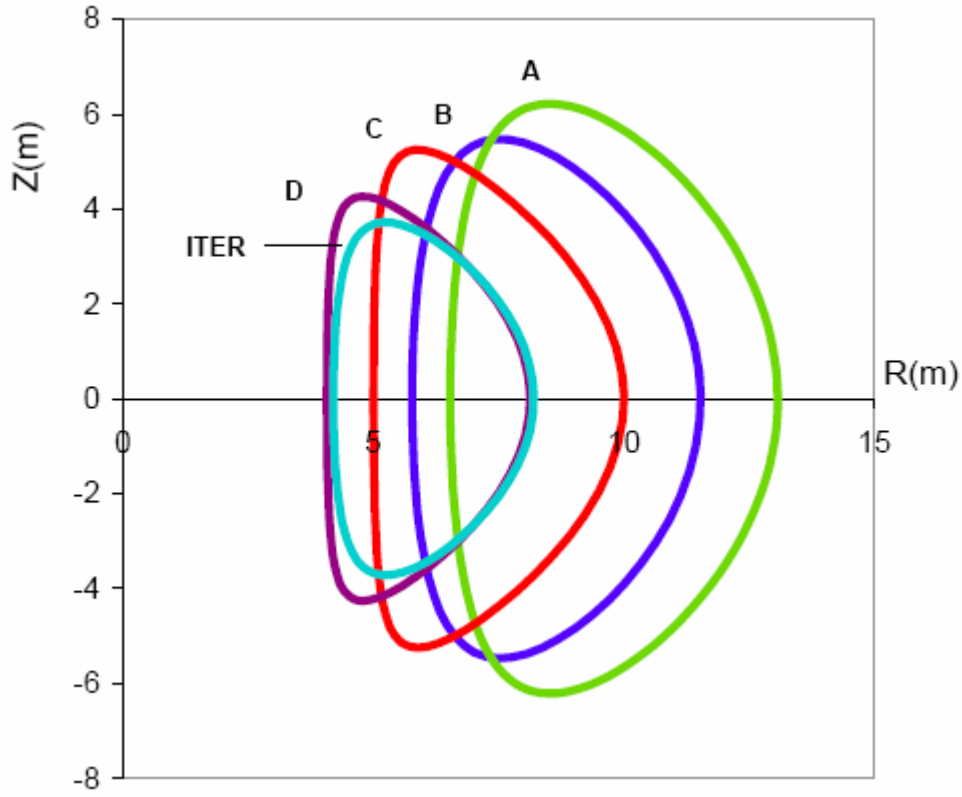
Critical Physics Issues for DEMO

L.D. Horton

with thanks to the speakers at the recent
European Fusion Physics Workshop

Background

- The necessary plasma current and size of tokamak fusion reactor depends strongly on a few key physics parameters
- As part of the EU DEMO study, these key parameters are being re-visited with a view to identifying priority work for the short term and for ITER



(European Fusion Power Plant Conceptual Study)

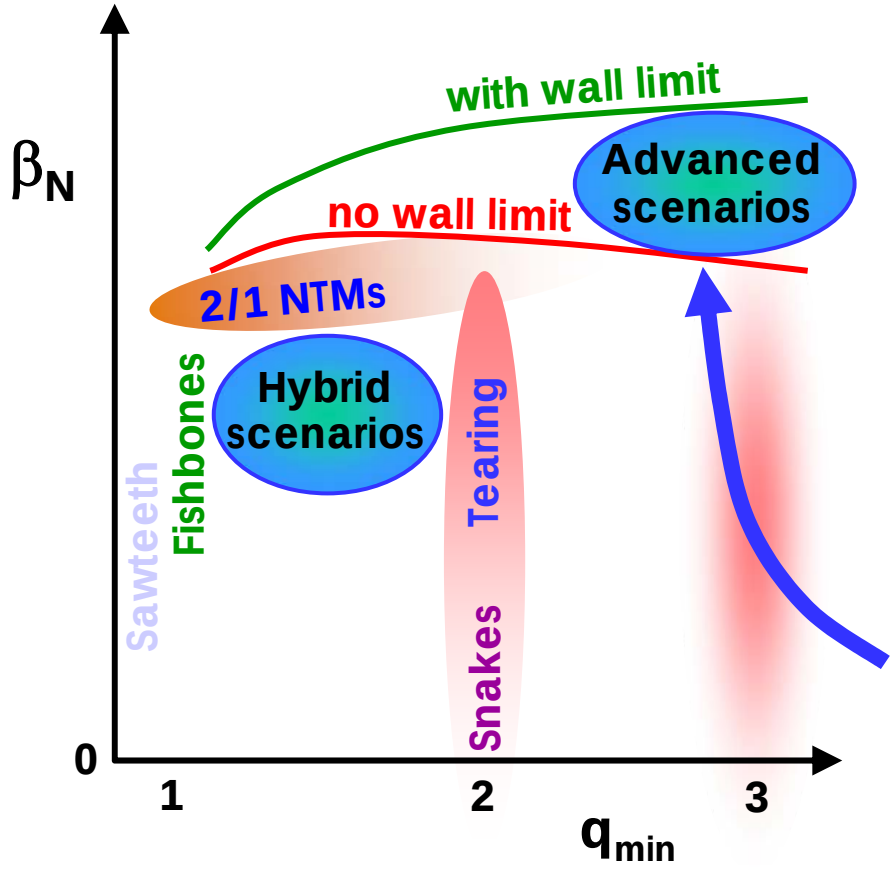
Background

Parameter	Model A	Model B	Model C	Model D
Unit Size [GW_e]	1.55	1.33	1.45	1.53
Fusion Power [GW]	5.00	3.60	3.41	2.53
Major Radius [m]	9.55	8.6	7.5	6.1
TF on axis [T]	7.0	6.9	6.0	5.6
Plasma Current [MA]	30.5	28.0	20.1	14.1
Average Temperature [keV]	22	20	16	12
Average Density [m^{-3}]	1.1	1.2	1.2	1.4
β_N (thermal, total)	2.8, 3.5	2.7, 3.4	3.4, 4.0	3.7, 4.5
H_H (IPB98y2)	1.2	1.2	1.3	1.2
Bootstrap Fraction	0.45	0.43	0.63	0.76
P_{add} [MW]	246	270	112	71
n/n_G	1.2	1.2	1.5	1.5
Divertor Peak Load [MW/m^2]	15	10	10	5
Z_{eff}	2.5	2.7	2.2	1.6

Beta limit

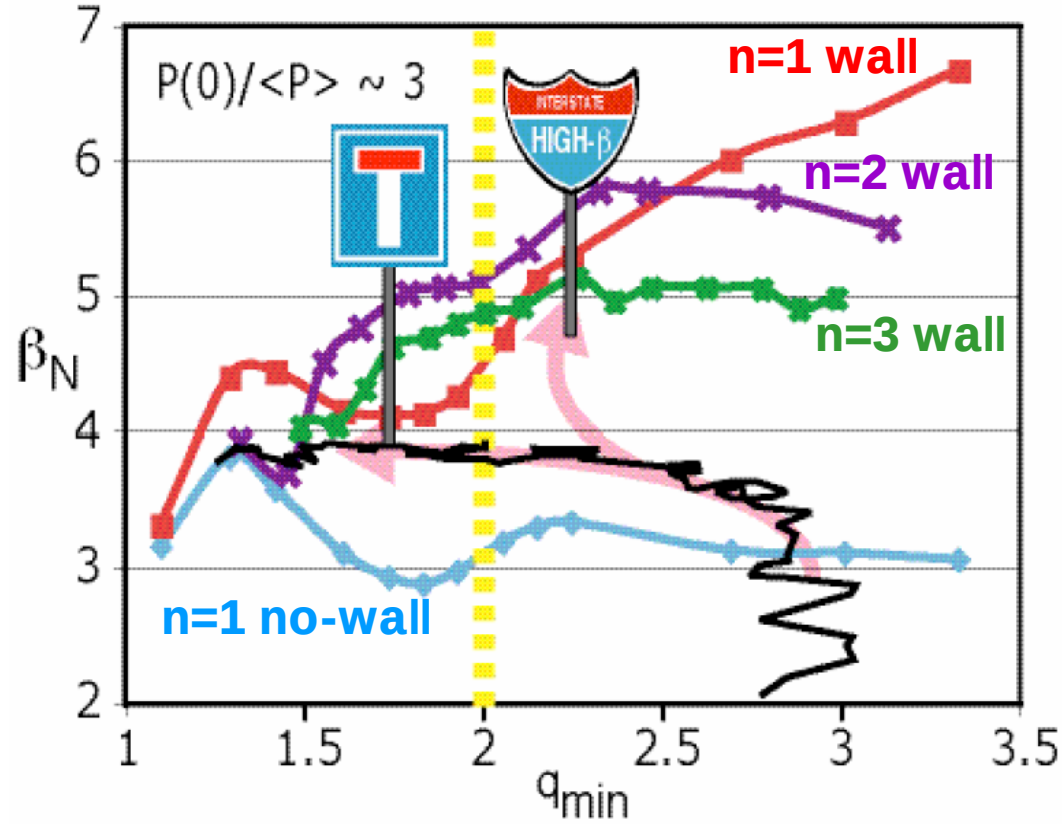
- Two high β regimes being tested:
  - 'Advanced' regimes which require strong current profile control and wall stability of ideal MHD but which hold out the hope of steady-state operation
  - Improved H-mode or 'Hybrid' regimes which are limited by NTMs but allow long pulse operation

(R. Buttery, 13th EFPW)



Beta limit: Advanced regimes

- In the presence of a conducting wall, higher q_{min} and broader pressure profiles allow access to high β
- In DIII-D, β_N of 5.1 is theoretically possible at q_{min} = 2.1

