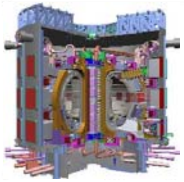

The concept of ECRH/ECCD for ITER

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- Physics objectives of ECRH/ECCD in ITER
- The present system design
- Performance of the present design
- Discussion and conclusions

Acknowledgements – thanks to all these people:

EU (upper launcher, carried out under EFDA technology programme):

CNR Milano: *D. Farina, S. Nowak, G. Ramponi*

EFDA Garching: *G. Saibene*

IPP Garching: *E. Poli*

FZ Karlsruhe: *R. Heidinger*

FOM Rijnhuizen: *A.G.A. Verhoeven, E. Westerhof*

UKAEA Culham: *B. Lloyd, F. Volpe*

CRPP Lausanne: *O. Sauter*

Japan (midplane launcher):

JAERI: *K. Sakamoto, K. Takahashi*

US (physics discussions)

GA: *R. Prater, F.W. Perkins*

CompX: *B. Harvey*

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

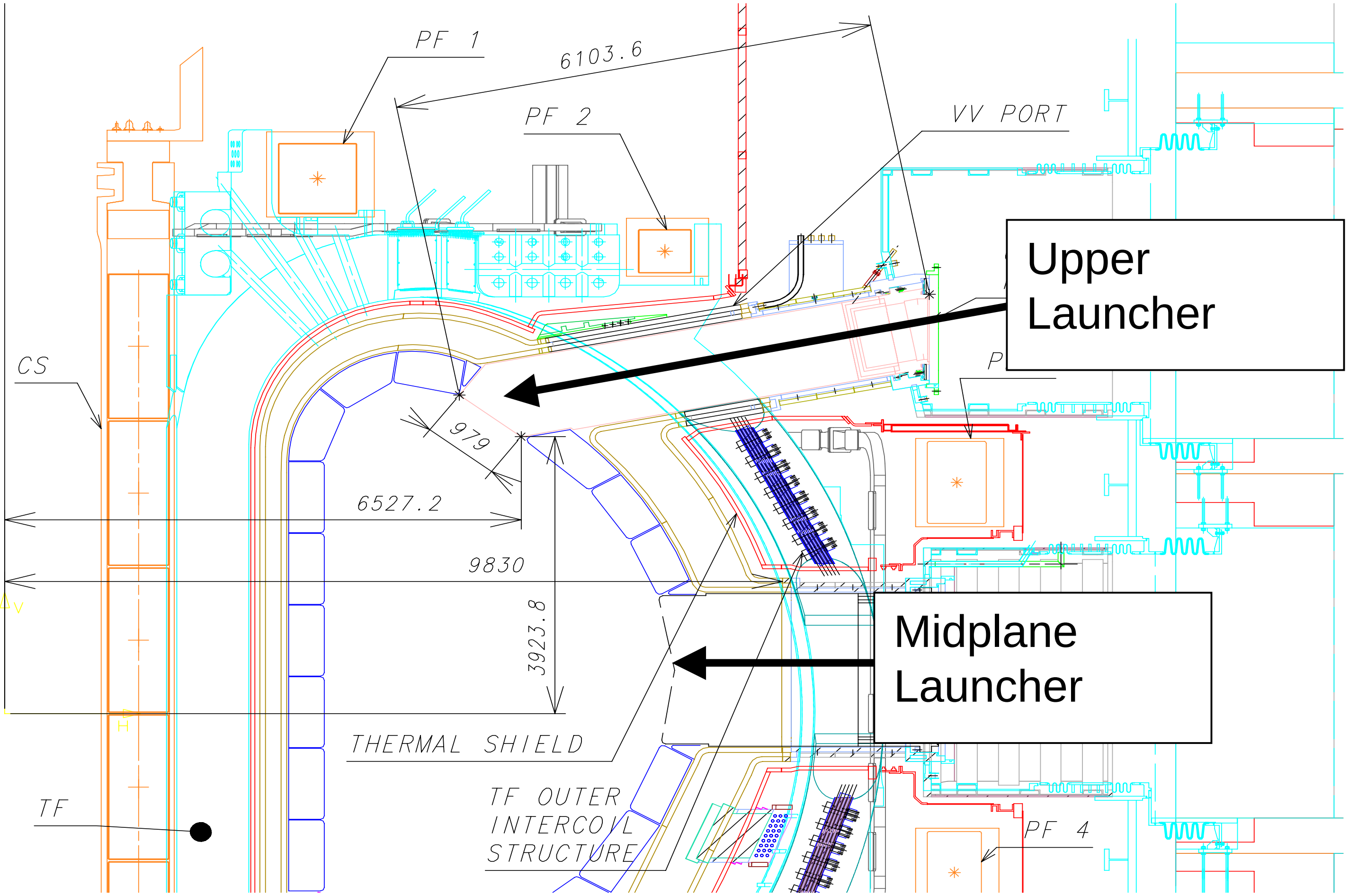
H&CD in steady state / long pulse scenarii (reversed shear / hybrid)

- 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

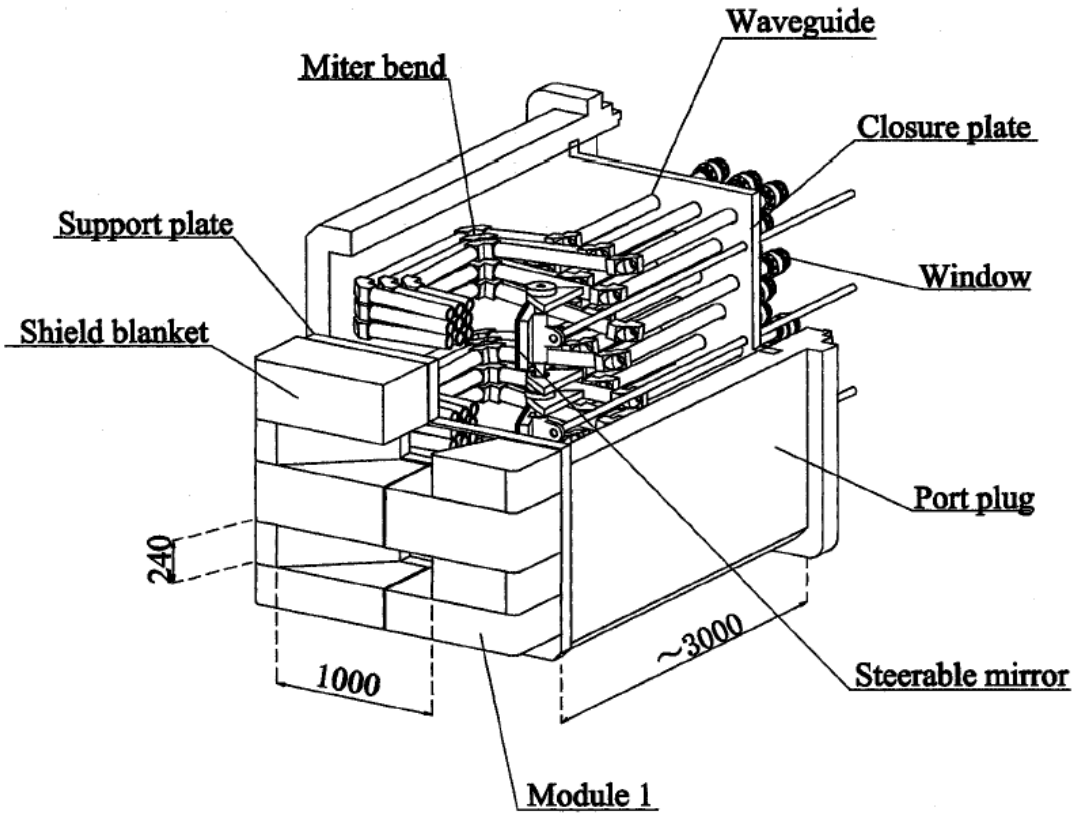
- sawtooth control – localised CD at q=1 surface ($\rho = 0.5$)
- NTM control
- needs far off-axis ($\rho>0.7$) CD with good localisation

