EFDA
EUROPEAN FUSION DEVELOPMENT AGREEMENT

Max-Planck-Institut
für Plasmaphysik

IPP

# Critical Physics Issues for DEMO

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with thanks to the contributors to the EFDA
DEMO physics tasks in 2006 and to
D.J. Campbell, who organized this effort

# Background

- An effort has been launched in the EU to better define a demonstration reactor, with the goal of providing guidance to the reactor-oriented European fusion programme
- Both physics and technology studies are being undertaken
- On the physics side, tasks are being undertaken to better understand the key unresolved issues and to provide better input to the 0D systems code which is used to set the physics rules for the technology studies
- This is an iterative process and I will report today on the progress which has been made in 2006

# Background

- At last year's workshop, I reported on the critical physics issues for DEMO which were discussed in the 2005 European Fusion Physics Workshop: beta limits, confinement, current drive efficiency and density limits
- These areas formed the basis for the tasks executed in 2006

# Initial Systems Studies

(J. Johner / D. Ward)

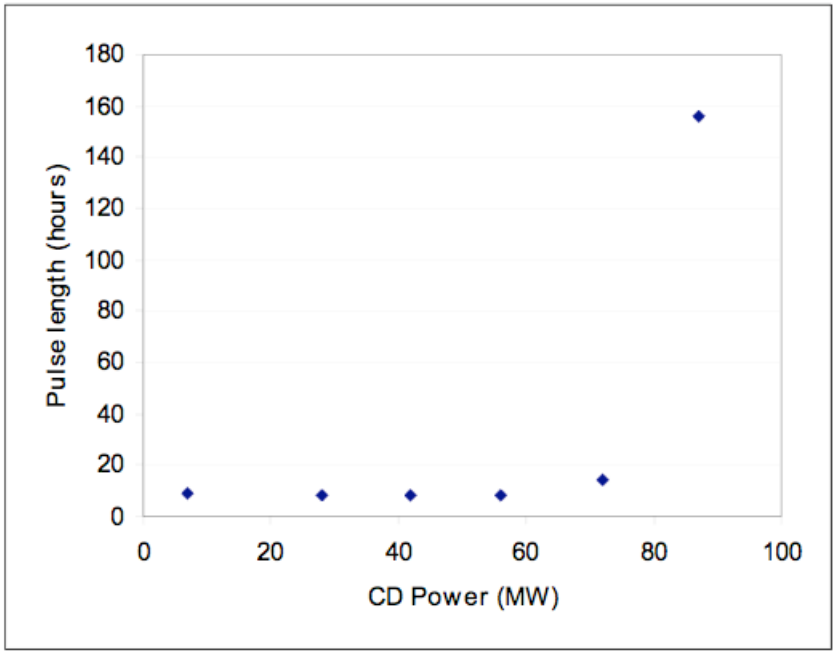
- An important aspect of the physics studies is a comparison and benchmarking of different codes (more later)
- Comparisons of the (0D) predictions for PPCS and DEMO have been made between the PROCESS and HELIOS codes, resulting in improvements to the model in PROCESS:
  - Credit is now taken for a more realistic (higher Z) impurity mix
  - A more general model for the fast ion content is now implemented
- A main goal of the present work is further improvement based on results of 1D modelling

| | **Low Z** | **High Z** |
|---|---|---|
| B [T] | 6.8 | 5.5 |
| I [MA] | 27.5 | 22.4 |
| $Z_{eff}$ | 2.7 | 2.7 |
| ne [$10^{20}$ $m^{-3}$] | 1.20 | 0.97 |
| $P_{add}$ [MW] | 250 | 167 |
| Div. Load [$MW/m^2$] | 10 | 10 |

