Assessment of DEMO Challenges by the German DEMO Working Group

H. Zohm for the German DEMO Working Group (FZJ / KIT / IPP)

- introduction
- our approach at FZJ / KIT / IPP
- special topic: steady state and H&CD
- summary and conclusions
- topics treated in more detail in other contributions:
  - **- exhaust, PWI and materials (poster by Boccaccini and Kallenbach)**
  - **- high density operation and fuel cycle (talks by Day and Wolf)**
  - **- DEMO design options (talk by Biel)**
  - **- Stellarator DEMO designs (talk by Beidler)**
  - **- Tokamak operational limits (talk by Zarnstorff, not part of German DEMO WG ☺)**

International MFE Roadmapping Workshop, Princeton, USA, 9.9.2011

Introduction

Introduction: DEMO designs

There is also no generally accepted DEMO machine design

Study	Ward 06	Ward 06	Garcia 08	Garcia 08	Pereverzev 06	Pacher 07	Kolbasov 08 (DEMO-S)	Tobita 08 (Slim CS)	Hiwatari 05 (DEMO-CREST)	Najmabadi 06 (ARIES-AT)
Operation mode	Pulsed	Steady state	Pulsed	Steady state	Steady state	Pulsed	Steady state	Steady state	Steady state	Steady state
P_{th} (GW)	2.4	3.3	3	3	2.5	3	2.4	3.6	3.3	1.9
$P_{el,net}$ (GW)	1	1	1	1	—	—	0.65	1	0.5	1
R_e (m)	9.5	6.9	7.5	7.5	7.5	8.1	7.8	5.5	7.25	5.2
A	4	3	3	3	3	2.9	5.2	2.6	3.4	4
B_t (T)	7.4	5.8	6	6	6	5.7	7.7	6	7.8	5.9
I_P (MA)	15.5	19	19	19	16	18	11.2	16.6	14.7	12.8
f_{bs}	0.43	0.44	0.53	0.53	0.56	0.61	0.59	0.77	0.5	0.91
γ_{CD} (A/(W 10^{20} m^{-2}))	—	0.44	0.52	0.52	0.56	0.7	0.47	0.41	0.3	0.4
P_{CD} (MW)	—	237	98	128	95	50	117	60	191	35
H	1.3	1.05	—	—	—		1	1.3	1.2	−1
β_N	2.4	3	—	—	—	3.1	4.7	4.3	3.4	5.4
Reference	3	3	4	4	5	6	7	8	9	10

(Tokamak) designs cluster around R ≈ 7.5 m, $P_{el,net}$ ≈ 1 GW (P_{th} 2-3 GW)

[3]D. Ward et al., EFDA Report TW6-TRP-002 (2007).
[4]J. Garcia et al., Nucl. Fusion 48 (2008) 075007.
[5]G. Pereverzev et al., Proc. 21st FEC, Chengdu, (2006).
[6]G. Pacher et al., Nucl. Fus. 47 (2007) 469.
[7]B. Kolbasov et al., Fus. Eng. Des. 83 (2008) 870.
[8]K. Tobita et al., Fus. Eng. Des. 81 (2006) 1151.
[9]R. Hiwatari et al., Nucl. Fusion 45 (2005) 96.
[10]F. Najmabadi et al., Fus. Eng. Des. 80 (2006) 3.

Introduction: DEMO designs

Study		Hiwatari 05 (DEMO-CREST)	Najmabadi 06 (ARIES-AT)
Operation mode		Steady state	Steady state
P_{th} (GW)		3.3	1.9
$P_{el,net}$ (GW)		0.5	1
R_e (m)		7.25	5.2
A		3.4	4
B_t (T)		7.8	5.9
I_P (MA)		14.7	12.8
f_{bs}		0.5	0.91
γ_{CD} (A/(W 10^{20} m^{-2}))		0.3	0.4
P_{CD} (MW)		191	35
H		1.2	−1
β_N		3.4	5.4
Reference		9	10

However, there is quite a spread in optimism of assumptions

- ARIES-AT: operation close to all physics and technology limits
- DEMO-CREST: moderate assumptions (plasma physics of ITER Q=10)

DEMO is a moving target!

Determine the range of DEMO parameters with a realistic ‘level of optimism’!

This must be done for physics and technology ***together*** to avoid too much optimism (or pessimism) in the assumptions about the ‘other side’

Thus, an important goal is to

Understand, on a basic level, the interlinks between physics and technology and the constraints arising from them

From such an understanding, an important second goal can be derived

Devise future directions of research based on the importance of progress in the individual field for DEMO as a whole

German fusion centres FZJ, KIT and IPP, have a large part of the necessary expertise $\Rightarrow$ initiation of a ‚German DEMO Working Group‘

The work is done in mutual collaboration with the EU 3PT programme.

Our approach at FZJ, KIT and IPP

FORSCHUNGSZENTRUM

Karlsruher Institut für Technologie

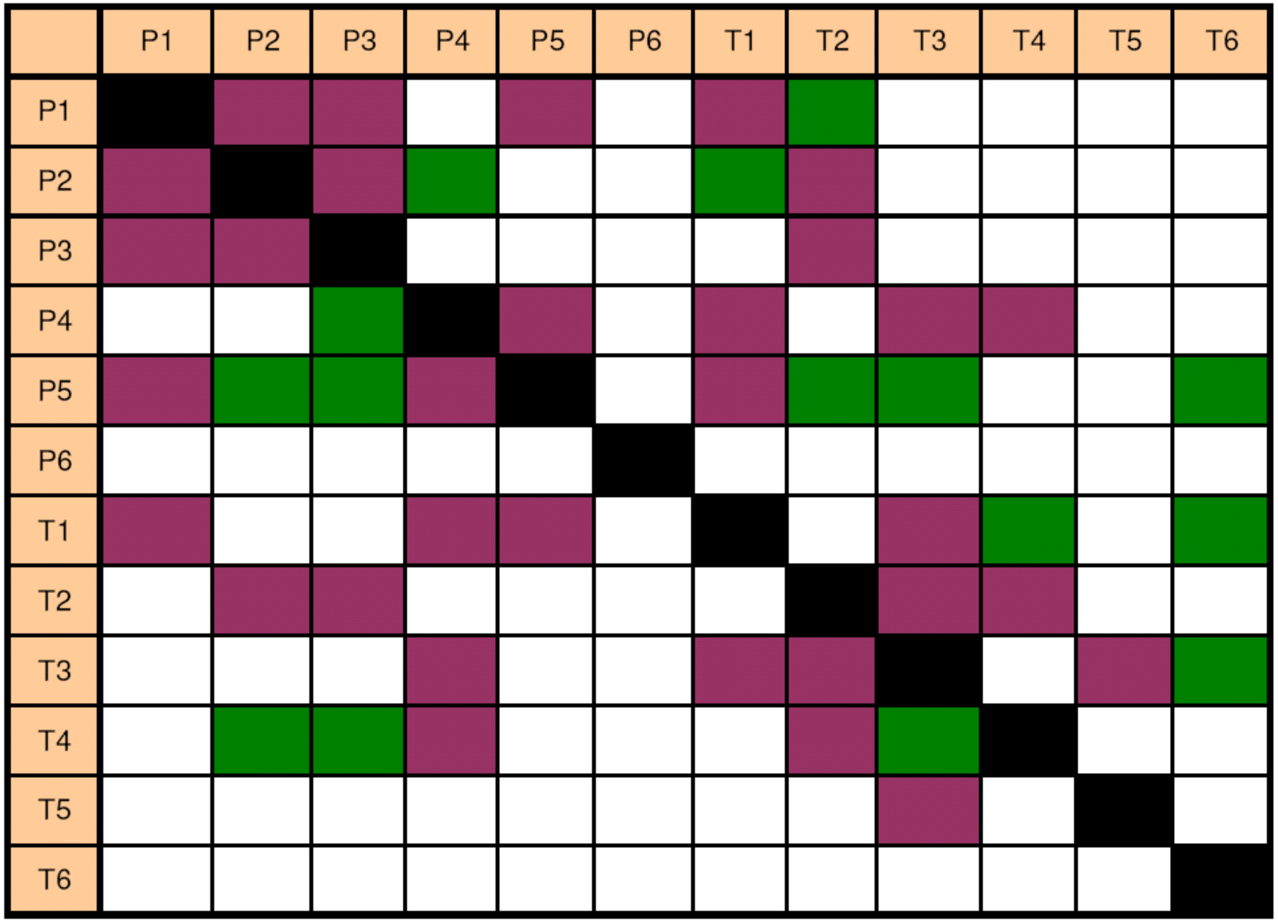
FZJ, IPP and KIT Group on DEMO

A common group has been set up that discusses *together* ‚Physics and Technology Topics' for DEMO

- two meetings so far, papers are being prepared that summarise the present status of Topics and work to be done

P1	Long pulse / steady state / high beta **(Lead: IPP)**
P2	High density operation **(IPP)**
P3	Plasma Wall Interface **(IPP)**
P4	Disruptions **(FZJ)**
P5	Plasma Diagnostics / Integrated Control **(FZJ)**
P6	Combination of first principles and reactor codes **(IPP)**
T1	Heating and Current Drive **(KIT)**
T2	Structural and functional materials **(KIT)**
T3	In vessel components (divertor, blankets, He-cooling) **(KIT)**
T4	Fuel cycle (T-technology, vacuum technology) **(KIT)**
T5	Magnet design **(KIT)**
T6	Maintenance incl. remote handling **(KIT)**
T7	Safety & licensing **(KIT)**
S1	Co-ordination / exploration of consistent solutions **(IPP)**

Finding the interlinks between topics



One way is to analyse the interlinks is to ask the topic contact persons. The results is shown in the matrix above. Nice but not very conclusive.

green = unidirectional link **violet = bidirectional link**

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Three areas have been highlighted for ‚cross-disciplinary' working groups:

- exhaust (P2, P3) and materials (T2, T3)
- high density operation (P2, P3) and fuel cycle (T4)
- steady state operations (P1) and H&CD systems (T1)

Goal on intermediate timescale is to establish 3 conceptual designs: conventional tokamak, advanced tokamak, stellarator

Exhaust working group

Technology sets the limit for average power load on target

- with water (safety issues, low side of T-range (DBTT)): ≤ 5-**10** MW/m^2
  W not used as structural material (only few first mm armor)
- with He cooling (large pumping power needed): W could be used as structural material (600 ^{o}C < T < 1300 ^{o}C): ≤ **5**-10 MW/m^2
- for both variants, embrittlement due to *n*-irradiation aggravates problem
- in addition, $T_{e,div}$ ≤ 4 eV to limit erosion

This sets restrictive boundary conditions on the plasma physics side:

- divertor must be detached to avoid narrow power load (Eich/Goldston!)
- excursions (ELMs) must be limited to a minimum
- radiative losses also in pedestal and core (P/R = 60 MW/m!)
- divertor geometry must allow easy detachment, spreading of power

See poster by Boccaccini and Kallenbach (today)

Prototype of He cooled divertor element (KIT)

