off axis)

Impact on Q in case of continuous stabilisation (worst case):

- Q drops from 10 to 5 for a (2,1) NTM and from 10 to 7 for (3,2) NTM
- with 20 MW needed for stabilisation, Q recovers to 7, with 10 MW to Q > 8
- note: if NTMs occur only occasionally, impact of ECCD on Q is small
- partial stabilisation might be better in Q than complete !

Progress in validating physics requirements



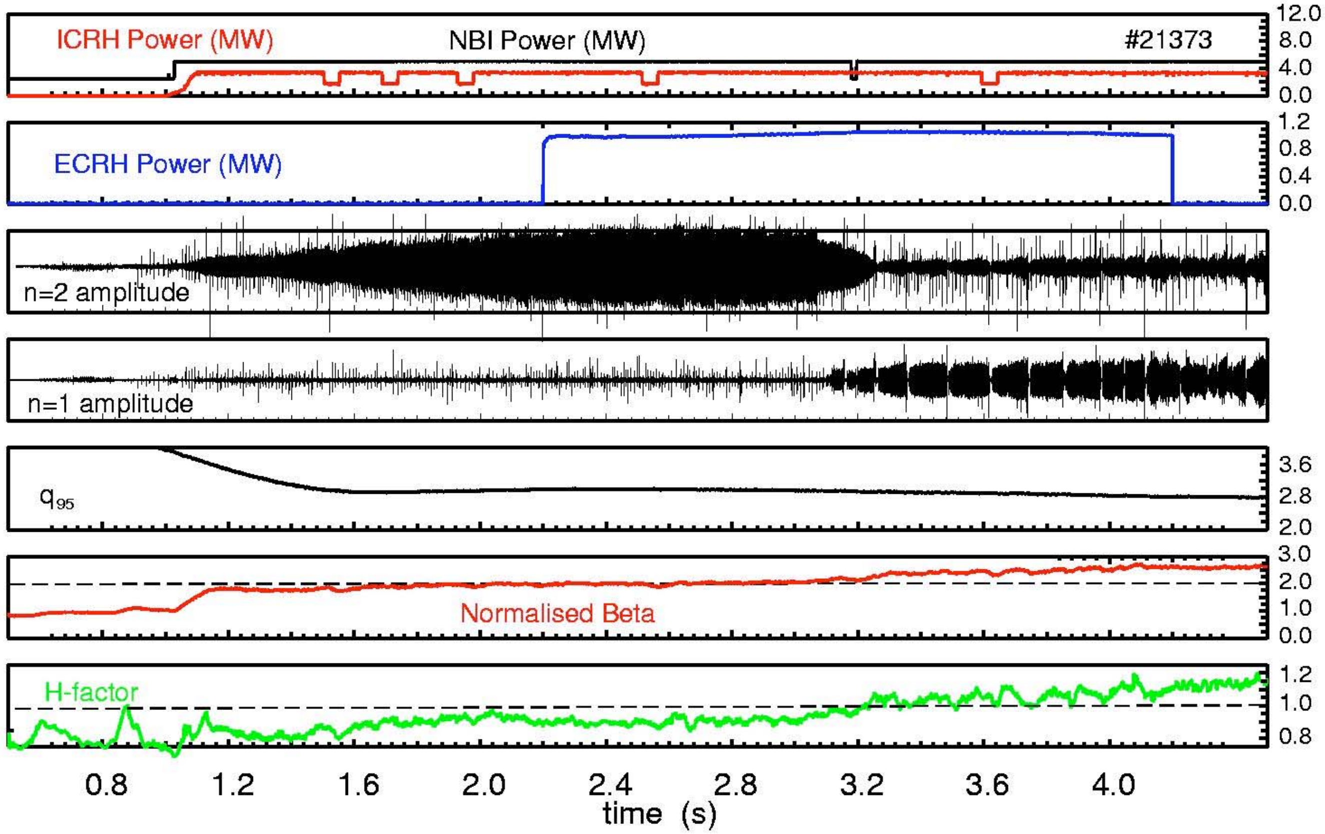


NTM stabilisation predicted to be most efficient at max(I_{ECCD}/d)

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

⇒ detailed discussion of modulation: next talk by M.Maraschek

NTM stabilisation in improved H-mode



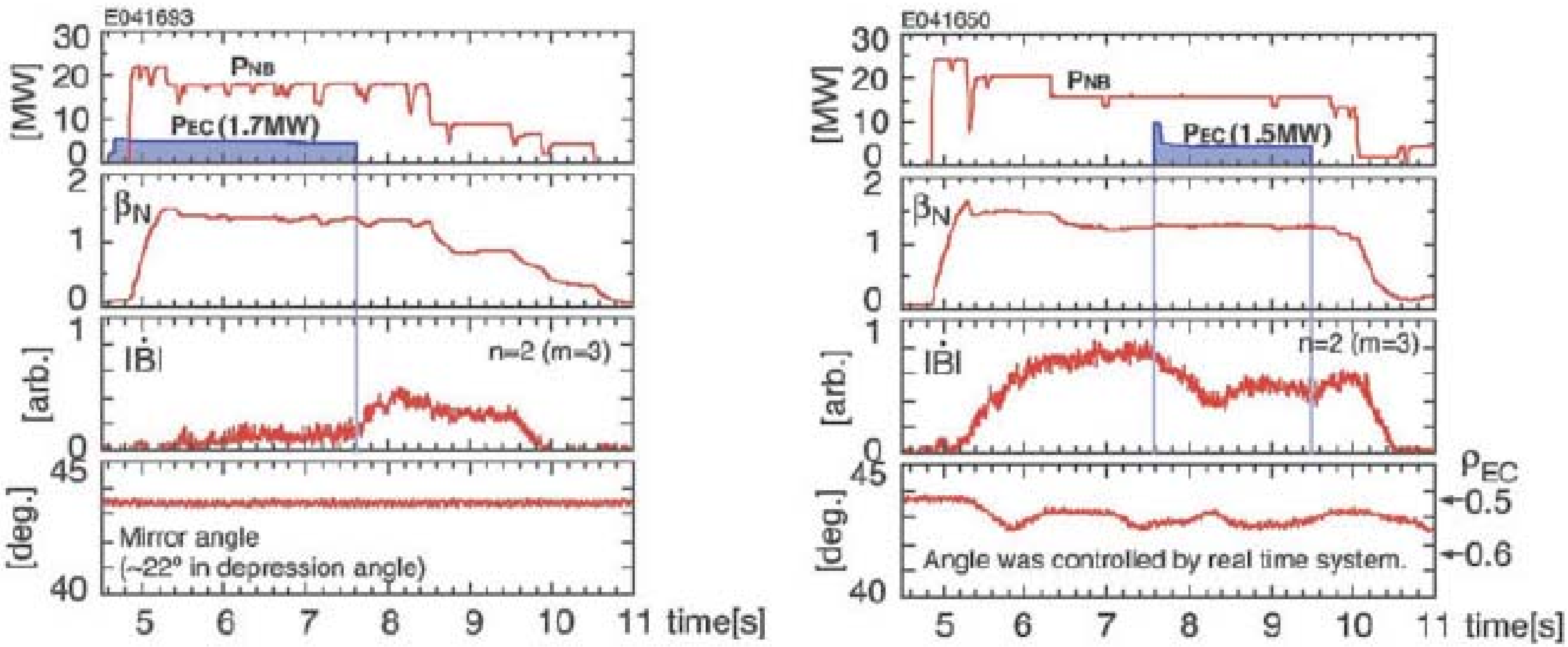
(3,2) NTM stabilisation in improved H-mode at low q_{95} = 2.9 (ITER value)

- after stabilisation, good improved H-mode conditions recovered (q-profile!)

Central MHD mode activity plays key role in achieving flat central shear

- NTM stabilisation may be used to optimise improved H-mode scenario!

Avoidance of NTMs as alternative ?



- early application of ECCD in JT 60-U
- first experiments at ASDEX Upgrade in 2005
- sawtooth avoidance with ECCD to remove NTM trigger

K. Nagasaki, et al., NF 43 (2003), L7-L10

Conclusions

main physical points:

- narrow deposition beneficial for NTM stabilisation
- for broad deposition modulation of ECCD needs to be foreseen
- including misalignment and / or c_j can resolve marginal stabilisation in present day experiments, but gives different predictions for ITER

technical considerations:

- Front Steering Upper Launcher is the main tool:
  - further optimisation for localisation d
  - extension towards q=1 for sawtooth avoidance ?
  - modulation should be considered

- note: the optimum system is purely based on Front Steering

open questions to resolve:

- marginal required ECCD power for stabilisation ⇒ better predictions

END

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% larger	~ 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

- consider polarisation current versus transport model
- neglect Δ´-effect of ECCD completely → conservative
- $c_j = 0.5$ → most pessimistic assumption

CW case

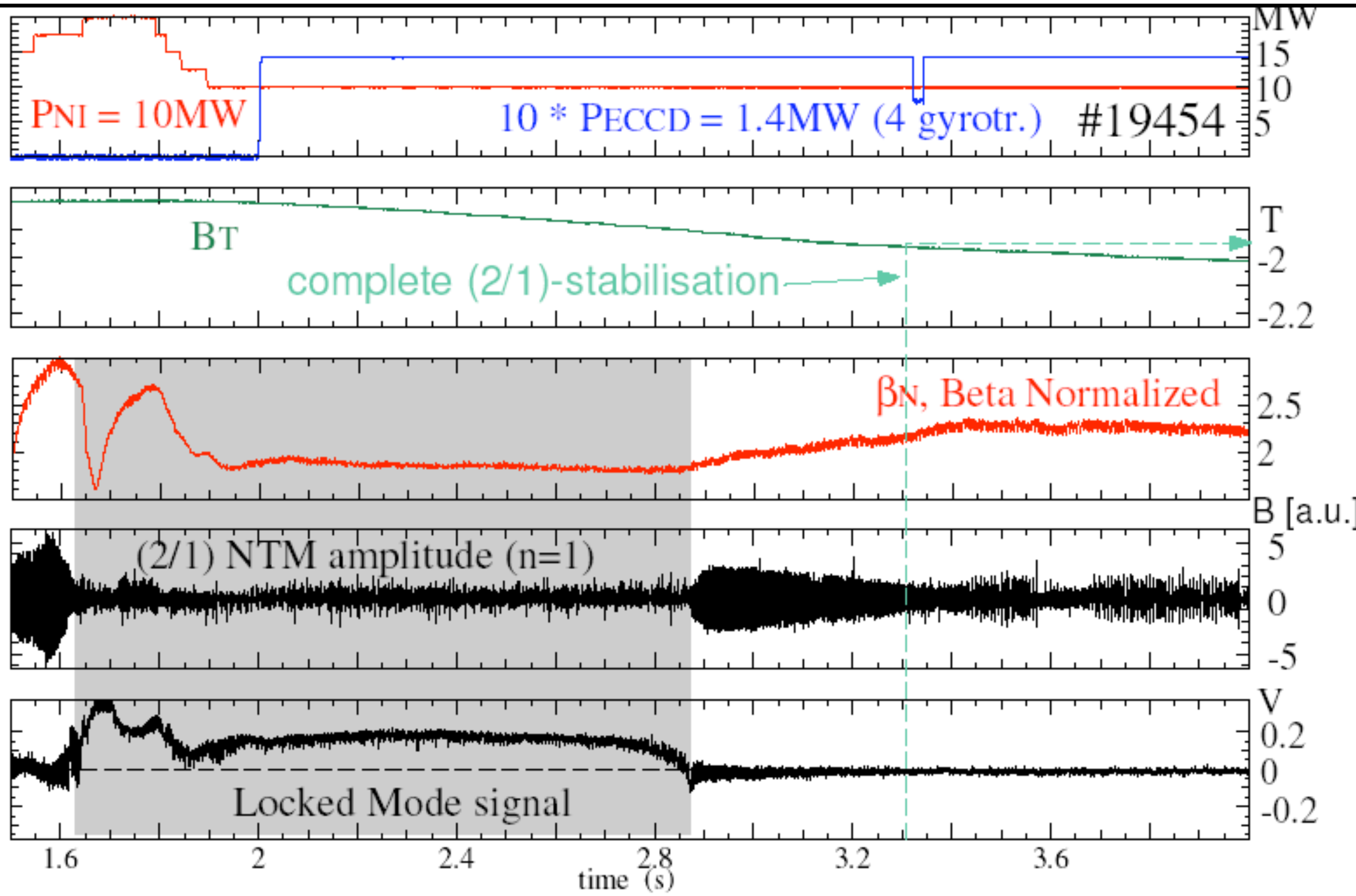
w_{marg}	$\chi_\perp$, 2.5cm	*pol*, 2.5cm	$\chi_\perp$, 5cm	*pol*, 5cm	$\chi_\perp$, 10cm	*pol*, 10cm
2cm	2.8	1.5	4.2	2.9	8.5	4.3
4cm	2.2	1.3	1.8	1.3	3.5	1.8
6cm	1.7	1.2	1.0	0.8	1.8	0.9
η_{NTM} ; $\eta_{NTM}W_{cd}$	2.23 ; 5.58	1.33 ; 3.33	2.33 ; 11.65	1.67 ; 8.35	4.6 ; 46	2.33 ; 23.3
η_{NTM} ; $\eta_{NTM}W_{cd}$	**1.78 ; 4.5**		**2.0 ; 10.0**		**3.47 ; 34.7**	

50% modulation case:

w_{marg}	$\chi_\perp$, 2.5cm	*pol*, 2.5cm	$\chi_\perp$, 5cm	*pol*, 5cm	$\chi_\perp$, 10cm	*pol*, 10cm
2cm	2.9	1.5	2.0	1.1	1.9	1.1
4cm	2.4	1.4	1.6	1.0	1.4	0.9
6cm	2.0	1.3	1.3	0.9	1.3	0.7
η_{NTM} ; $\eta_{NTM}W_{cd}$	2.43 ; 6.1	1.4 ; 3.5	1.63 ; 8.15	1.0 ; 5.0	1.53 ; 15.3	0.9 ; 9.0
η_{NTM} ; $\eta_{NTM}W_{cd}$	**1.92 ; 4.8**		**1.32 ; 6.6**		**1.22 ; 12.2**	

(O. Sauter and H. Zohm,
EPS 2005, IAEA 2006)

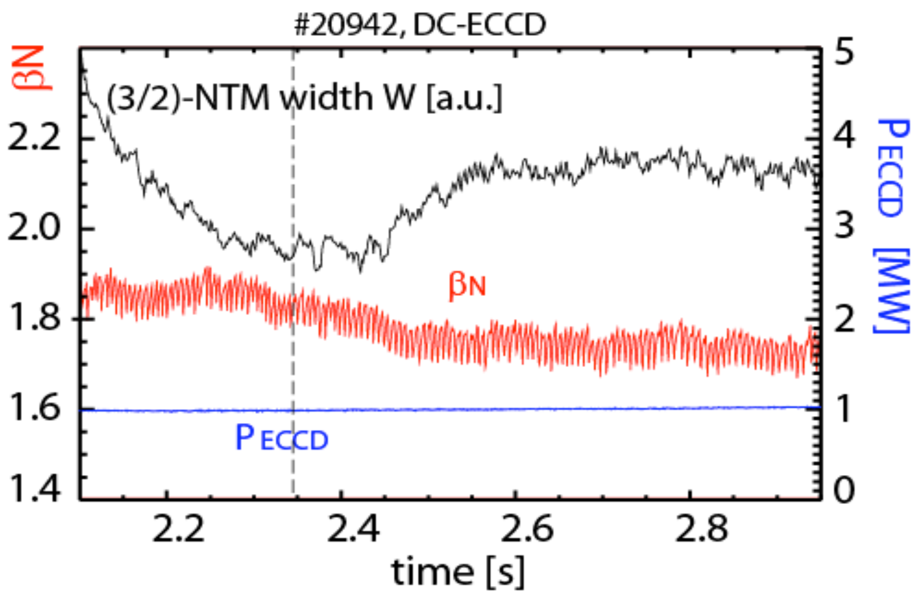
(2/1)-NTM stabilisation in ELMy H-mode with narrow ECCD

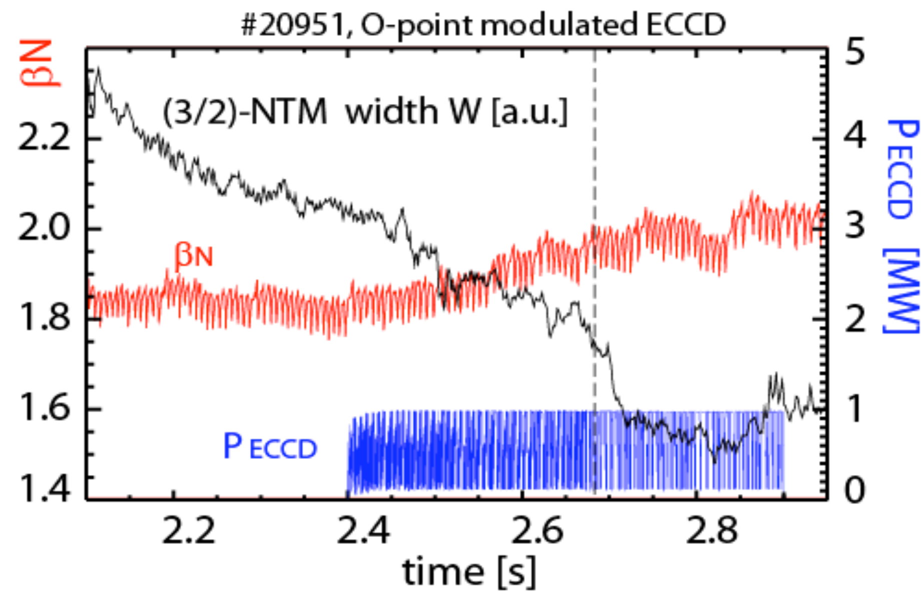


Narrow deposition allows (2,1) stabilisation at higher β_N than before

- 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!)