# Initial Systems Studies: Pulsed vs. SS

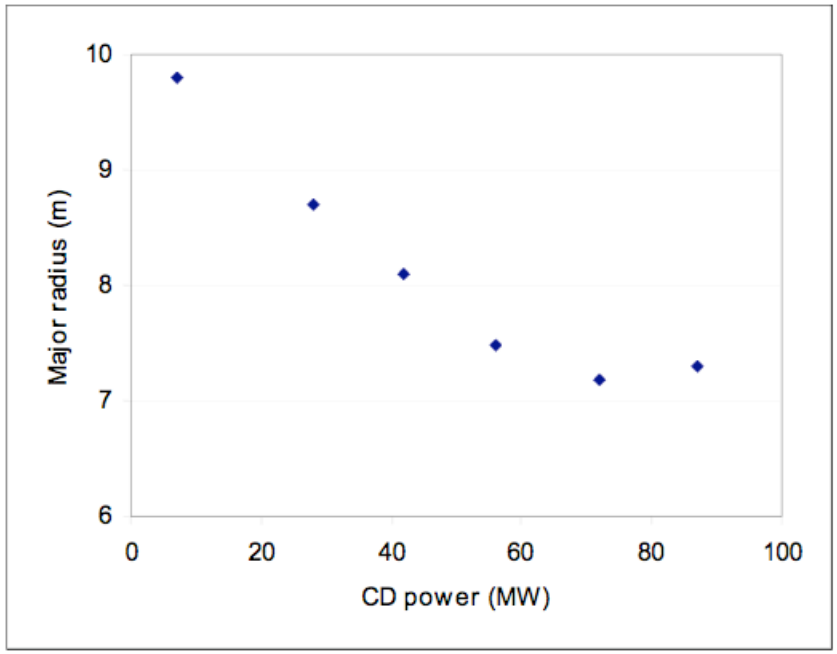
(D. Ward)

- Following discussion in the DEMO Working Group and at the EFPW, it was agreed to re-visit the issue of pulsed vs. steady-state operation *with the same physics assumptions*
- "Hybrid-like" performance parameters
- Start with an optimised pulsed machine (R=9.55 m, A=4, Ip=15.5 MA) and add CD power (holding A and pulse duration (>= 8 hr) constant)
- 90 MW of CD power is sufficient to drive the system to steady-state



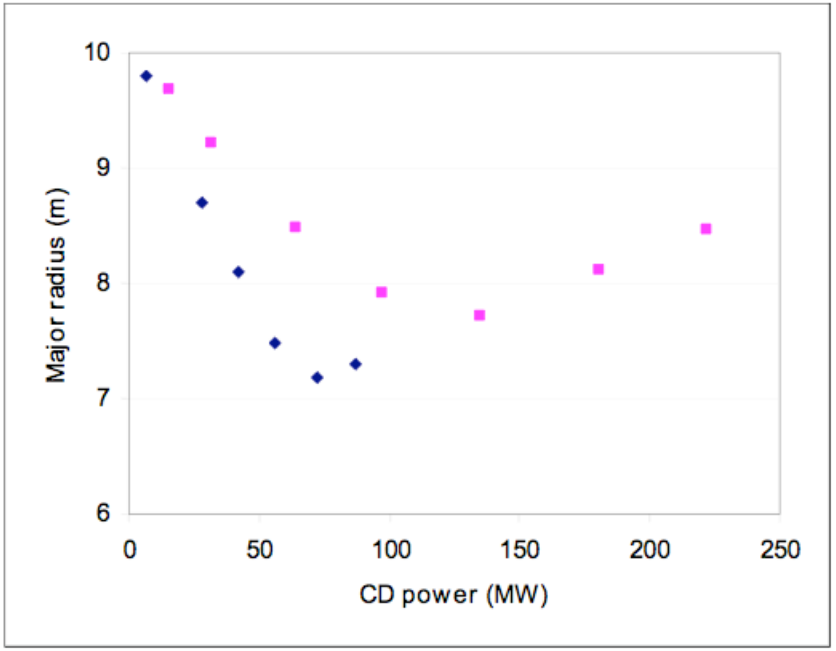
# Initial Systems Studies: Pulsed vs. SS

- Adding CD significantly reduces the size of the device and thus its cost, even when accounting for the extra cost of the CD system
- The solution becomes more like an optimised steady-state machine (albeit at A=4) in that divertor power load limits become a crucial ingredient in the optimisation



# Initial Systems Studies: Pulsed vs. SS

- Reducing the assumed CD efficiency by a factor of 5 (relative to the Mikkelsen & Singer prescription for NBI) only shifts the optimum to 75% CD
- Accounting for issues such as cyclic loading and energy storage seems very likely to shift the balance to a full steady-state machine, even for these very pessimistic assumptions



# Initial Systems Studies

- As a first step in the iterative process, a DEMO based on PPCS Model C technology & hybrid-like physics assumptions was generated using the PROCESS systems code
  - Compromise between sufficient extrapolation to clearly demonstrate the areas requiring advances and sufficient realism to connect to the present knowledge base and to match the envisaged time scale (final design and start of construction in parallel to ITER technology phase)
  - Giving some weight to capital cost restrictions for a demonstration plant (as opposed to pure CoE for a power plant), 1 GWe chosen as reference

# Initial Systems Studies

(D. Ward)