The present system design



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

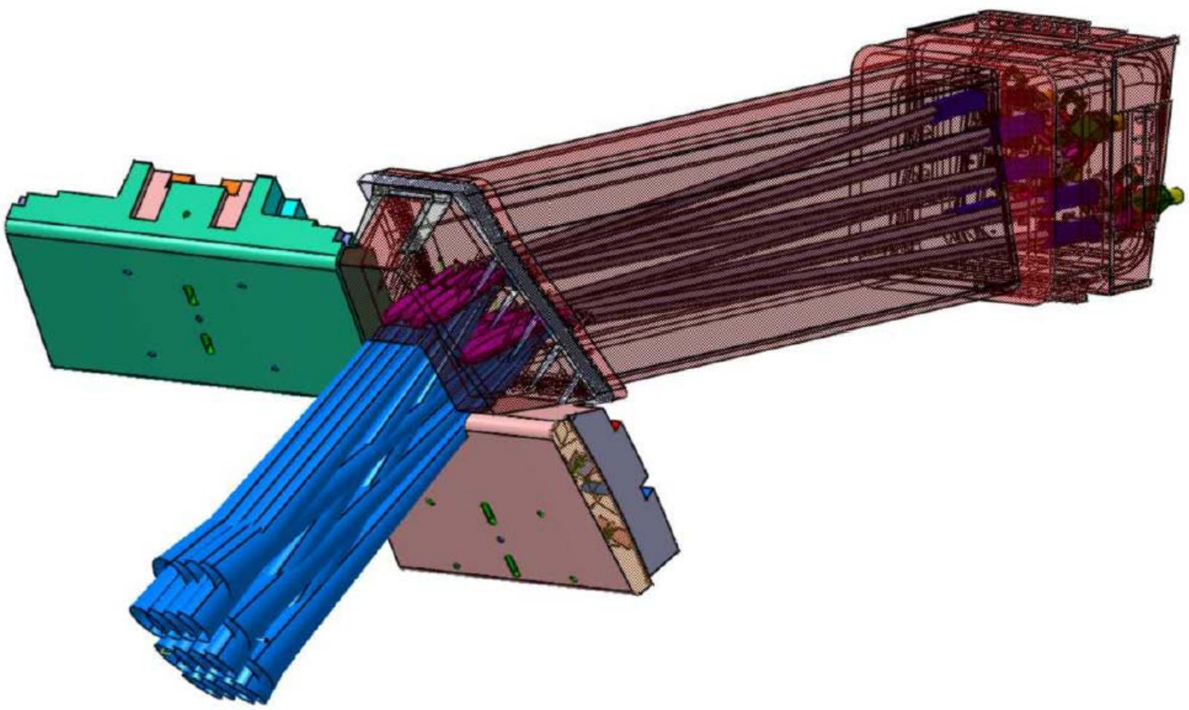
The present system design



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

- midplane launcher: toroidal (front) steering, $20^o < \beta < 45^o$
  launched horizontally from 3 mirrors combining 8 beams each

The present system design



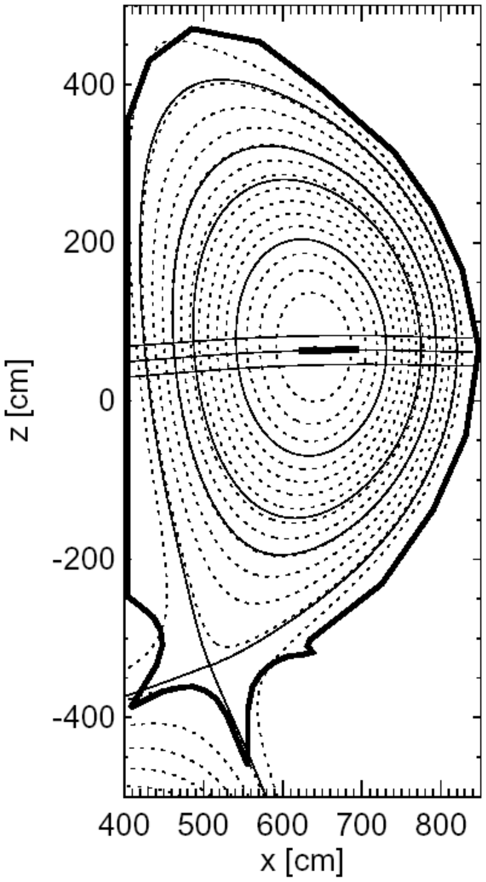
20 MW (24 MW installed) to be launched into the plasma from two positions

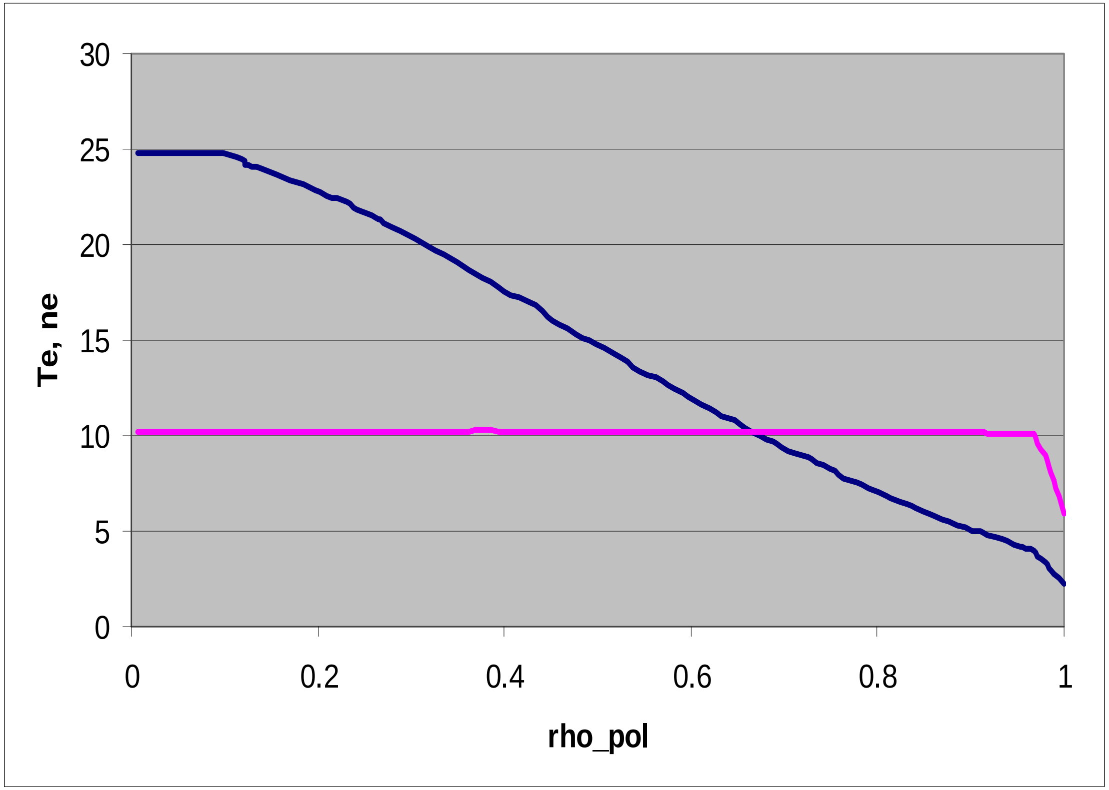
- upper launcher: poloidal (remote) steering range ±8° at front mirror