Recent progress in validating physics requirements

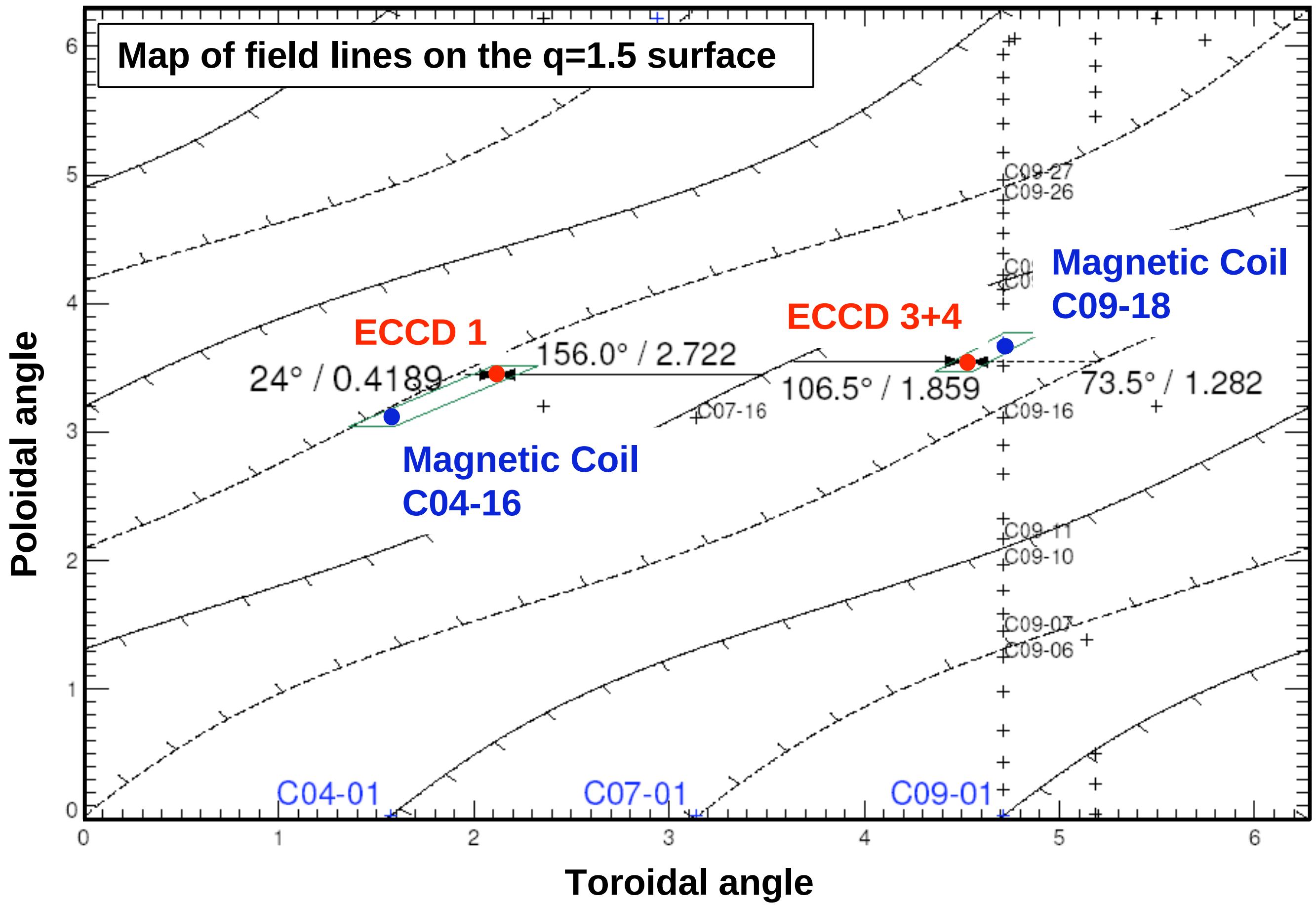




ASDEX Upgrade: NTMs rotate past ECCD antennae due to plasma rotation

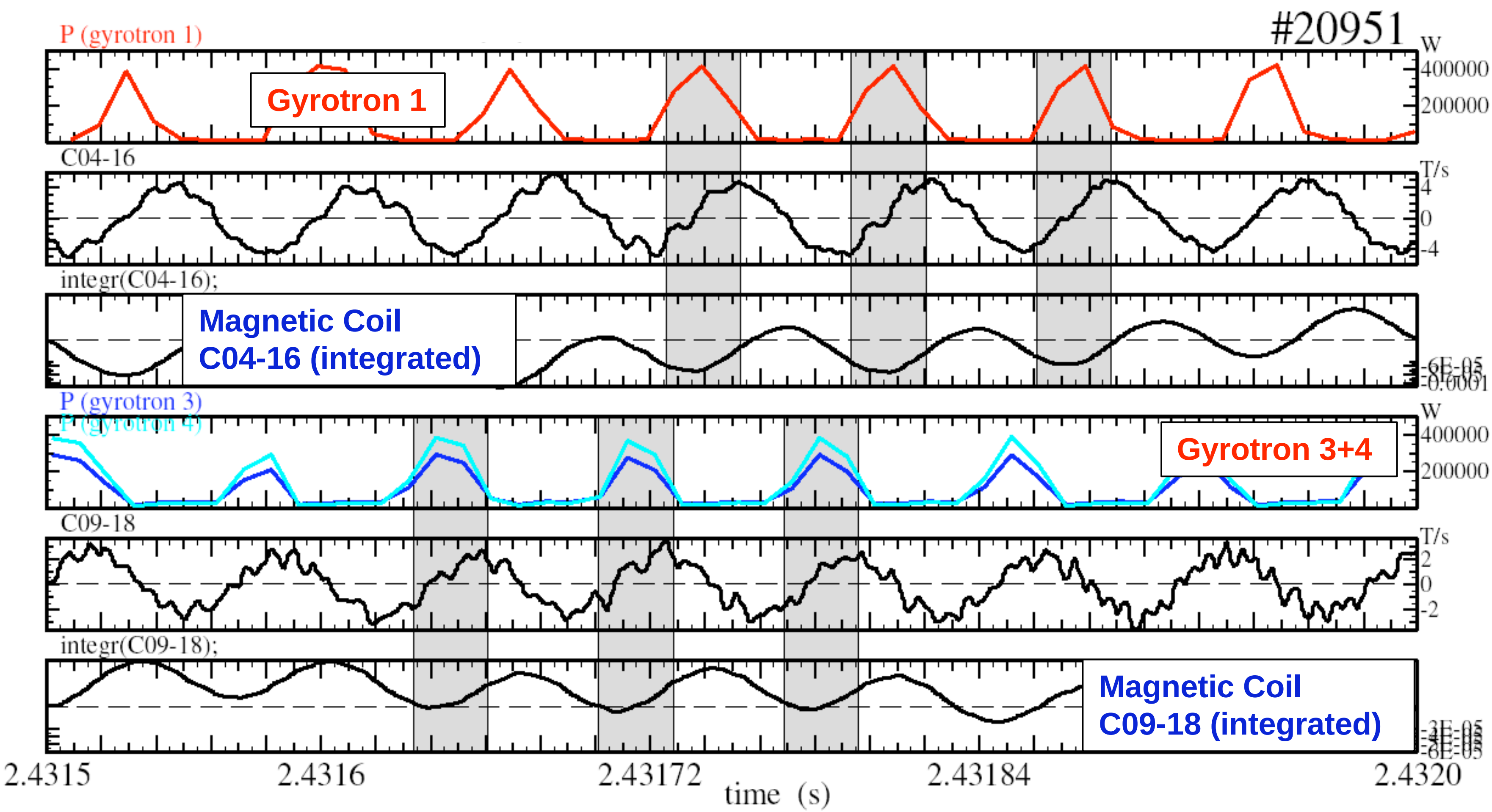
- need to modulate gyrotron with island frequency
- …or develop successfully FADIS switch ☺

Note: this is a non-trivial experiment!



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

Note: this is a non-trivial experiment!



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

??? wird nicht gezeigt !!! ???

- For j_{ECCD}/j_{bs}, this means
- 1.11 for the (3/2) NTM (c_j = ?, mismatch = ?)
- 1.26 for the (2/1) NTM (c_j = ?, mismatch = ?)
- …and modulation is needed!

Das war auf der Folie mit Rob's Bildern. Sind das Werte von Rob oder Dir, und wie sind sie berechnet (c_j, mismatch) ??? In Rob's Fall ist in den ExpDaten ein mismatch angenommen, der fuer ITER=0 ist, bei uns ist c_j an die ExpDaten angefittet.

Physics requirements for NTM stabilisation

Figures of merit for NTM stabilisation by ECCD

- equilibrium current profile: change in Δ' is determined by dj/dr: I_{ECCD}/d^2
- helical component: current within island counts: I_{ECCD} for $d < W$

  I_{ECCD}/d for $d > W$

$\Rightarrow$ no unique criterion, but *localised current profile* (small d) is favourable

Required power difficult to predict (physics at small island width uncertain)

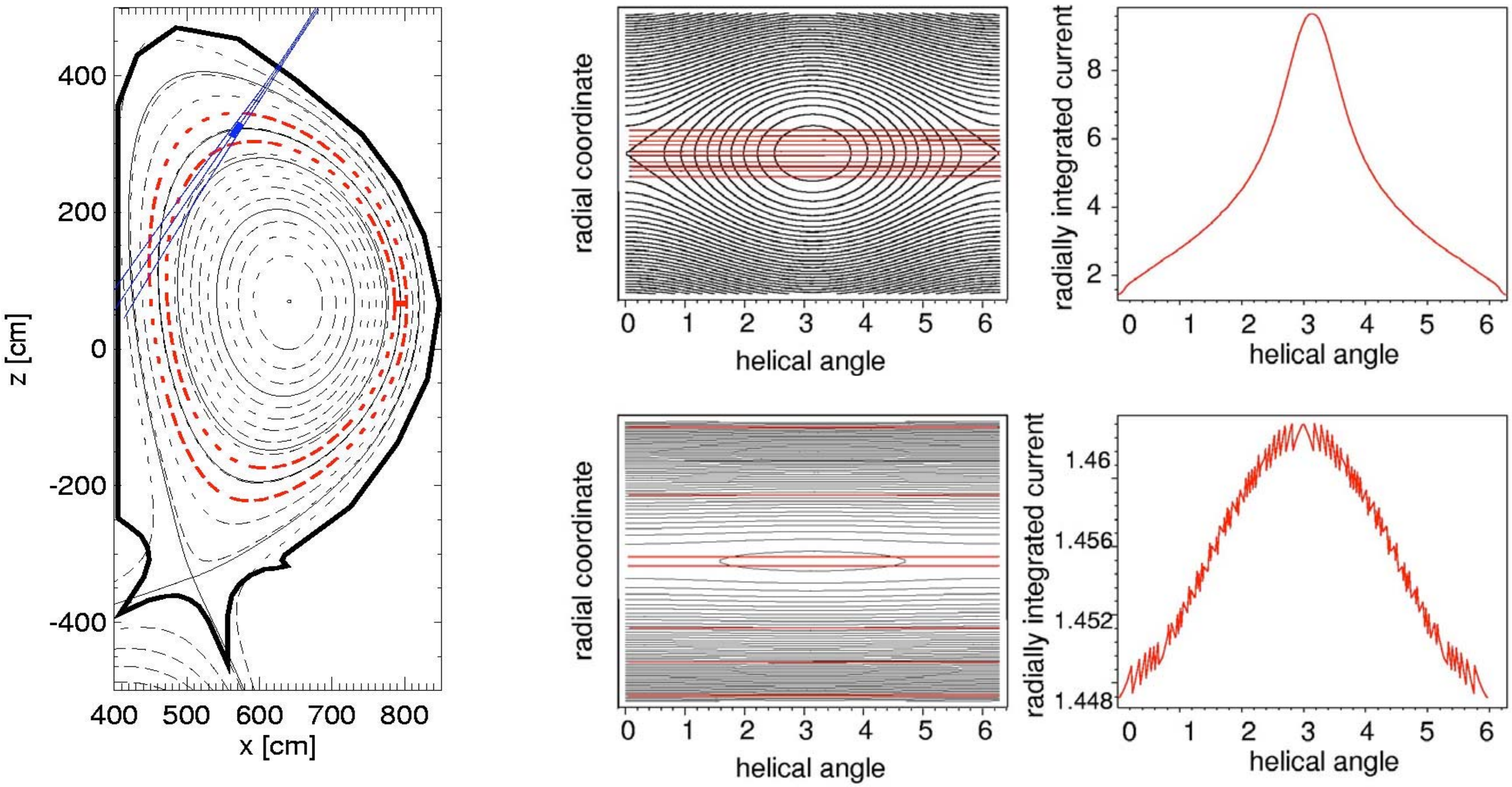
- full stabilisation: preferable if NTMs occur occasionally in ITER
- partial stabilisation: preferable if NTMs are standard in ITER, impact on Q

Compromise: assume that W has to be of order of ion poloidal gyroradius

- mode either vanishes or is insignificant (less than 5% confinement loss)
- for full stabilisation, j_{ECCD} has to exceed j_{bs} by 20-60%