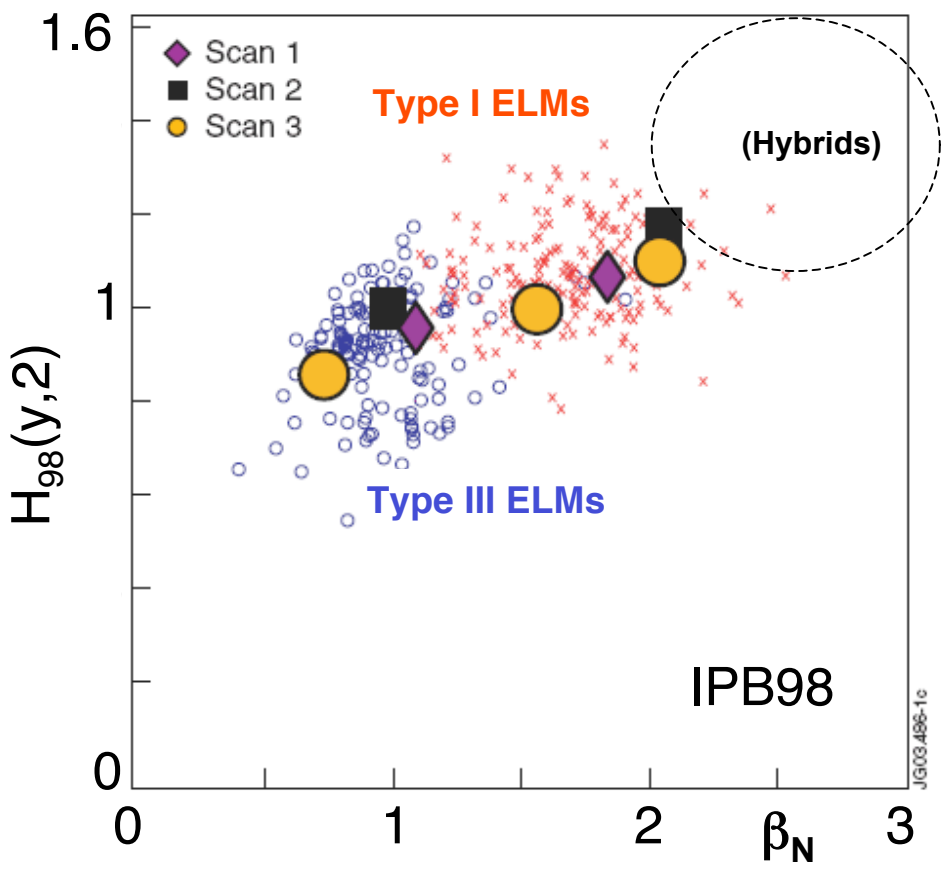
| Parameter | DEMO-C | Model C |
|---|---|---|
| Unit Size [$GW_e$] | 1.0 | 1.5 |
| Fusion Power [GW] | 2.55 | 3.45 |
| Major Radius [m] | 7.5 | 7.5 |
| TF on axis [T] | 6.1 | 6.05 |
| Plasma Current [MA] | 17.6 | 18.6 |
| $\beta_N$ (thermal) | 3.0 | 3.6 |
| $H_H$ (IPB98y2) | 1.28 | 1.3 |
| $P_{add}$ [MW] | 137 | 100 |
| Divertor Peak Load [$MW/m^2$] | 10 | 10 |

# Confinement & Modelling

- Operation in the so-called improved H-mode regime or hybrid mode of operation exceeds the standard scaling and is already close to the confinement assumed for DEMO

⇒This regime should be considered in the DEMO physics studies

(G. Sips, 13th EFPW)