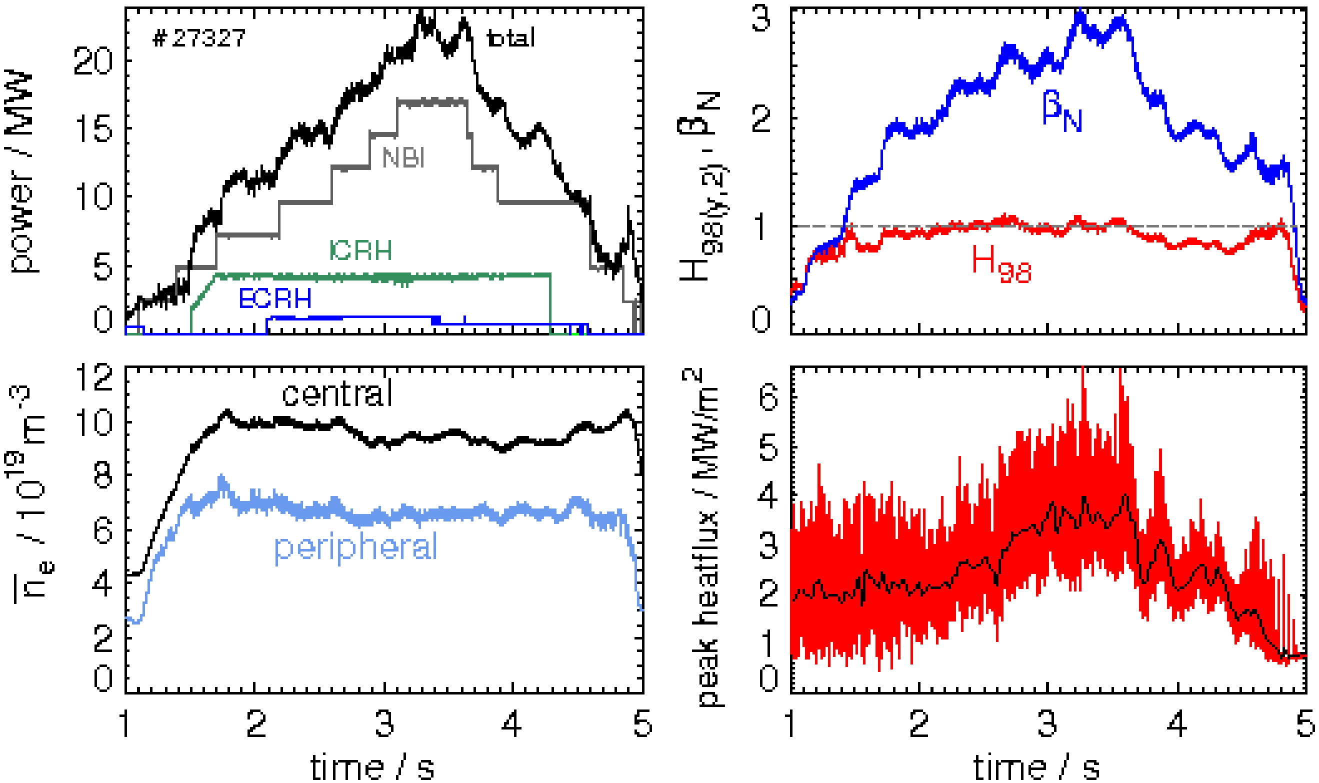
He-jet cooled fingers with W-caps were produced and tested successfully

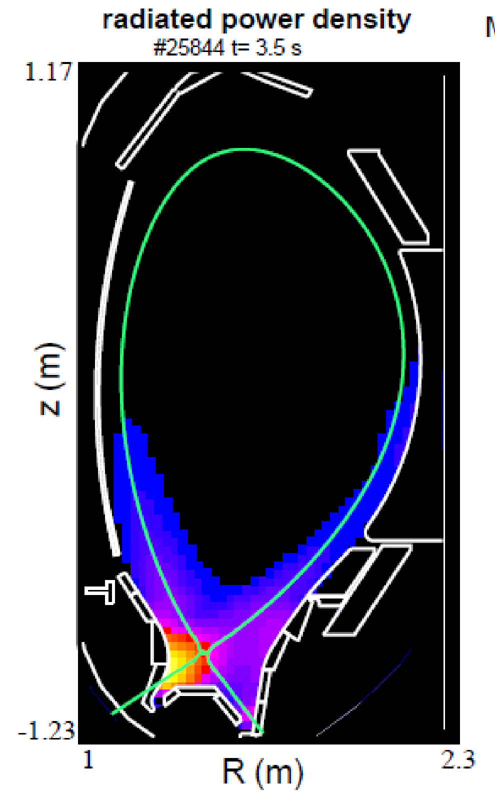
- survived > 1000 load cycles at 10 MW/m^2
- under n-irradiation, number should be reduced to 5 MW/m^2

Poses serious constraints on plasma operation!

Karlsruher Institut für Technologie

Experiments at high P/R in ASDEX Upgrade





Nitrogen seeding allows P_{div} < 5 MW/m^2 at ~ 15 MW/m with good confinement and stability (H ~ 1, β_N ~ 2.8)

High density / fuelling and pumping working group

On the physics side, low density (beneficial for CD efficiency) implies

- temperature beyond the optimum for fusion
- problems to exhaust the power (radiative losses and detachment eased at higher n_e)

In stellarators usually no problem, in tokamaks Greenwald limit scales unfavorable (at constant q_{95} and B_t, $n_{GW} \times R = const.$)

On the technology side, fuelling and particle exhaust needs determine the technology for the pumps

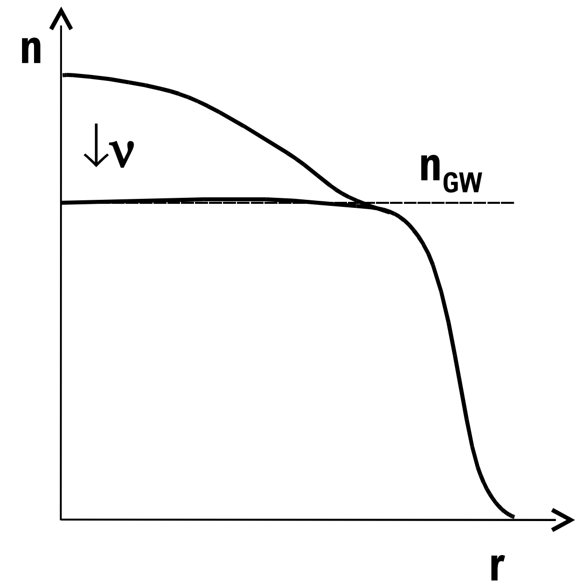
- pellets may reduce the pumping needs w.r.t.. gas puff (which may run against the fuelling limit)
- if neutral pressure high enough, cryo pumps can be avoided

See talks by Day and Wolf (today)

Can we count on Density peaking in DEMO?

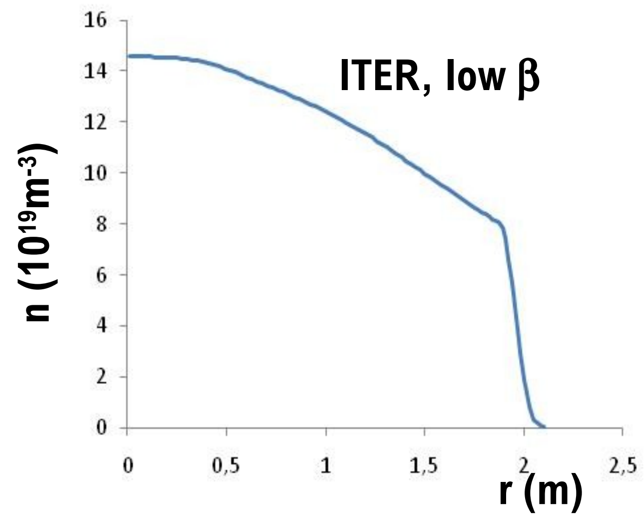
Working hypothesis:

- Greenwald limit is edge / pedestal limit
- density peaking increases with decreasing collisionality
- density profiles in present day devices near the density limit are flat due to high collisionality (unless driven by central fuelling)



Use this assumption to model DEMO density profiles

- have to assess possible influence of high β



G. Pereverzev et al NF 2005

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P. Lang, EPS 2011

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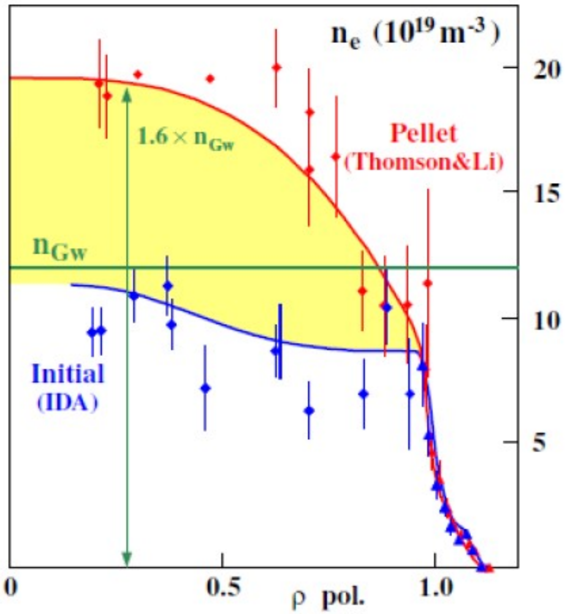
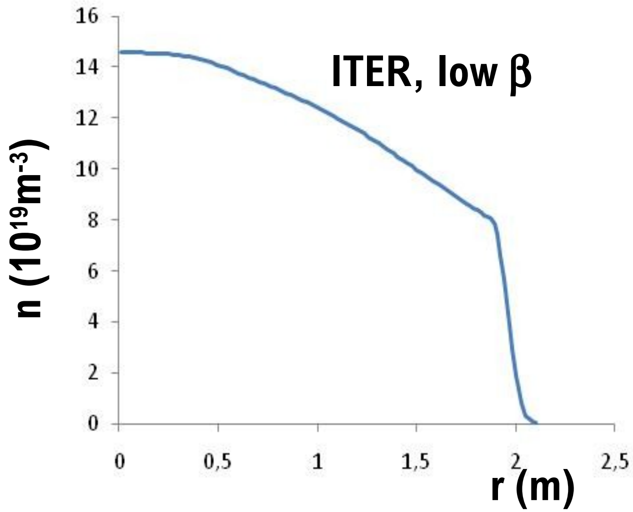


Use this assumption to model DEMO density profiles

- have to assess possible influence of high β

Large positive impact if this can be achieved

- higher fusion power at same β_N
- higher bootstrap fraction at same β_N



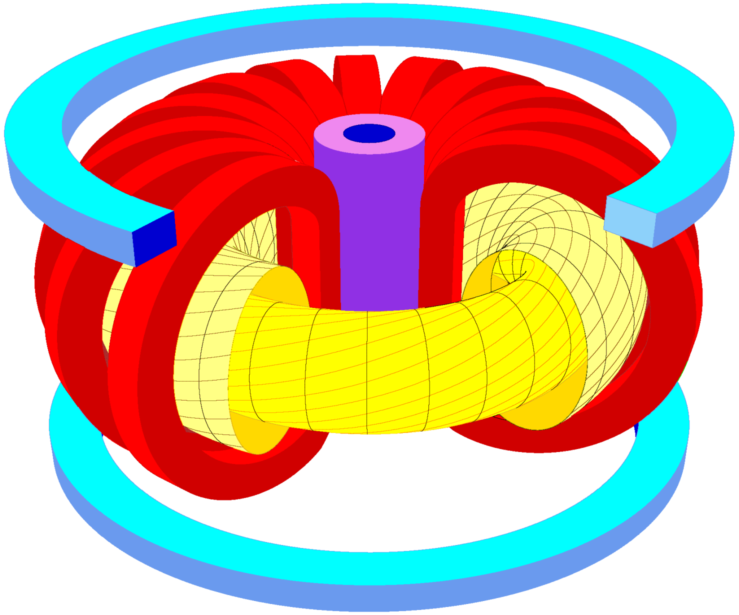
G. Pereverzev et al NF 2005

Special topic: steady state and H&CD

Simple scaling law for tokamak pulse length

Total solenoid flux Φ_{tot} is consumed by ramp-up Φ_0 and flat top Φ_{res}. It is proportional to the hole in the centre:

$$\Phi_{tot} = c_3 R_0^2 \left(\frac{A-1}{A} - \frac{b}{R_0} \right)^2 = \Phi_0 + \Phi_{res}$$



b: extension of blanket and inner TF leg

The flux needed for ramp-up is given by

$$\Phi_0 = (L_p + \mu_0 c_{Ejima} R_0) I_p = c_4 \left(\frac{R_0}{A} \right)^2 \frac{B}{q_{95}}$$