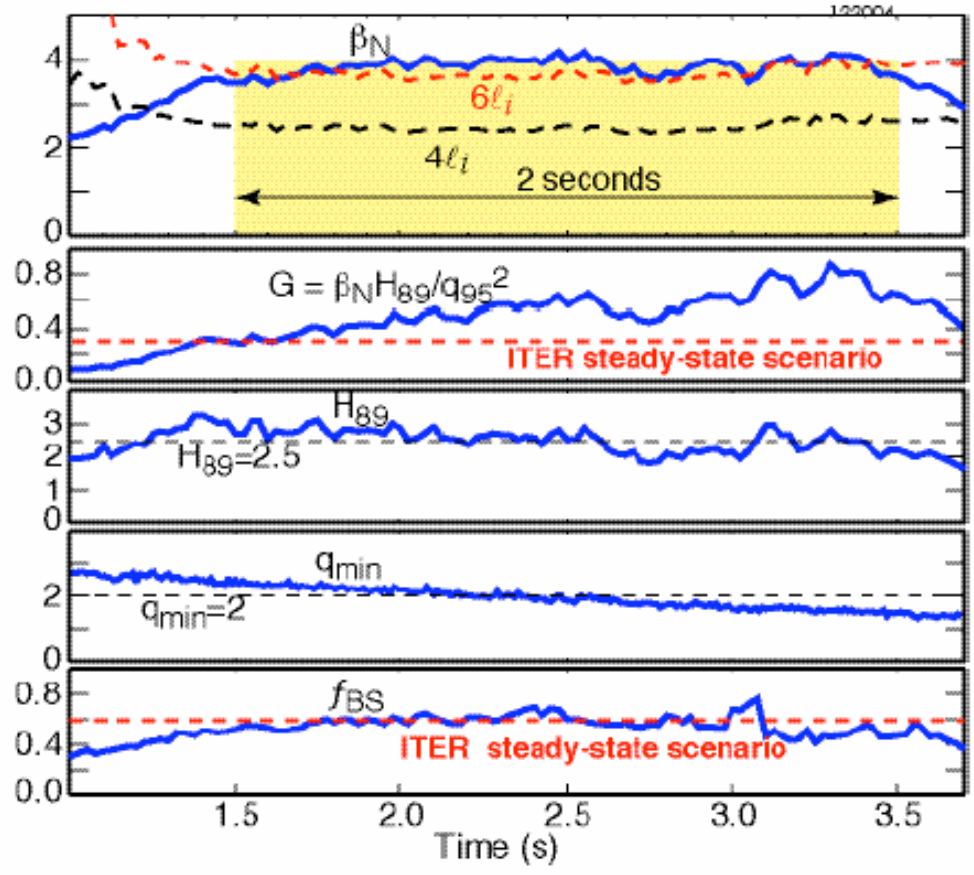


(A. Garofalo, 2005 APS)

Beta limit: Advanced regimes

- β_N of 4 has been demonstrated in DIII-D
- The regime is transient as no one has the current drive capability to hold the current profile constant

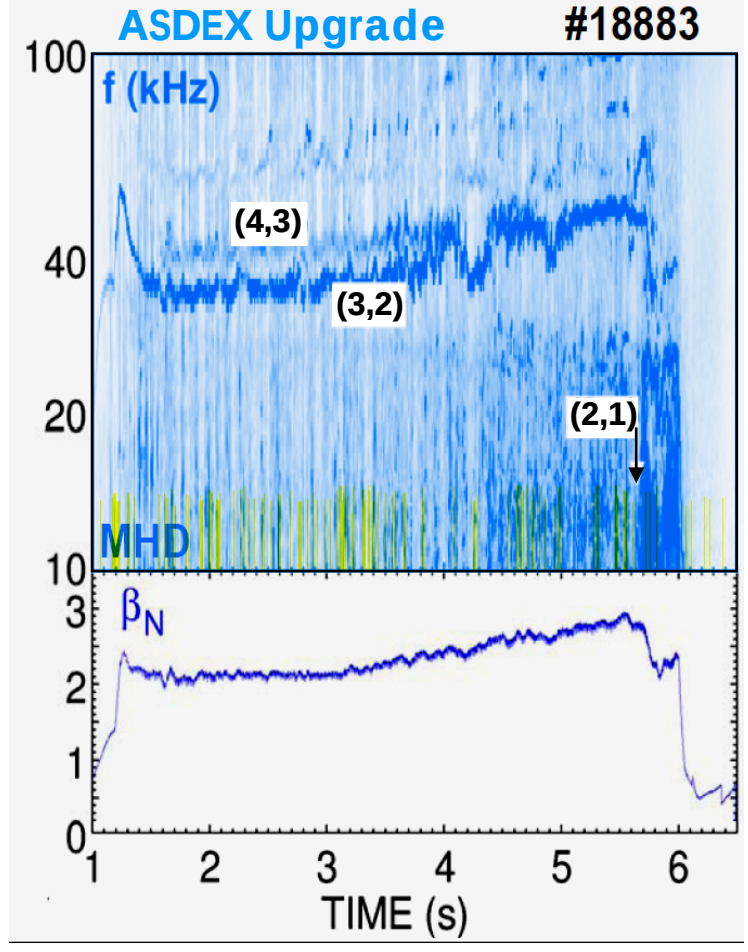
⇒ We need (at least) one divertor tokamak with strong off-axis CD capability and a conducting wall



(A. Garofalo, 2005 APS)

Beta limit: Improved H-mode

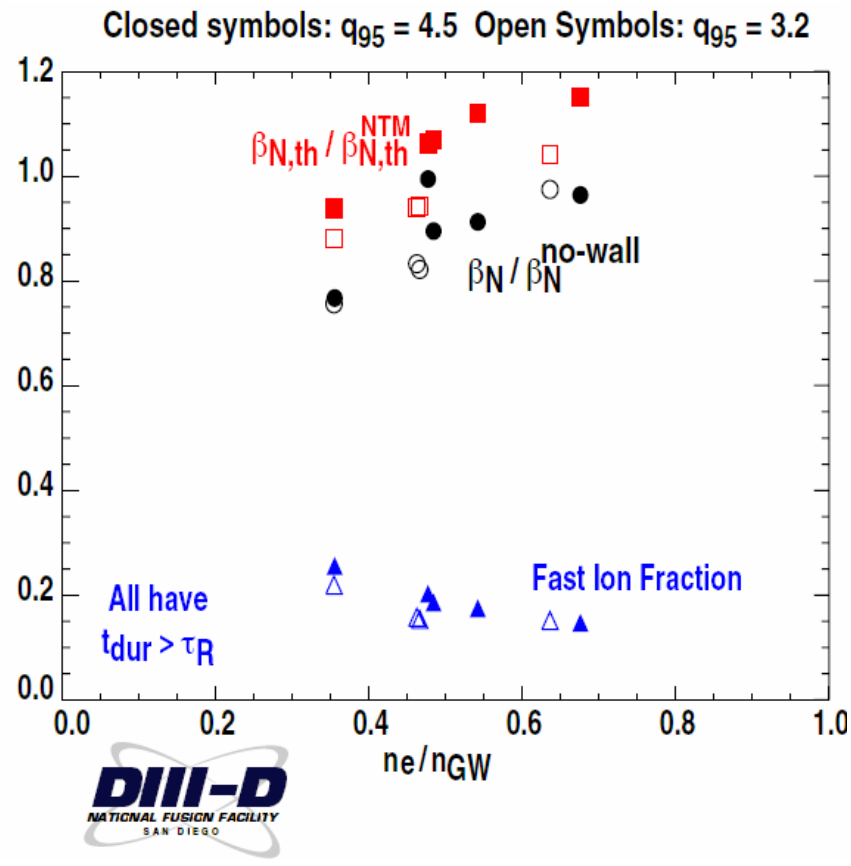
- The improved H-mode is often accompanied by neoclassical tearing mode activity
- There is an on-going debate about whether the NTMs help to control the current profile, allowing very long pulse operation
- The regime is limited at the highest β by (2,1) NTMs



(A. Stäbler, 2004 IAEA)

Beta limit: Improved H-mode

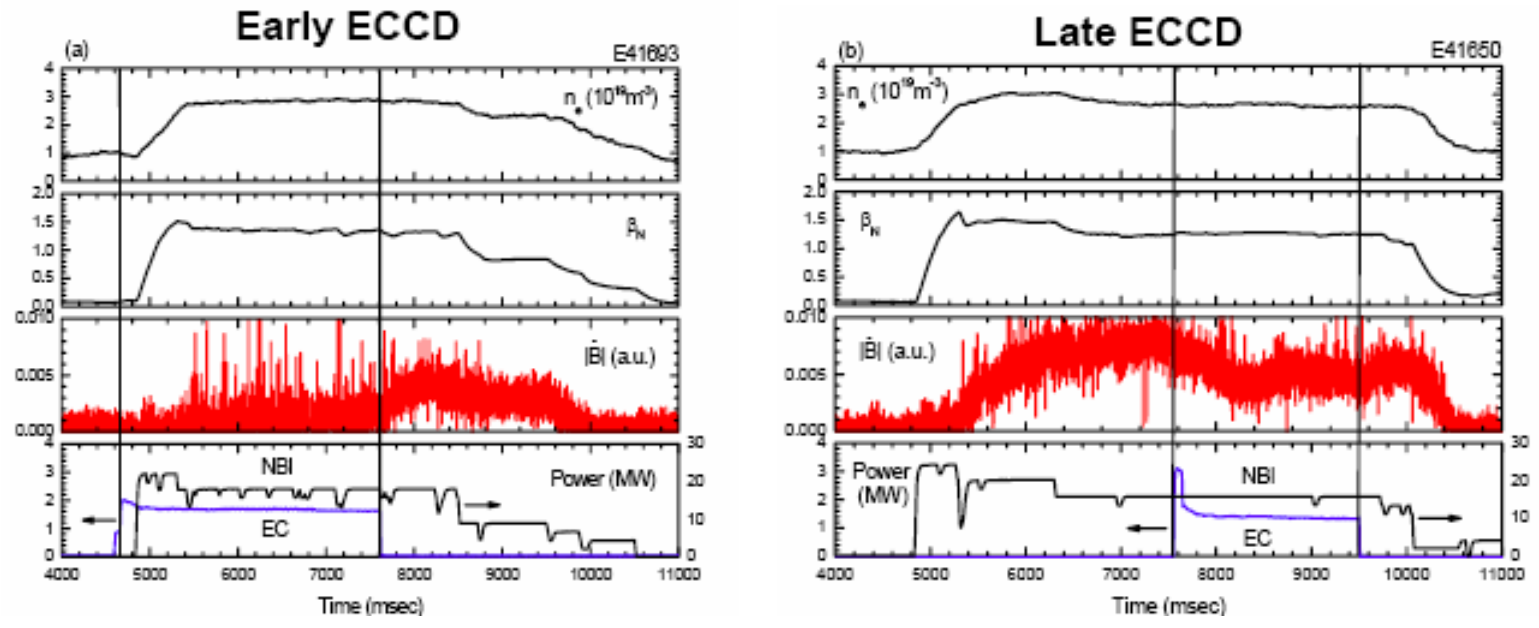
- The β limit for the improved H-mode is usually close to the ideal no-wall limit
- β_N~3 has been achieved, for durations longer than the current resistive diffusion time
- High density operation has been shown to be compatible with improved H-modes