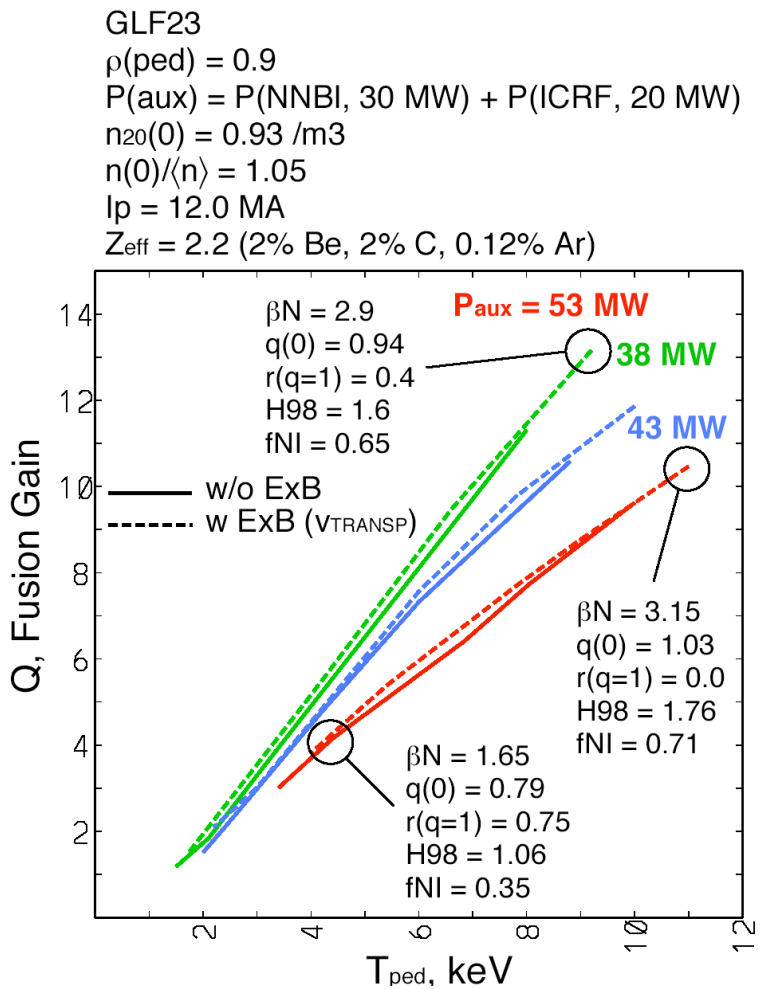



(D. McDonald, PPCF **46** (2004) A215)

# 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)

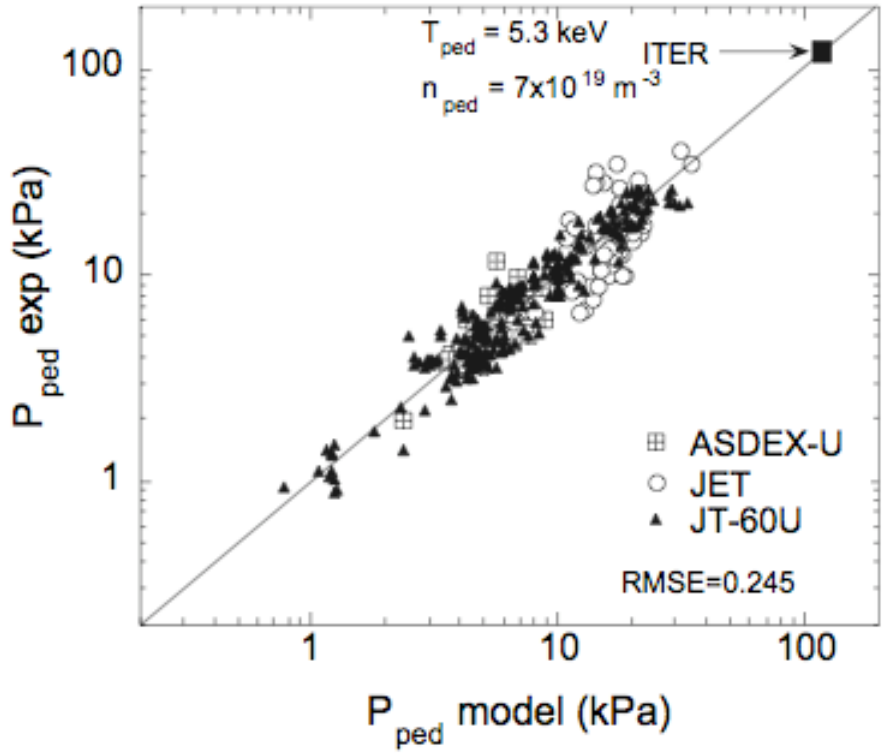



(C. Kessel, SSO ITPA meeting,Nov. 2005)

# Confinement & Modelling

- Scaling of the pedestal-top pressure to DEMO is very uncertain:
  - The measurements are difficult
  - We lack a fundamental model for transport barriers
- Here, an example which fits to AUG JET & JT-60U but not to DIII-D & C-mod
- BUT: 'Identity' experiments indicate that DIII-D pedestal-top pressure does match that of JET & AUG while JT-60U doesn't!