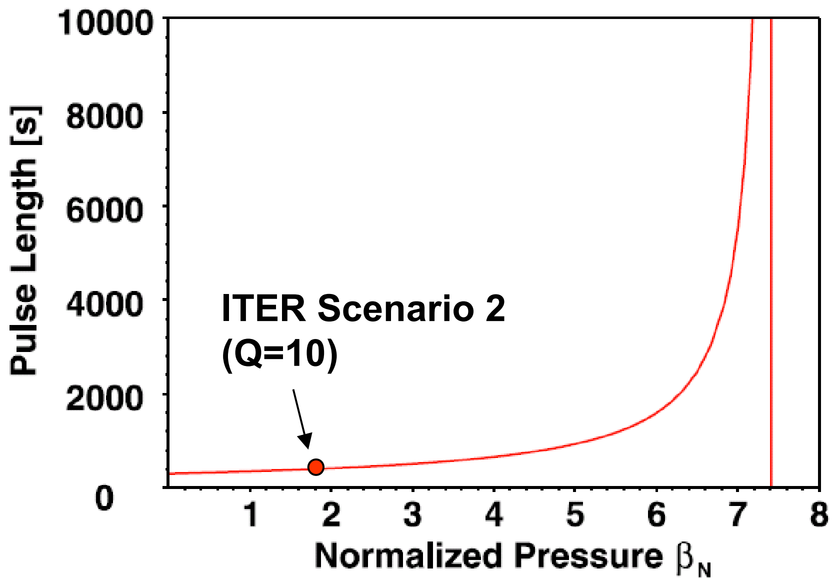
The flux consumed in flattop is given by

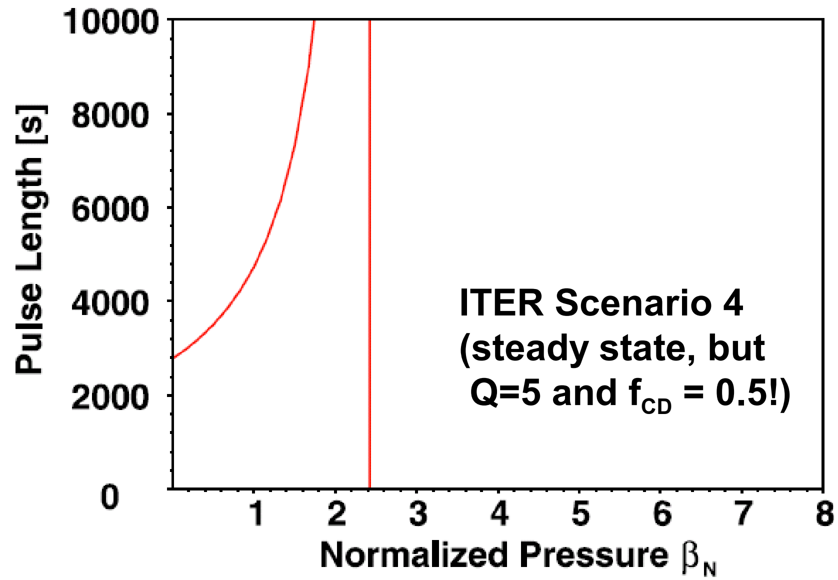
$$\Phi_{res} = c_5 \tau_{pulse} \frac{B_t}{q_{95}} (1 - f_{CD} - f_{bs}) = c_5 \tau_{pulse} \frac{B_t}{q_{95}} (1 - f_{CD} - c_6 0.7 q_{95} \sqrt{A} \beta_N)$$

f_{CD} = fraction of externally driven plasma current **f_{bs} = fraction of internally driven 'bootstrap' current**

Thus, a formula for τ_{pulse} can be easily obtained. Steady state for $\tau_{pulse} \rightarrow \infty$

Noninductive current drive in a tokamak DEMO





Intrinsic bootstrap current needs high β_N

External current drive (e.g. by RF waves) consumes additional power

$$\tau_{pulse} = R_0^2 \frac{c_3 \frac{q_{95}}{B}\left(\frac{A-1}{A} - \frac{b}{R_0}\right)^2 - c_4 \frac{1}{A^2}}{c_5(1 - f_{CD} - c_6 0.7 q_{95}\sqrt{A}\beta_N)}$$

- ‚offset‘ generated by external current drive calls for large unit size
- strongly coupled to technology (efficiency of technical systems)

N.B.: the stellarator does not have these issues (no plasma current)

Simple scaling for overall power balance

The total thermal power is given by

$$P_{th} = 1.18P_{fus} + P_{CD} + \eta_{BOP} P_{BOP}$$

P_{CD} = power needed for external current drive

where the **B**alance **O**f **P**lant power may contribute by a fraction η_{BOP}.

This generates a total electric power with thermodynamic efficiency η_{TD}:

$$P_{el,tot} = \eta_{TD} P_{th}$$

The total auxiliary electrical power needed to run the plant is given by

$$P_{el,AUX} = \frac{P_{CD}}{\eta_{CD}} + P_{BOP}$$

where η_{CD} is the wall plug efficiency of the CD system. Hence

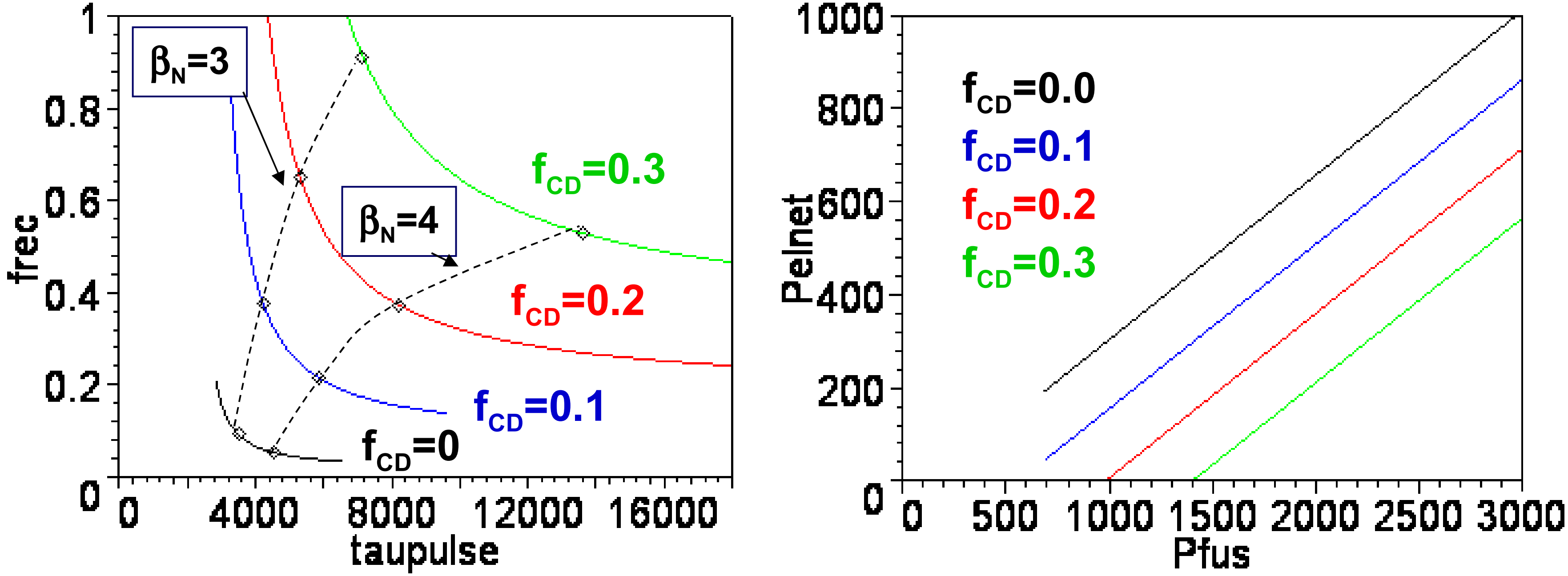
$$f_{rec} = \frac{P_{el,AUX}}{P_{el,tot}} = \frac{P_{CD}/\eta_{CD} + P_{BOP}}{\eta_{TD}\left(1.18P_{fus} + P_{CD} + \eta_{BOP}\right)}$$

and

$$P_{el,net} = P_{el,tot}(1 - f_{rec})$$

Example: ITER-like case with R_0=7.5 m

Vary β_N between 2 and 5 and f_{CD} between 0 (ohmic) and 0.3 and assume conventional technology (η_{CD}=0.25, η_{TD}=0.3, P_{BOP}=50 MW, η_{BOP}=0)

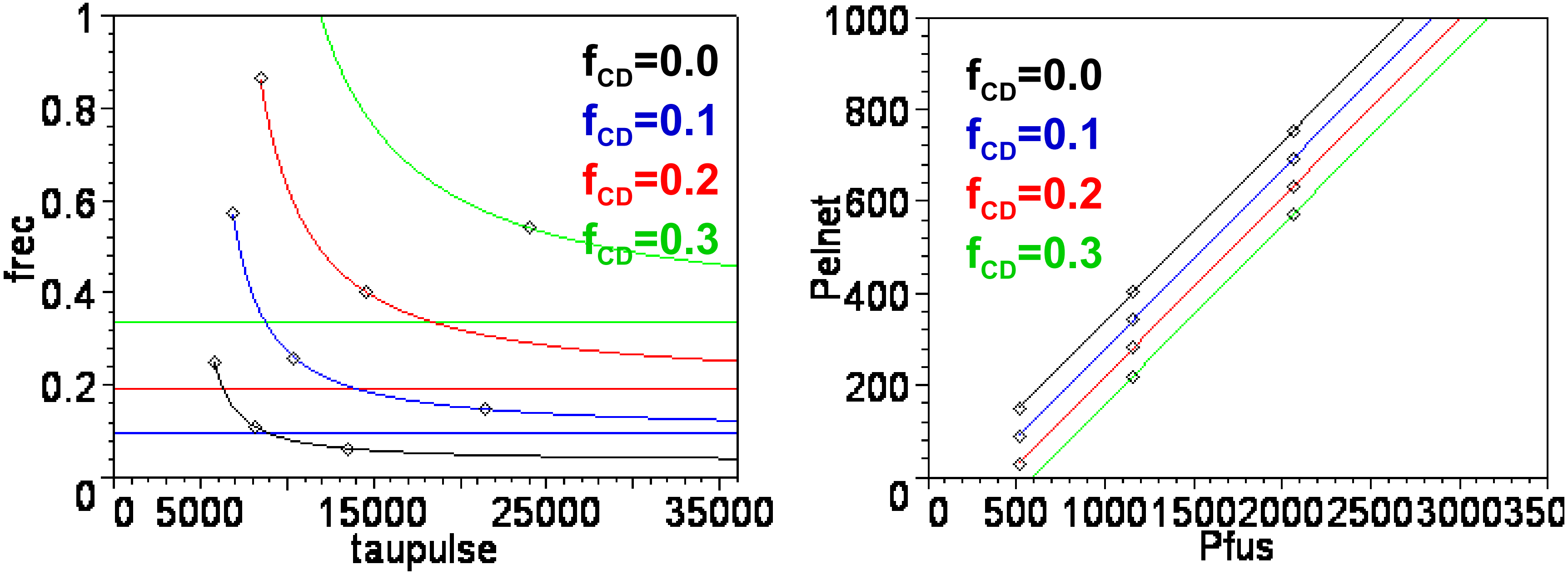


Acceptable f_{rec} and significant $P_{el,net}$ can be obtained relatively easily but pulse length is nowhere near the target!