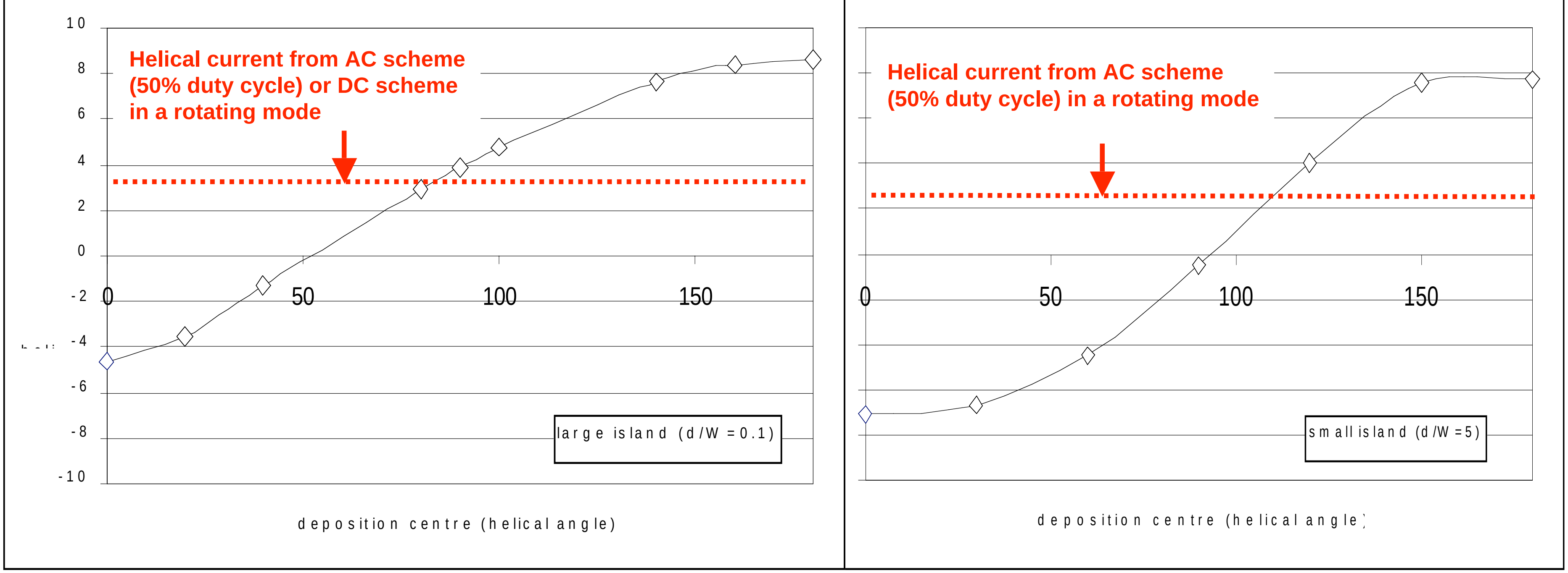
  definition of 'marginal' performance: $1.0 < j_{ECCD}/j_{bs} < 1.2$

Rotating small islands are difficult to stabilise



- for d > W, continuous injection does no longer generate a helical component
- may require modulation of ECCD power in phase with island
- present extrapolation: 3-5 kHz modulation frequency required for (3,2) NTM

For locked modes, finite toroidal extent is important



Locked mode:

- large island: for δξ up to 100º, helical current exceeds AC and DC schemes
- small island: for δξ up to 80º, helical current exceeds AC scheme

⇒ no problem for our design, not even for the 4 port-option

Another approach of Optimisation of ITER ECRH

Three options for μ-wave beam steering:

The ‘conventional’ option

- single-frequency gyrotrons and steerable launchers
- used everywhere around the world

The ‘advanced’ option

- multi-frequency gyrotrons and steerable launchers
- soon to come on ASDEX Upgrade

The ‘ambitious’ option

- multi-frequency gyrotrons and fixed launchers
- needs dense frequency coverage – a technical challenge!

The ‘advanced’ option in ITER

To avoid window issues, we propose a 2-frequency solution

- need > 170 GHz for upper launcher (higher CD-efficiency)
- need < 170 GHz for midplane launcher (off-axis deposition)
- reasonable compromise: 185 / 154 GHz (resonant for 2.05 mm window)

Assumptions about the launchers

- use presently foreseen launch points
- midplane with -20 to -45 degrees steering
- upper launcher with 40 to 60 degrees poloidal steering (β = 20)

Note: single frequency per launcher means that even RS could be used

The ‘ambitious’ option in ITER

Assume the super-duper gyrotron exists

- step-tuneable with 2.1 GHz frequency spacing
- tuning time of 1 sec allows feedback application in ITER

Assumptions about the launchers

- use presently foreseen launch points, but no steering at all
- midplane fixed to 35 degrees toroidal angle ($\theta = 0$)
- upper launcher fixed to 55 degrees or 46 degrees poloidal ($\beta = 20$)

Physics Introduction: Summary

NTMs are predicted to endanger the Q=10 mission of ITER

- ECCD predicted to recover from Q=5 (in presence of (2,1) NTM) to at least Q = 8 even under pessimistic assumptions

Stabilisation of (2,1) and also (3,2) NTMs envisaged in scen. 2,3 and 5

- sets requirement for steering range
- garantuees experimental flexibility in ITER positive shear scenarii

NTMs stabilisation by ECCD needs localised CD in the island

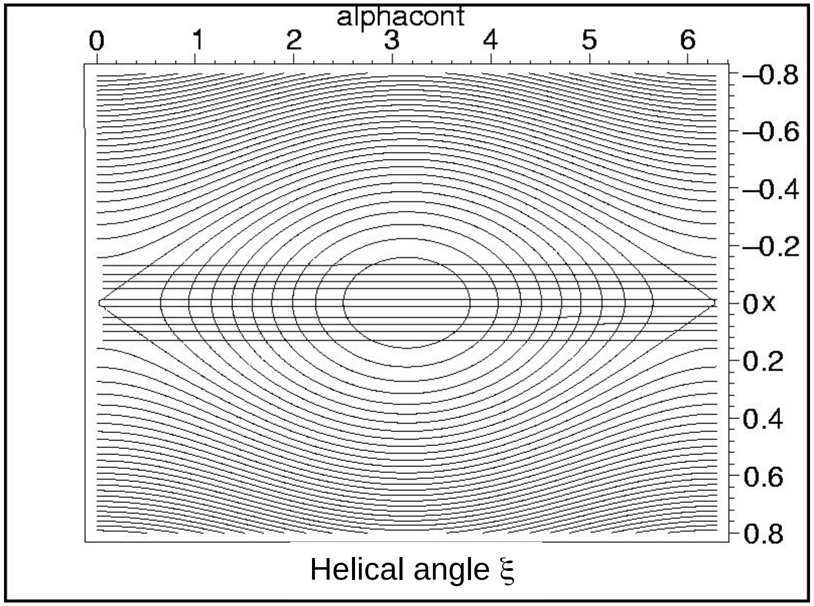
- figure of merit j_{ECCD}/j_{bs} > 1.2
- may need modulated ECCD (phase locked with island)

A methodology has been set up to analyse performance of UL designs

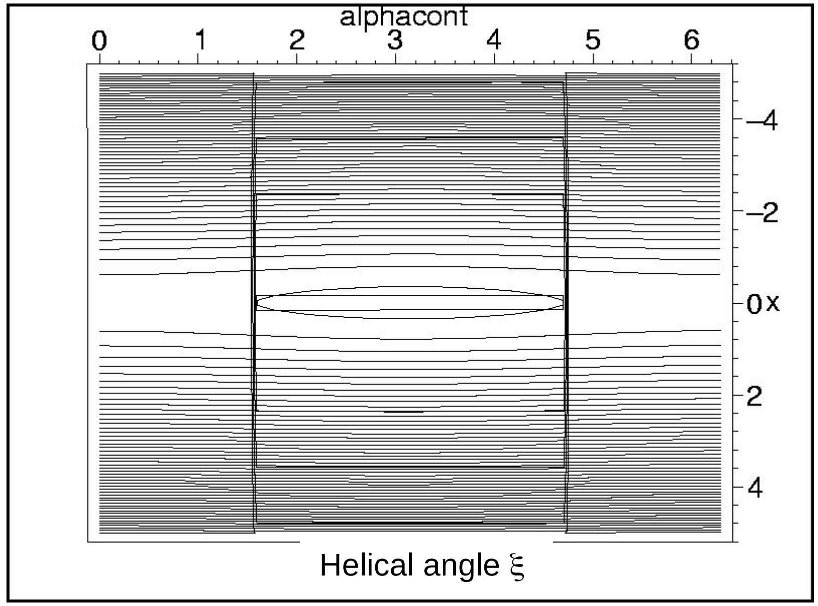
- results will be presented in ‚Objective Comparison' talk(s)

Recent progress in validating physics requirements

Tearing Mode stabilisation by generation of helical ECCD current in island



(typical for present day experiments)

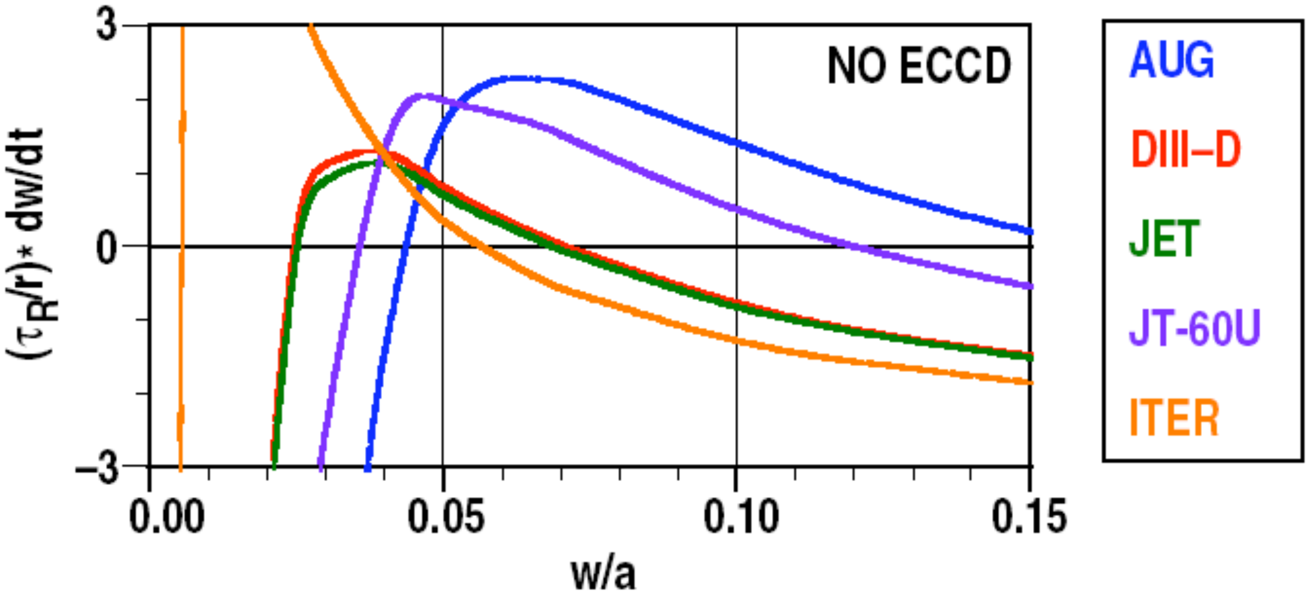


(typical for ITER)

Problem for ITER: magnetic island will be small compared to deposition

The proposed solution: injection only in the O-point of the island

Power requirements – ITPA Initiative



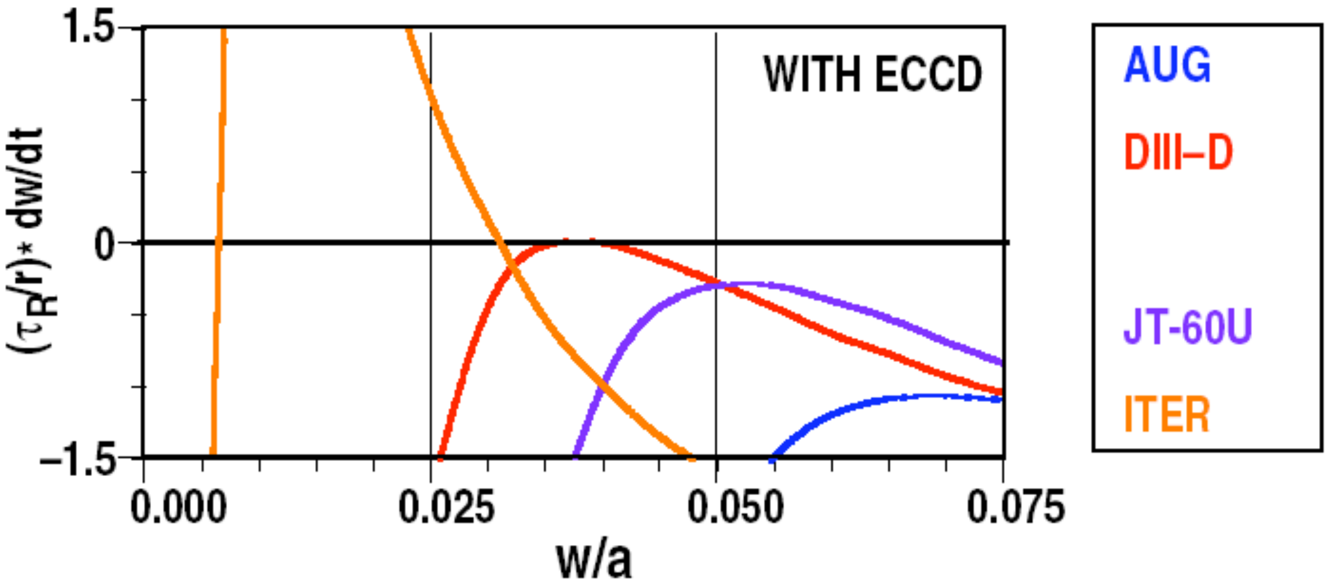
R. La Haye et al.,
Tokamak Physics Base

(3,2) NTM data from ASDEX Upgrade, JT-60U, DIII-D and JET (no ECRH)

Fitting approach with only one free parameter (a_{bs}) assuming similar profiles

- different q_{95} values – calls for further experiments at similar q_{95}
- ECCD effect on Δ' not consistently considered – to be improved in future

Power requirements – ITPA Initiative



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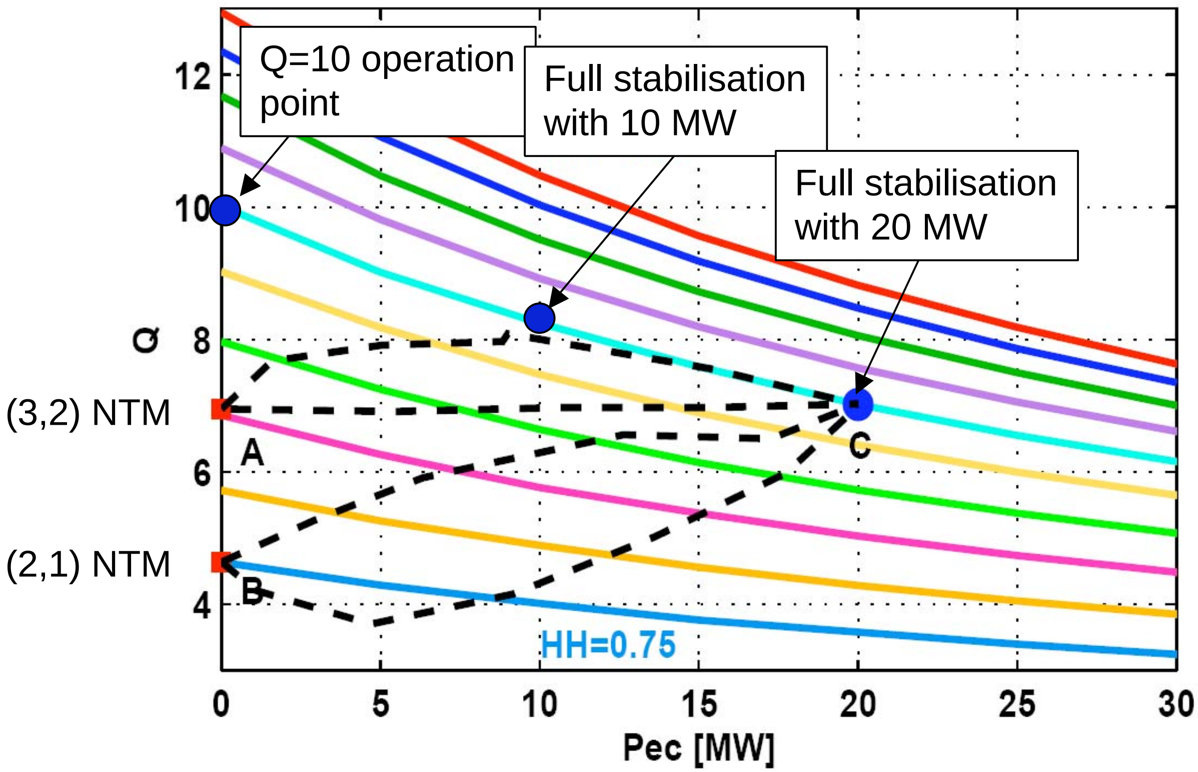
Gain in performance with suppressed NTM