⇒ ITER results are again crucial

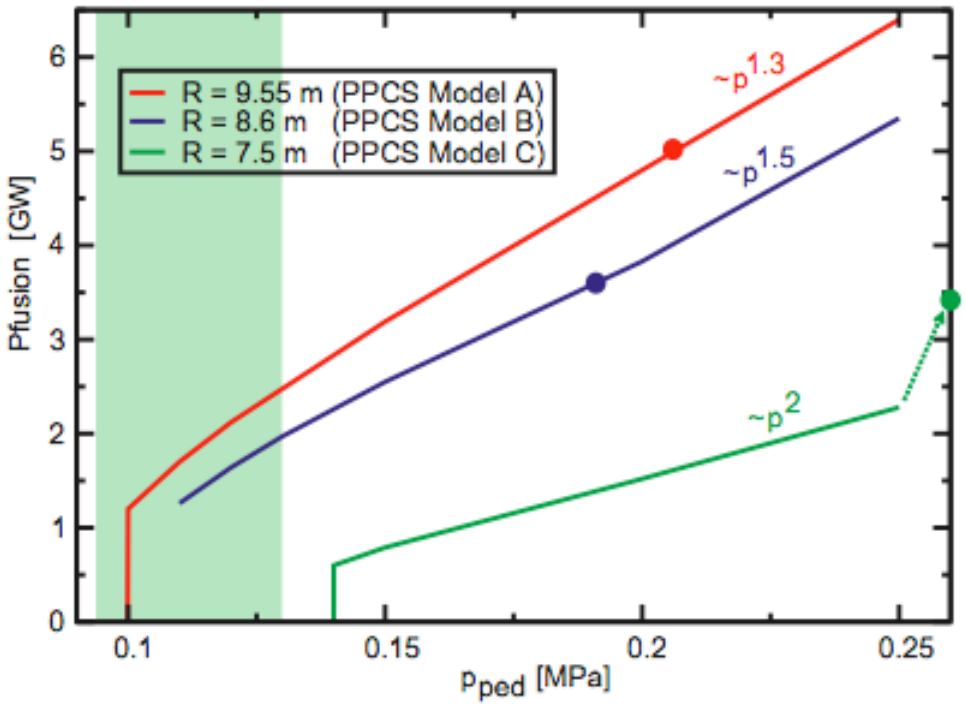



(M. Sugihara, PPCF **45** (2003) L55

# Confinement & Modelling

- The GLF23 theory-based transport model has now also been applied to DEMO
- For pulsed scenarios based on PPCS Models A&B, the required pedestal-top pressure is ~2x that predicted by the extrapolation of present results

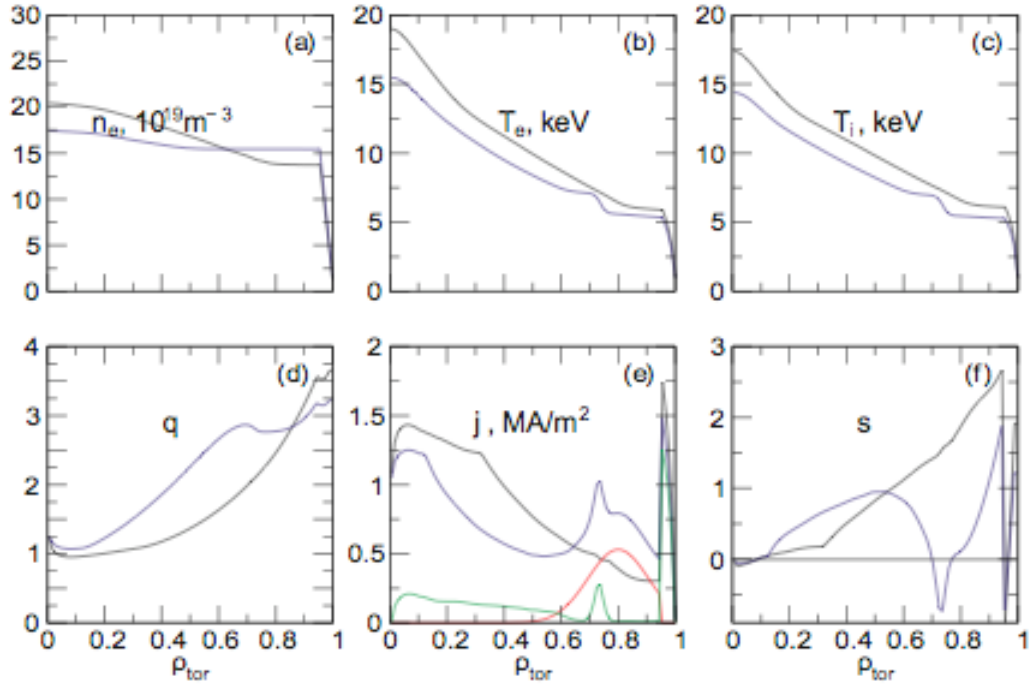
⇒ Such regimes are 'hardly compatible' with DEMO performance goals