Even P_{fus}=3 GW (β_N=4.2, f_{CD}=0.2, f_{rec}=0.33) only gives $\tau_{pulse} \approx$ 3 hrs

Increasing the pulse length by raising B_t, q_{95} and η_{CD}

A first shot: R=7.5 m, B=6.5 T, q=4.2, A=3.8 (i.e. 11 MA), H=1.2 and η_{CD}=0.4 (but keep conventional η_{TD}=0.33)

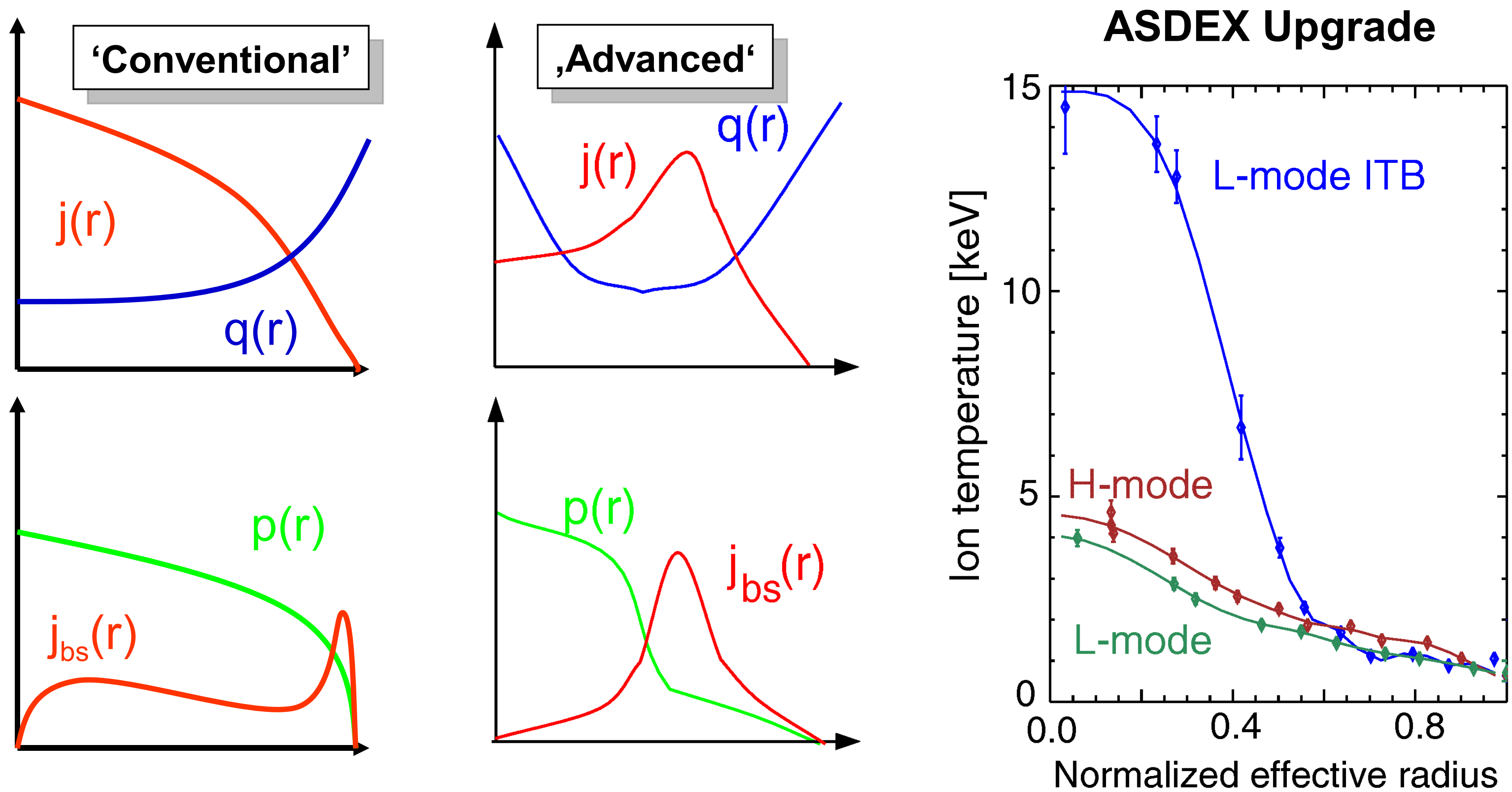


Clearly goes into the right direction. 16 hrs pulse length at f_{rec}=0.4, β_N=3.5

steady state at β_N=3.9, P_{fus} = 2 GW and f_{rec} = 0.32 (@ f_{CD}=0.3)

…but these are quite challenging parameters (note η_{CD} = 0.4!)…

Steady state tokamaks – profile alignment



Problem is not only 0-d but also alignment of bootstrap current is needed

- self-consistent solution involving Internal Transport Barrier (ITB) possible
- but – may need sophisticated profile control – also of impurity concentration!

Possible operation Scenarios for DEMO

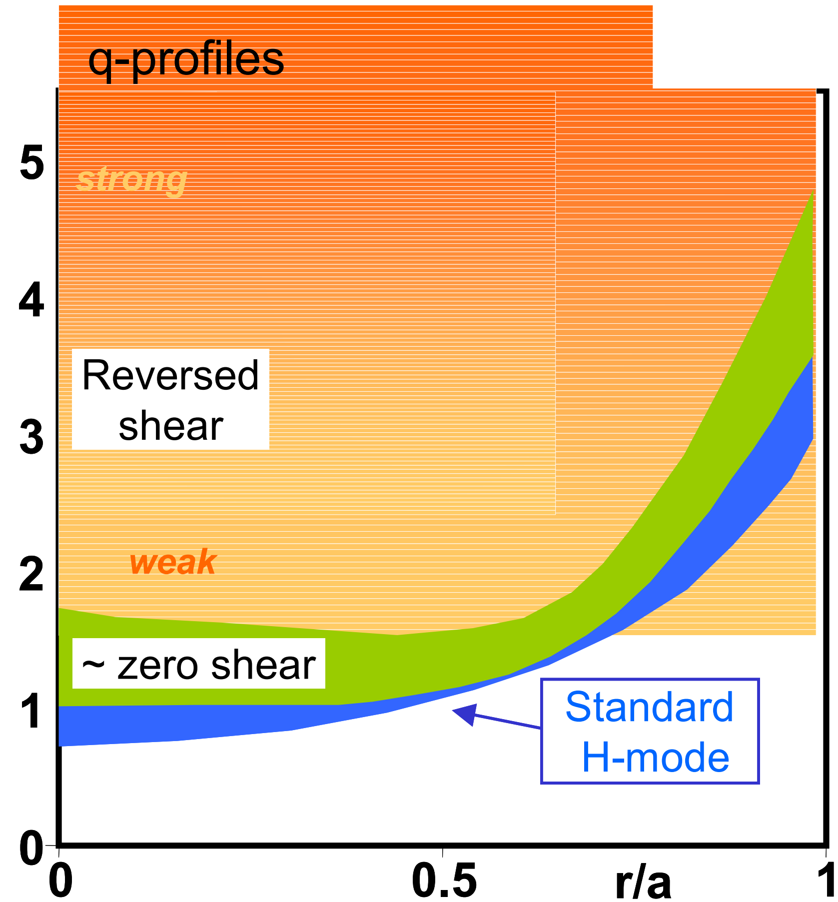
Conventional scenarios rely on an extrapolation of the H-mode

- improved H-mode a.k.a. hybrid
- high internal inductance

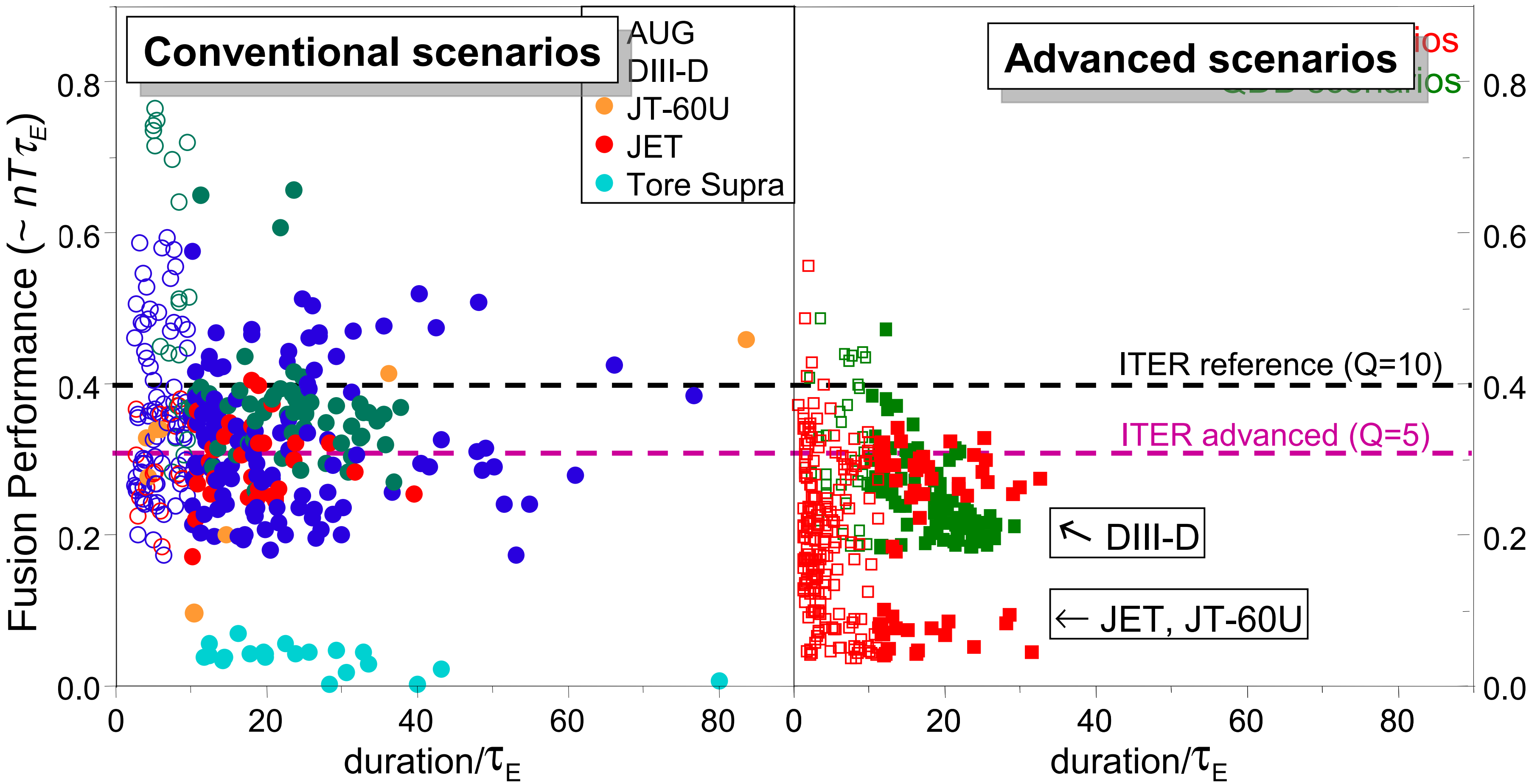
⇒ limited bootstrap fraction (~ 50%), auxiliary CD has to be supplied close to the centre

Advanced scenarios rely on reversed shear / ITB

⇒ high bootstrap fraction (~ 90 %), auxiliary CD has to be supplied roughly at half radius