(M. Wade, 2004 IAEA)

Beta limit: Improved H-mode

- Several machines are working on controlling NTMs using ECCD:
  - Replace the missing current in the island formed by the NTM
  - Suppress NTM trigger mechanisms (sawteeth)
  - Adjust the current profile to reduce the pressure gradient drive at the critical rational surface



(Nagasaki, 2004 IAEA)

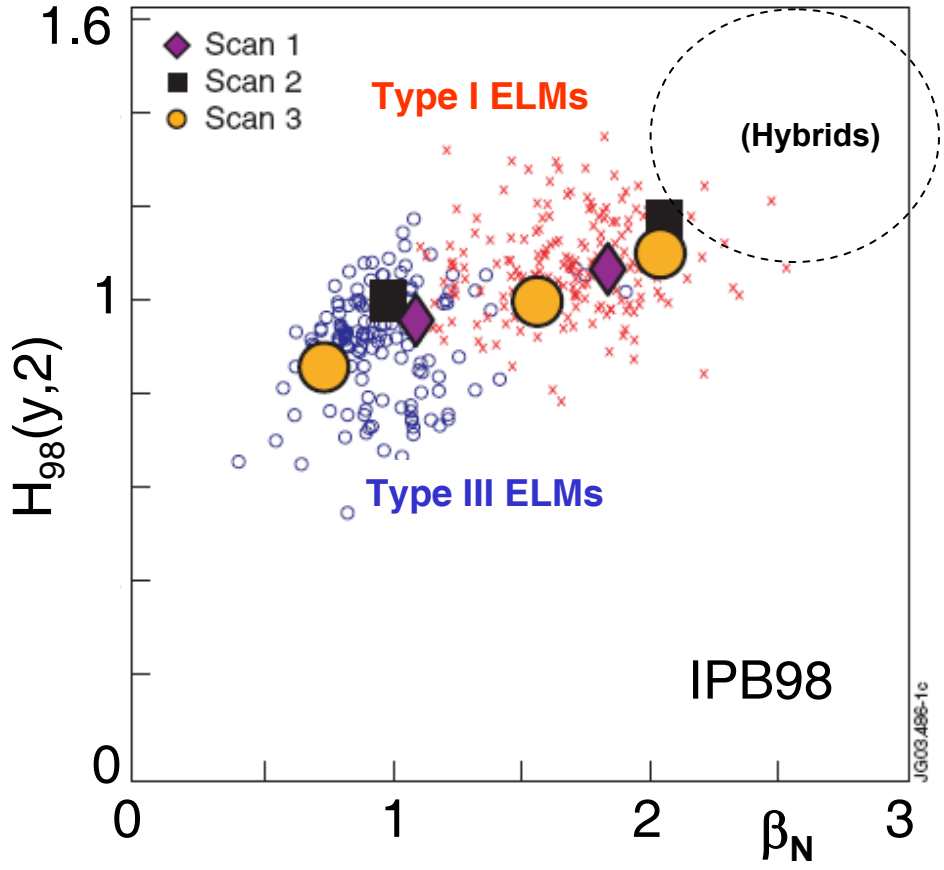
Beta limit: Issues

- We need to demonstrate true steady advanced regimes in a tokamak with a conducting wall and a large off-axis CD capability
- We need to demonstrate reliable feedback and control of resistive wall modes so as to allow operation above the no-wall limit
- We need to understand the role of NTMs in redistributing current in improved H-modes
- We need to study the scaling of the NTM limit with increasing machine size
- We need to demonstrate reliable tracking and control of NTMs using ECCD
- We need to quantify the influence of high beta operation on fast particle transport

Confinement & Modelling

- Here, the news is good!
- Confinement is clearly scaling more favourably with β than the normal scaling law predicts
- This is very positive for ITER (either long pulse or near-ignition is possible) and is already close to the confinement assumed for DEMO

(G. Sips, 13th EFPW)

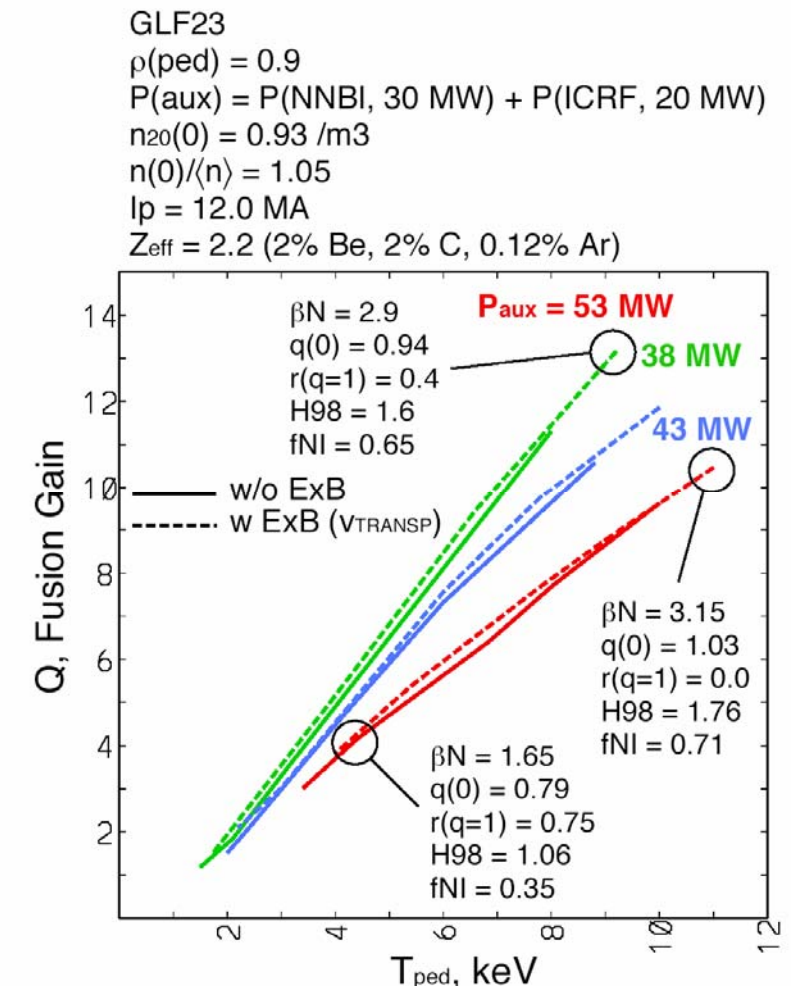


(D. McDonald, PPCF **46** (2004) A215)

Confinement & Modelling

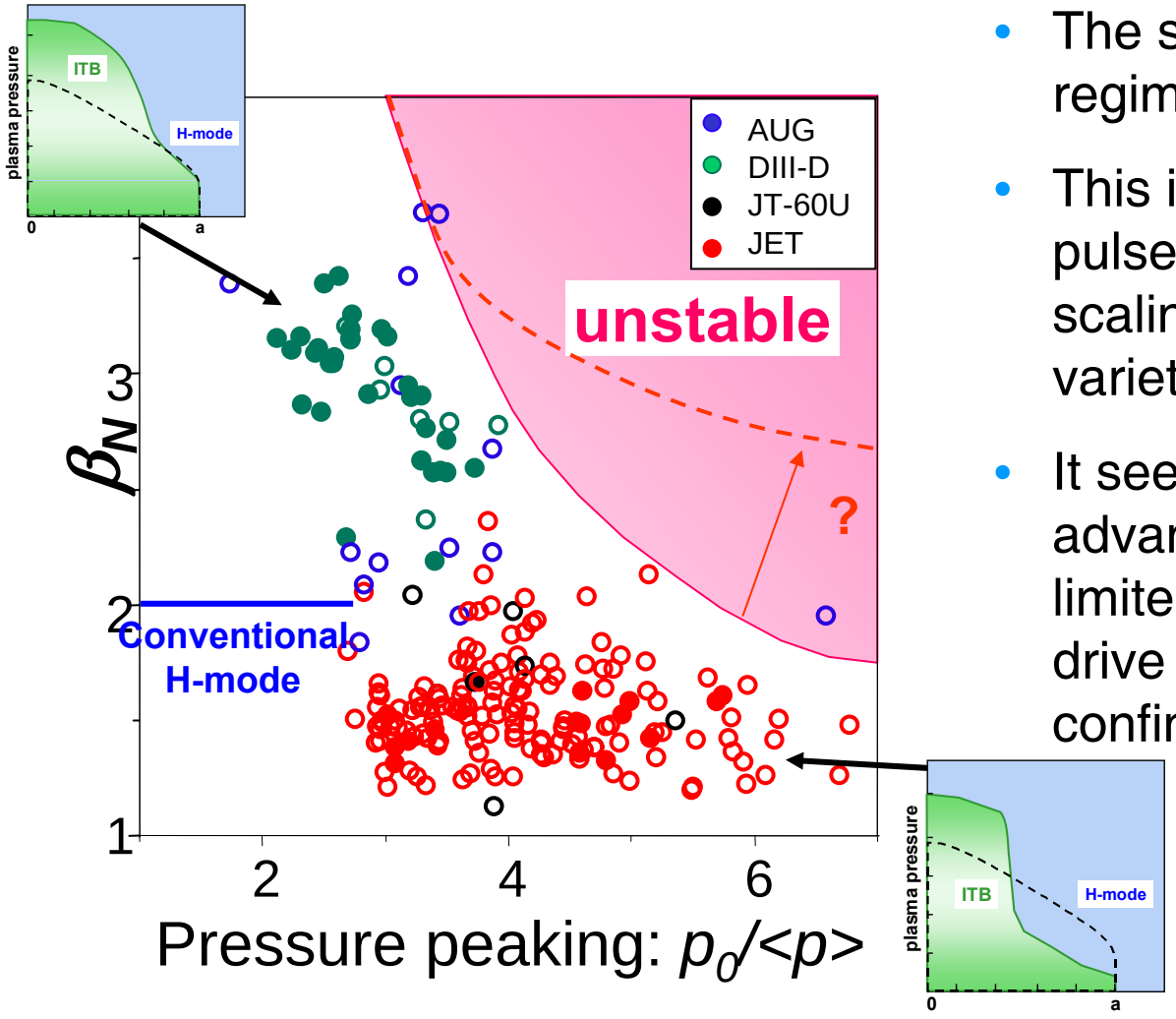
- 1D modelling using the turbulence-based codes is not so optimistic (Q~10 is typical)
- The beneficial effect of toroidal rotation shear is lost in ITER (and a reactor)
- The predictions depend very strongly on the assumed confinement in the edge transport barrier