HH = 1.0

ITER burn curves in the presence of ECCD at q=3/2 (A) and q=2 (B)

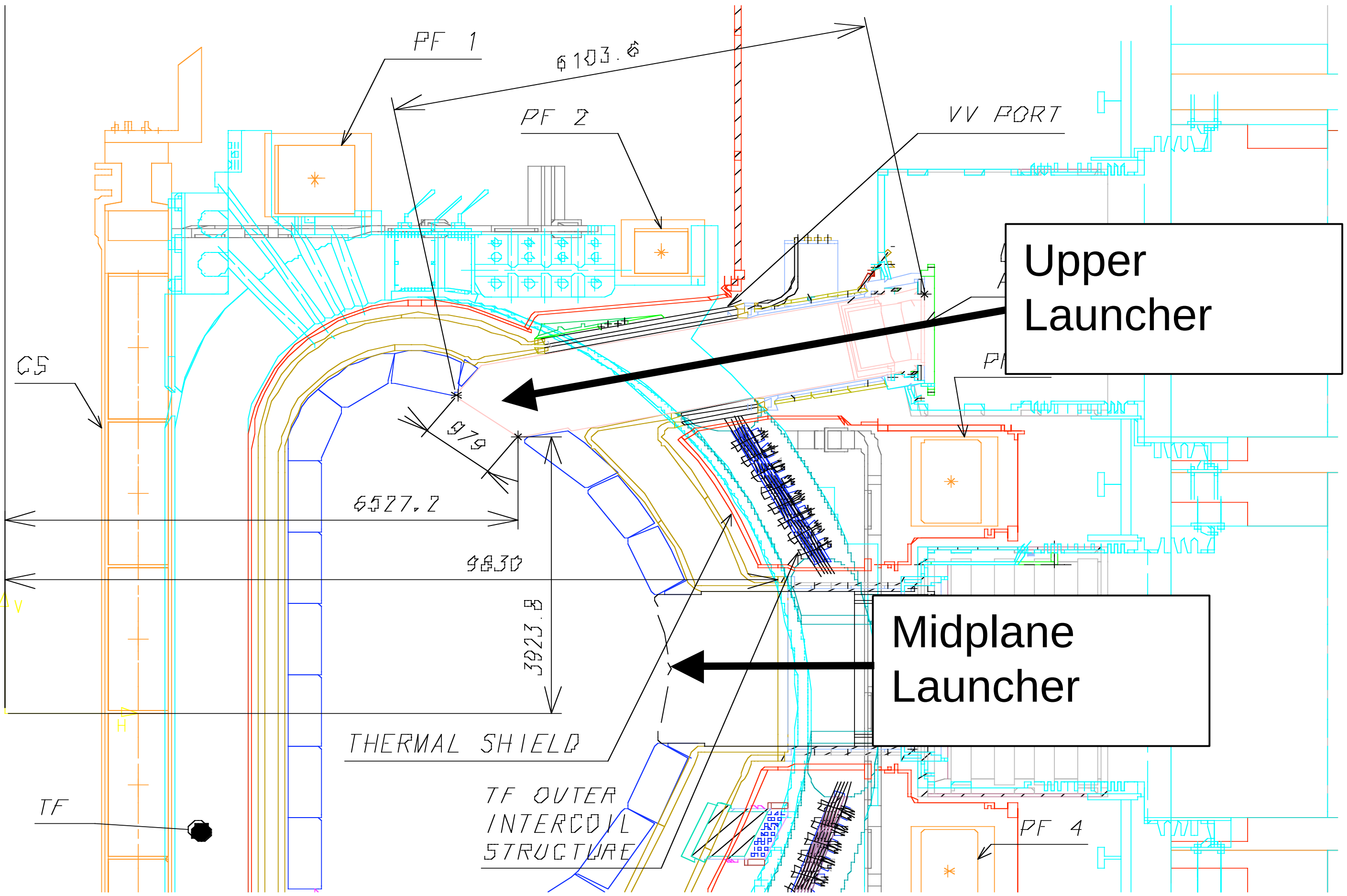
(O. Sauter and H. Zohm, EPS 2005, IAEA 2006)

P_{ECCD} only partially included in Q

Impact on Q in case of continuous stabilisation (worst case):

- Q drops from 10 to 5 for a (2,1) NTM and from 10 to 7 for (3,2) NTM
- with 20 MW needed for stabilisation, Q recovers to 7, with 10 MW to Q > 8
- note: if NTMs occur only occasionally, impact of ECCD on Q is small

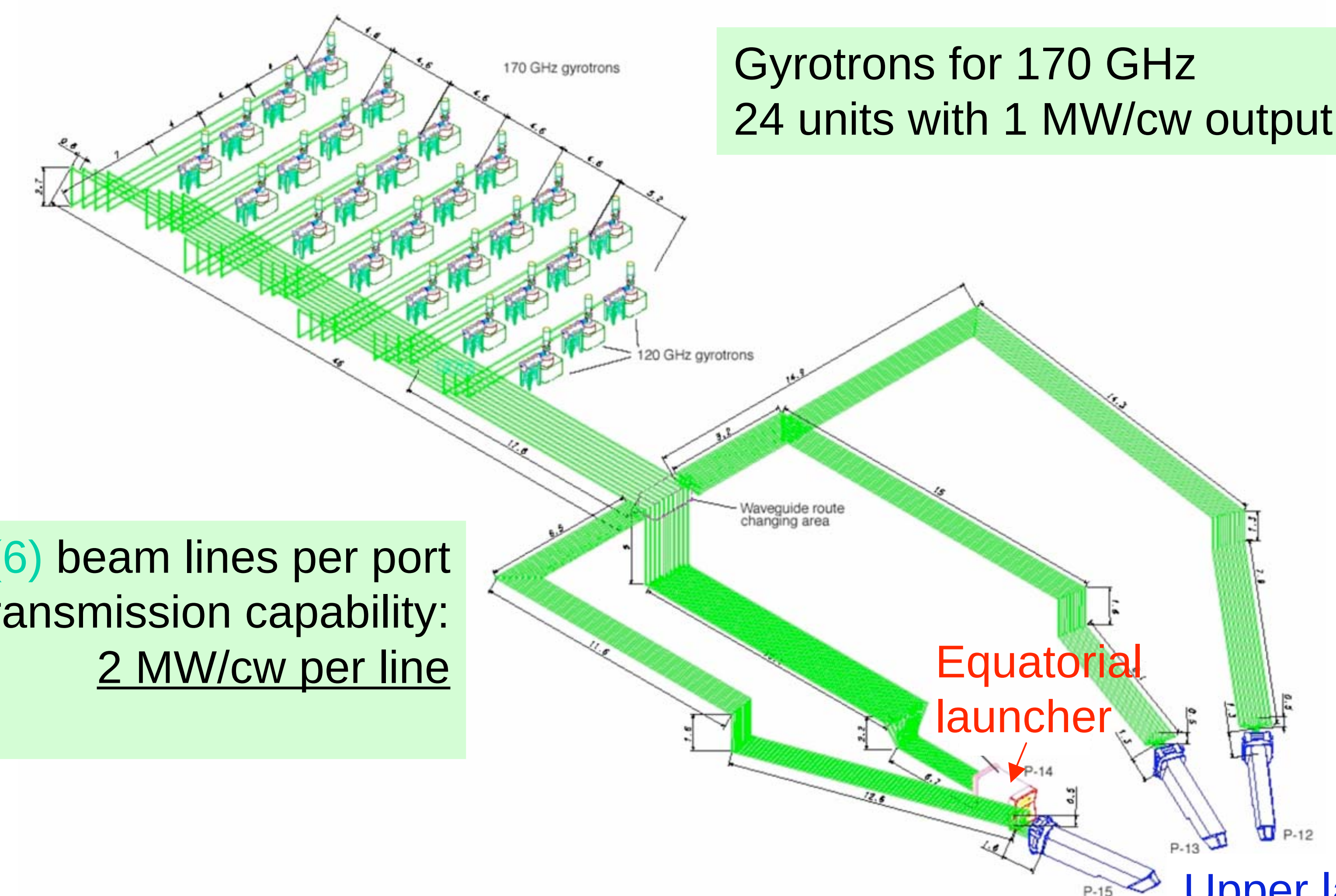
The present system design



20 MW (24 MW installed) to be launched into the plasma from two positions

The present system design

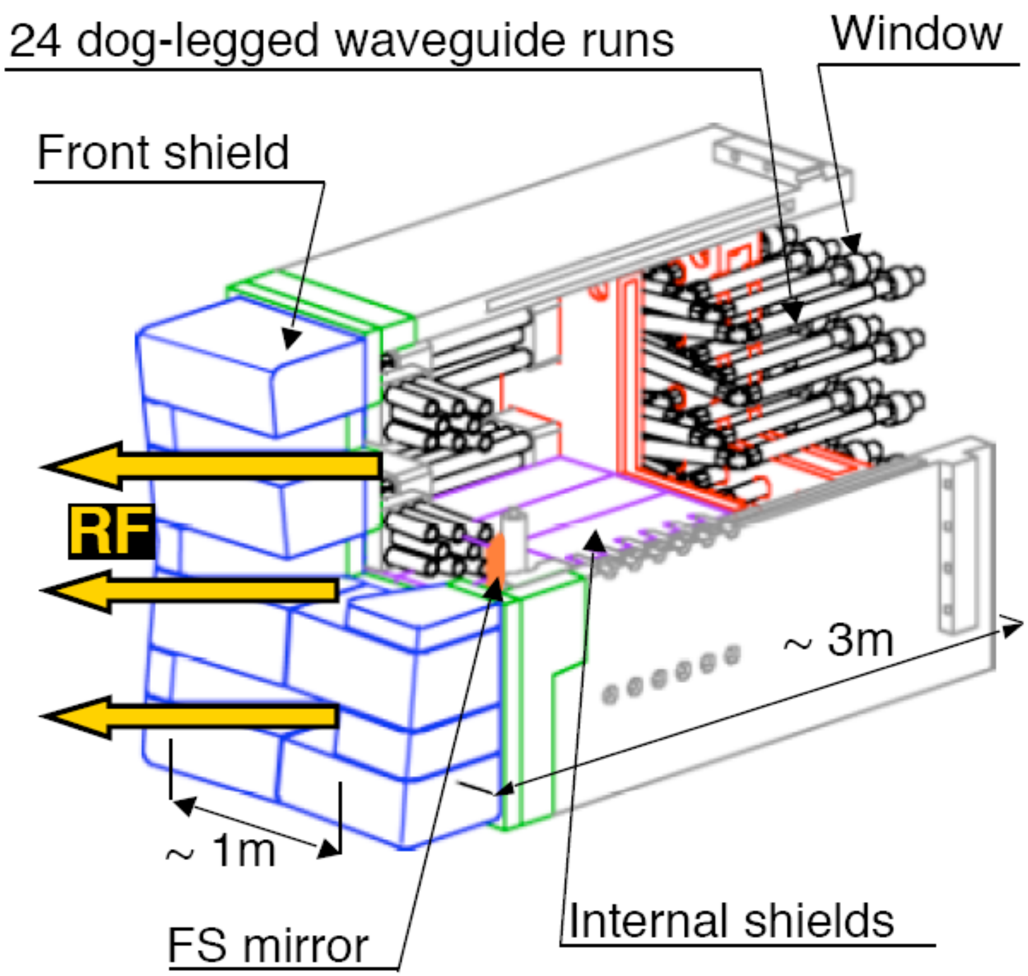
Gyrotrons for 170 GHz
24 units with 1 MW/cw output power



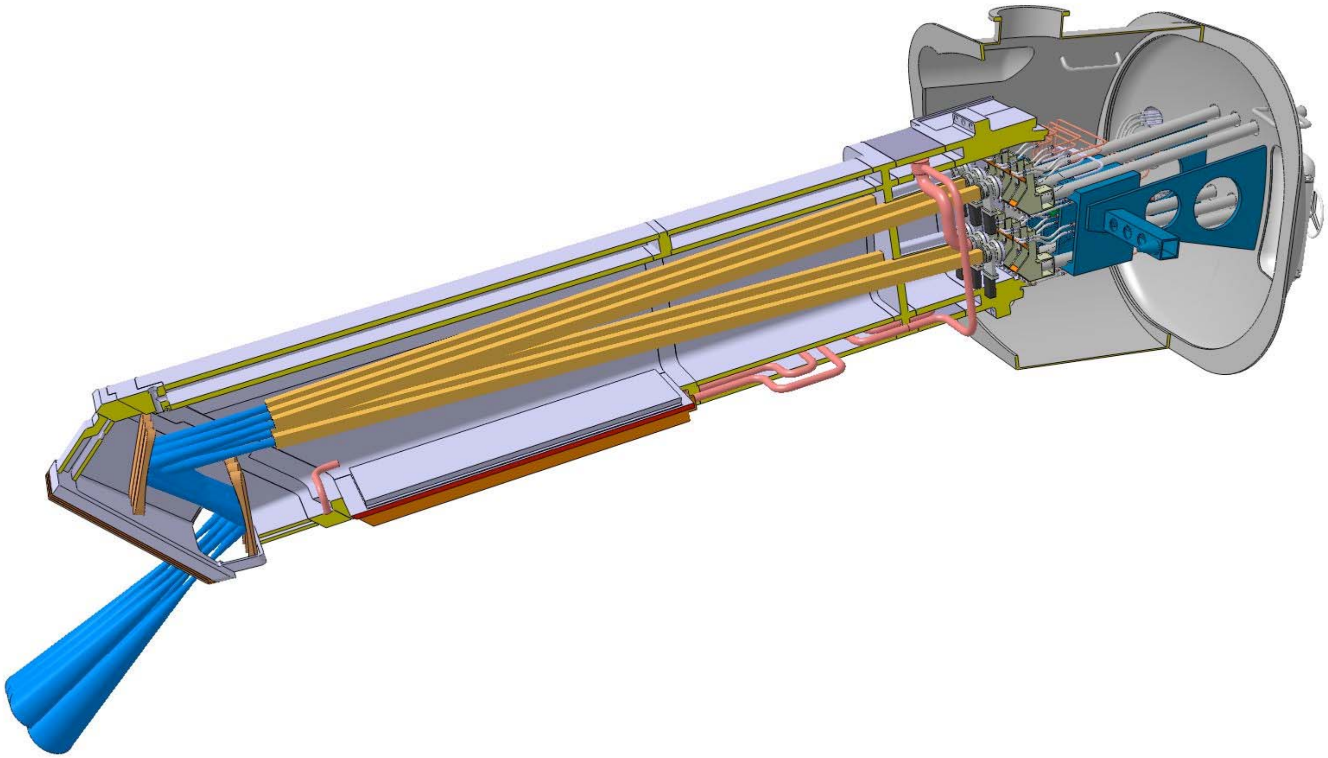
8 (6) beam lines per port
Transmission capability:
<u>2 MW/cw per line</u>