The present database for long pulse and steady state

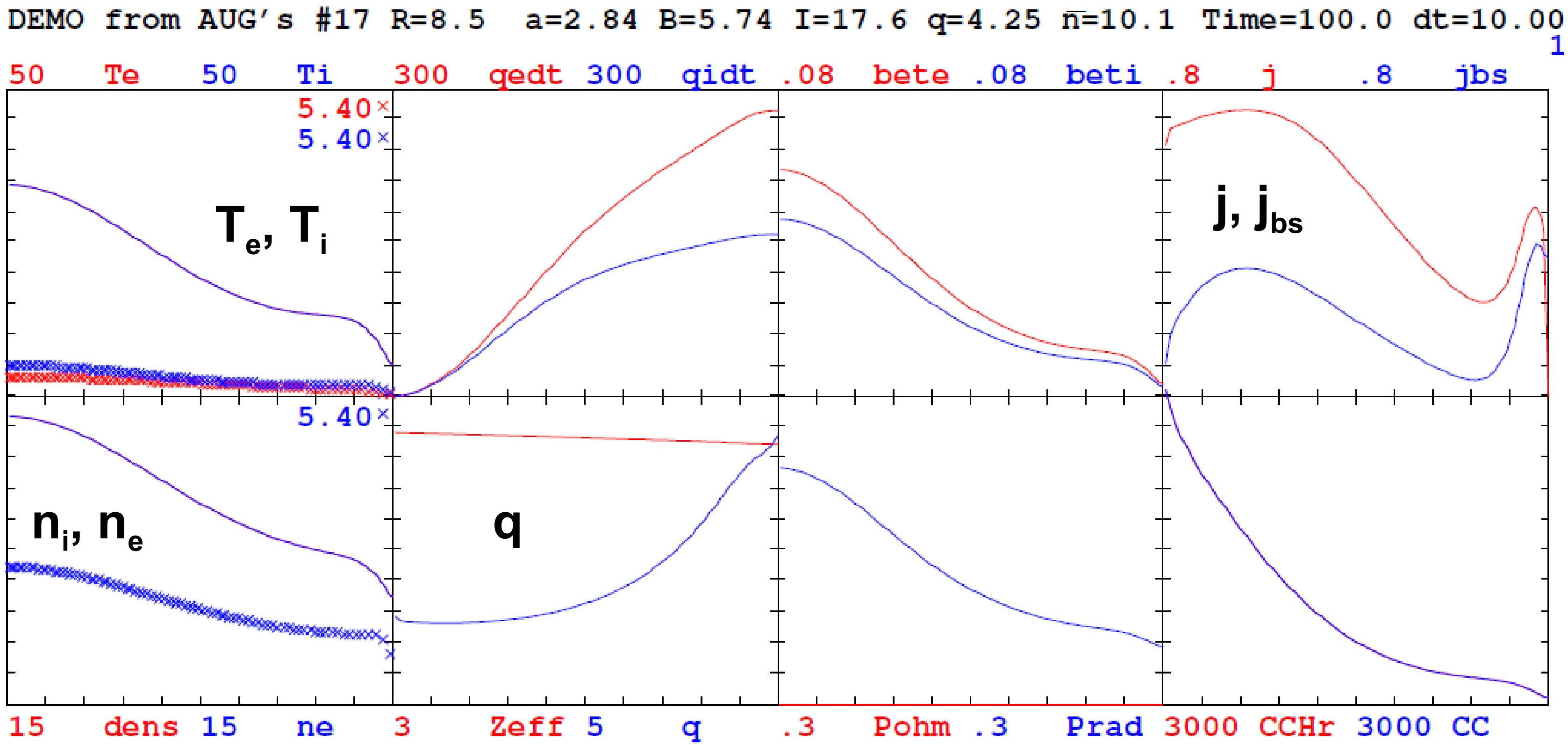


Conventional scenarios are easier to run than advanced scenarios – why?

We do not know the optimum q-profile yet and should study various options!

See following talk by M. Zarnstroff

Example: an 'improved H-mode' DEMO



R=8.5 m, a =2.84 m, B=5.75 T, Ip = 17.6 MA (q_{95}=4) β_N = 3, P_{fus}=2.2 GW

f_{bs} ~ 0.5, depending on model (facilitated by peaked n_e)

For f_{rec} = 0.4 at η_{TD}=0.35, need to drive 8.8 MA with 150 MW (γ_{CD} = 0.5) at η_{CD} = 0.5 ⇒ severe constraint on the efficiency of the CD system!!

At present, 4 CD systems are considered for ITER

Lower Hybrid Current Drive (LHCD)

- injected wave is Landau damped on electrons at high energies ($v \gg v_{th}$)
- electrons travelling with the wave carry current

Ion Cyclotron Current Drive by Fast Waves (FWCD)

- injected wave Landau damped on electrons at *low* enerigies ($\sim v_{th}$)
- ion resonances in the plasma should be avoided!

Neutral Beam Current Drive (NBCD)

- injection of energetic neutrals (D, T) which are ionised in the plasma
- directed fast ion beam incompletely shielded by electrons ($Z_{eff} > 1$ and trapping effects) $\Rightarrow$ current is driven

Electron Cyclotron Current Drive (ECCD)

- injected wave increases perpendicular electron energy
- relaxation of hot electrons slower than that of ‘holes’ $\Rightarrow$ current is driven

Figures of merit for Current Drive Systems

The current drive efficiency relates driven current to injected power

$$j_{CD} \sim P_{CD} / (n\ V) \quad \Rightarrow \quad I_{CD} \sim P_{CD} / (n\ R)$$

$$\gamma_{CD} = n\ R\ I_{CD} / P_{CD}$$

What matters in the power balance is the wall plug power per current

$$I_{CD} \sim \gamma_{CD}\ P_{CD} = \eta_{CD}\ \gamma_{CD}\ P_{el,CD}$$

$$\Rightarrow \text{compare } \eta^* = \eta_{CD}\ \gamma_{CD}$$

For methods which scale with v_{th}, γ_{CD} increases roughly with T_e:

$$\Rightarrow \text{definition of } \zeta = \gamma_{CD}\ 32.7 / T_e$$

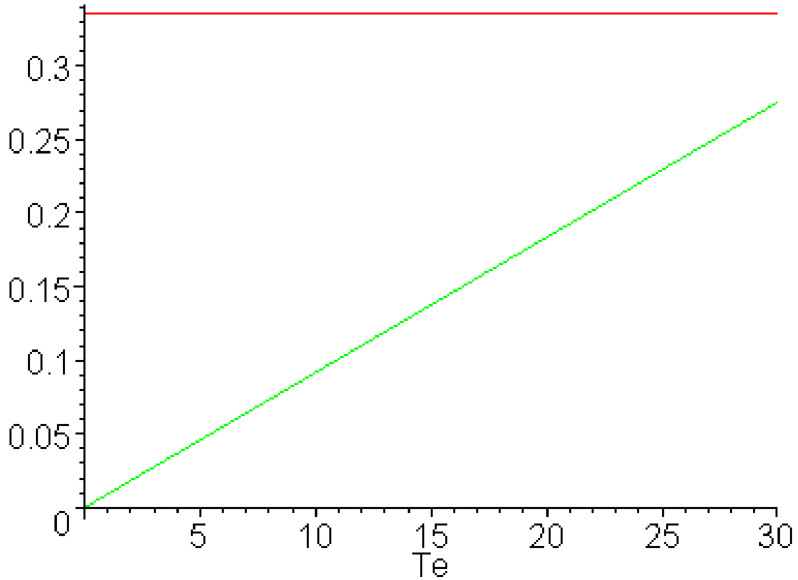
Figure of merit to compare ECCD, NBCD, FWCD independent of T_e

Different physics – different CD efficiencies

	LHCD	ECCD	FWCD	NBCD
γ [A/(Wm²)]	0.3-0.4 (indep. of T_e)	$\geq$ 0.2 (ITER prediction)	0.07 (ITER prediction)	0.5 (2 MeV) (DEMO prediction)
ζ [A/(Wm² keV)]	n.a.	$\geq$ 0.3	0.1-0.2	0.4-0.5
η_{CD}	0.3 (present) 0.5 (goal) (100 % coupling)	0.3 (present) 0.5 (goal)	0.5 (present) 0.7 (goal) (100 % coupling)	0.3 (present) 0.5 (goal)
γ*η_{CD} (compare to **0.25**)	0.09-0.2	0.09 - 0.15	0.05-0.15	0.12-0.25
Remark	n.a. for DEMO (next slide)	potential for optimisation (next slides)	small exp. Basis	off-axis CD not fully understood

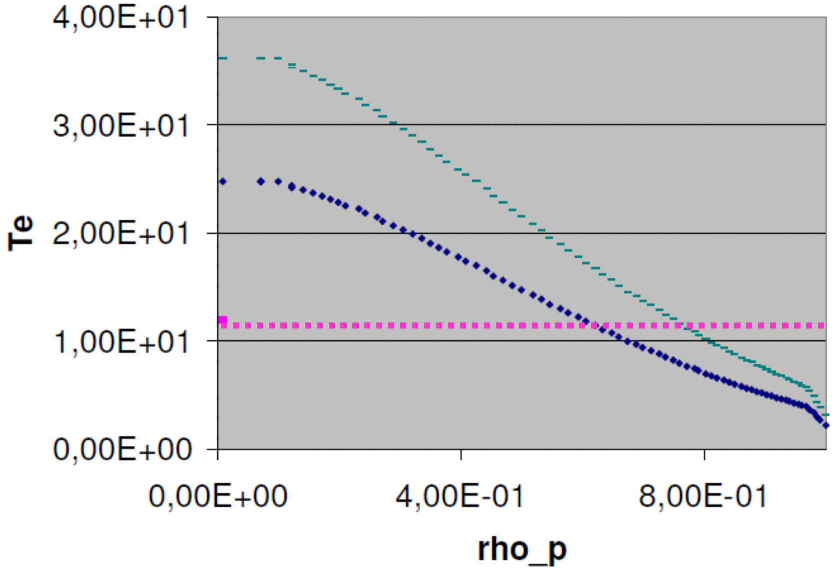
LHCD seems not suited for DEMO

γ_{LHCD} does not increase with T_e – would lose its advantage at 20-30 keV



ECCD (ζ= 0.3)

LHCD ($N_{||}$ = 1.8, Z_{eff}=1.7)



Single pass absorption at

- $T_e > (6.4/N_{||})^2$, i.e. 12 keV for $N_{||}$ = 1.8 (constrained by accessibility)

⇒ Absorption too far out in the plasma!

Optimisation of ECCD for DEMO

Due to experience with ECRH technology and physics in the German fusion centres, ECCD has been studied as a prime candidate

In ITER, the ECRH system is a compromise between central deposition (lower f_{ECRH}) and efficient current drive (higher f_{ECRH})

For DEMO, address optimisation of the system for off-axis ECCD on the expense of the system flexibility (DEMO is no longer an experiment)

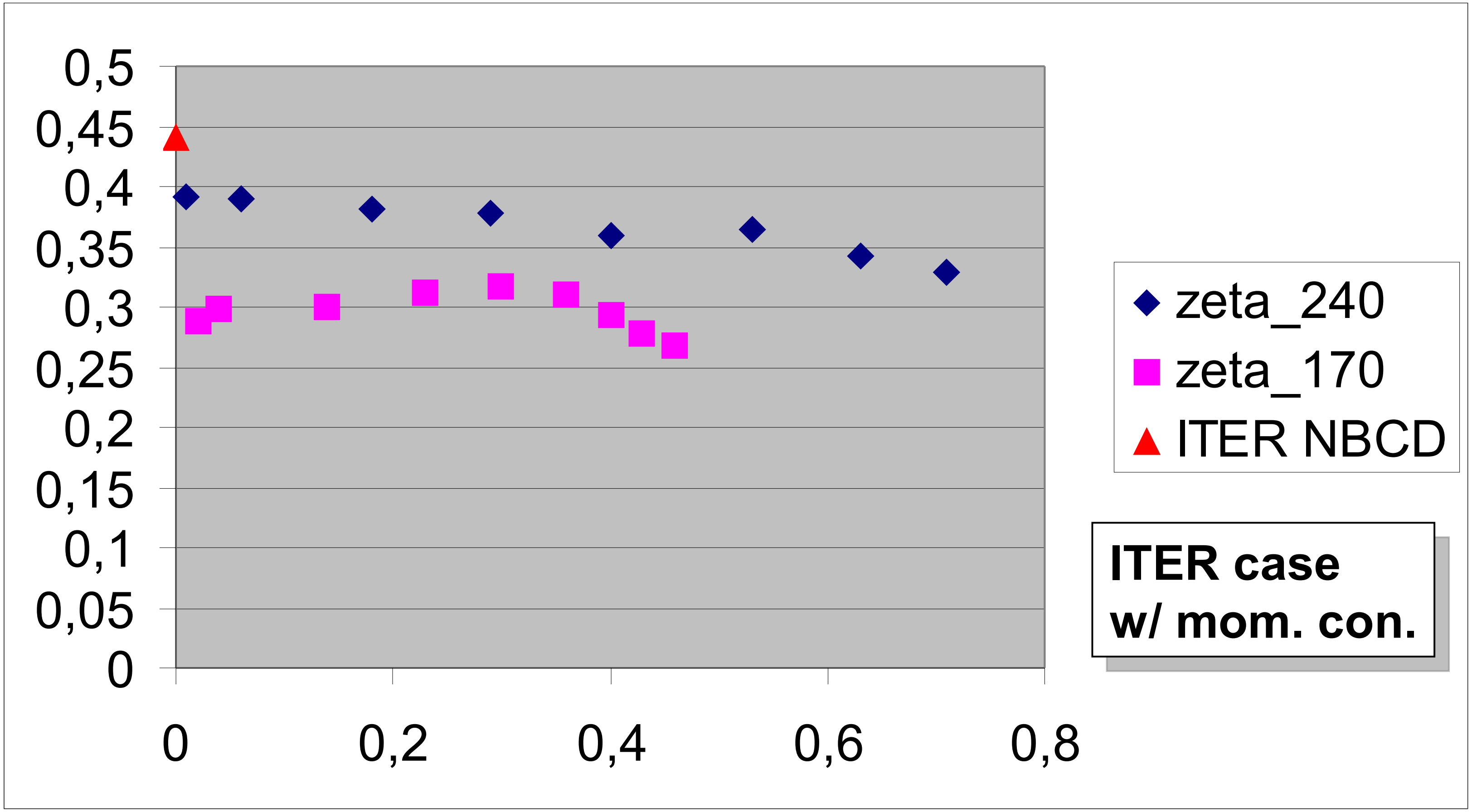
Also: discuss the implications for gyrotron technology