⇒ The role of the ETB needs to be investigated & a co-ordinated modelling effort is required (and is underway)



(C. Kessel, SSO ITPA meeting,Nov. 2005)

Confinement & Modelling



- The situation with advanced regimes is much more uncertain
- This is due to the lack of long pulse data to build a confinement scaling and the relatively wide variety of possible regimes
- It seems likely, however, that advanced regimes will be more limited by stability and current drive requirements than confinement

(G. Sips, PPCF **47** (2005) A19)

Confinement & Modelling: Issues

- We need to understand the role of the edge transport barrier in the observed confinement improvement in improved H-modes
- We need to build a database of steady advanced H-mode discharges which will allow the construction of a confinement scaling
- We need more data in discharges with Ti~Te and with low momentum input
- We need to co-ordinate our analysis of these regimes, testing codes against the results from a variety of machines

Current Drive

- The PPCS designs assumed a current drive efficiency γ_{CD} which follows the Mikkelsen-Singer formula:

$$\gamma_{CD} \equiv \frac{I_{CD} n_e R_0}{P_{CD}} \quad [AW^{-1} 10^{20} m^{-2}] \propto T_e$$

- The assumed temperature dependence of the CD efficiency drives the plant designs to high temperature
- PPCS Model C has 7.4 MA of CD using 112 MW of power and thus γ_{CD} ~ 0.6

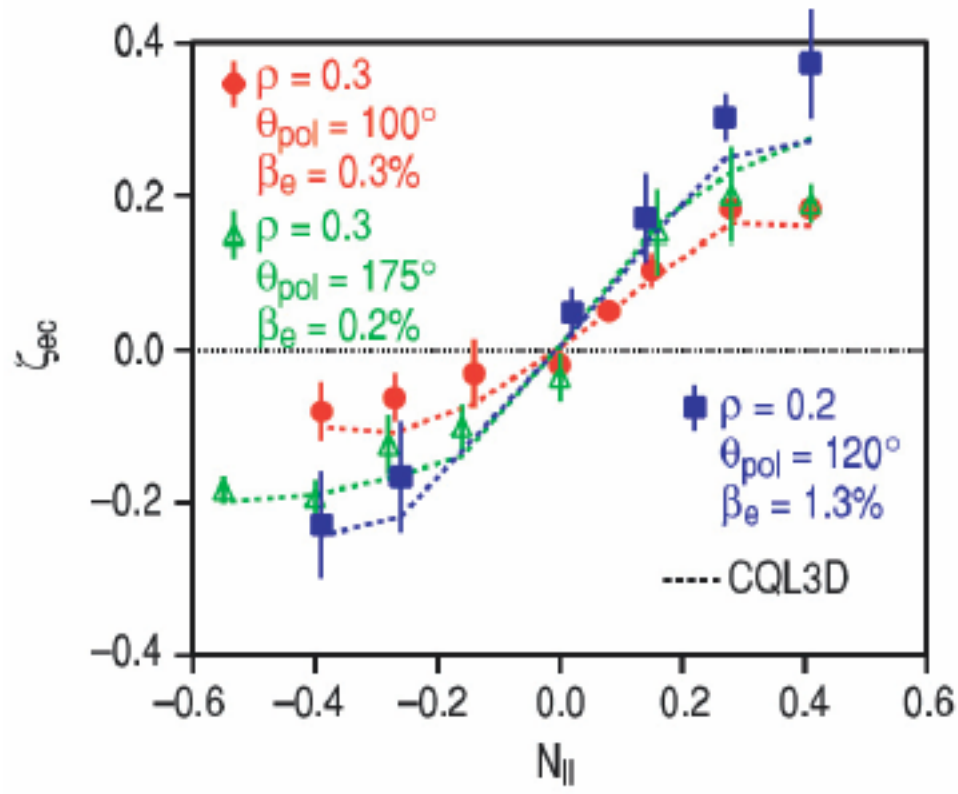
Current Drive: ECCD

- Theory is advanced enough to describe accurately the CD efficiency:

$$\gamma_{CD} \equiv \frac{T_e[keV]}{32.7}\varsigma_{ec}$$

- Taking ζ_{ec}=0.2, one finds γ_{CD} ~ 0.1 for DEMO (at 20 keV)
- ECCD is not suitable for bulk current drive

(S. Alberti, 13th EFPW)

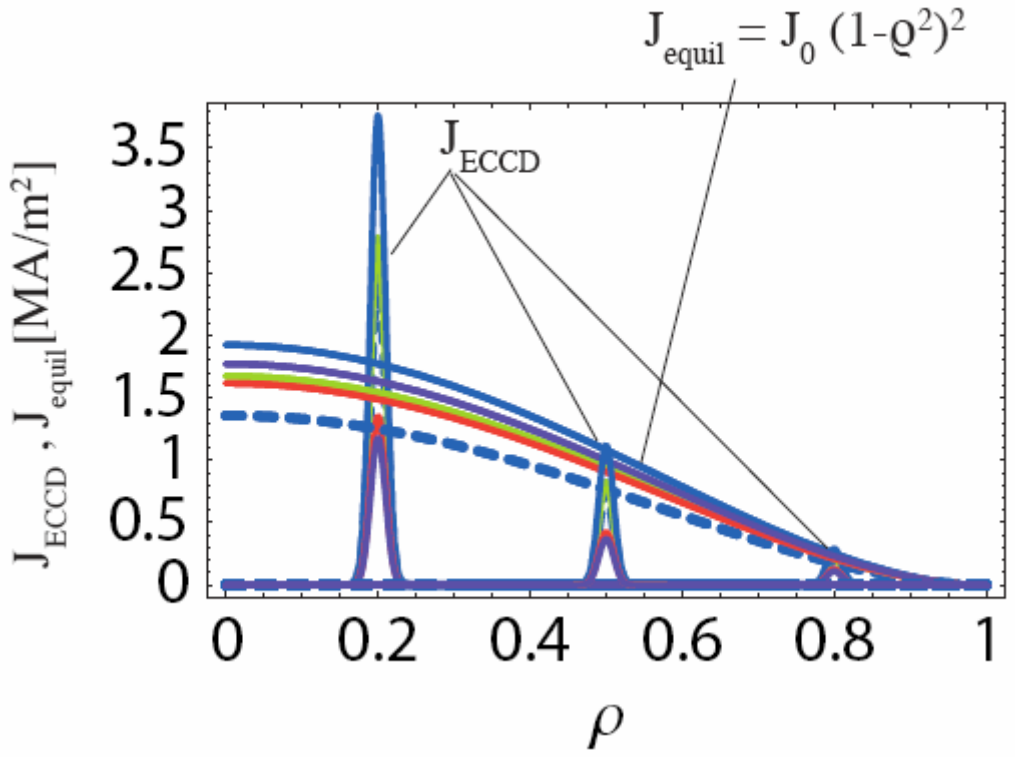


(C. Petty, NF **43** (2003) 700)

Current Drive: ECCD

(S. Alberti, 13th EFPW)

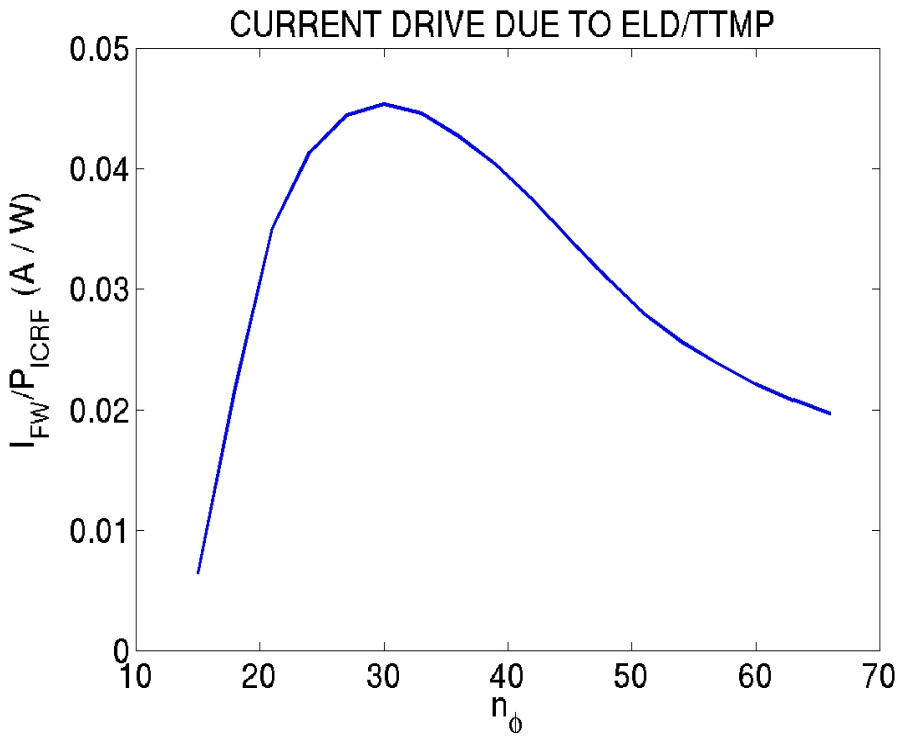
- Assuming ~1/3 of the auxiliary power in DEMO could be allocated to ECCD, the local current density can significantly altered
- ECCD is a viable option for mode control in DEMO (given the need for real-time control, it is presently the only option)



Current Drive: ICCD

(L-G. Eriksson, 13th EFPW)