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

  fourth port could be available to ECRH

Performance evaluation – midplane launcher

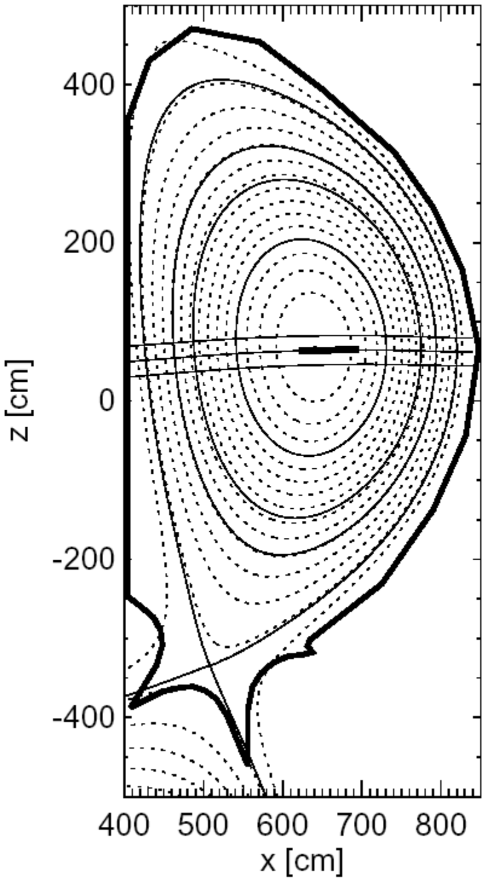


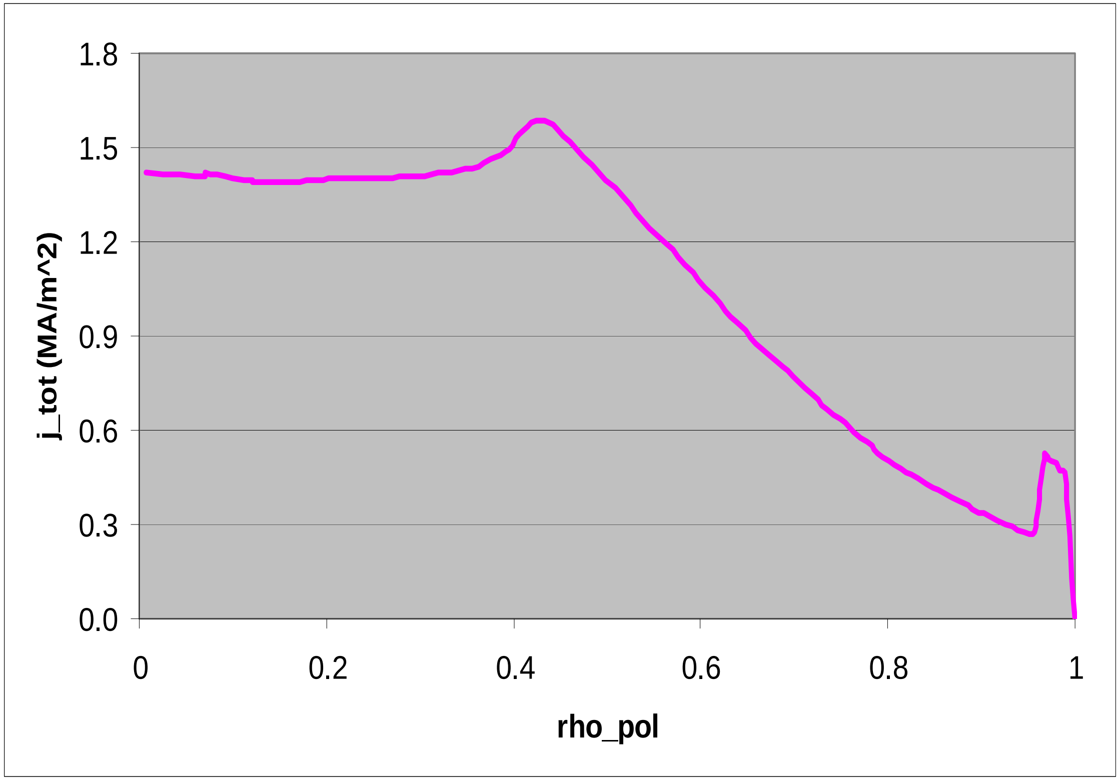


TORBEAM code was used to evaluate capabilities in scenario 2 (Q=10)

- one beam per mirror to mock up 8 combined beams (!) – to be improved
- similar results obtained by E. Westerhof (TORAY)

Performance evaluation – midplane launcher





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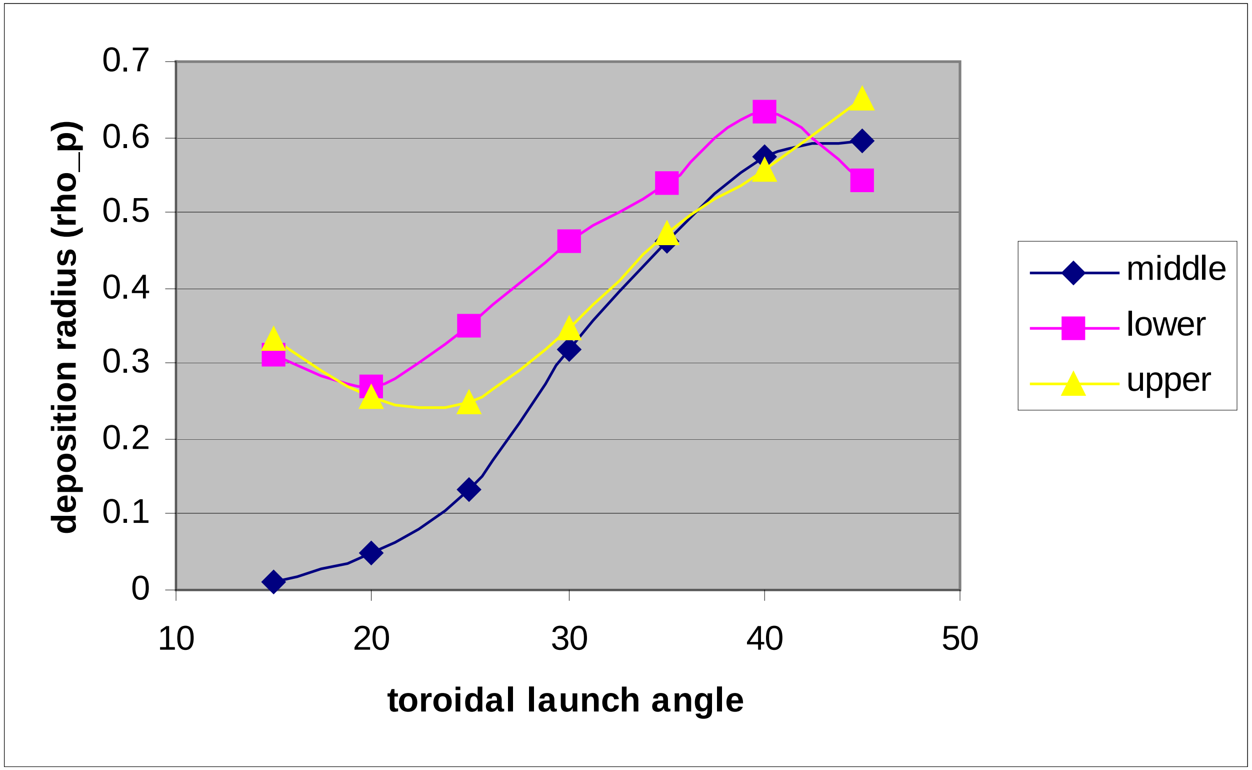
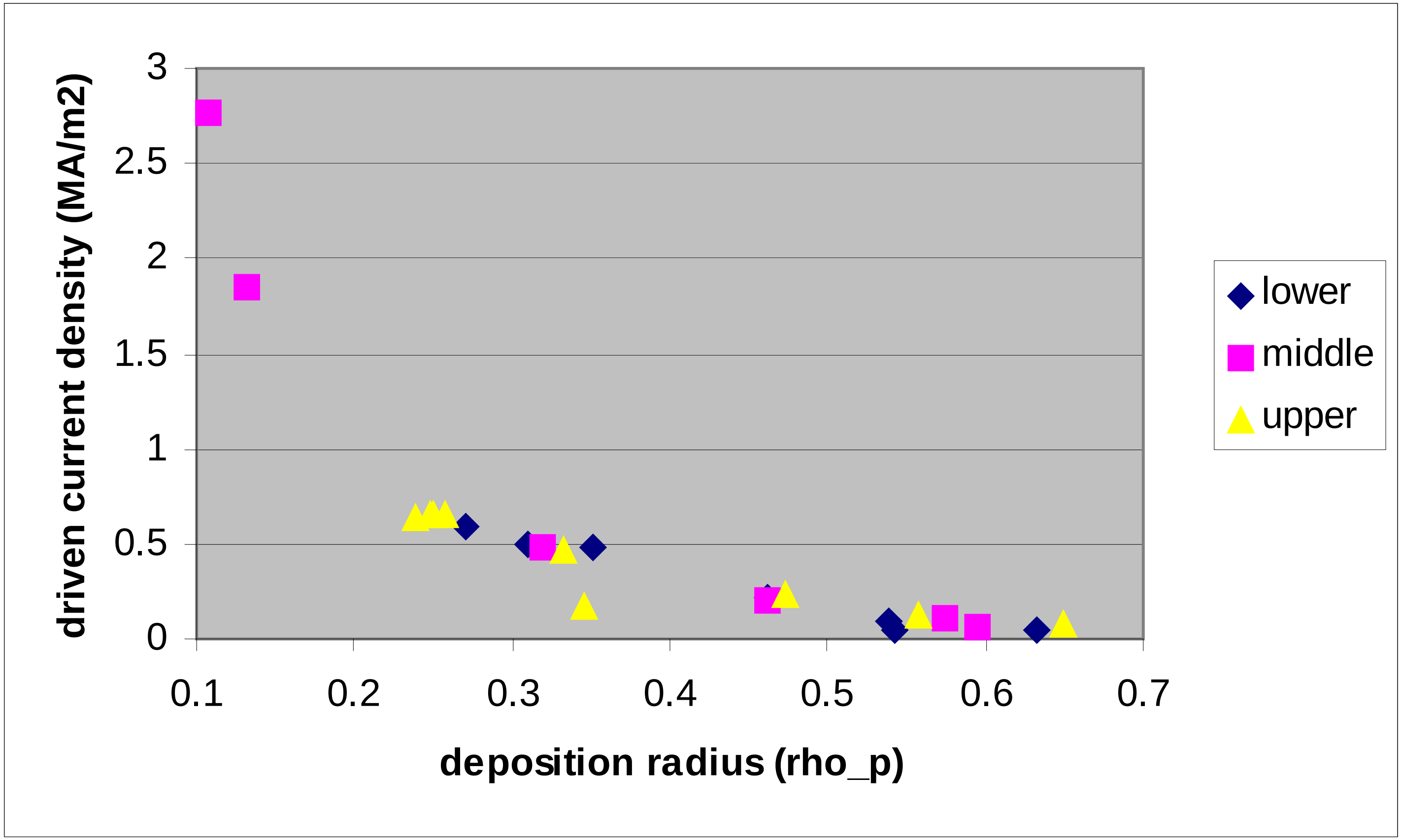