20 MW (24 MW installed) to be launched into the plasma from two positions

Front steering(FS) type launcher



The present system design: Upper Launcher



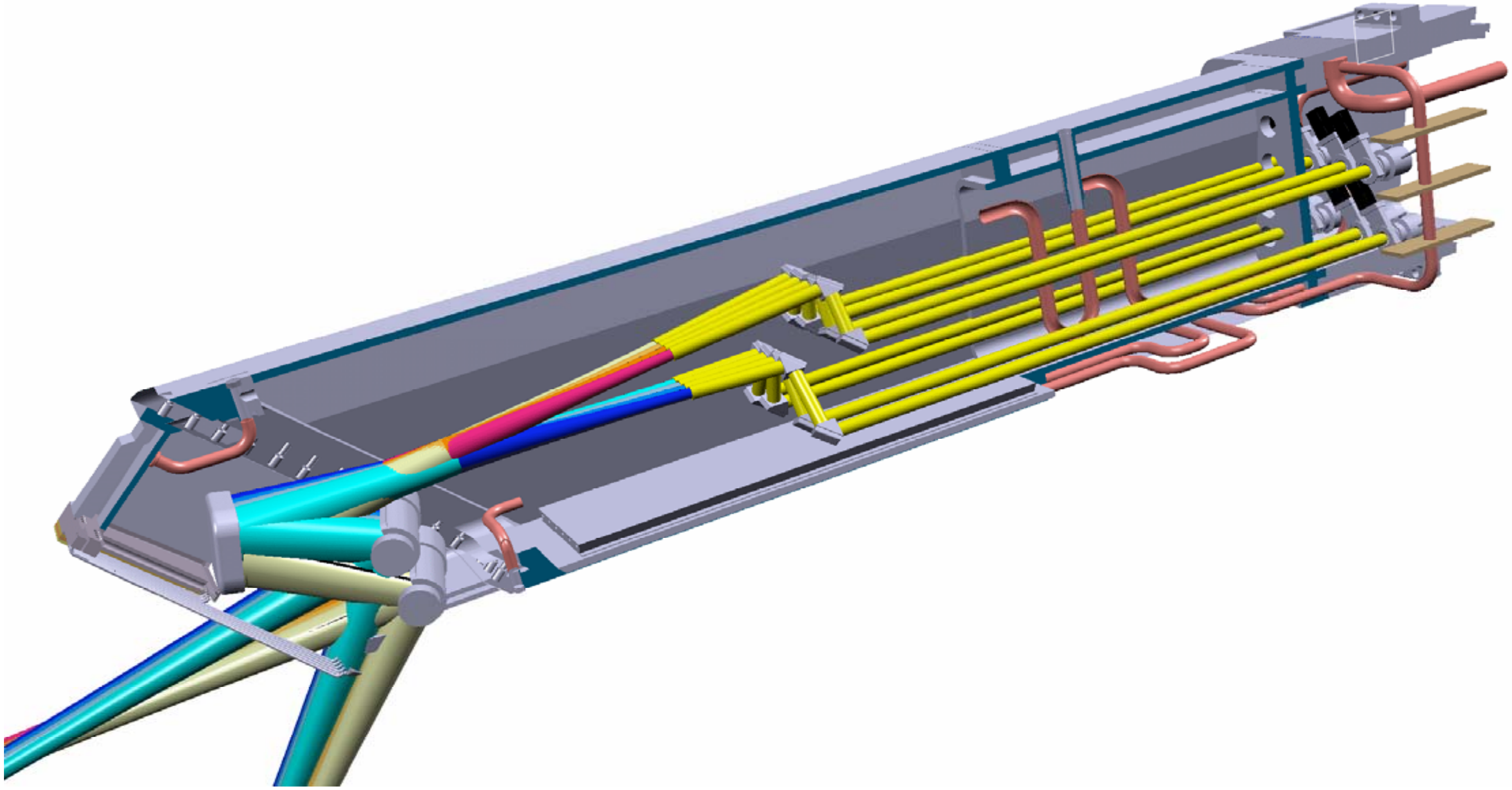
Alternative design based on remote steering

- 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

Performance analysis - methodology

We use a database of ITER equilibria with kinetic data:

- scenario 2 (Q=10), 3a (Hybrid) and 5 (low q_{95})
- β_p and l_i variations have been analysed – general trend is not changed

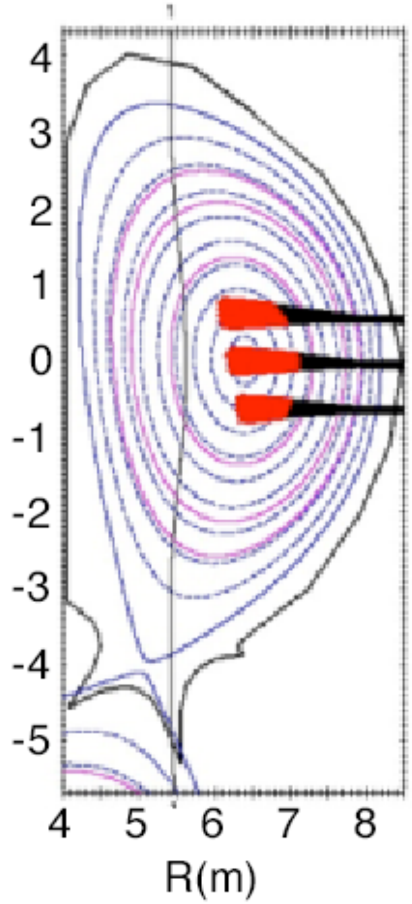
We evaluate $j_{ECCD}(r)$ for all scenarii and all options

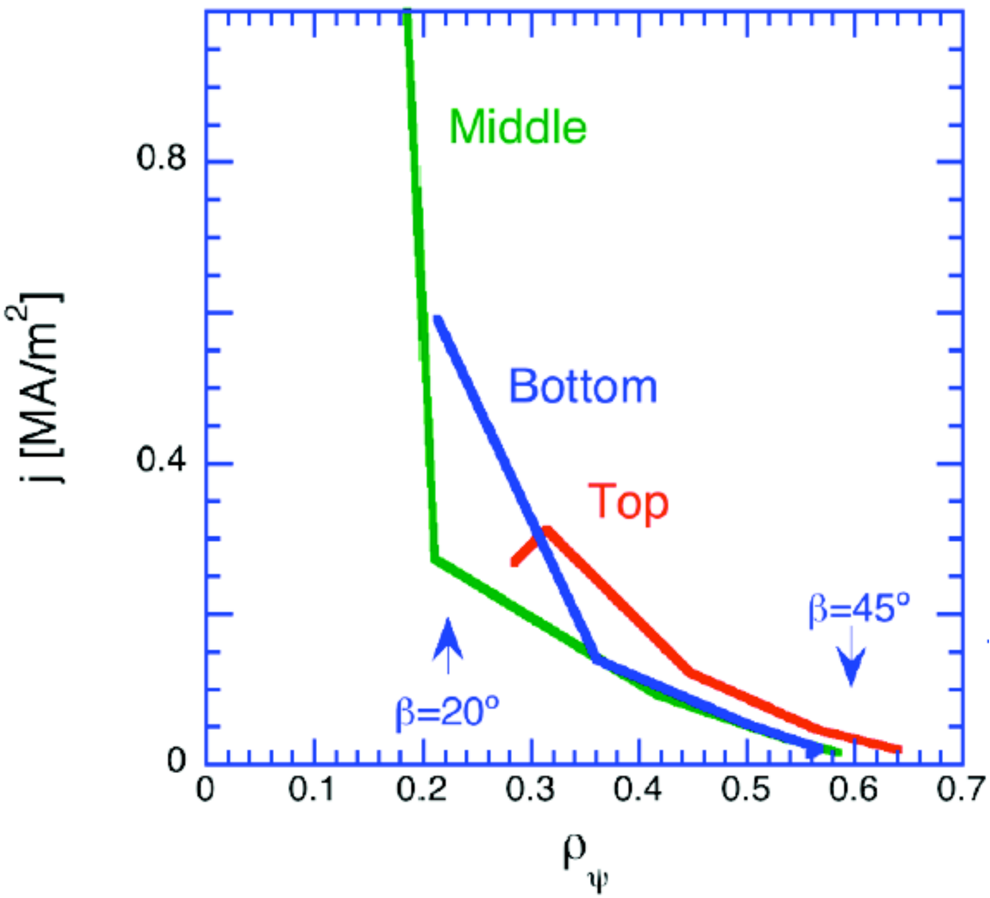
- use of benchmarked bem tracing codes (TORBEAM, GRAY)

Assumptions:

- 20 MW at 170 GHz absorbed, 20 x 1 MW result
- no alignment errors (!)

Performance analysis: Results for Equatorial Launcher



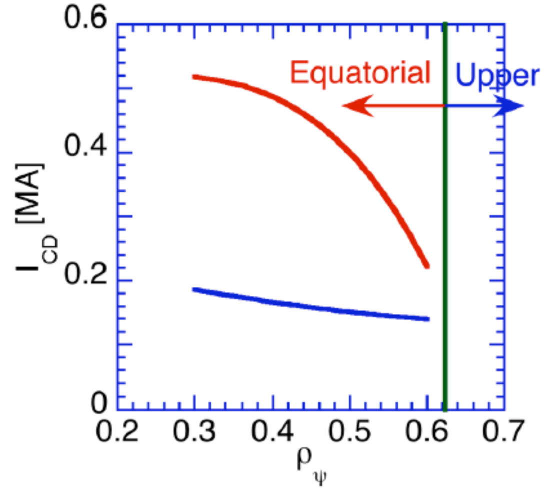


Significant central (co)-CD

- off-axis CD-efficiency is not too great
- no ctr-heating or pure ECRH → unfavourable for sawtooth avoidance

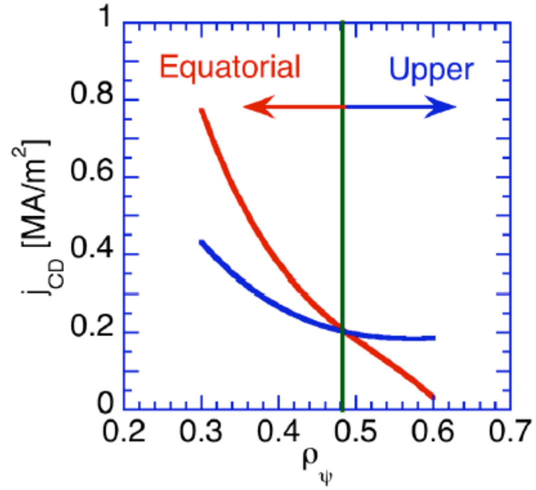
Performance analysis: Results

Total driven current



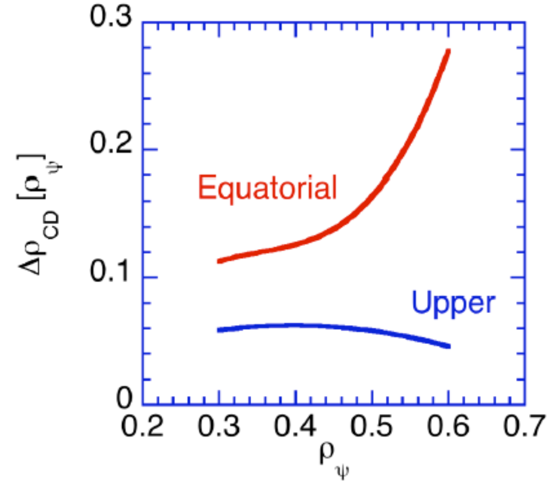
Equatorial port optimum $\rho_\psi \leq 0.6$

Maximum current density



Upper port optimum $\rho_\psi \geq 0.4$ to 0.5

Current density profile width

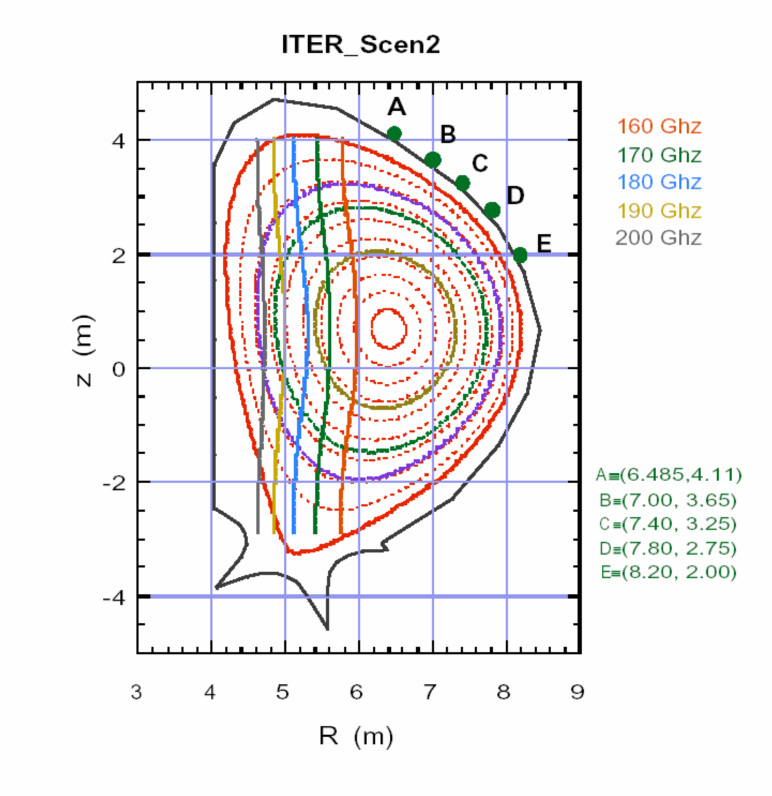


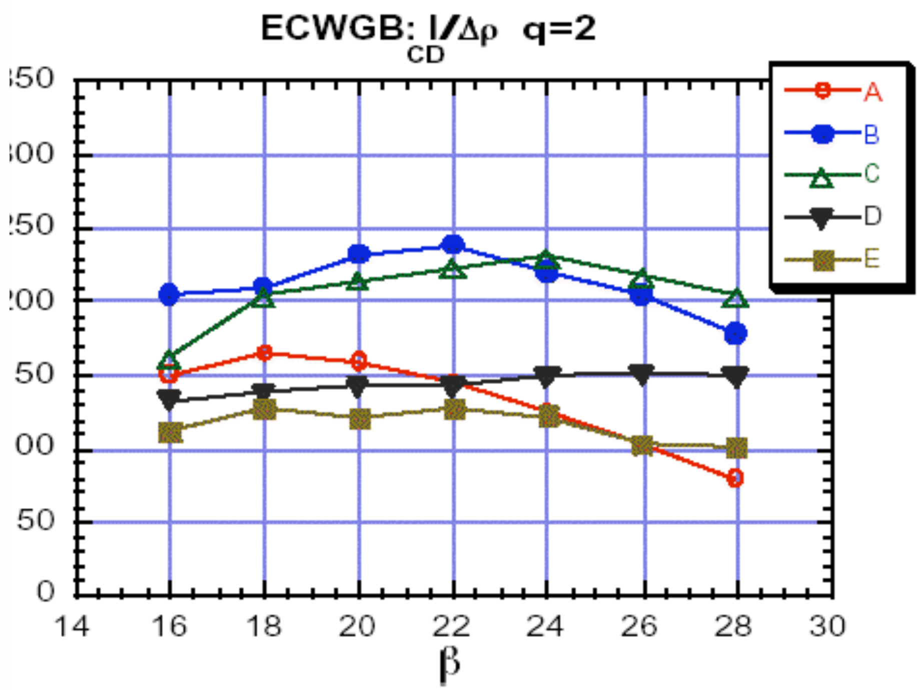
Upper port optimum $\rho_\psi \geq 0.3$

But present Upper Launcher only goes down to $\rho > 0.65$

⇒ present task sharing is not optimum

Present Lines of Optimisation: RS Upper Launcher





Possibilities to enhance j_{ECCD} from the RS Upper Launcher:

1. lower launch point (major impact on ITER design)
1. longer RS waveguide → larger beam at output → smaller spot size in plasma

Multi purpose (8 beams/port)	Scenario 2	Scenario 3	Scenario 5
q=1.5	0.81	0.6	0.59
q=2	1.07	0.81	0.62

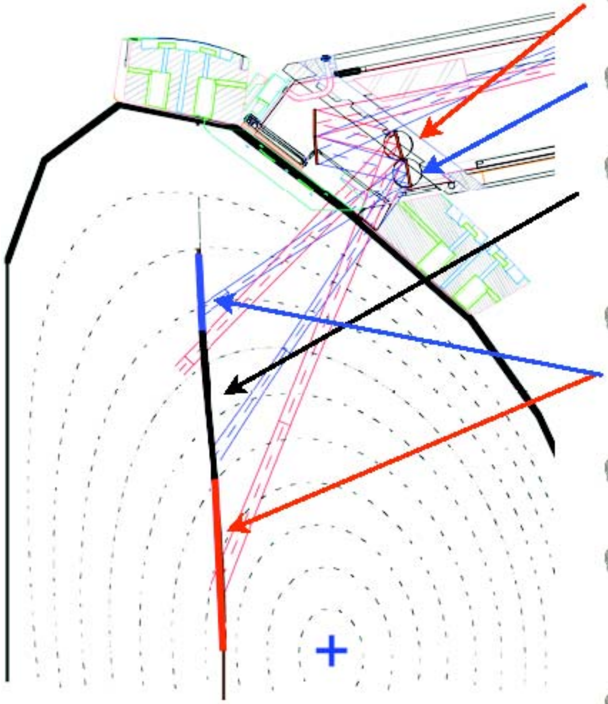
Front steering	Scenario 2	Scenario 3	Scenario 5
q=1.5	2.12	1.63	1.67
q=2	3.05	2.16	1.64

Criterion: $\eta_{NTM} = j_{ECCD}/j_{bs}$ should exceed 1.2

Front steering gives large gain in all cases

- from physics point of view, this is the preferred option

Present Lines of Optimisation: FS Upper Launcher



- 4 Ports or 32 entries for 24 gyrotrons
- 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 $0.88<\rho_\psi\leq0.93$
- Decreases opening in first wall
- Decreases overall rotation (fatigue) of steering mechanism
- Maintains η_{NTM}=1.2 (with ≤13MW)

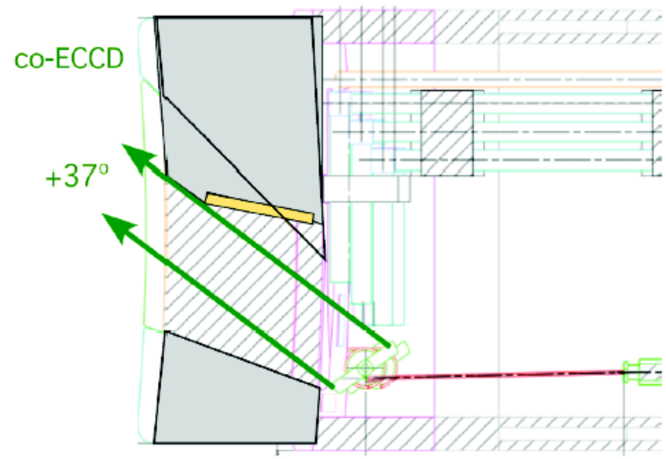
Possibilities to enhance FS Upper Launcher performance:

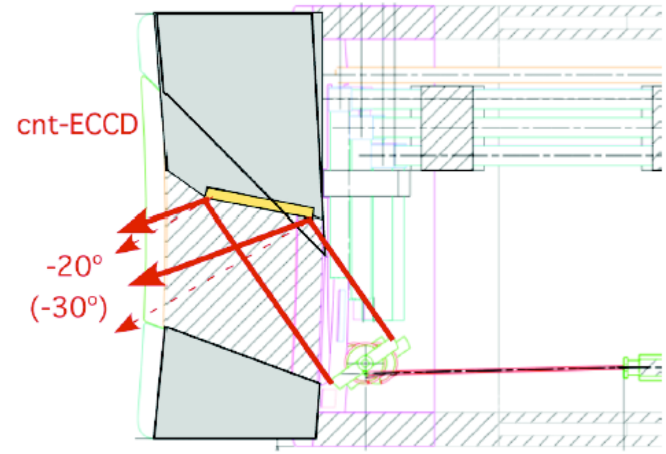
- since j_{ECCD} is more than sufficient, steering range can be expanded
- partitioning of power in the different rows can enhance flexibility

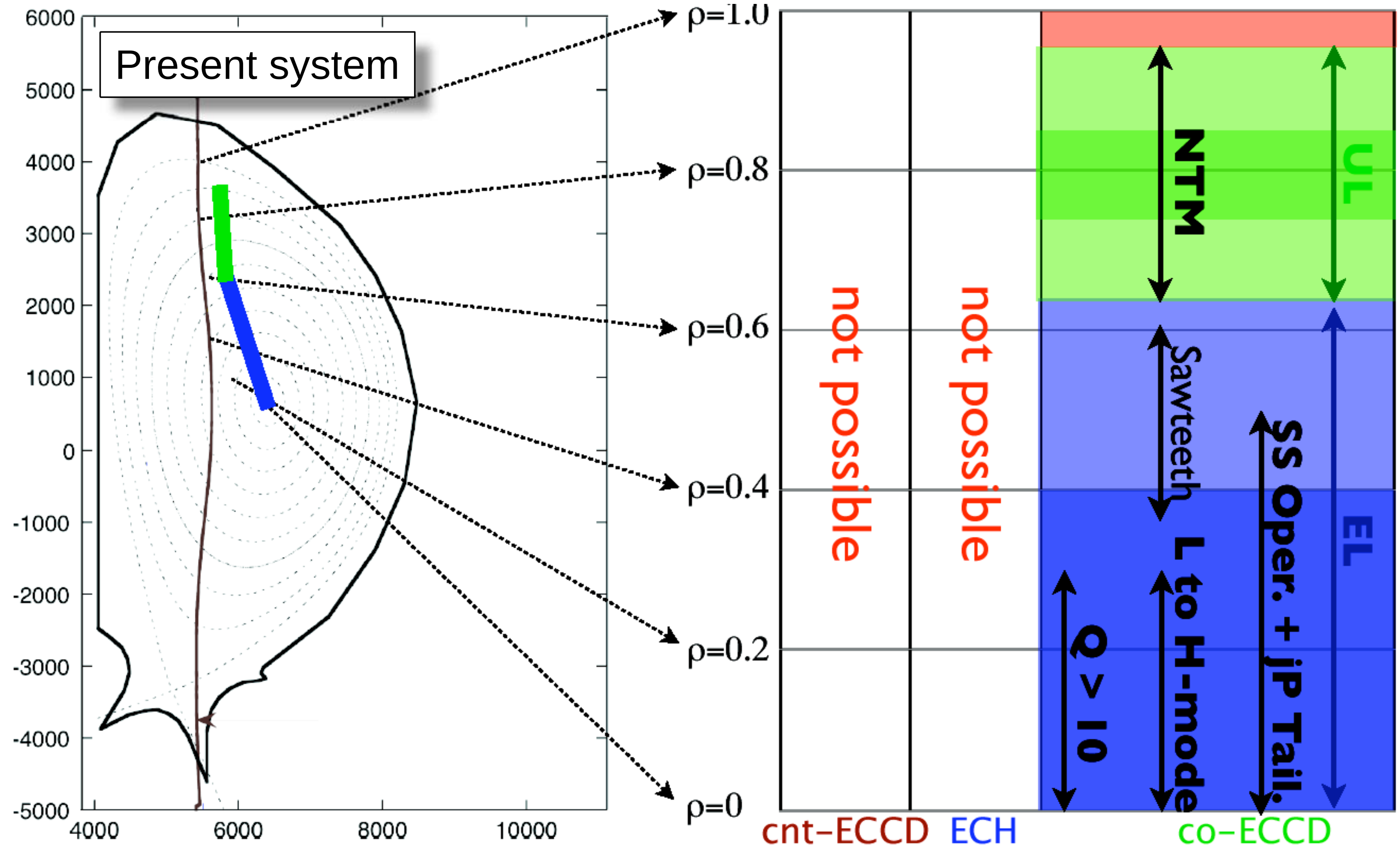
Present Lines of Optimisation: Midplane Launcher

Fixed mirror in BSM can be used to reflect beam in counter direction
(idea compliments of P. Barabaschi)

- Full 20MW in co or cnt-ECCD
- Full essential steering in co-ECCD
  $20^{\circ} \leq \beta \leq \sim 37^{\circ}$
- Limited steering or
  fixed β for cnt-ECCD
- Optimize cnt-ECCD deposition
  for desired current profile tailoring
- Disadvantage: increase
  steering mirror rotation ~±8.5° (±6.5°)

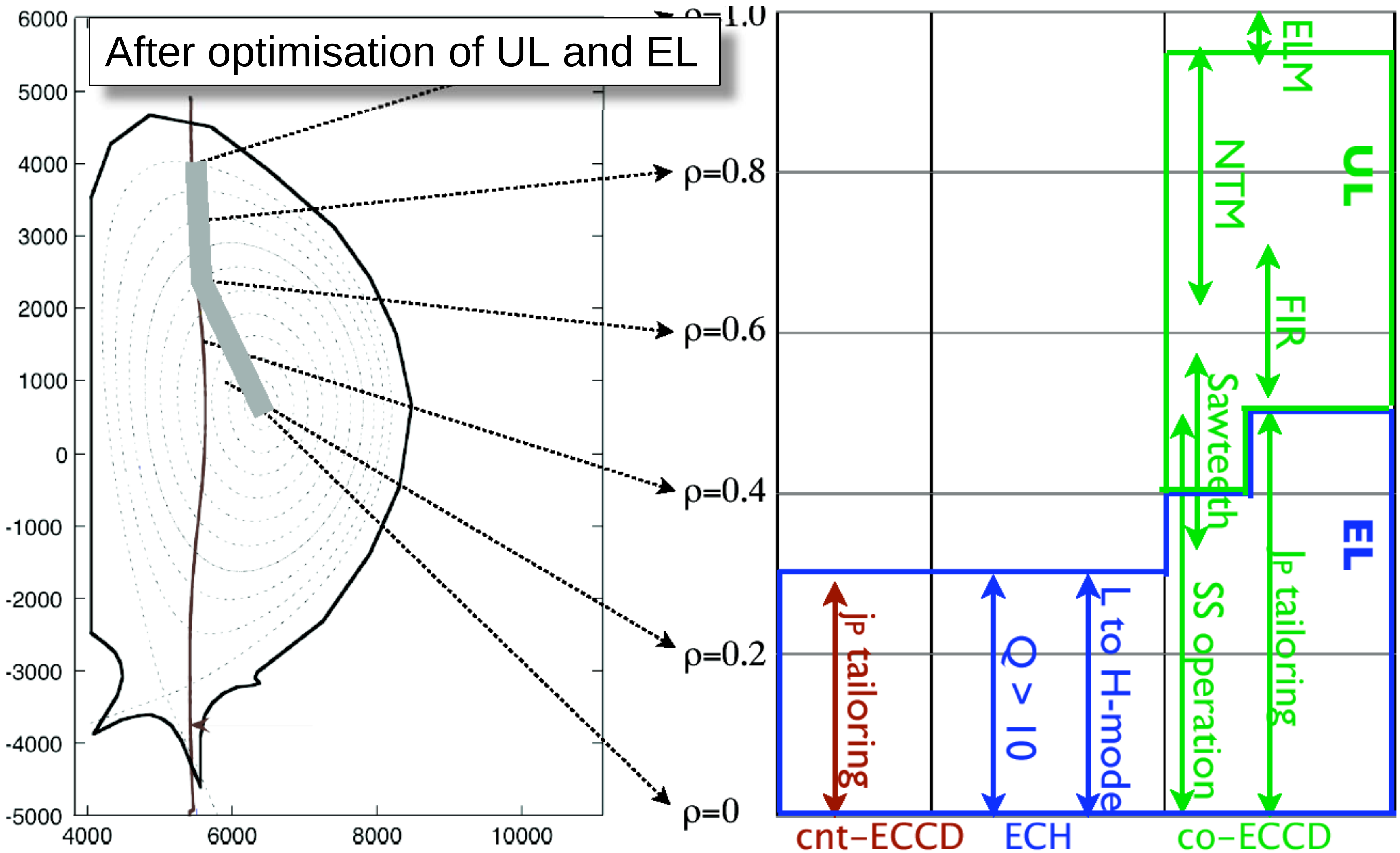




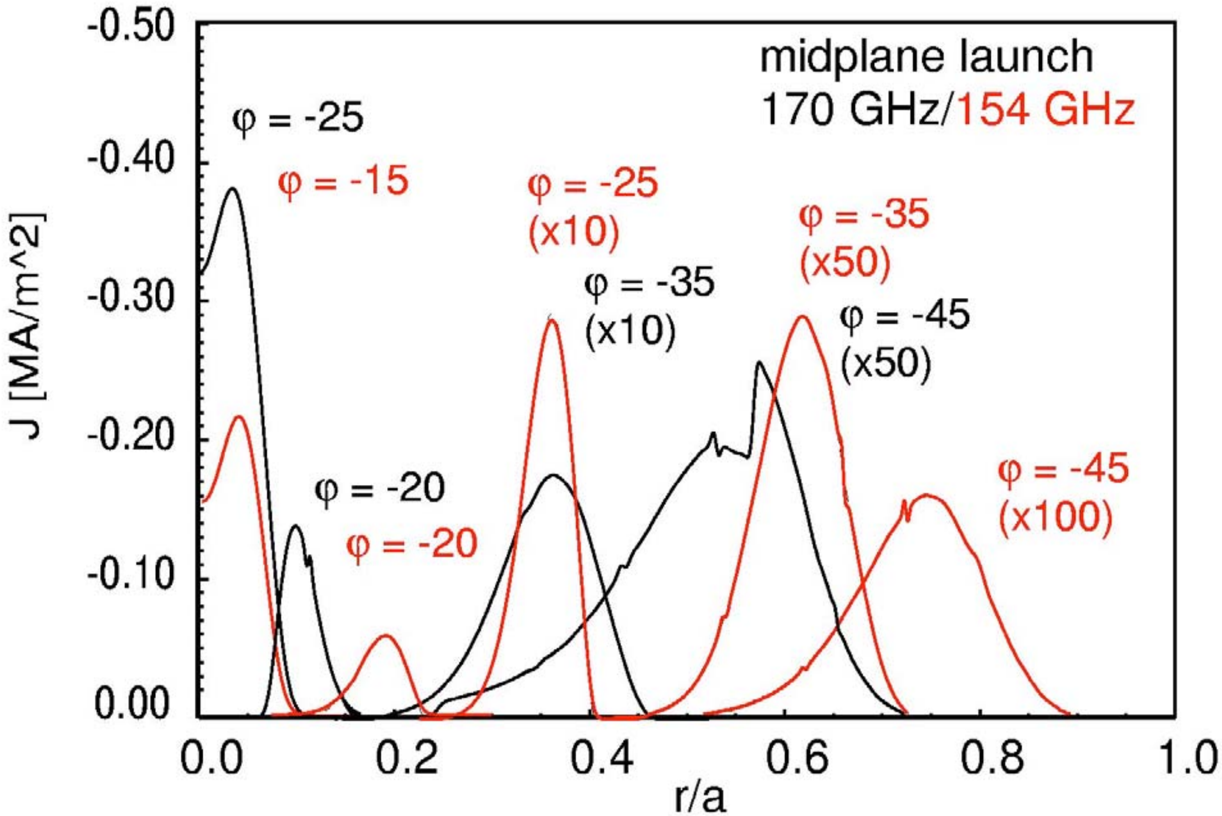


Present system
6000
5000
4000
3000
2000
1000
0
-1000
-2000
-3000
-4000
-5000
4000
6000
8000
10000
ρ=1.0
ρ=0.8
ρ=0.6
ρ=0.4
ρ=0.2
ρ=0
not possible
not possible
NTM
UL
Sawteeth
SS Oper. + jP Tail.
EL
L to H-mode
Q > 10
cnt−ECCD
ECH
co−ECCD