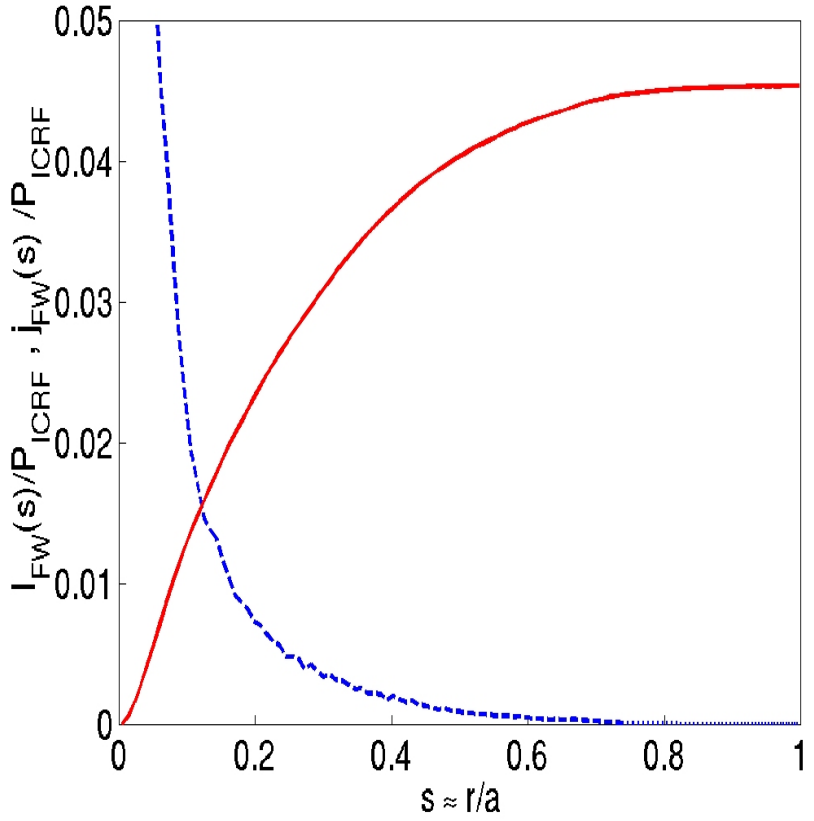
- Ion cyclotron waves could provide CD in DEMO via electron Landau damping
- For 78 MHz in PPCS Model A, the simulated CD efficiency is 0.45



Current Drive: ICCD

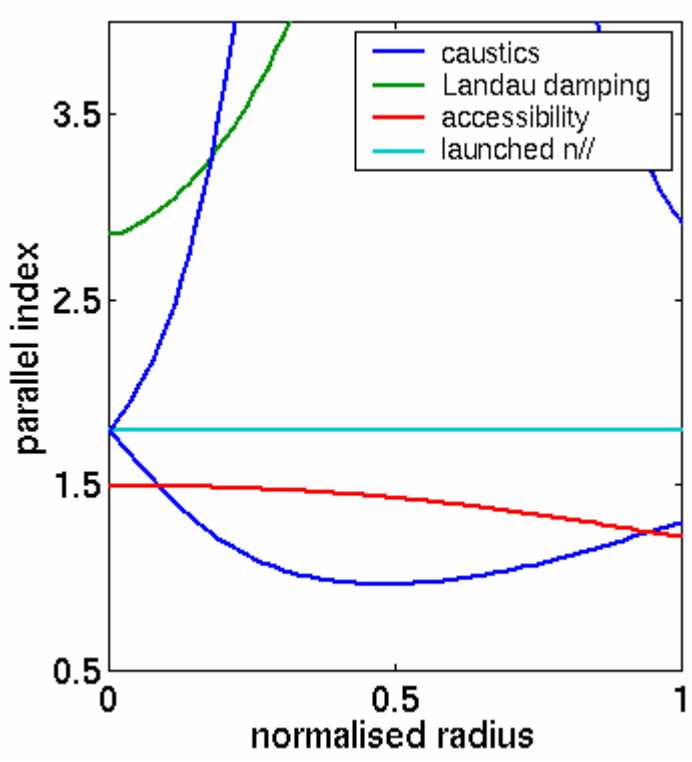
(L-G. Eriksson, 13th EFPW)

- The resulting CD is on-axis - it could be used for bulk CD but not for control in advanced regimes



Current Drive: LHCD

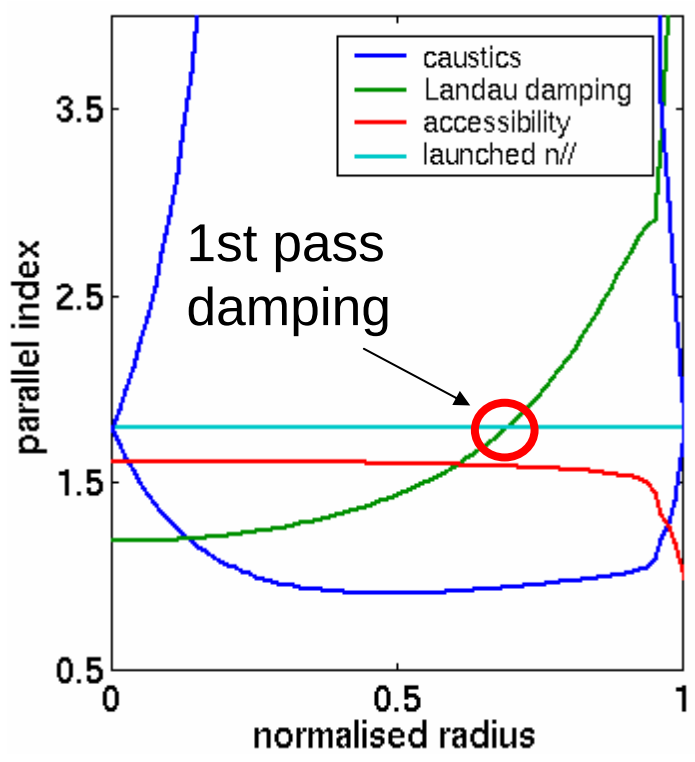
Tore Supra, T_{e0} = 5 keV



$n_{||} = n_{||}(T_e)$

(G. Giruzzi, 13th EFPW)

ITER, T_{e0} = 30 keV



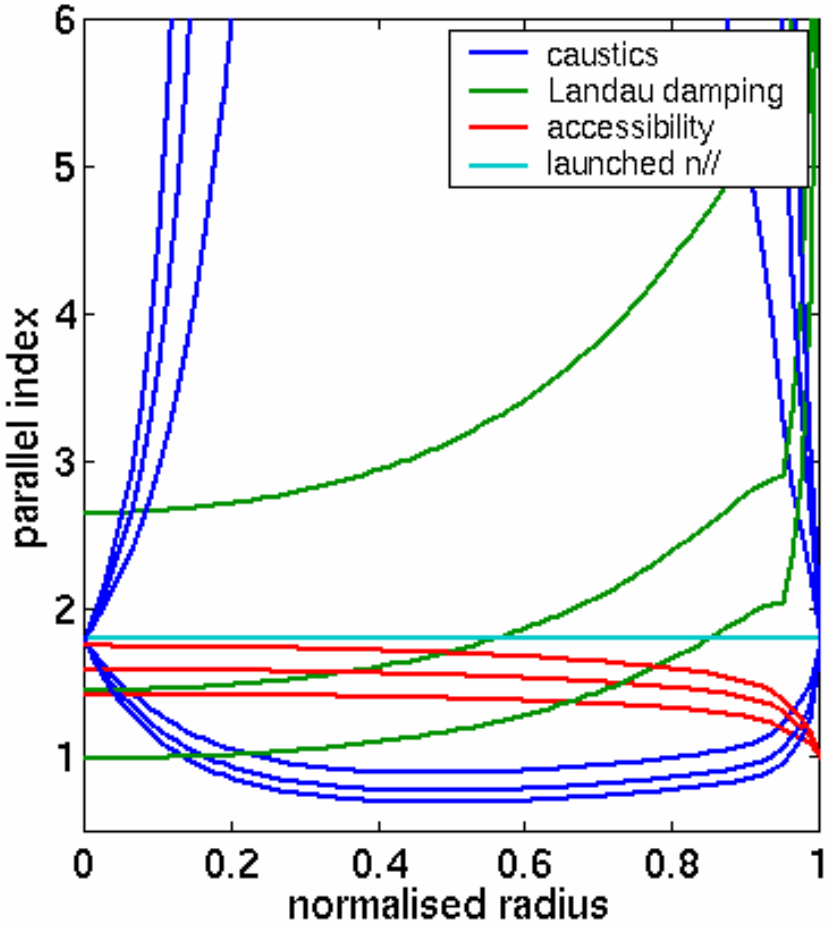
$n_{||} \approx n_{||}$-launched

$\Rightarrow \gamma_{CD} < 0.4$

Current Drive: LHCD

- In DEMO, where the temperatures are predicted to be very high, the Landau damping restricts LHCD to the outermost 20% of the plasma

⇒ Advanced regimes with such far off-axis CD must be developed

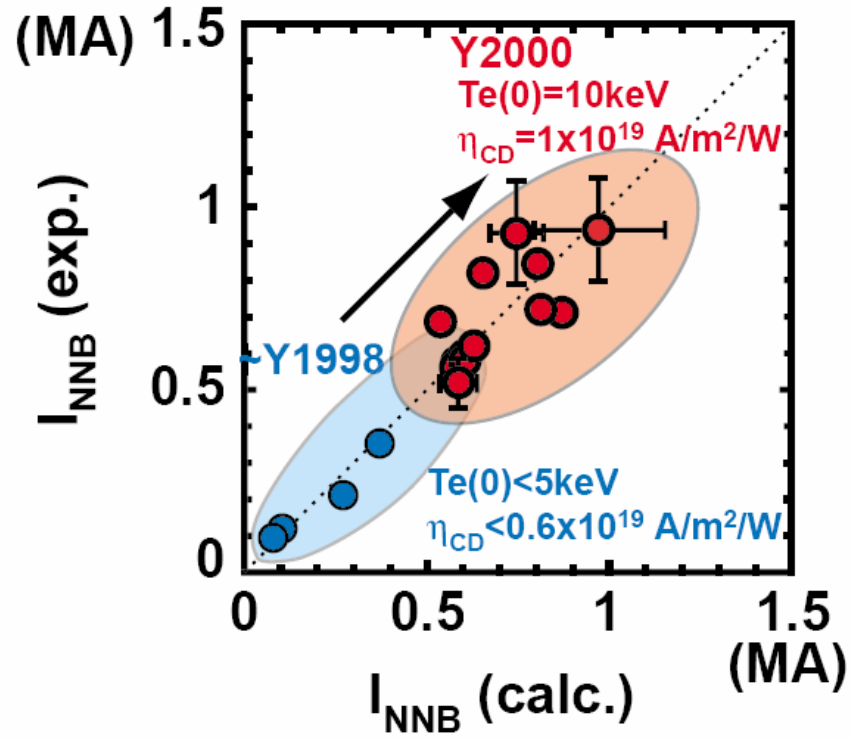


(G. Giruzzi, 13th EFPW)

Current Drive: NBI

(S. Günter, 13th EFPW)

- The current driven by neutral beam injection is found to experimentally to be consistent with (numerical) theory predictions