Steering range gives access to $0 < \rho_p < 0.65$

- only beams from middle mirror hit magnetic axis (due to horizontal launch)
- larger toroidal angle does not lead to $\rho_p > 0.65$ (beam already tangential)

Performance evaluation – midplane launcher



Current density can be comparable to (or exceed) total current density

- will significantly contribute to central current density
- note: very simplified beam, should be carefully looked at

Discussion – midplane launcher

System can fulfill basic requirements, but some optimisation possible

- finite poloidal angle for upper/lower mirrors – all beams go though centre

More interaction between physics and engineering design needed

- beam focusing could be optimised for q=1 (sawtooth control)
  - central deposition still localised enough?
- system always drives finite co-current – may be undesirable!
  - additional steering possibility –20^o to -45^o would cure the problem
- radial range ρ_p < 0.7 not accessible by upper launcher
  - 'gap' in radius (where AT needs off-axis current) – should be avoided

$\Rightarrow$ Not possible by toroidal steering – need poloidal steering instead?

...lower gyrotron frequency?

Performance evaluation – upper launcher

The main physics goal for the upper launcher is NTM stabilisation

- system should be capable of suppressing (3,2) and (2,1) NTMs
- (2,1) NTM expected to be most detrimental in ITER – higher emphasis

$$\frac{\tau_{res}}{r_s}\frac{dW}{dt} = r_s\Delta' - r_s\Delta'_{other} + a_{bs} r_s \beta_p \sqrt{\varepsilon}\,\frac{L_q}{L_p}\frac{1}{W} - L_q r_s\left(a_{m,n}\frac{I_{ECCD(m,n)}}{I_p(r_s)}\frac{1}{W^2} + a_{0,0}\frac{I_{ECCD(0,0)}}{I_p(r_s)}\frac{1}{d^2}\right)$$

ECRH has two main effects on NTM stability

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

Performance evaluation – upper launcher

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)
- ECCD current density has to exceed bootstrap current density by 20-60%

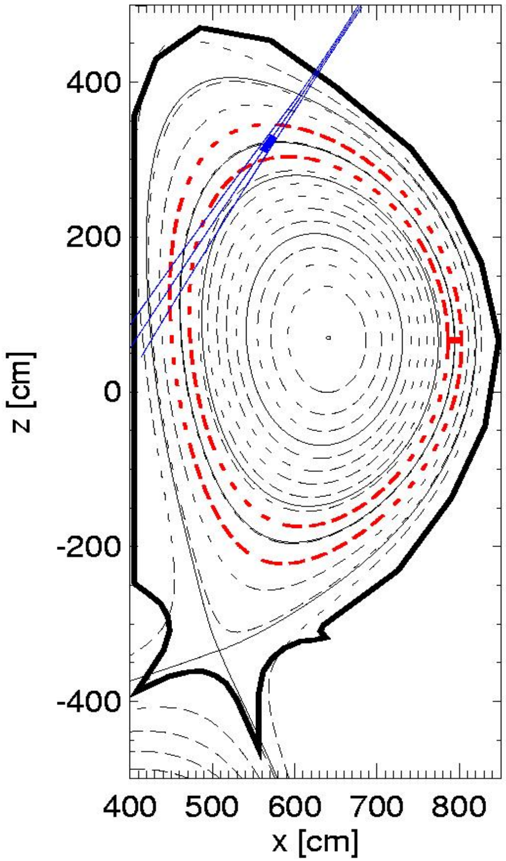
Figures of merit for NTM stabilisation by ECCD