(K. Lackner & G. Pereverzev)

# Confinement & Modelling

- The situation is improved if one avoids the profile stiffness by including an internal transport barrier (ITB) in the model
- In the standard theory-based model, this is done by driven off-axis current sufficient to generate a region of negative shear

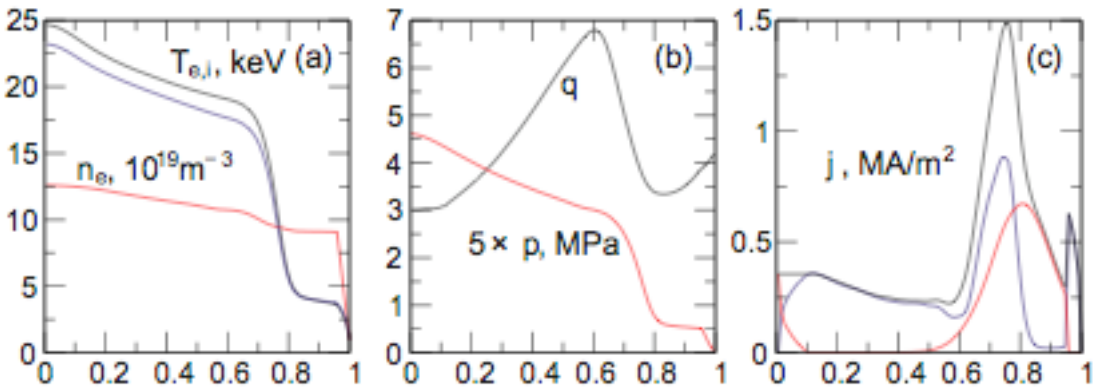


# Confinement & Modelling

- It is possible to achieve such profiles in a stationary state using a feedback control algorithm based on an external loop voltage signal
- Here the pedestal-top pressure is assumed to be 100 kPa

⇒ These regimes are difficult to produce in existing machines due to the high requirements on central power and off-axis current drive

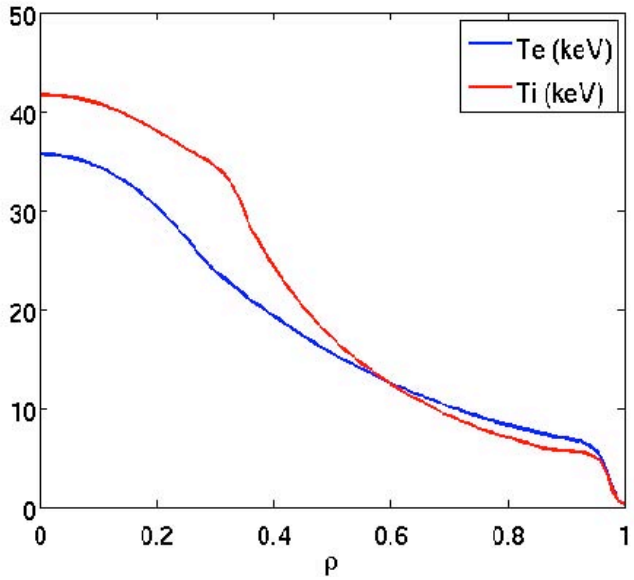
⇒ Stability of such regimes is an issue (see below)

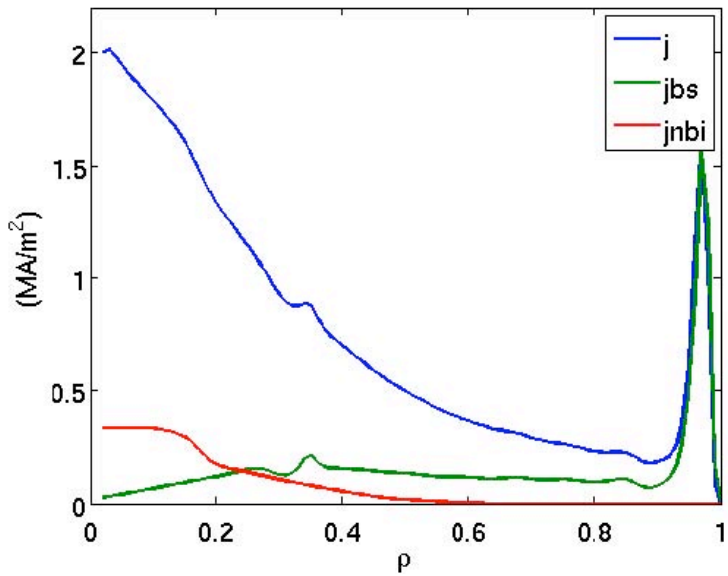



(K. Lackner & G. Pereverzev)