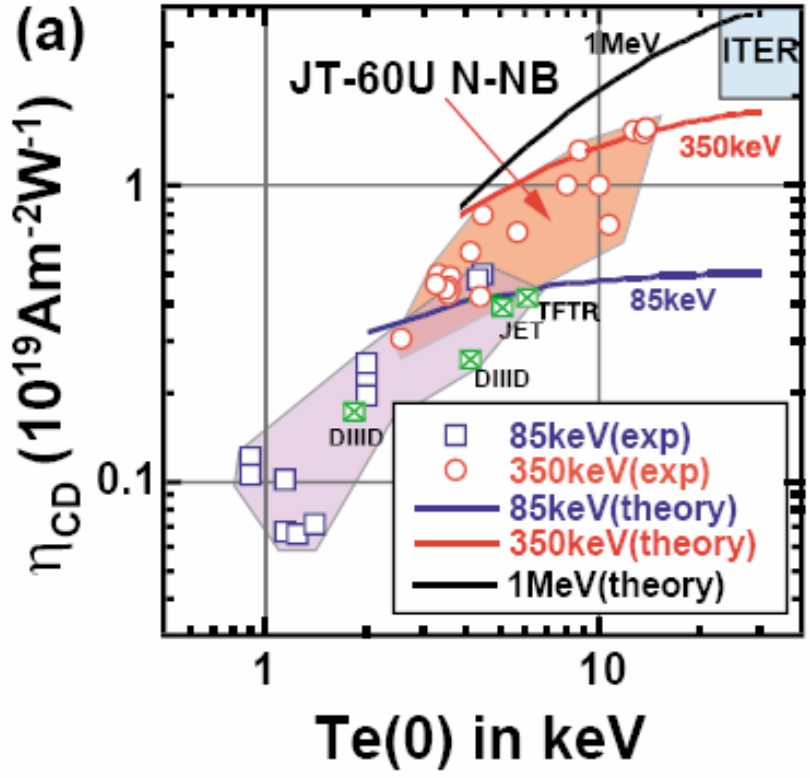
(T. Oikawa, NF **41** (2001) 1575)

Current Drive: NBI

(S. Günter, 13th EFPW)

- The current drive efficiency increases with electron temperature and beam energy

⇒ High beam energies and negative ion-based plasma sources will be required for ITER and DEMO

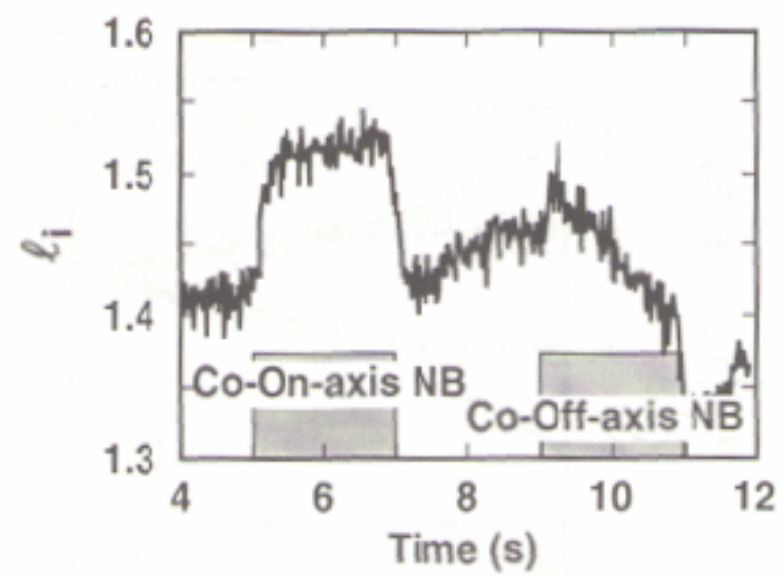


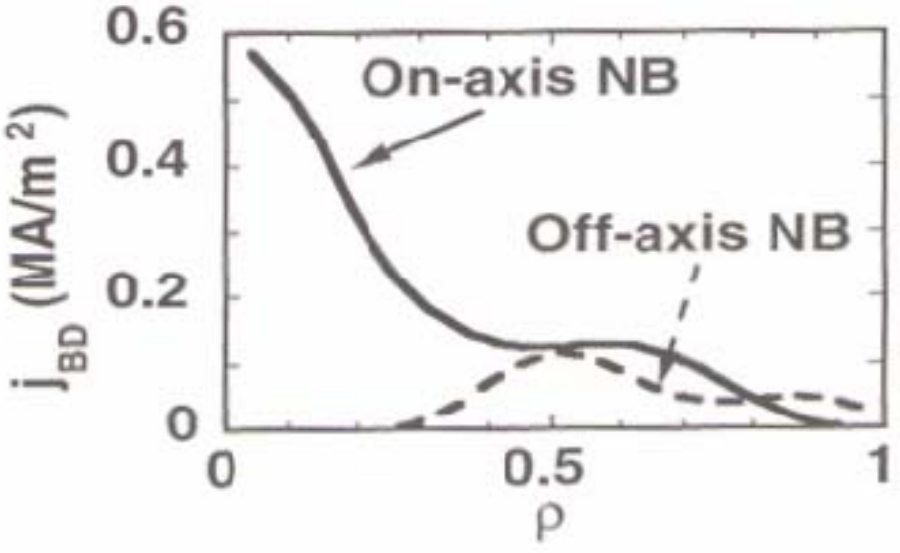
(T. Oikawa, NF **41** (2001) 1575)

Current Drive: NBI

(S. Günter, 13th EFPW)

- Current profile control has been observed in JT-60U
- This was done at low input power (2 MW). Similar results more recently in AUG





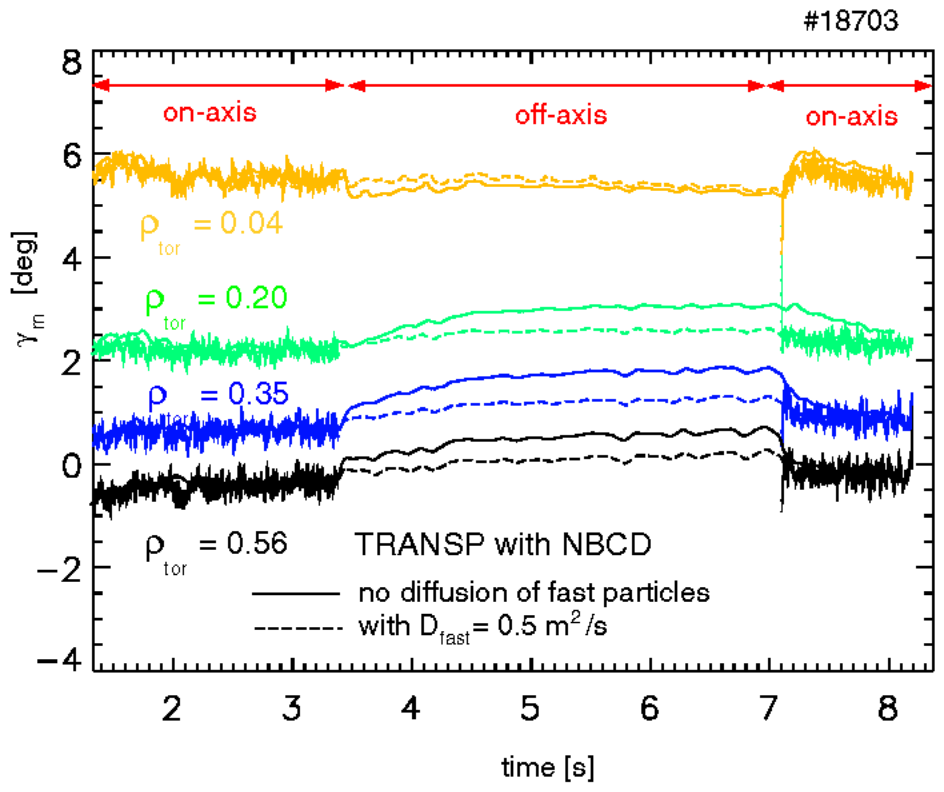
(S. Ide, IAEA (1994))

Current Drive: NBI

(S. Günter, 13th EFPW)

- In AUG, at higher input powers, the observed current profile modification is not consistent with standard theory
- Additional fast particle diffusion is required

⇒ Priority to determine how generally this applies (and why)



(S. Ide, IAEA (1994))

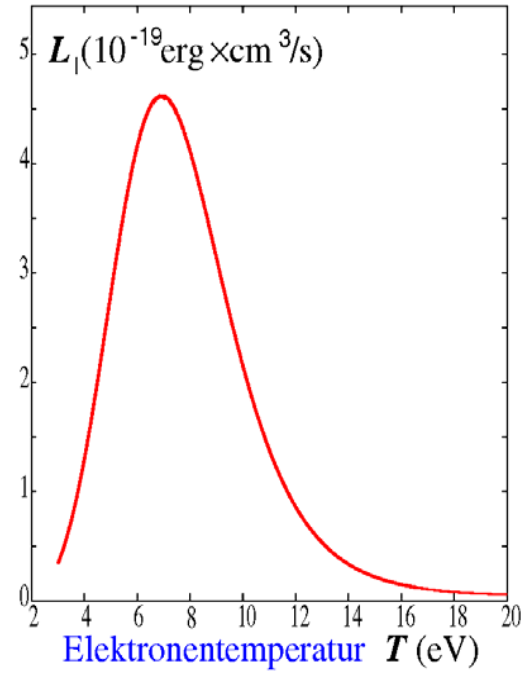
Current Drive: Issues

- We need to prove that we can dynamically detect and control NTMs (and then increase the beta)
- We need to demonstrate that the assumed figure of merit is applicable to ITER and DEMO
- We need to demonstrate the compatibility of advanced regimes with strongly off-axis current drive as would be available from LHCD in a reactor
- We need to determine the conditions which lead to anomalous spreading of the current drive by NBI
- We need to prove the temperature scaling of NBI at high temperature and beam energy (ITER)

Density & Radiation Limits

- One might expect the density limit in a tokamak to be set by the maximum density at which the plasma can support its radiative losses
- This would lead to a power-dependent limit
- Experimentally, one sees evidence of at least two other effects:
  - Poloidally-localised recycling leading MARFE formation
  - A density-dependent increase in transport

(M. Tokar, 13th EFPW)