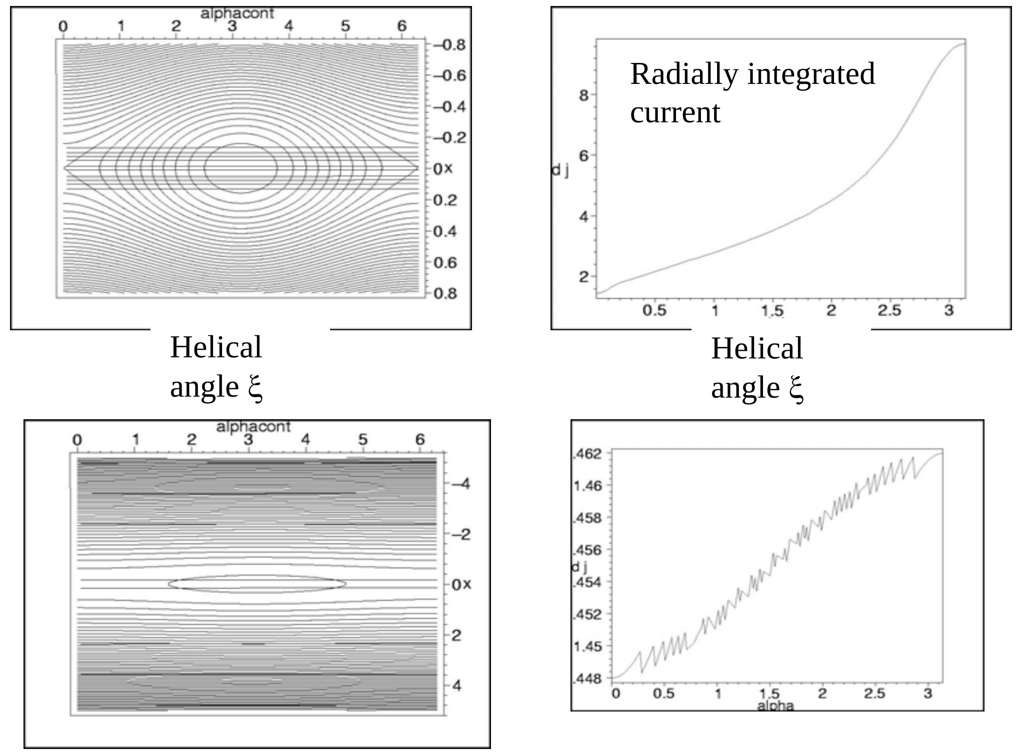
- equilibrium current profile: change in Δ' is determined by dj/dr: I_{ECCD}/d^2
- helical component: current within island counts: I_{ECCD} for $d < W$

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

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

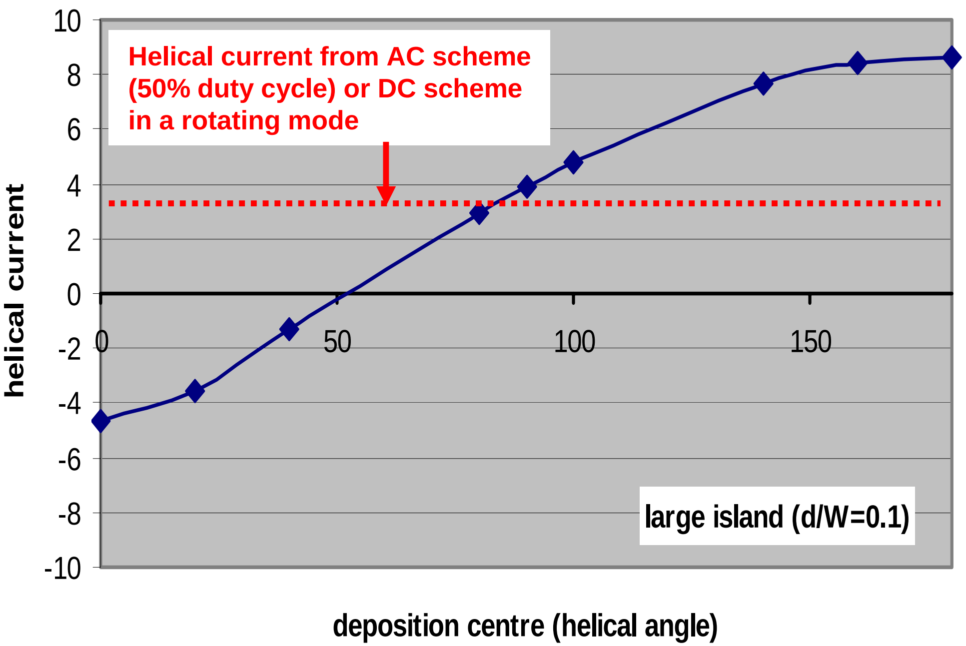
Rotating small islands are difficult to stabilise

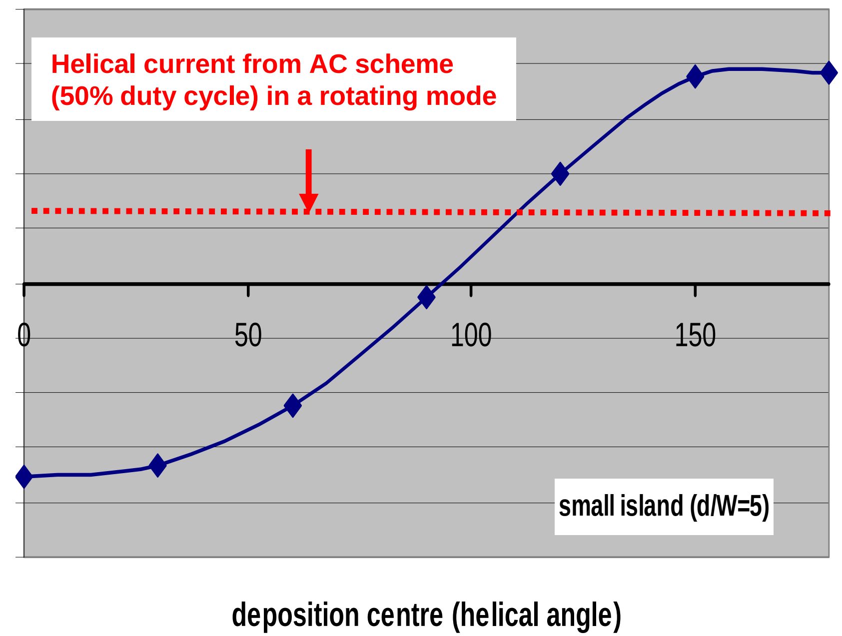




- for d > W, continuous injection does no longer generate a helical component
- may require modulation of ECCD power in phase with island
- present extrapolation: 3-5 kHz modulation frequency required for (3,2) NTM

For locked modes, finite toroidal extent is important





Rotating mode:

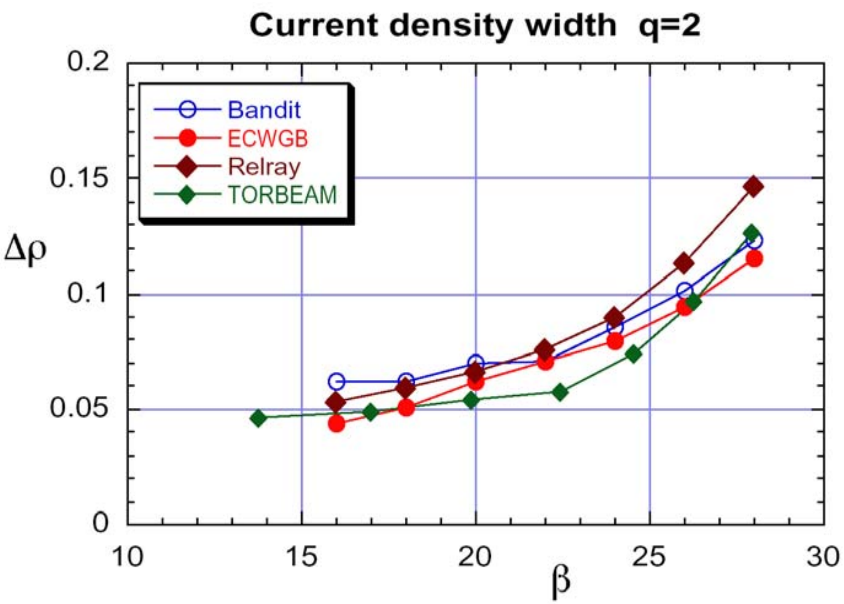
- large island: AC and DC have comparable efficiency
- small island: AC generates finite current, but DC cancels (see before)