A fiirst shot: start from existing ITER case and…

- increase frequency to access resonance with large $k_{||}$
- ensure accessibility by optimising launch angle

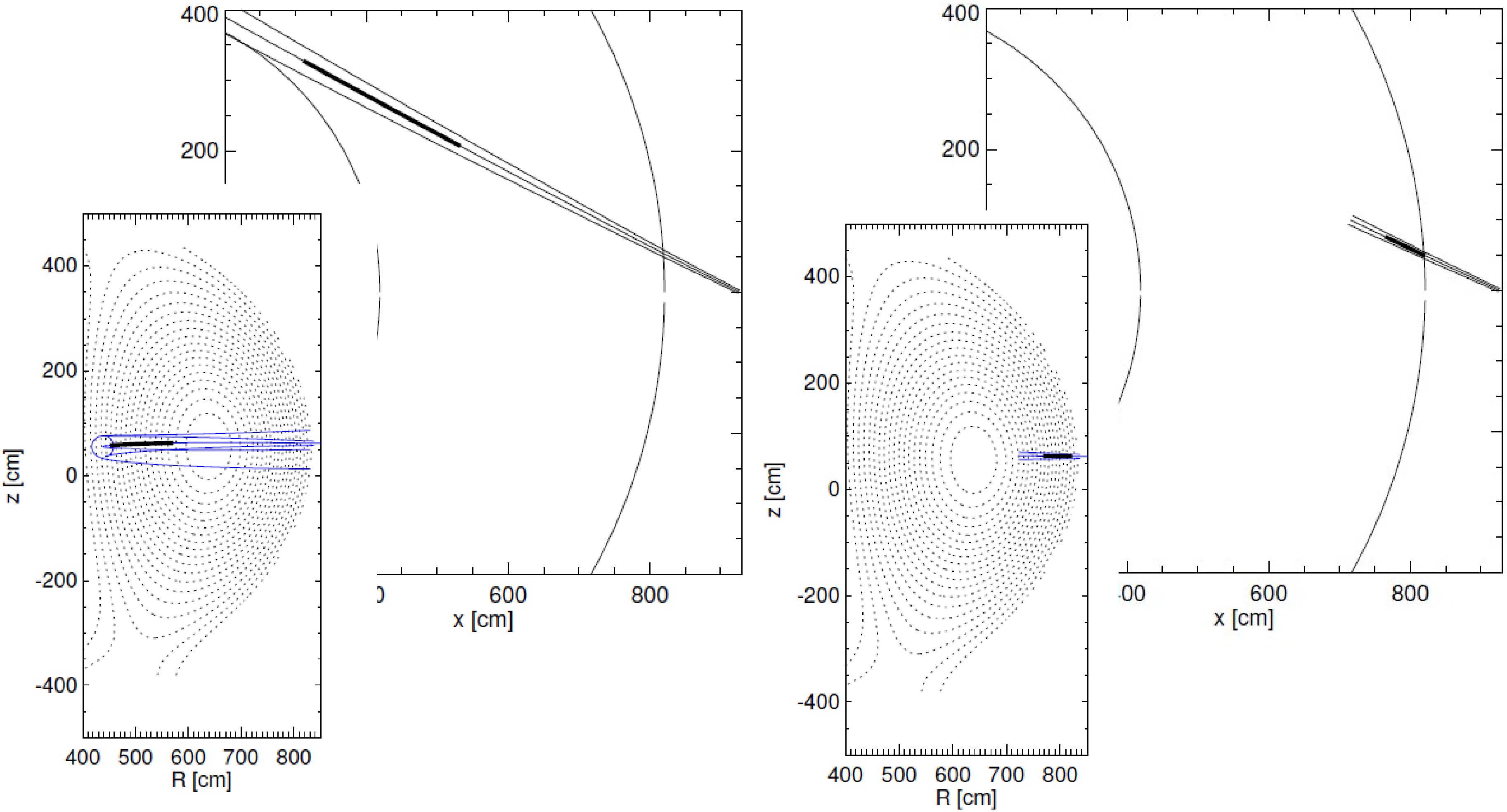
Note: this is only a start, full optimisation for DEMO has now started in a 3PT task by IPP, KIT and CRPP

Optimisation of ECCD for DEMO



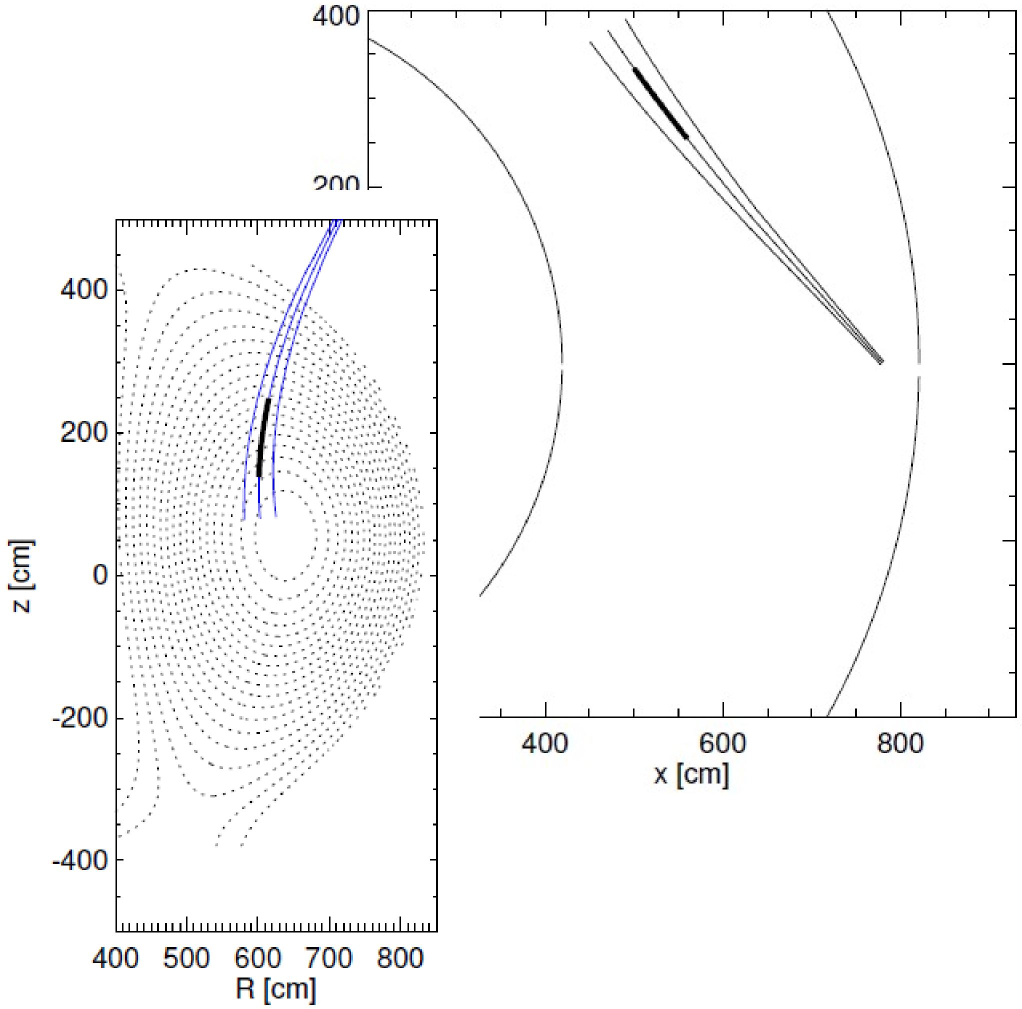
Increase to 240 GHz increases ζ close to NBI values, but…

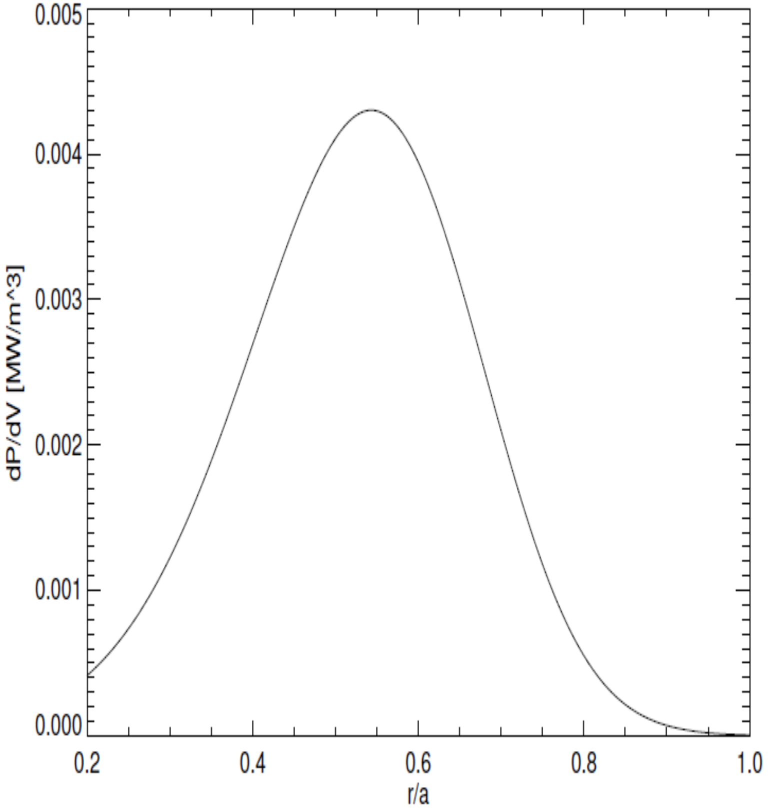
Optimisation of ECCD for DEMO



Increase to 240 GHz increases ζ close to NBI values, but including downshifted 2nd harmonic absorption rules out midplane launch