Present Lines of Optimisation: Synergy



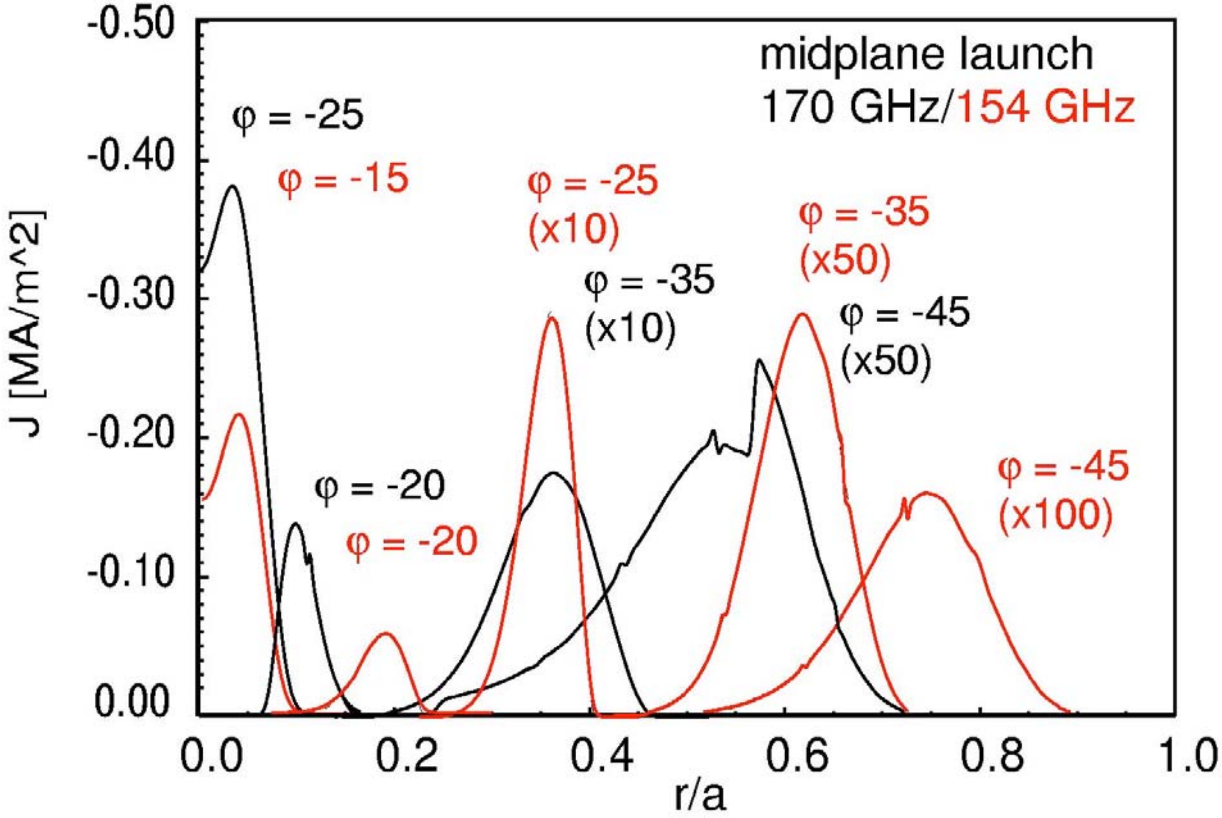
The ‘advanced’ option in ITER: midplane launch



At 154 GHz, central deposition only possible if -15 degrees are allowed

- CD efficiency is smaller (smaller angle) – less central current
- Could be recovered (increased!) using 185 GHz for central deposition

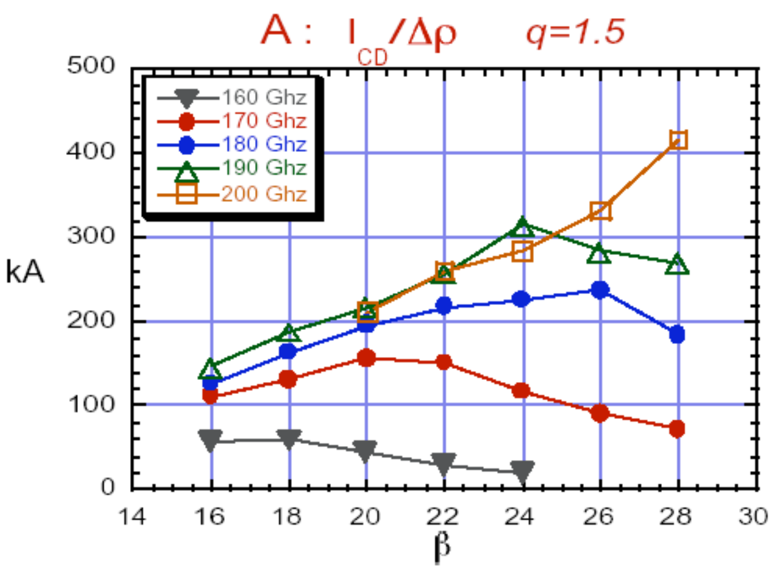
The 'advanced' option in ITER: midplane launch

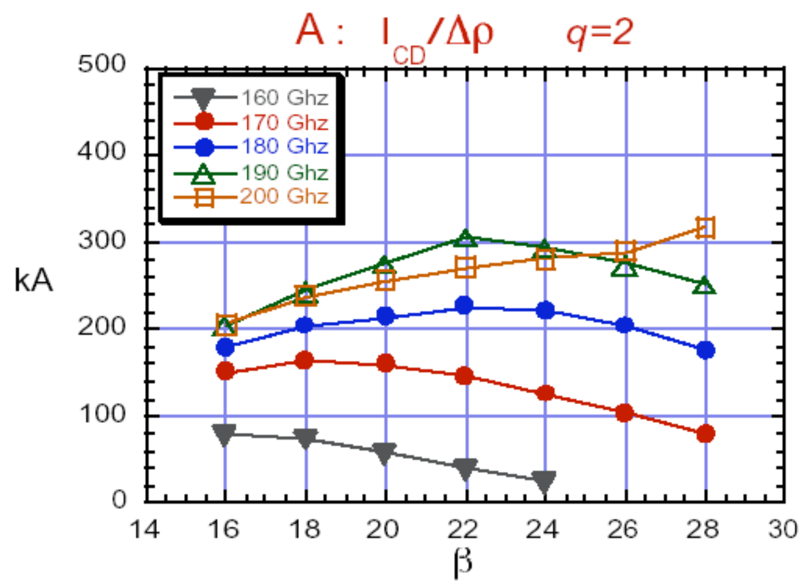


At r/a > 0.2, 154 GHz leads to higher current density

- favourable for sawtooth control and also for AT off-axis CD
- note: with ϕ = -45, significantly larger radii can be accessed

The ‘advanced’ option in ITER: upper launch



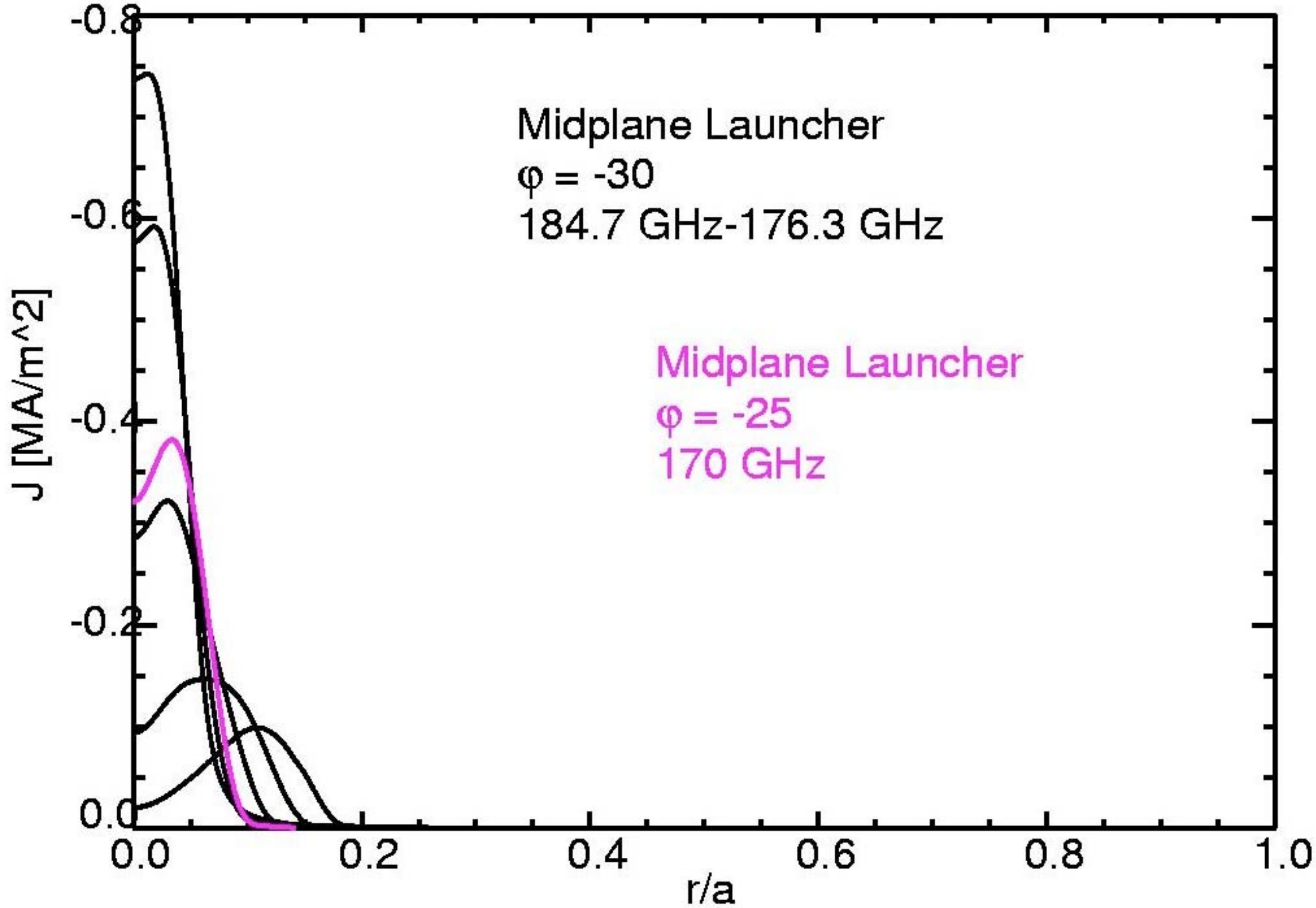


G. Ramponi, Seeon IAEA TM 2003

With 185 GHz in the upper launcher, current density can be much higher

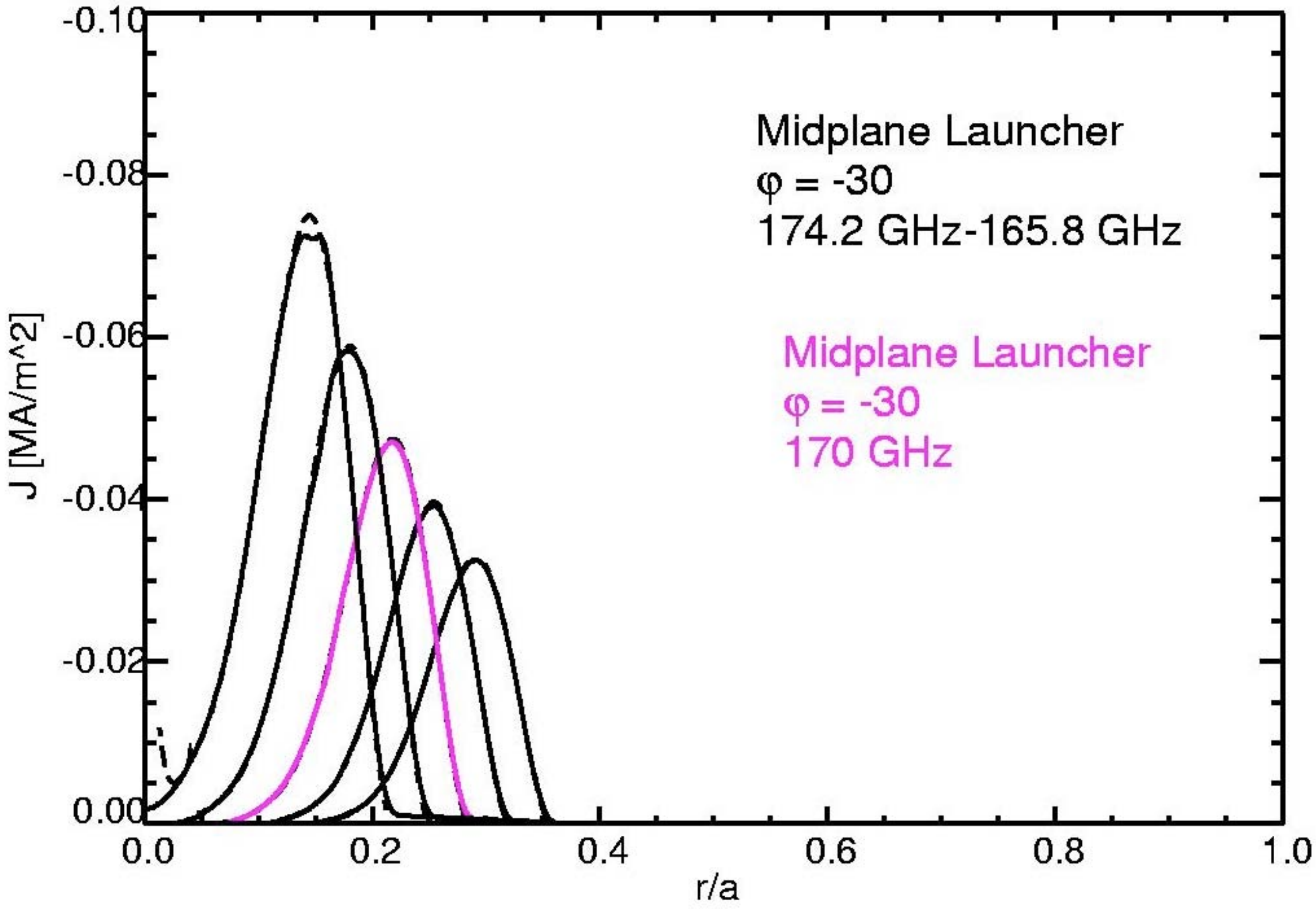
- figure of merit I/d can be alsmost doubled
- would greatly benefit the performance of the present RS design