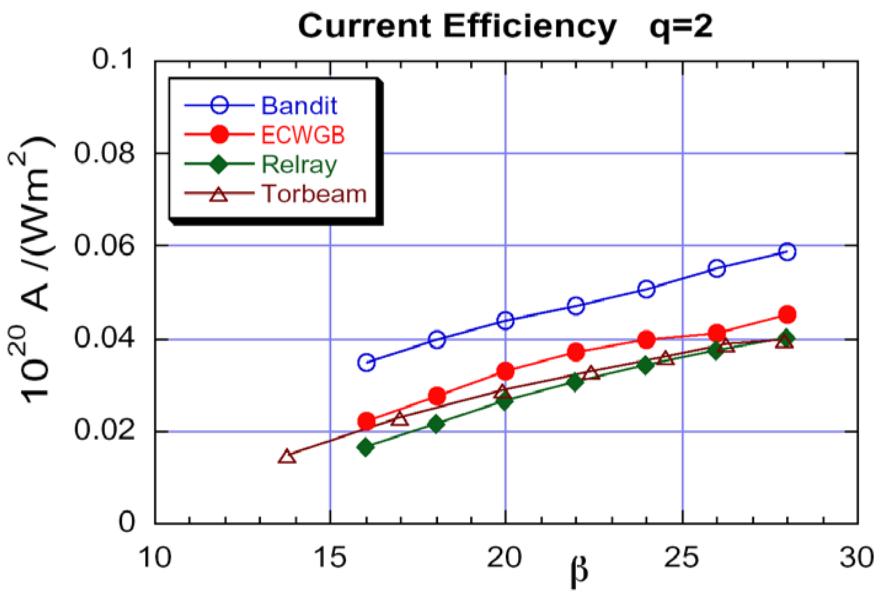
Locked mode:

- large island: for $\delta\xi$ up to 100^o, helical current exceeds AC and DC schemes
- small island: for $\delta\xi$ up to 80^o, helical current exceeds AC scheme

Benchmarking of ECRH codes

- ray tracing, analytical H&CD: TORAY (FOM)
- beam tracing, analytical H&CD: ECWGB (CNR), TORBEAM (IPP)
- ray tracing with Fokker-Planck H&CD: BANDIT-3D (UKAEA)

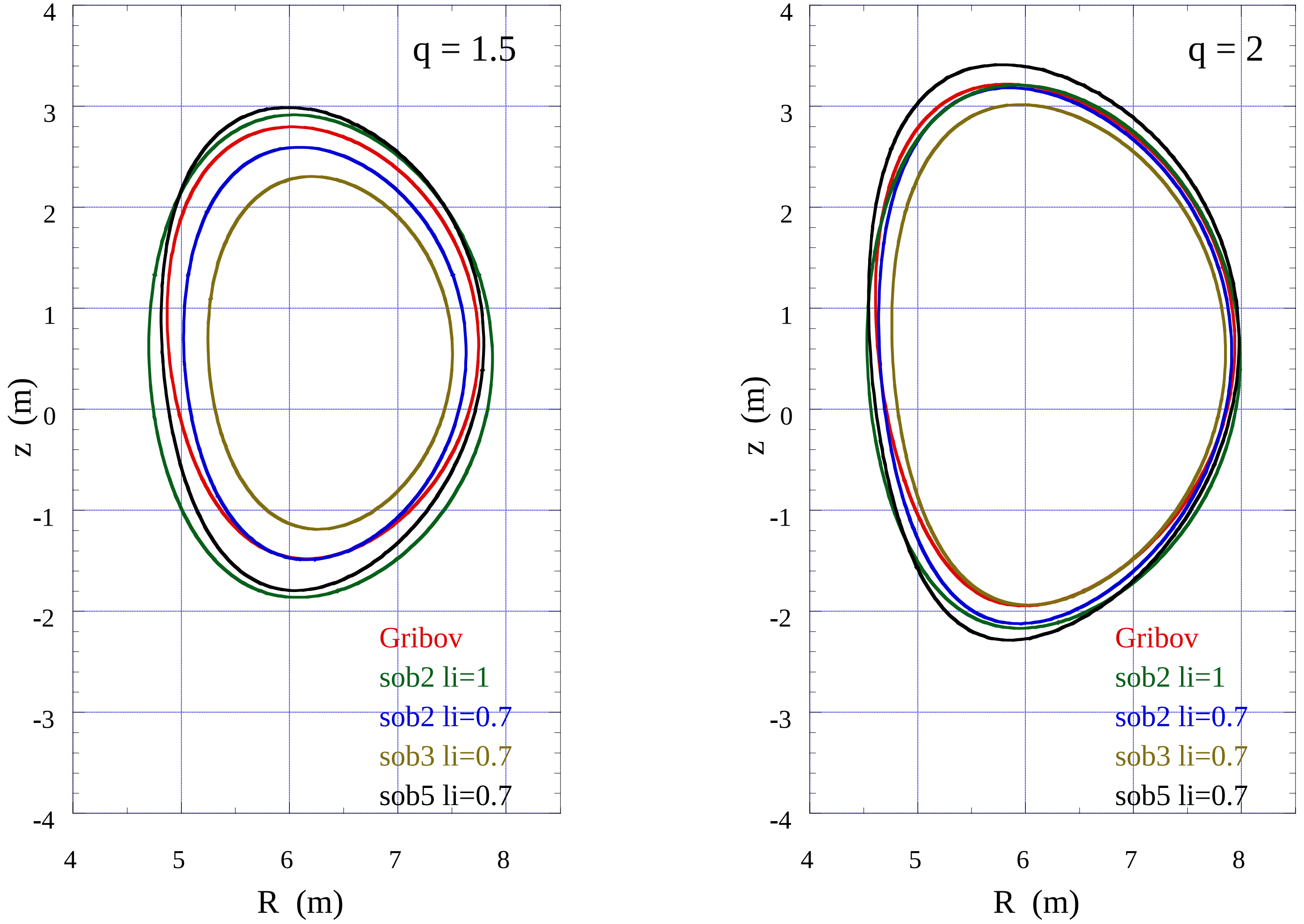




In general, codes show remarkably good agreement

- typically, driven current from BANDIT-3D higher by approximately 20%

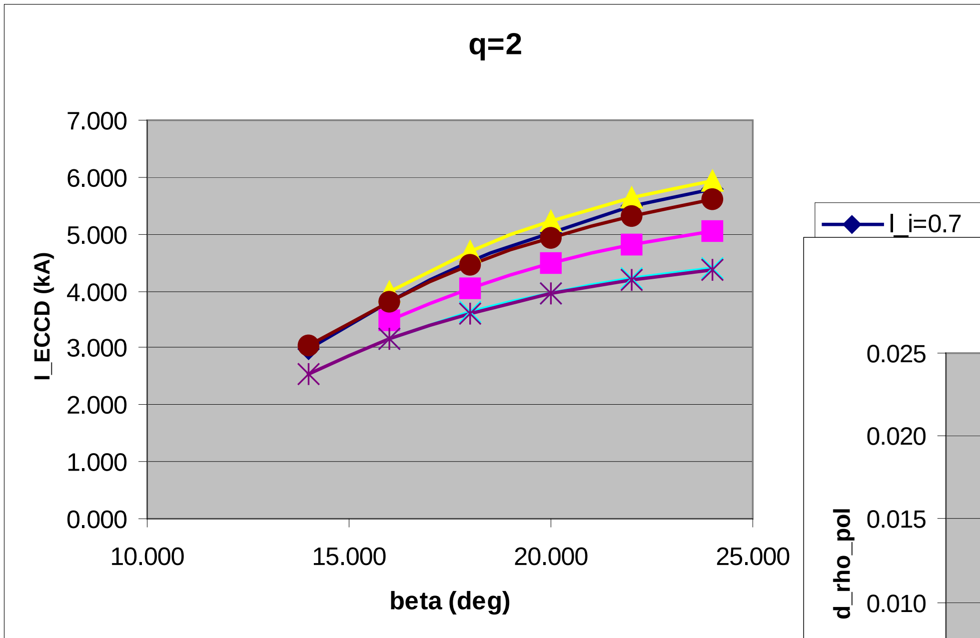
Equilibria account for typical experimental variations