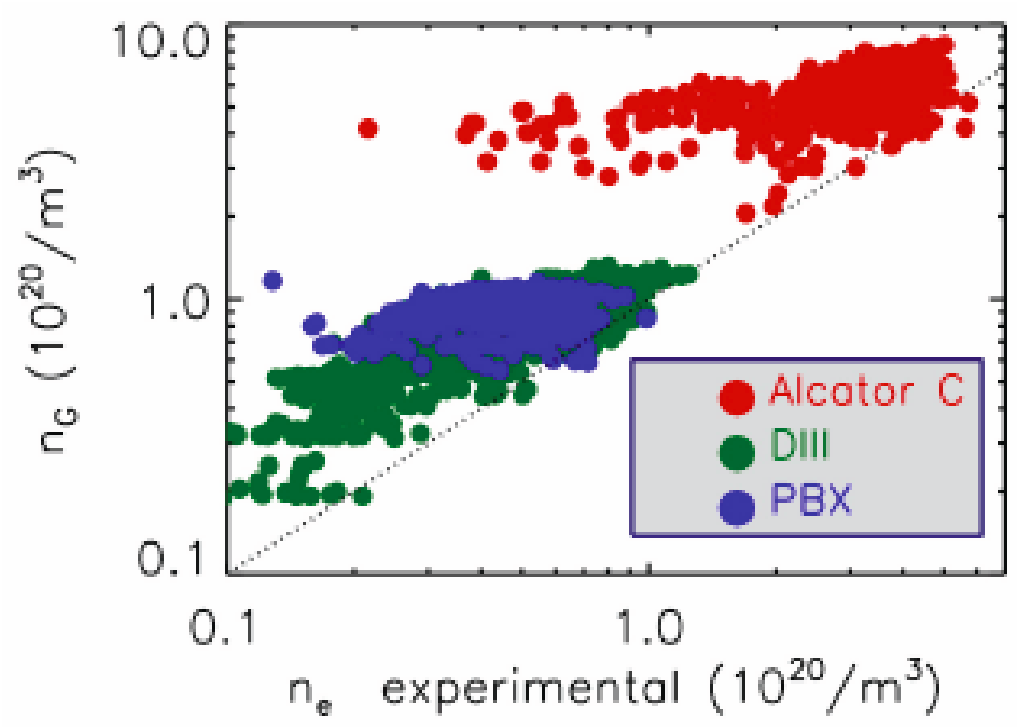
Density & Radiation Limits

- The empirical Greenwald density limit describes experimental results to +/- 20%

$$n_G = I_p \big/ (\pi a^2) = 1.59\, g \frac{B_T}{q_{95} R}$$

- Very weak power dependence has been verified experimentally
- No firm physics basis (thus poor confidence in extrapolations)

(J. Schweinzer, 13th EFPW)

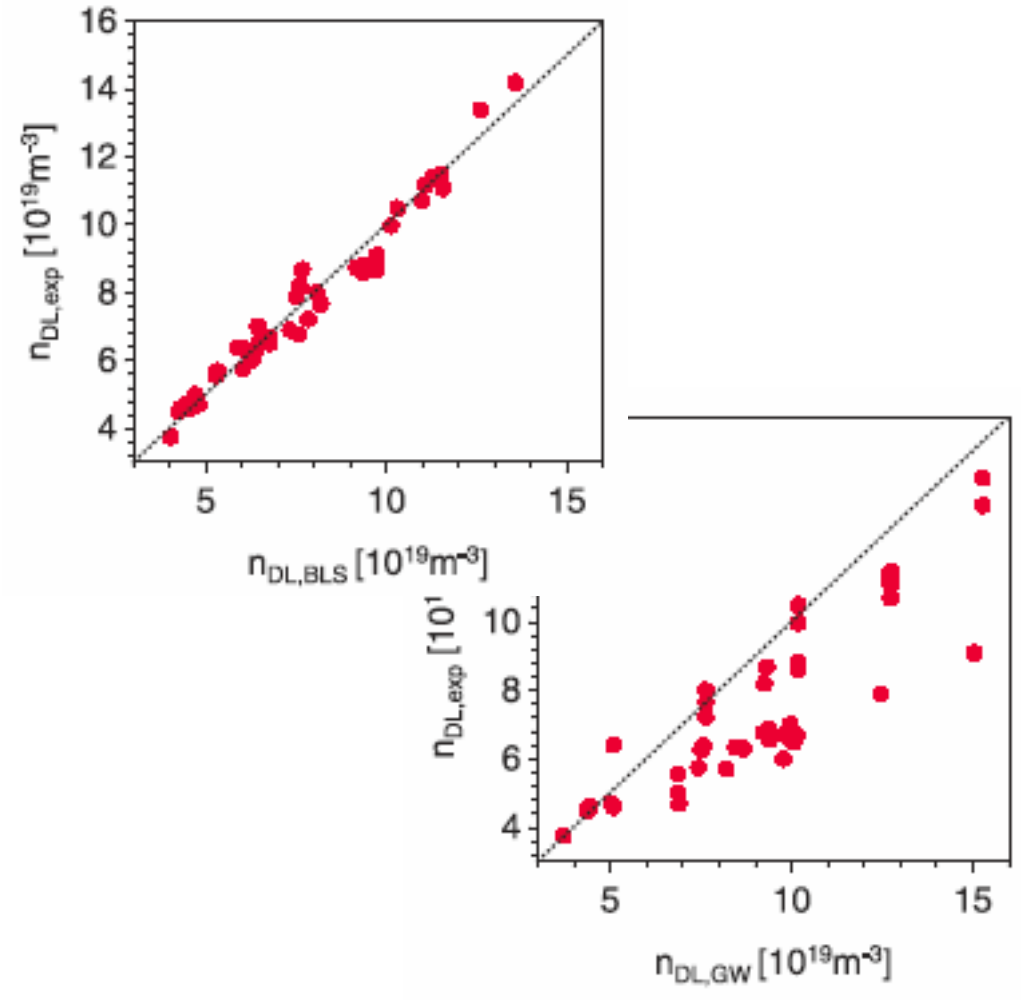


Density & Radiation Limits

- Data from AUG & JET are consistent with a scaling based on SOL detachment:

$$n_{BLS} = 4.06 \frac{P^{0.094} B_T^{0.53}}{(q_{95} R)^{0.88}}$$

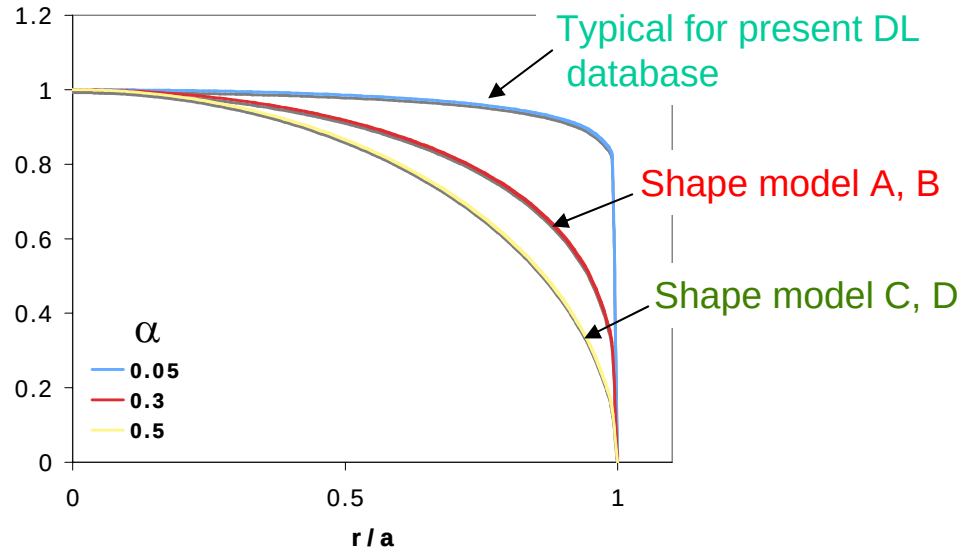
- This applies to H-mode discharges with heavy gas fuelling and thus flat density profiles



(Borrass, Contr. Plasma Phys. **38** (1998) 130)

Density & Radiation Limits

- A Borrass-like scaling is significantly more pessimistic than Greenwald for reactors:

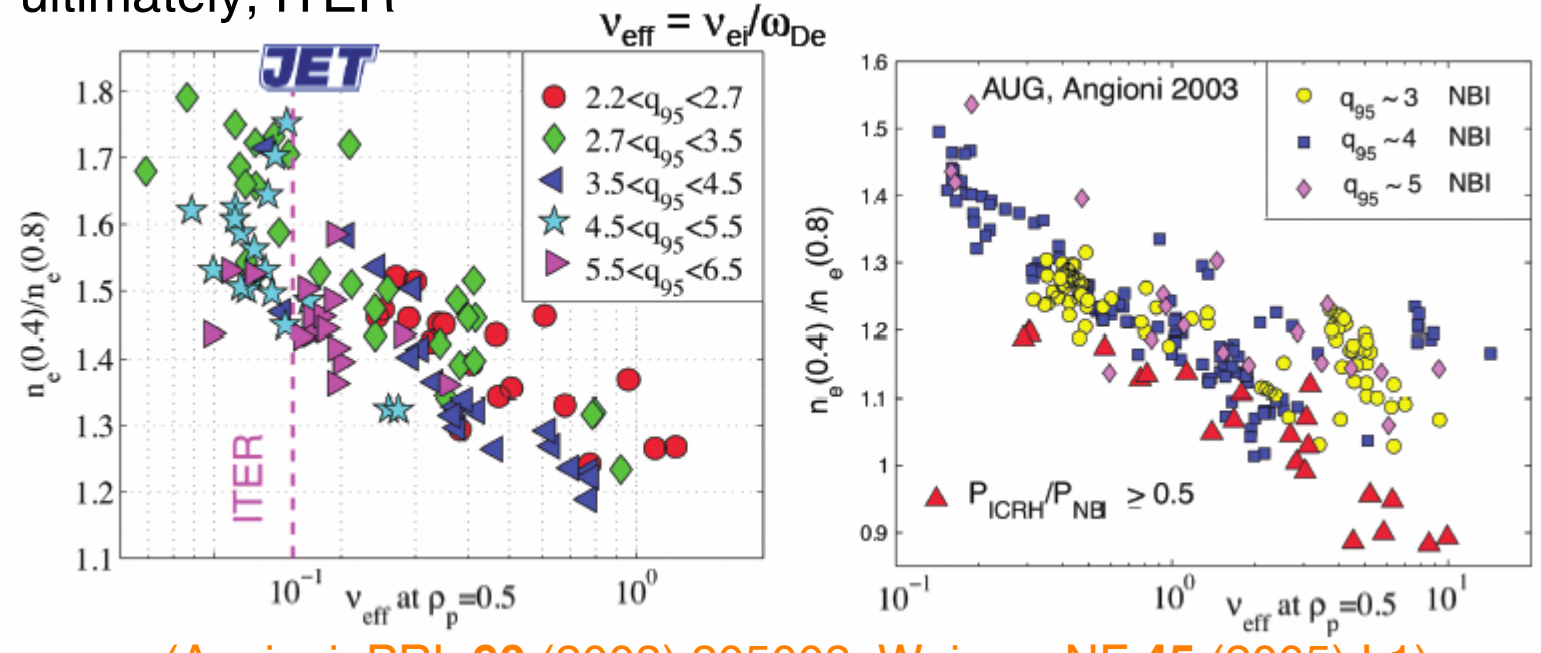


Model	n_e	Peaking	$n_e(0)/n_{GW}$	$n_e(0.8)/n_{GW}$	$n_e(0.8)/n_{BLS}$
A	11	0.3	1.34	0.99	1.77
B	12	0.3	1.29	0.95	1.78
C	12	0.5	1.49	0.89	1.45
D	14	0.5	1.64	0.98	1.42