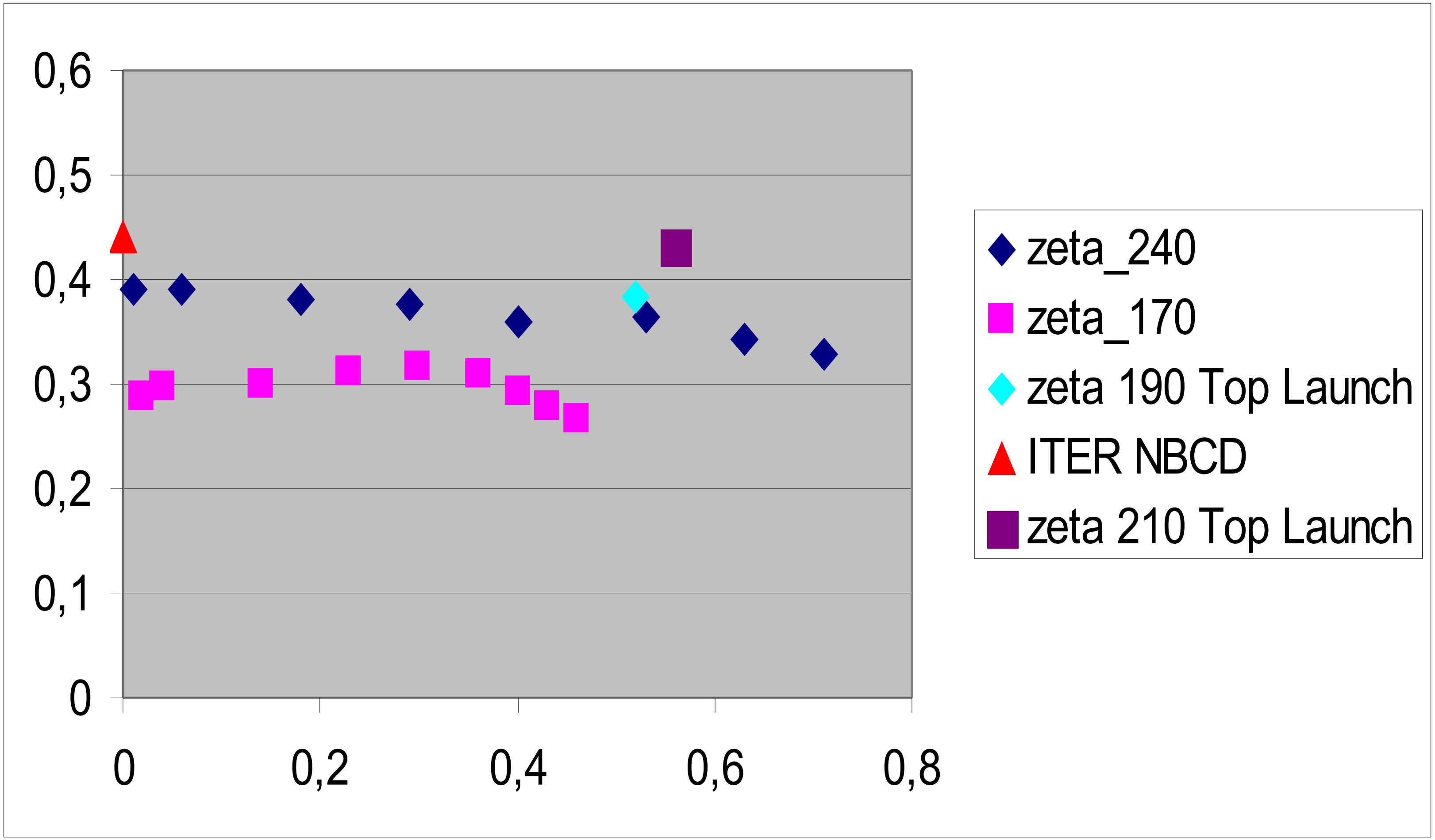
Optimisation of ECCD for DEMO





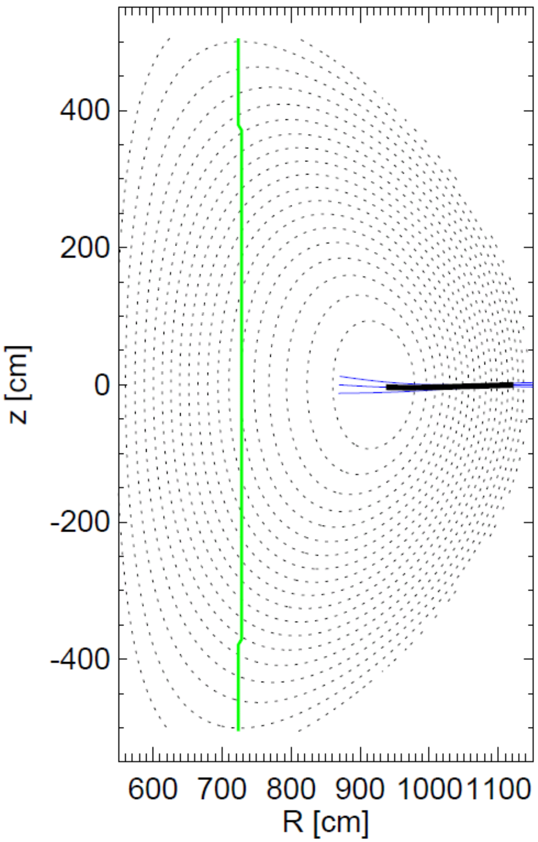
This problem can be circumvented by using top launch!

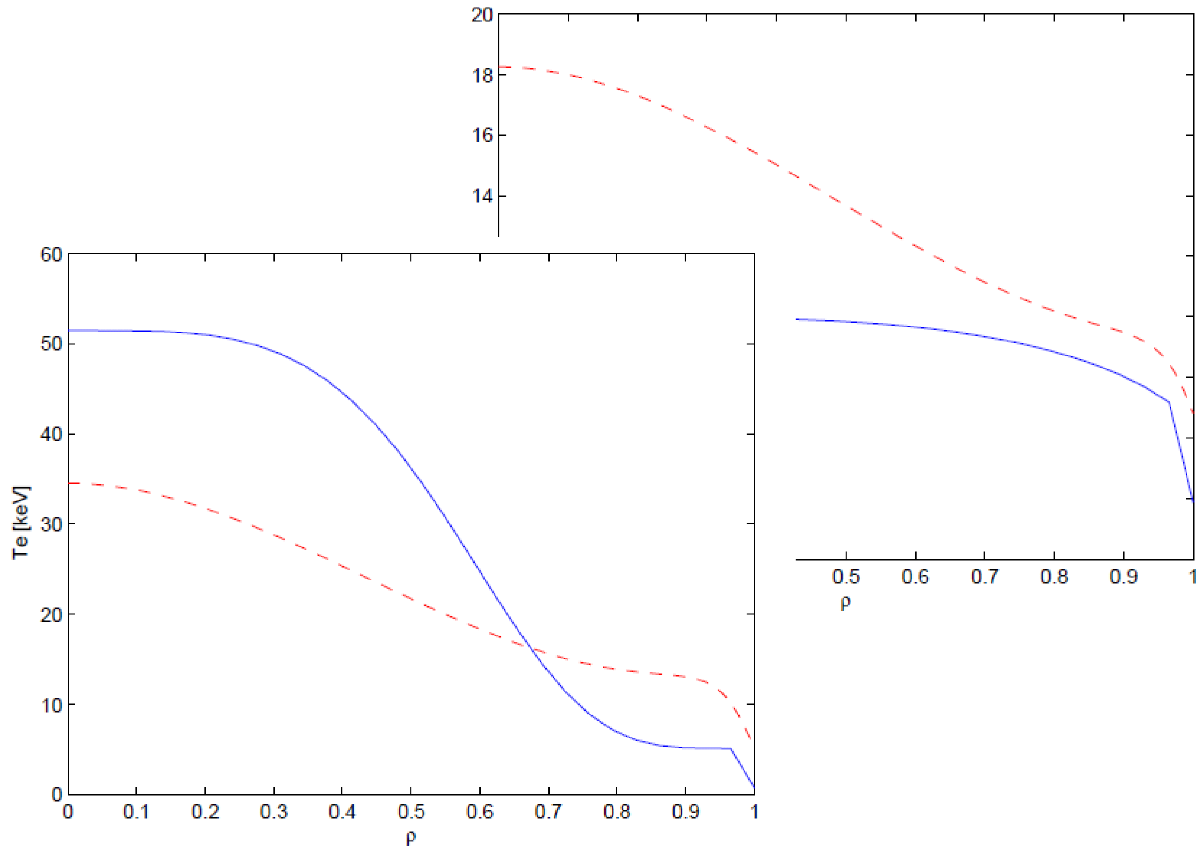
Optimisation of ECCD for DEMO



A complete optimisation should be done to find the ‘ultimate limit’ for DEMO paramters (this was ITER!)

First results for DEMO-like parameters



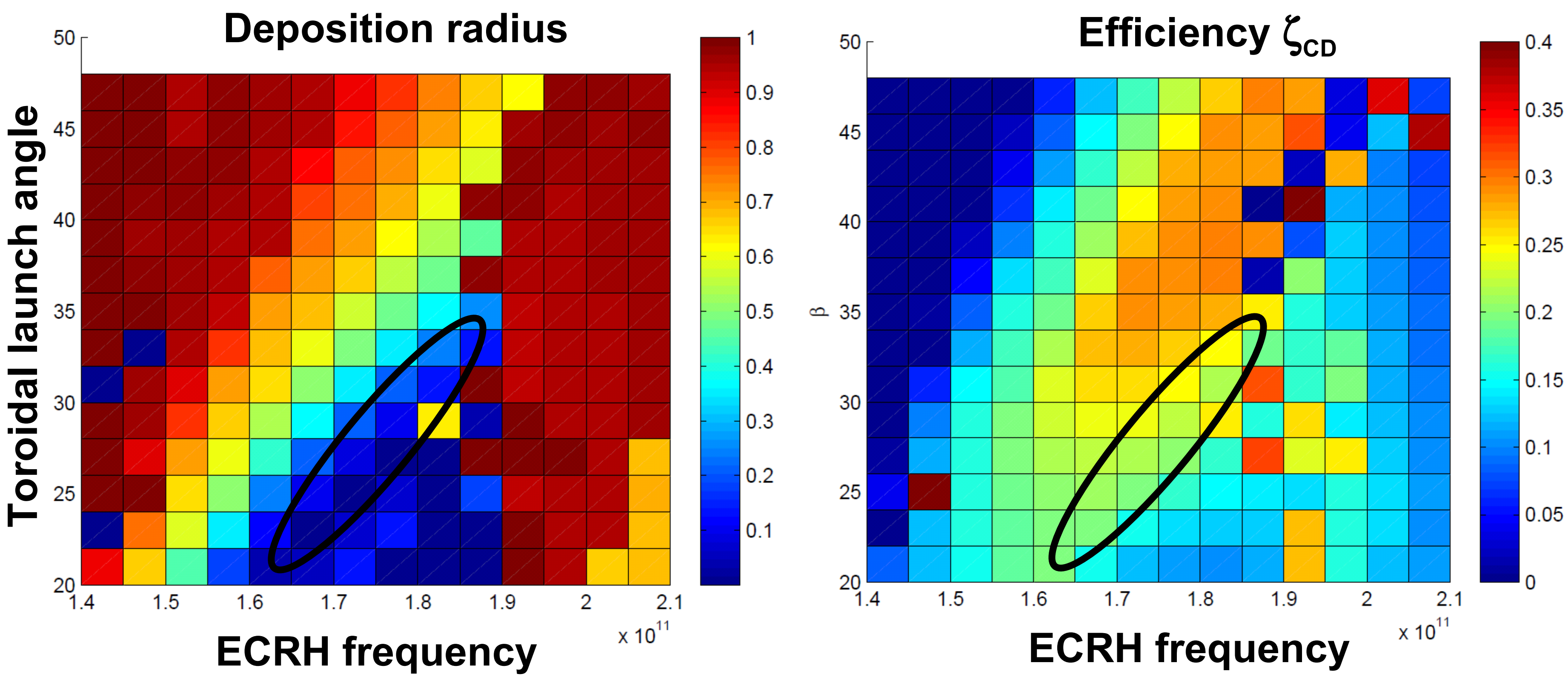


Use a DEMO device as shown before (R=8.5 m, a =2.84 m, B=5.75 T)

Assume flat and peaked density profiles with $n_{ped} = n_{GW}$ at β = const.