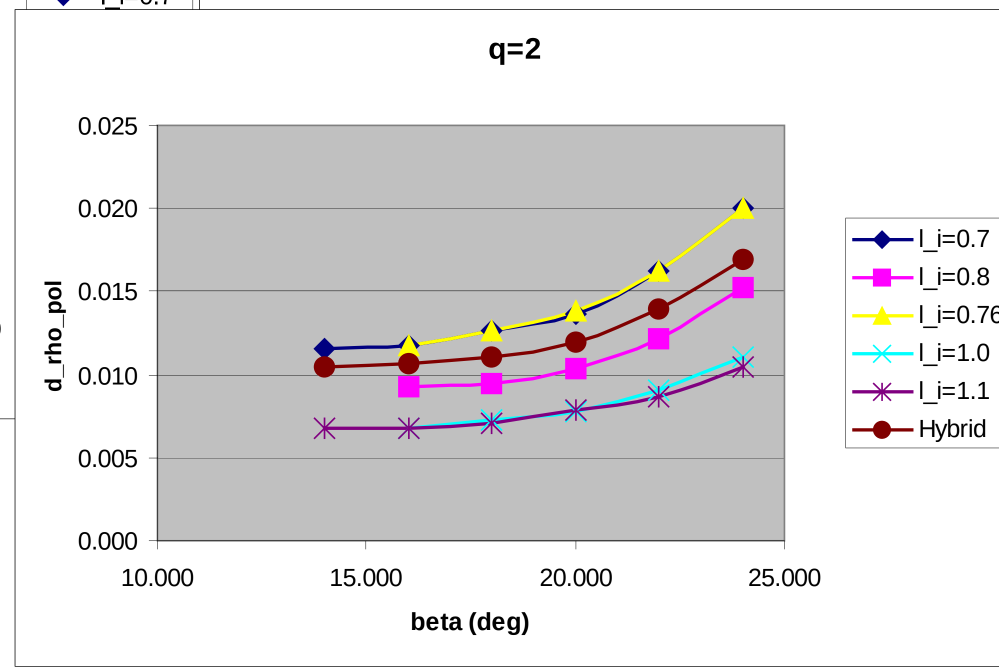


- scen. 2 (Q=10), scen. 3 (hybrid, reduced I_p) and scen. 5 (low q, higher I_p)
- for scen. 2, current profile variation done (0.7 < li < 1.0, reference has 0.76)

Evaluation of figure of merit for NTM stabilisation

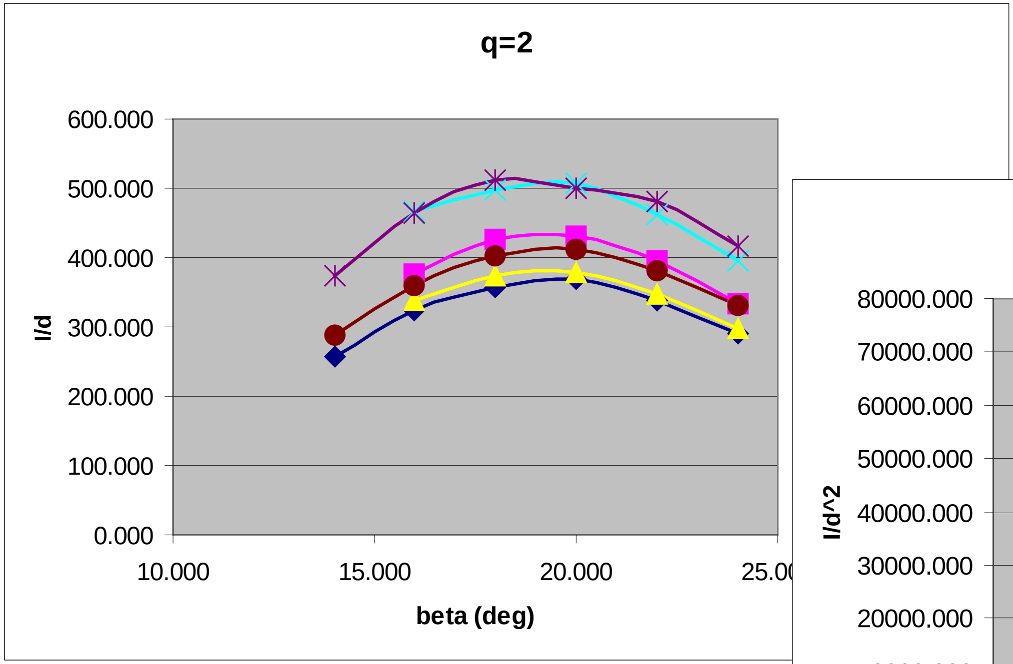
Toroidal angle β scanned from 15º to 25º, poloidal angle adjusted to hit ρ_{res}