# Current Drive

- A full assessment of the feasibility of advanced regimes of operation requires good models for current drive
- Modelling of an advanced regime in DEMO with only on-axis neutral beam current drive does not result in an ITB nor in a steady-state scenario (inductive current drive is required)



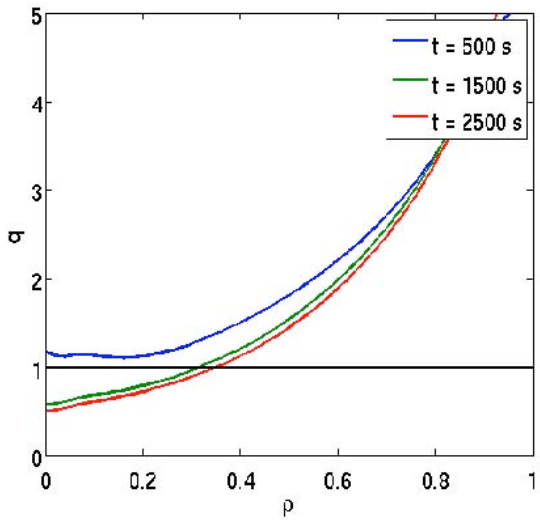

(G. Giruzzi et al.)

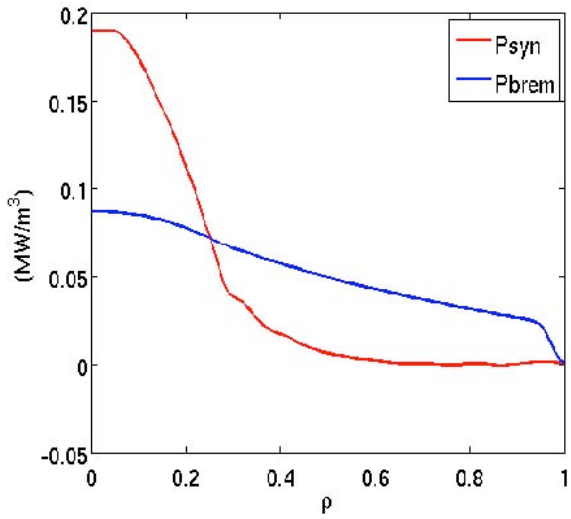
# Current Drive

- The current profile relaxes so that $q_0<1$; sawtooth instabilities then degrade the core confinement

⇒ Off-axis current drive is required to hold $q_0>1$, the candidates being neutral beam current drive and lower hybrid current drive

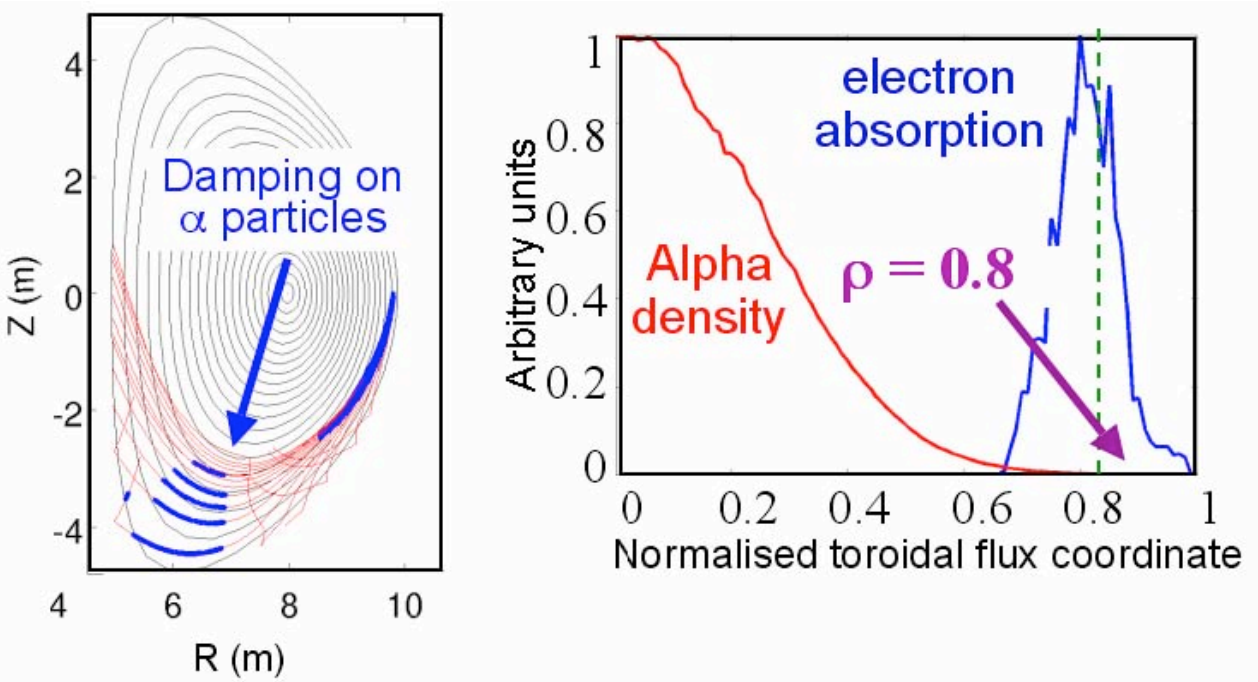
- An improved synchrotron radiation model has been incorporated and is important also for the core power balance