The ‘ambitious’ option in ITER: midplane launch



Due to the larger ϕ, central CD is even more efficient than at 170 GHz

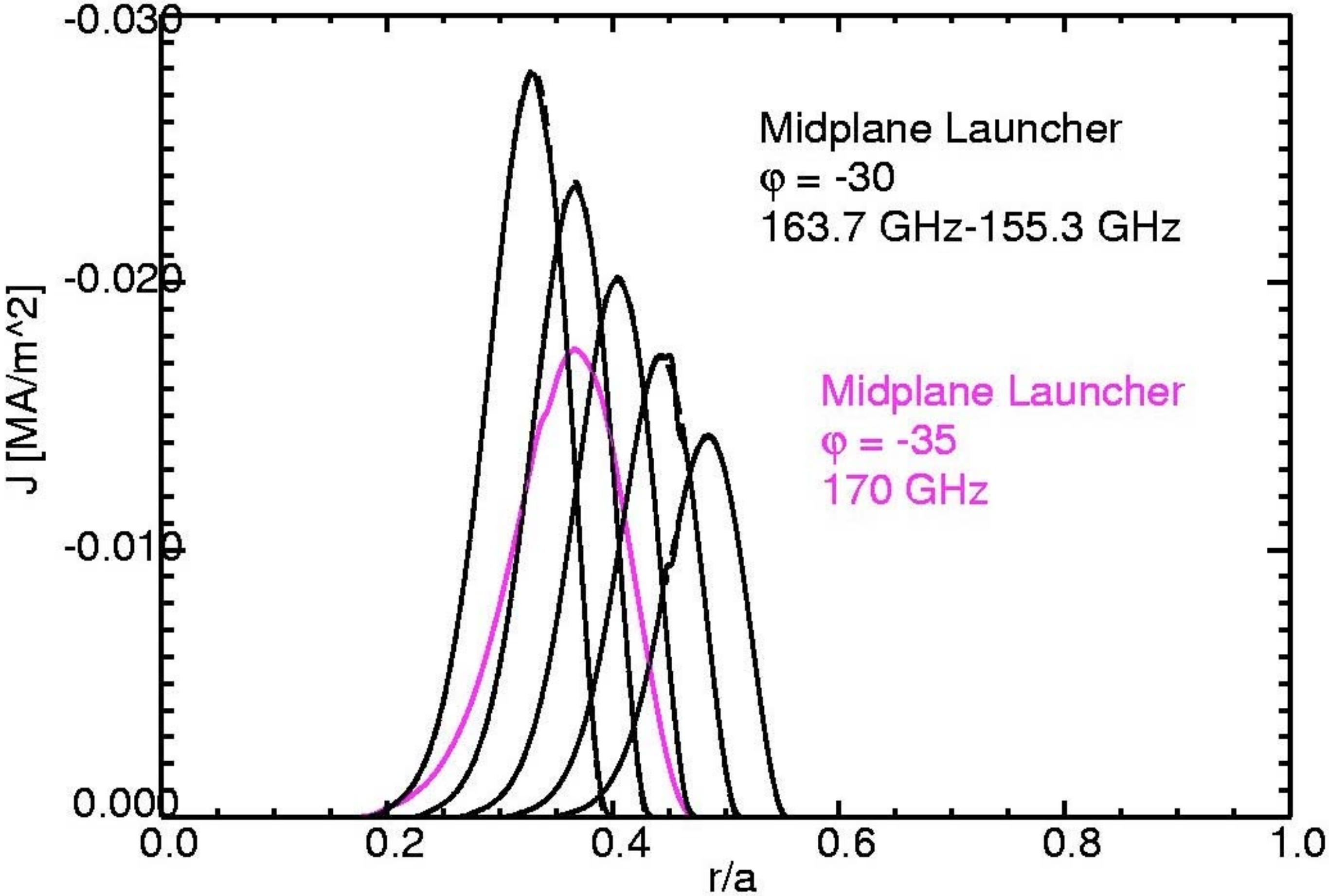
The ‘ambitious’ option in ITER: midplane launch



‘Breakeven’ at r/a = 0.2, outer radii have lower f < 170 GHz

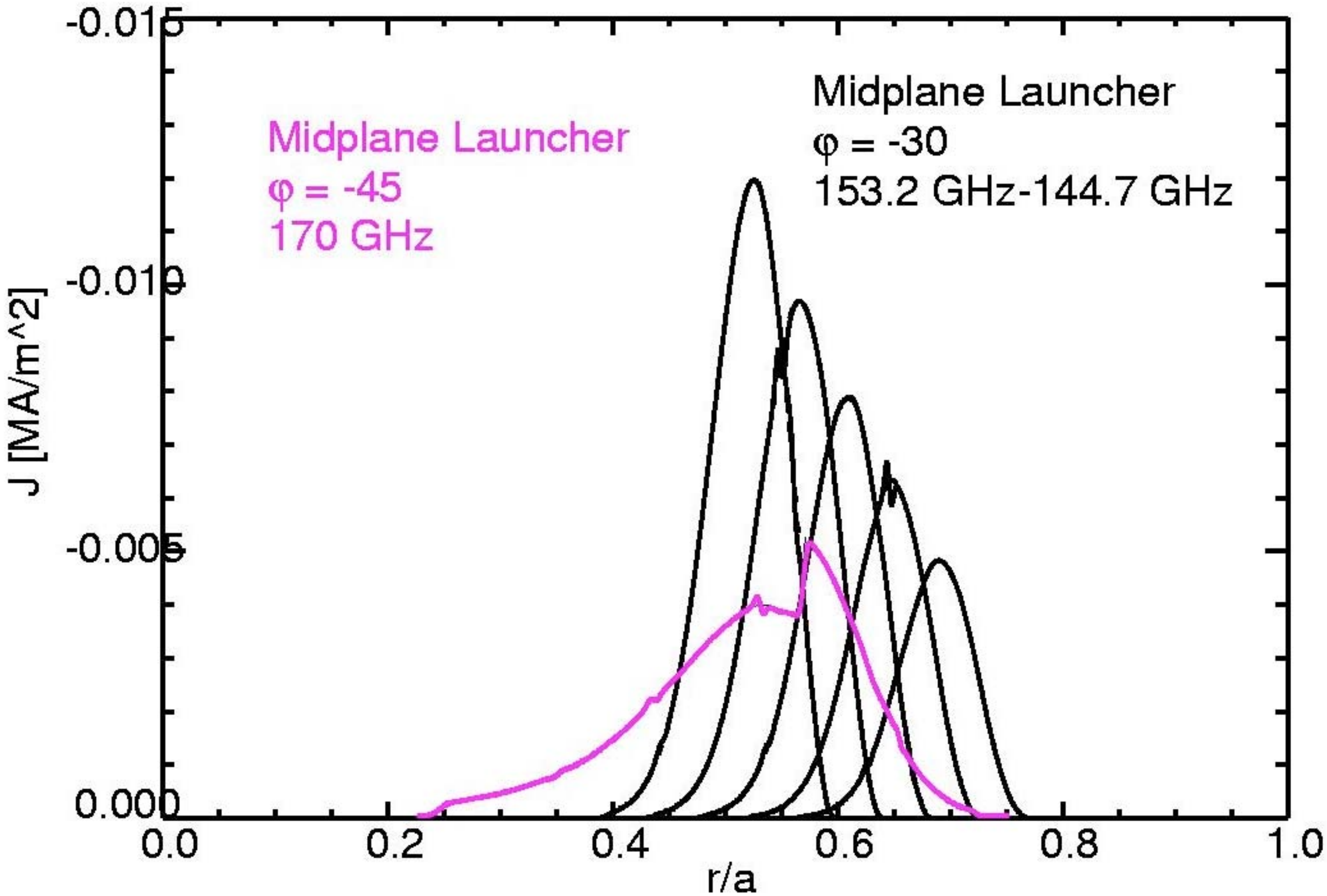
Note: quasi-continuous steering due to small frequency steps

The ‘ambitious’ option in ITER: midplane launch



For r/a > 0.2 higher current density is achieved (smaller ϕ)

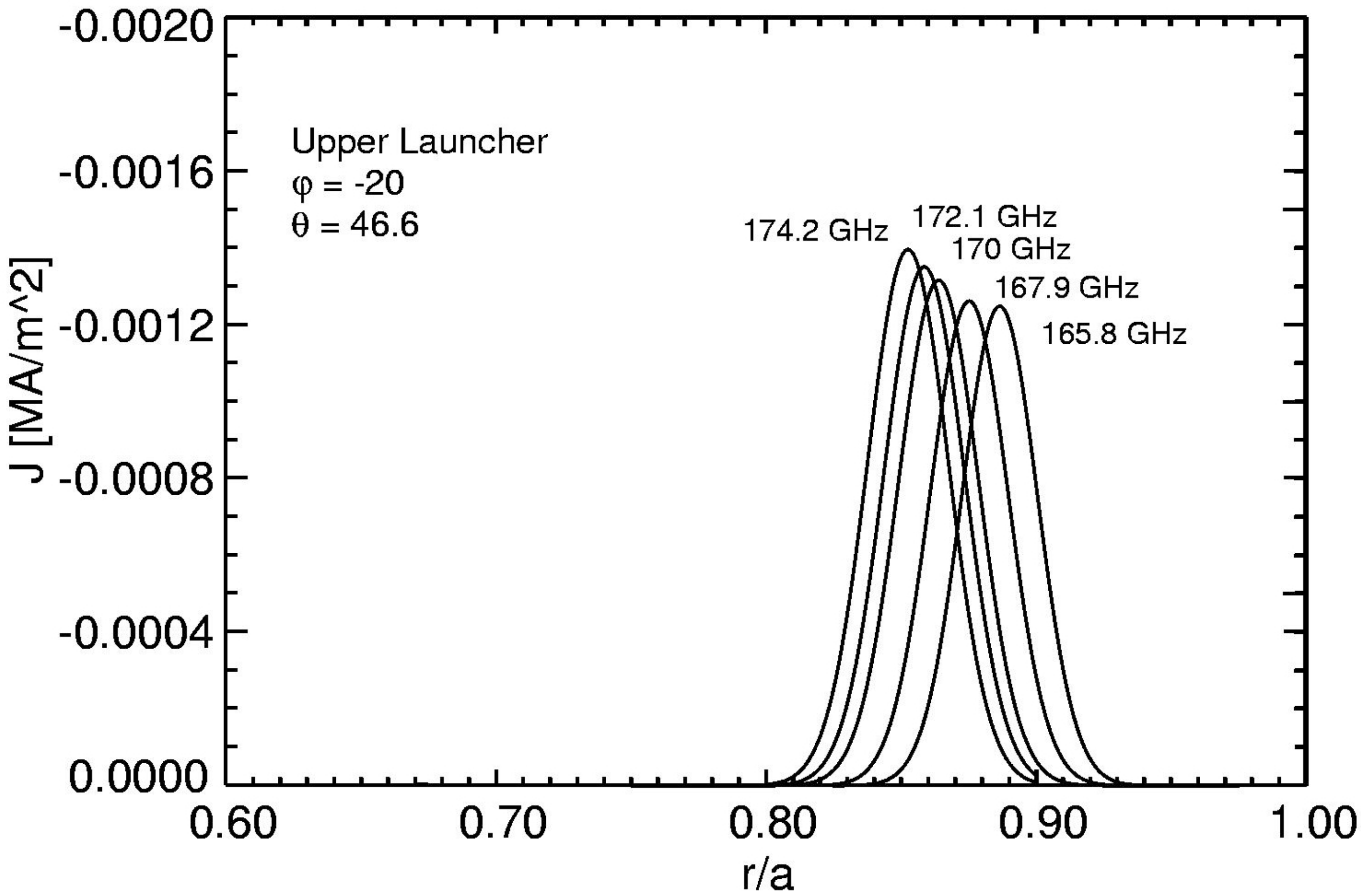
The ‘ambitious’ option in ITER: midplane launch



Deposition can be further out than at 170 GHz with good localisation

⇒ Performance of midplane launcher improved over whole radial range

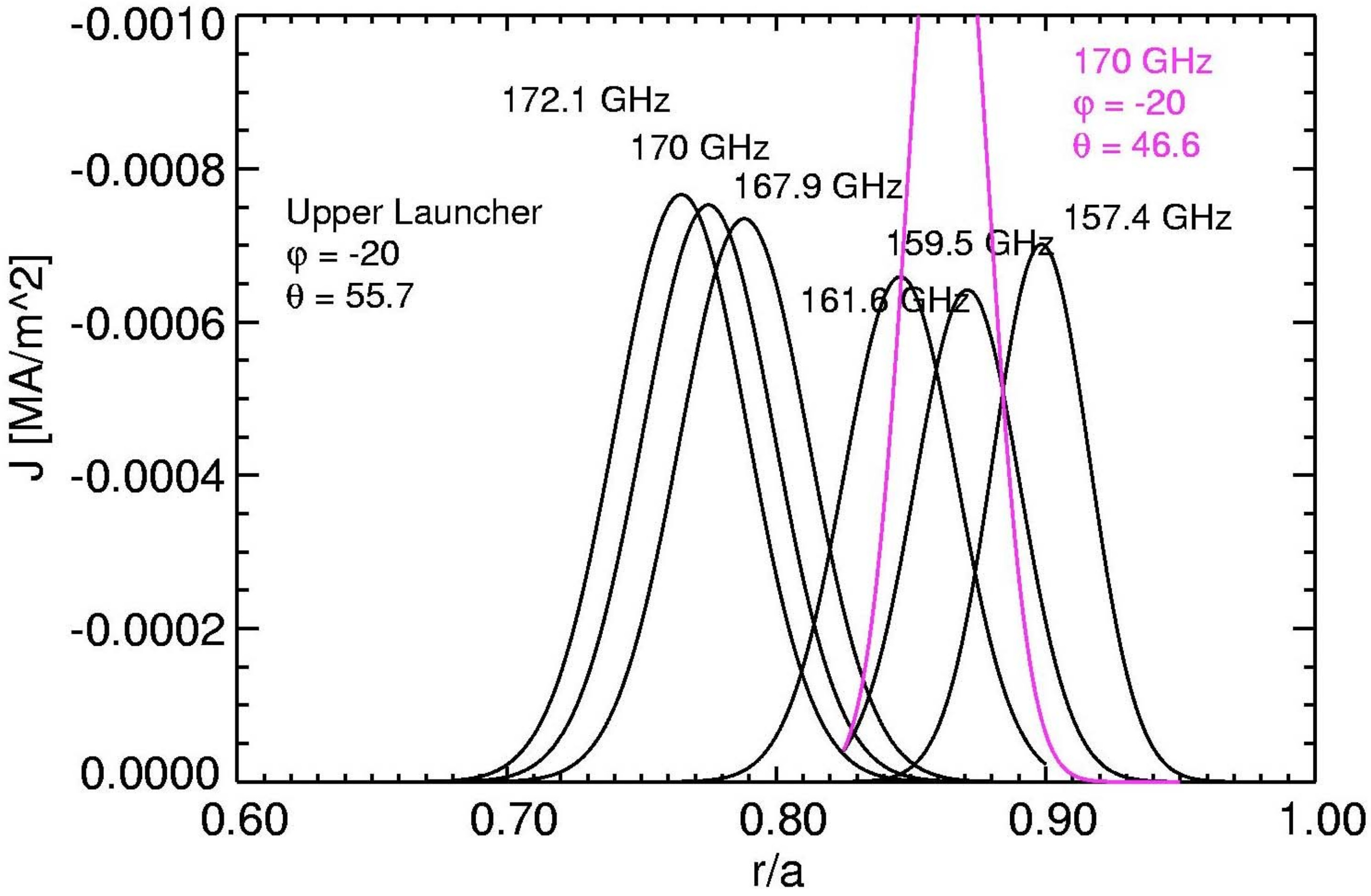
The ‘ambitious’ option in ITER: upper launch



Beam tangential to q=2 surface: quasi-continuous steering possible

⇒ But: with this geometry, q=1.5 cannot be reached

The ‘ambitious’ option in ITER: upper launch



Beam tangential to q=1.5 surface:performance at q=1.5 less than at 170 GHz

⇒ But: this is by no means optimised (RS beam, frequency interval)

Conclusions

Present ITER ECRH system is not fully optimised for physics applications

- localisation of CD around q=1 cam be improved
- at present no central ECH or ctr-ECCD

In the present system, room for improvement exists:

- FS UL coverage can be extended to include q=1 with better localisation
- EL can be changed to provide ctr – ECCD and ECH as well
- note: the optimum system is purely based on Front Steering

2-frequency solution would already cure most of the present problems:

- higher CD efficiency for NTM stabilisation with upper launcher
- larger radial coverage and better localisation with midplane system

A multi-frequency system could avoid any beam steering at all!

⇒ We should at least consider this option when we develop the ITER sources!