Evaluate CD efficiency ζ_{ECCD} as function of f_{ECRH} and launch geometry

Results for equatorial launch

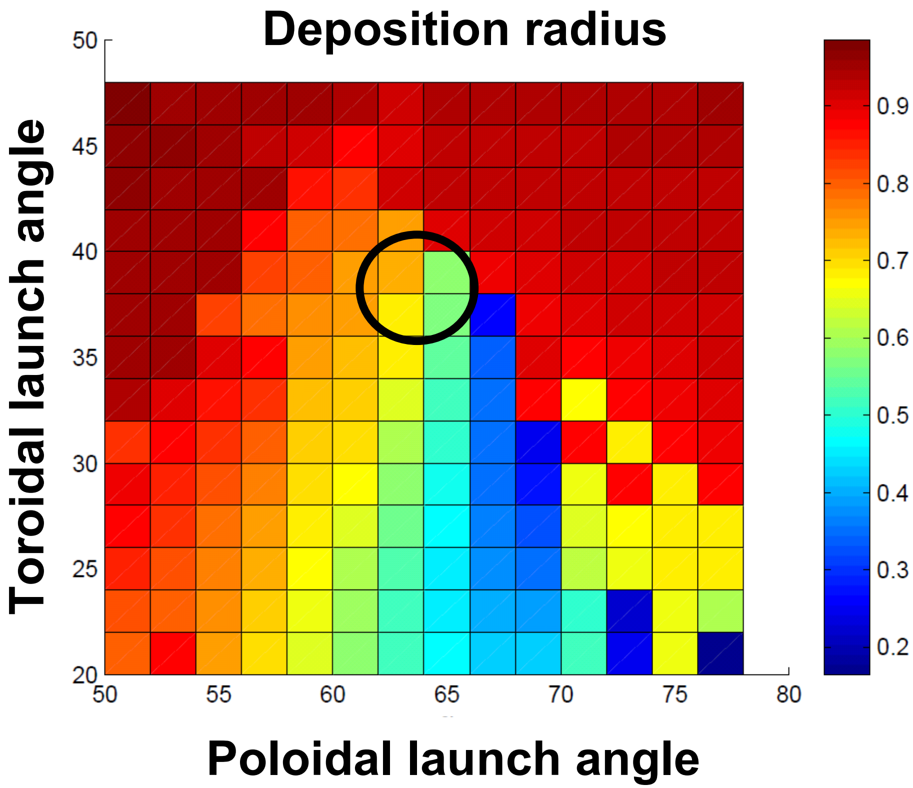


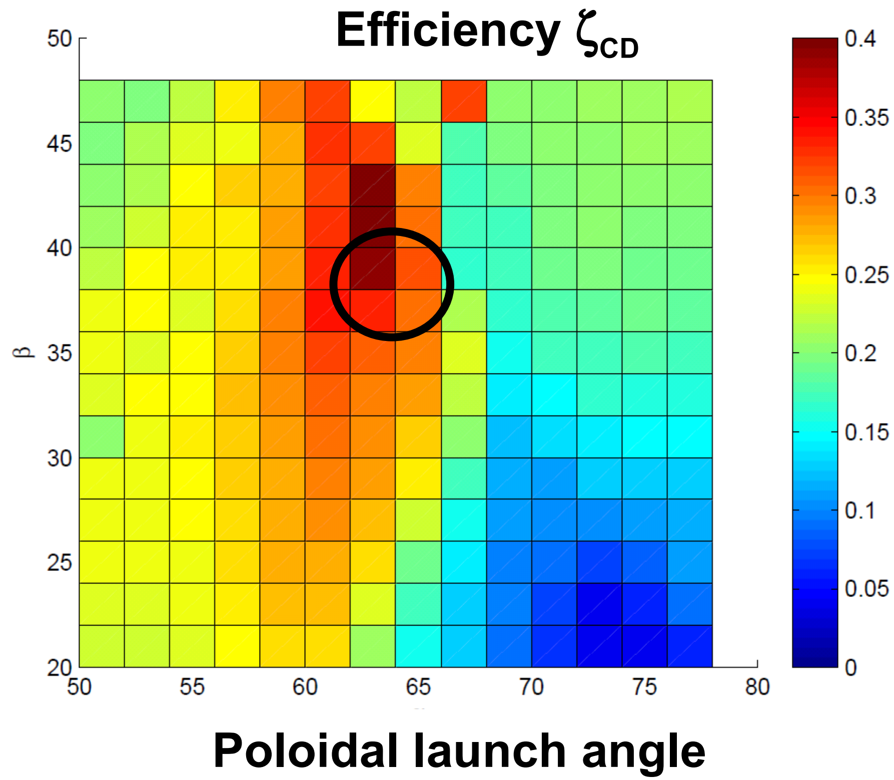
On-axis CD efficiency is confirmed to be of the order of previous findings (0.15 – 0.25).

For off-axis CD, an increase is encountered (up to 0.3 @ half radius)

For higher frequencies, efficiency is low due to parasitic absorption

Results for top launch (here, f_{ECCD} = 200 GHz)

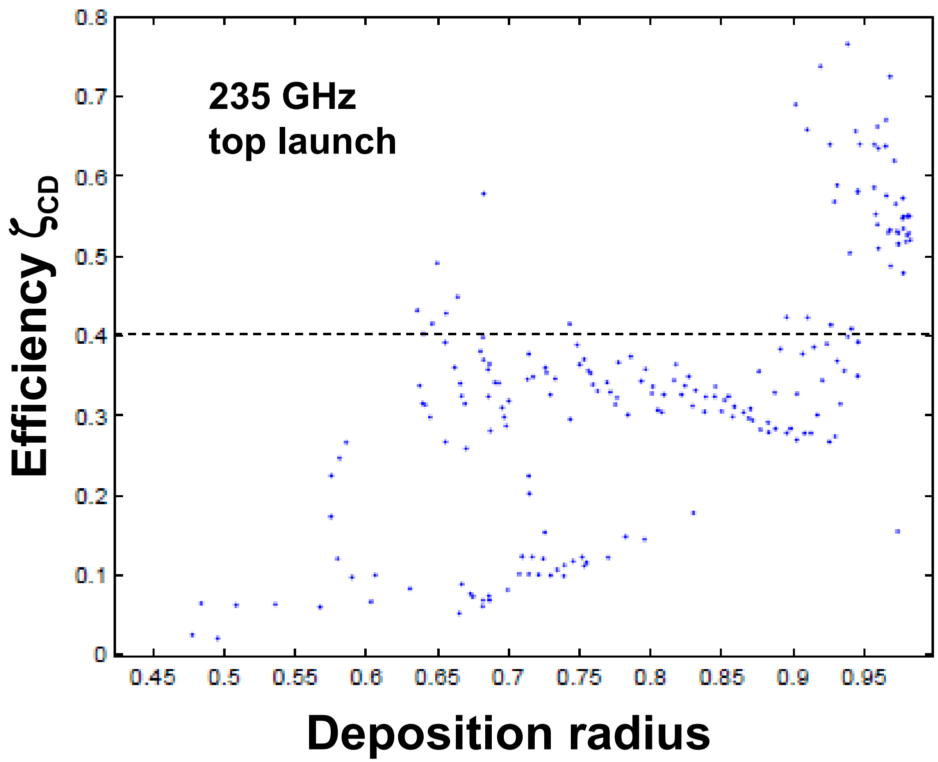




For top launch and higher frequency, ‘sweet spots’ can be found similar to the ITER case shown before, but off-axis (difficult to reach centre)

Much more sensitive to the injection geometry than midplane launch!

Results for top launch (frequency variation)



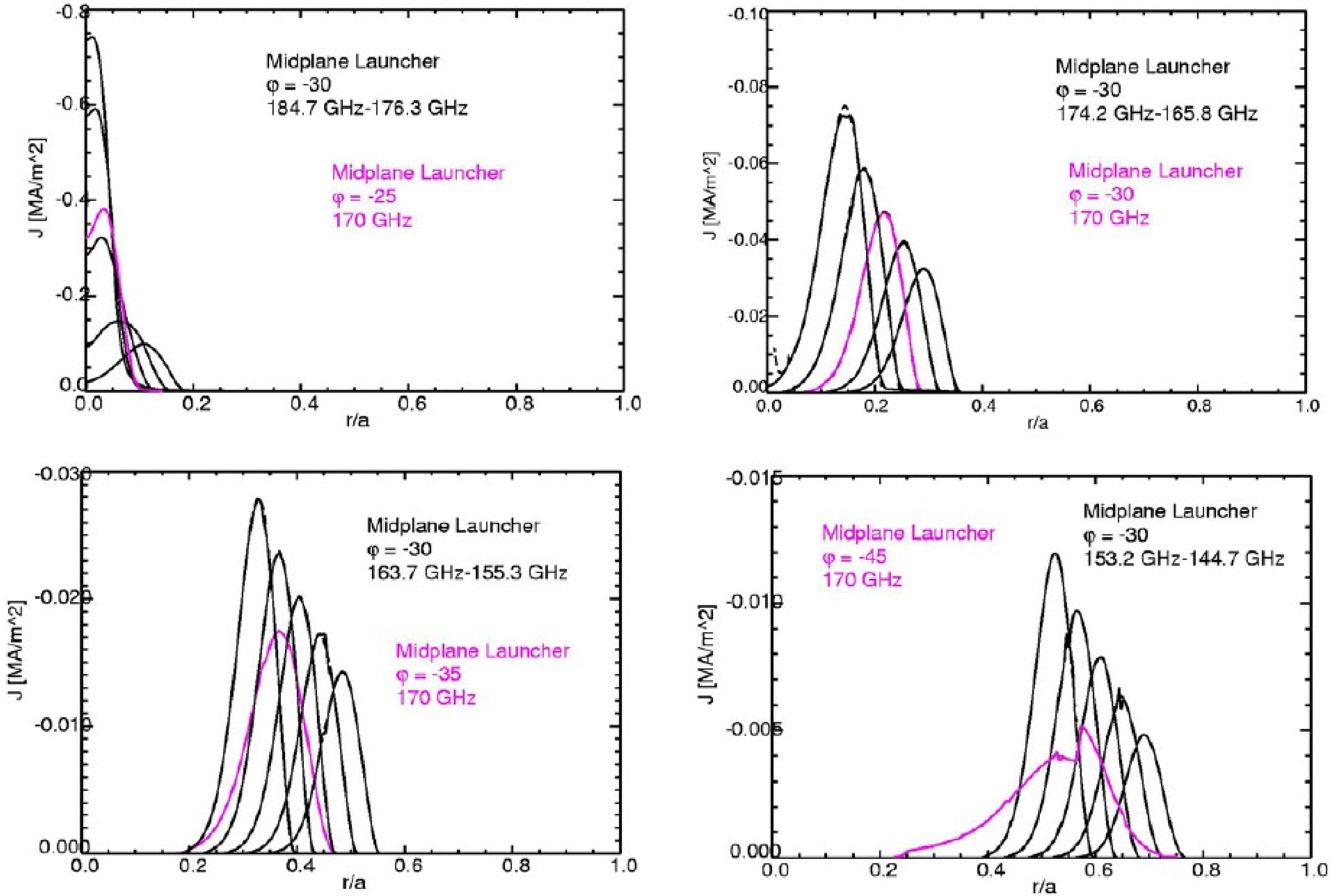
Increasing further f_{ECCD}, off-axis CD (≥ 0.5) efficiency can go up to 0.4

Below a certain radius, ζ_{CD} drops drastically (beam misses resonance), but central efficiency can still be 0.25-0.3 (from different top launch point)

⇒ Launch position must be optimised for each desired CD position

Optimisation still ongoing…

Deposition control with step-tuneable gyrotrons



Fixed launch angle sufficient for flexible deposition profile control (ITER case)

- make full use of ECRH advantages (just a 20 cm^2 hole in the wall per 2 MW)

H. Zohm and M. Thumm, J. Phys. Conf. Series 25 (2005) 274.

Implications for ECCD technology development

From these studies, several conclusions can be drawn for future ECRH technology development:

The frequency should be higher than for ITER (200 GHz$^+$ range)

- calls for higher field magnets (possible) and co-axial cavity (EU project)

The electrical efficiency should be further improved

- calls for multi-stage depressed collector, improved electron gun and optimised HVPS

Step-tuneability with narrowly spaced frequencies is desirable

- consistent with use of co-axial cavity
- have to solve the broadband window problem (at gyrotron and torus)

The work in the German fusion centres KIT and IPP is well aligned with these goals

Summary and Conclusions

Summary and conclusions

A ‚German DEMO Working Group‘ has been set up to coordinate DEMO relevant work done at FZJ, KIT and IPP in both physics & technology

This should ensure that

- expertise of the three centres is fully available to DEMO activities
- research topics are well aligned with DEMO needs
- stellarators are kept as serious options in DEMO and Fusion Power Plant design studies (all three centres strongly committed to W7-X)

In the area of steady state / H&CD, the first conclusions are

- the feasibility of a pulsed tokamak DEMO should be assessed
- R&D should emphasize high η_{CD} and robust high β scenarios
- each system should be carefully optimised (example ECCD)

In general, the exercise of joining physics and technology has already shown great synergy effects!