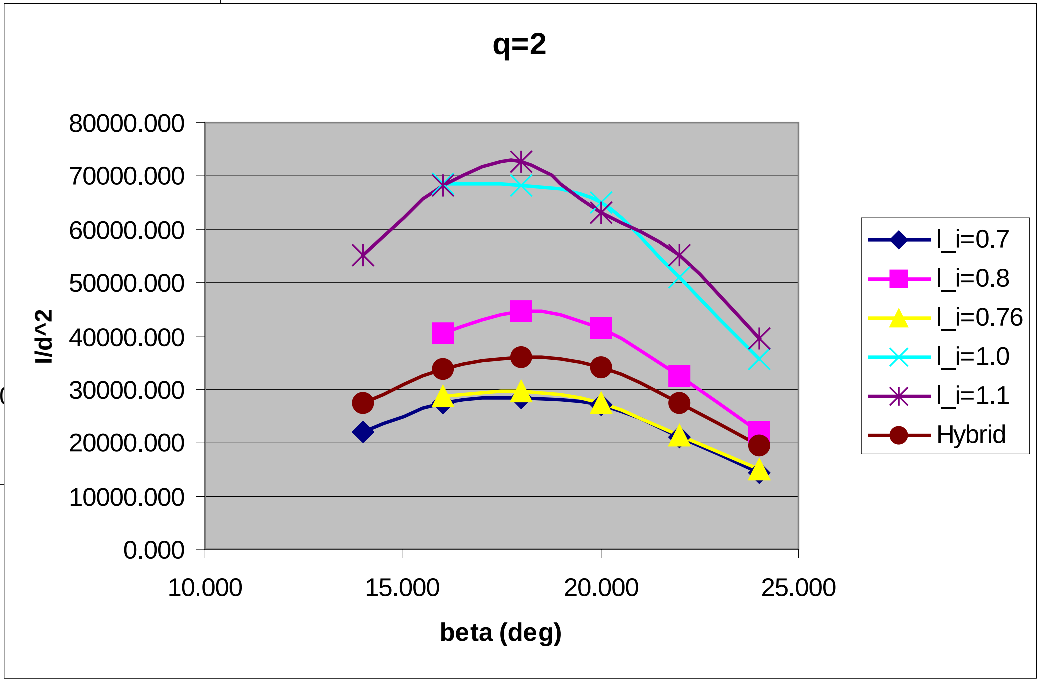




- both I_{ECCD} and d increase with angle, but with different powers

Evaluation of figure of merit for NTM stabilisation

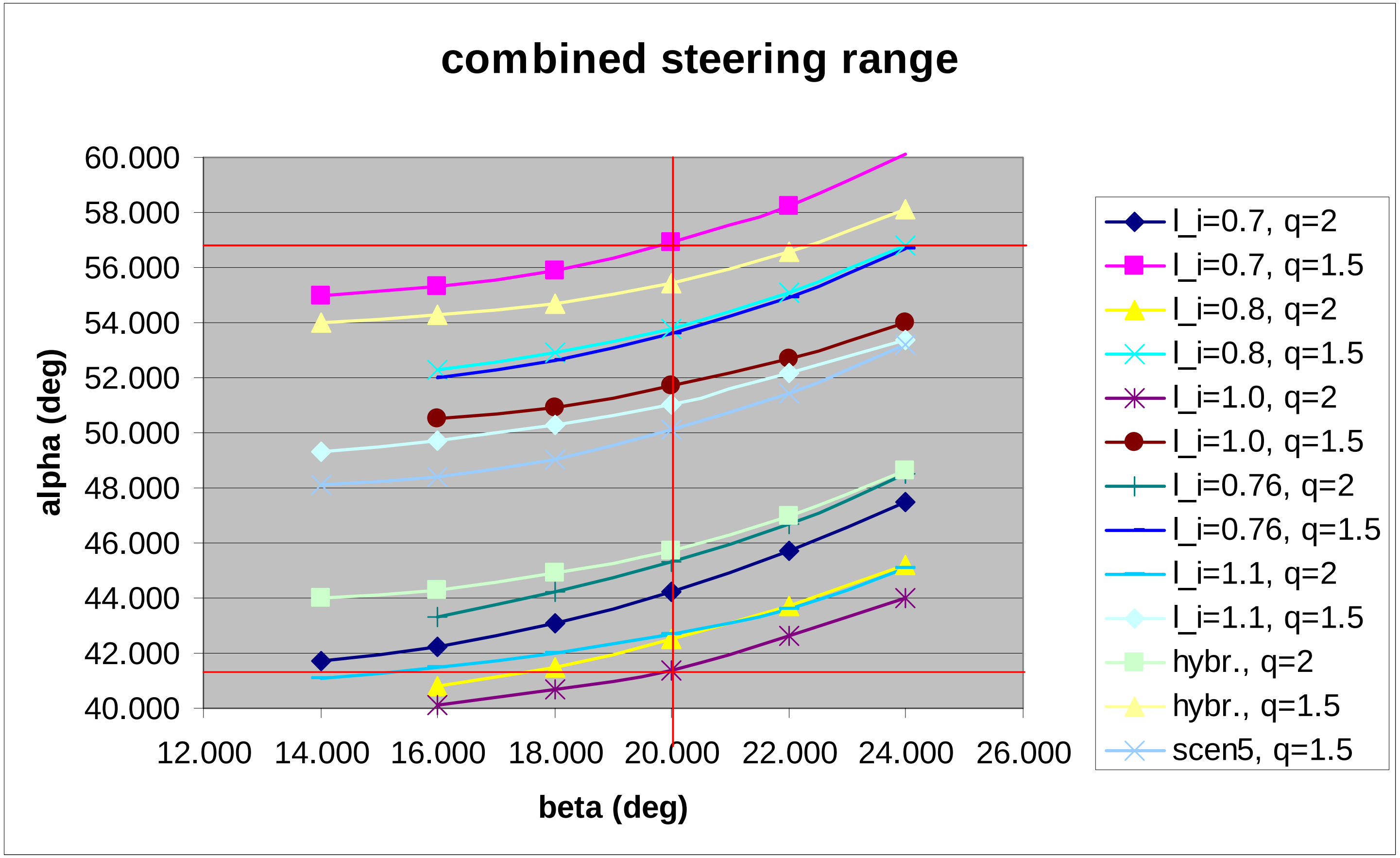




For all cases, similar optimum β – only poloidal steering needed

- lower row: optimum β 18°-20° for q=2 and 20°-22° for q=1.5 ⇒ fix at 20°
- similar for upper row, optimum angle is 18° (see poster by G. Ramponi)

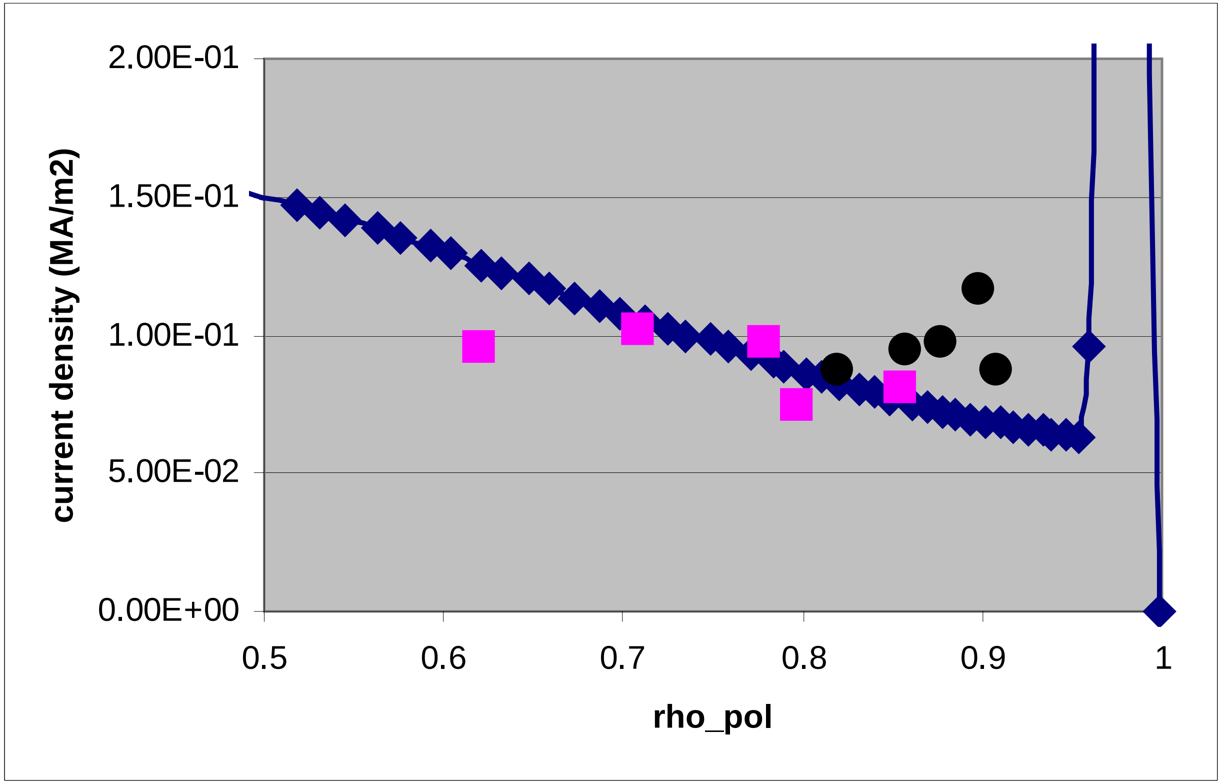
Evaluation of figure of merit for NTM stabilisation



Steering range should be ±8° (upper row) / ±10.5° (lower row)

- in conflict with present design limit of ±8° for both rows
- further increase in steering range will reduce focusing, i.e. lower j_{ECCD}

Evaluation of figure of merit for NTM stabilisation



Performance of present design is (sub)marginal for NTM stabilisation

- bootstrap current only marginally exceeded for q=1.5
- slightly better for q=2

$\Rightarrow$ situation should be improved

Discussion – upper launcher: possible improvements

Use of fourth upper port and assume 1.5 MW per line

- dedicated launchers/rows reduce steering requirement, increase focusing
- use only lower rows for both surfaces – better localisation
- advantage: does not require change in the ITER machine design

Use of front steering may also provide reduced spot size

Higher frequency enhances current drive efficiency

- Disadvantage: conflict with the physics objectives for the midplane system
- Possible way out: use of multi-frequency gyrotrons
  (but: remote steering can only at frequency which fulfills Talbot condition)

Relocation of the upper launcher to a somewhat lower location

- absorption most localized when beam hits resonant surface tangentially
- disadvantage: major change in the ITER machine design (!)

Conclusions

The ECRH/ECCD system for ITER should fulfill a variety of tasks

Present approach (midplane and upper launcher) would benefit from some refinement

- optimise deposition localisation for midplane launcher
- provide for ctr-CD (and therefroe also pure CD) with midplane launcher
- improve deposition localisation for upper launcher
- ensure that no 'gap' in accessible radius exists

All these requirements seem feasible with reasonable R&D effort

Detailled system engineering profits substantially from close interaction with physics integration activtity