Density & Radiation Limits

- Density peaking at low collisionality is observed in both JET and AUG
- BUT, the correlation between collisionality and Greenwald density is strong as are the correlations between ρ^*, ν^* and the fuelling profile

⇒ More cross-machine comparisons, high power wave heating and, ultimately, ITER

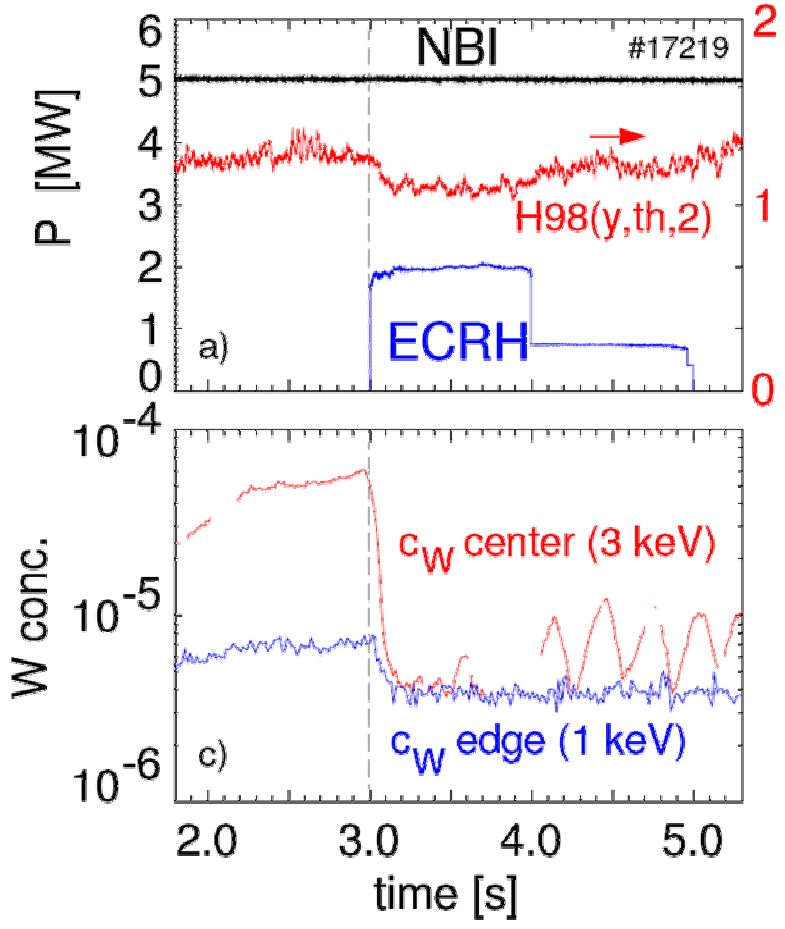


(Angioni, PRL **90** (2003) 205003; Weisen, NF **45** (2005) L1)

Density & Radiation Limits

- DEMO will have to operate with high Z PFCs and thus the tolerable density peaking is likely to be set by impurity accumulation
- This is already observed in some circumstances in AUG
- Impurity control can be re-established by applying central heating

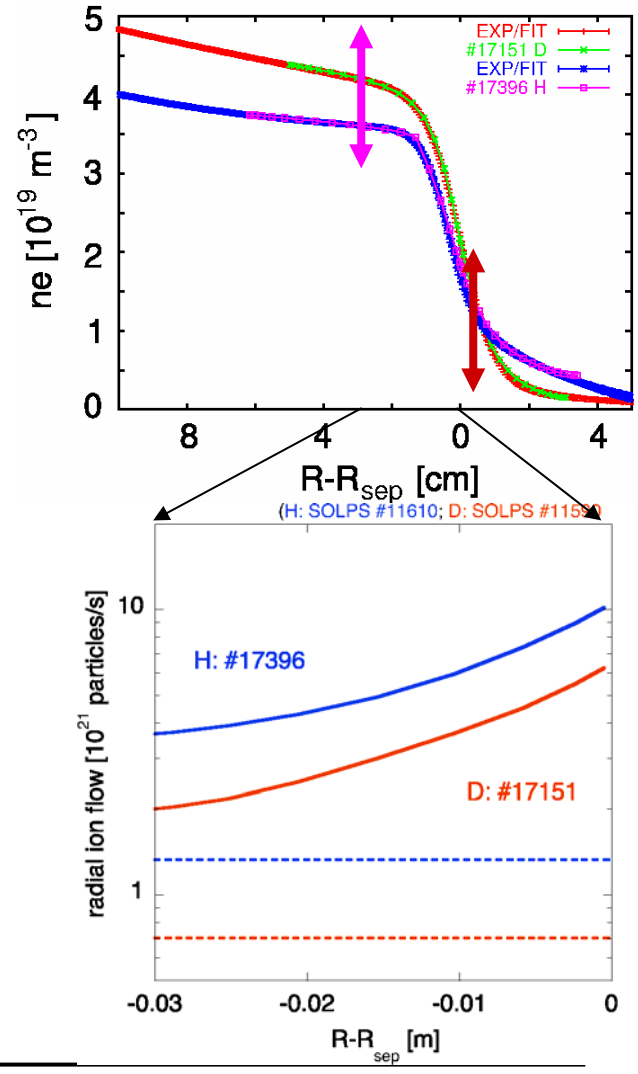
⇒ A high Z wall should be tested in ITER



(Neu et al., NF **45** (2005) 209)

Density & Radiation Limits

- One can only really address the complex interactions between confinement, density limits and divertor power loading in the frame of an integrated model
- Such modelling has highlighted an important link in the density limit model:
  - In present-day machines, edge thermal neutral fuelling is sufficient to strongly couple the separatrix and pedestal-top densities

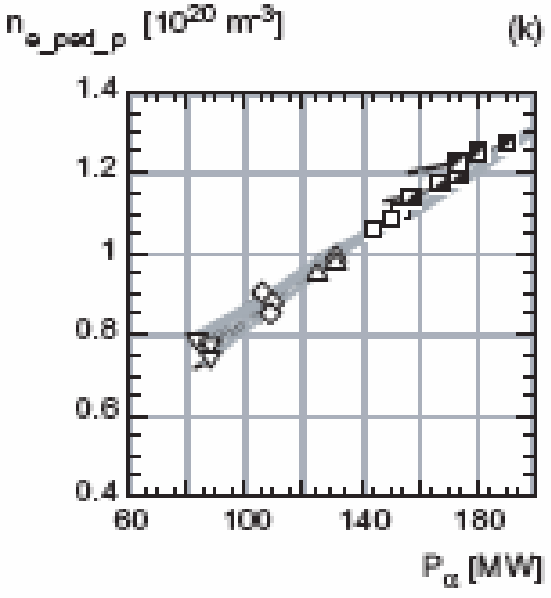


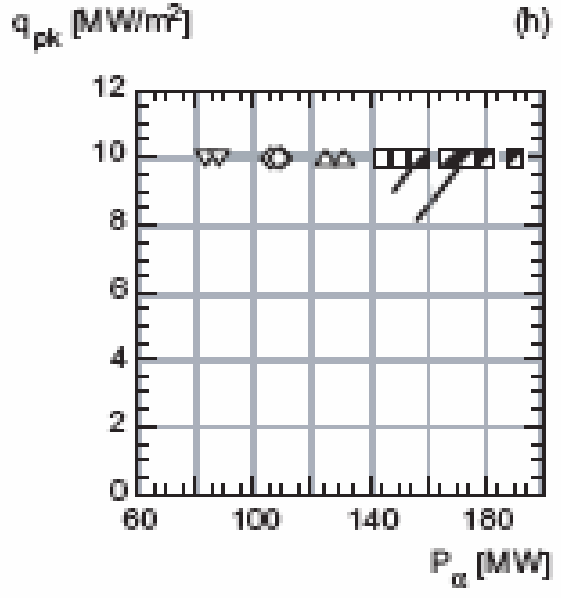
(Horton et al., NF **45** (2005) 856)

Density & Radiation Limits

- In DEMO (and in ITER), the increased machine size screens neutrals and the pedestal-top and separatrix densities are decoupled.
- It is then possible to separately optimise the core density for fusion performance and the separatrix density for divertor power load

⇒ Can we test this idea with pellets in JET at the highest currents?





(Janeschitz, 13th EFPW)

(G. Pacher, PPCF **46** (2004) A257)

Density & Radiation Limits: Issues

- We need to test the density limit and the separability of pedestal and separatrix densities in conditions of low thermal neutral penetration (high field in JET?)
- We need to systematically test the density limit in steady, pellet-fuelled conditions
- We need to determine the proper scaling of observed density peaking and thus its applicability to large machines
- We need to test the viability of high radiating power fractions in the regimes we propose to use in DEMO (hybrid & ITB) (confinement and confinement scaling)
- We need to perform an engineering assessment of the feasibility of exchanging the ITER first wall material
- We need to benchmark our integrated models more against existing machines, in particular against the new, higher resolution profile data which is now becoming available

Summary

- A main goal of the recently-launched EU DEMO studies is to identify and address the critical physics issues (today I have had time to discuss only four: beta limits, confinement, current drive efficiency and density limits.
- Priority research areas have been identified, with implications not only for the programmes of the present day machines but also for ITER.
- The results from this physics analysis, as well as from the newly launched tasks, are being fed back into the conceptual engineering design of DEMO. The goal is to establish a working dialogue between physicists and engineers.