# Current Drive: LHCD

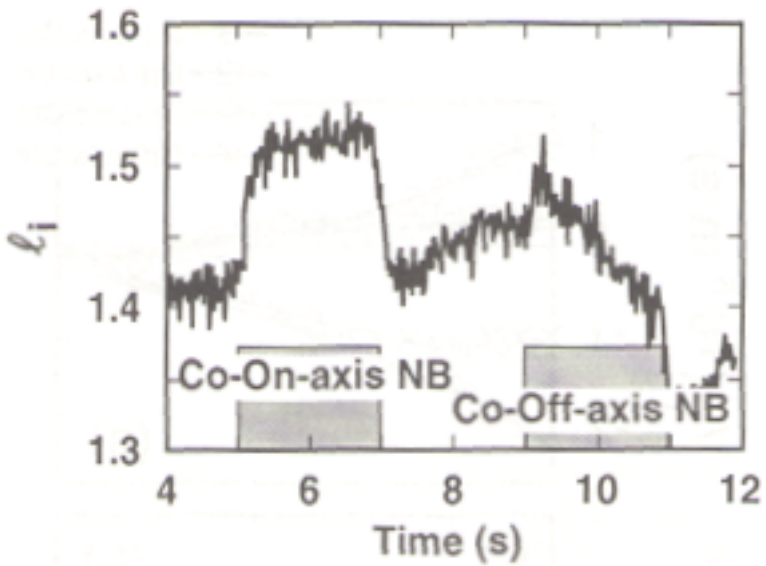
- Lower hybrid current drive is possible if the wave frequency is chosen high enough for the absorption of the wave by alpha particles to be negligible
- Calculations show that 5 GHz, the frequency planned for ITER, should also suffice for DEMO

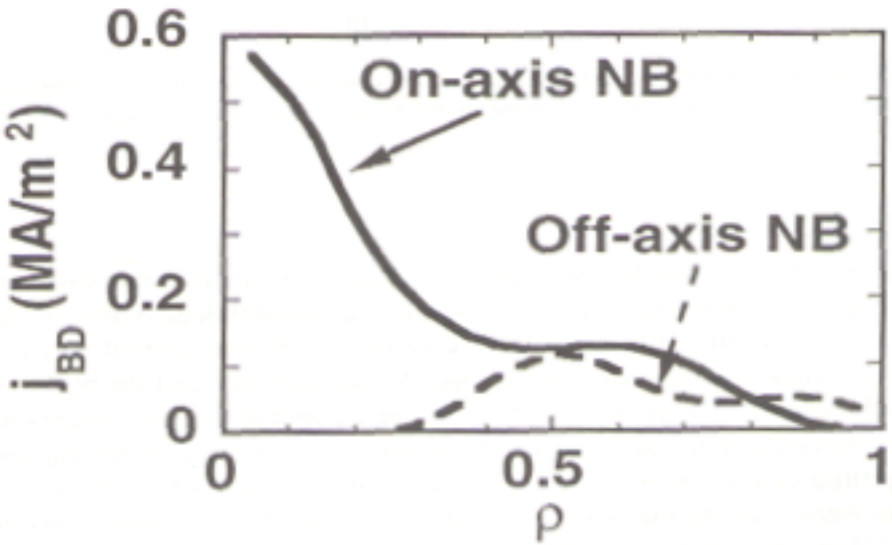


# Current Drive: NBI

(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



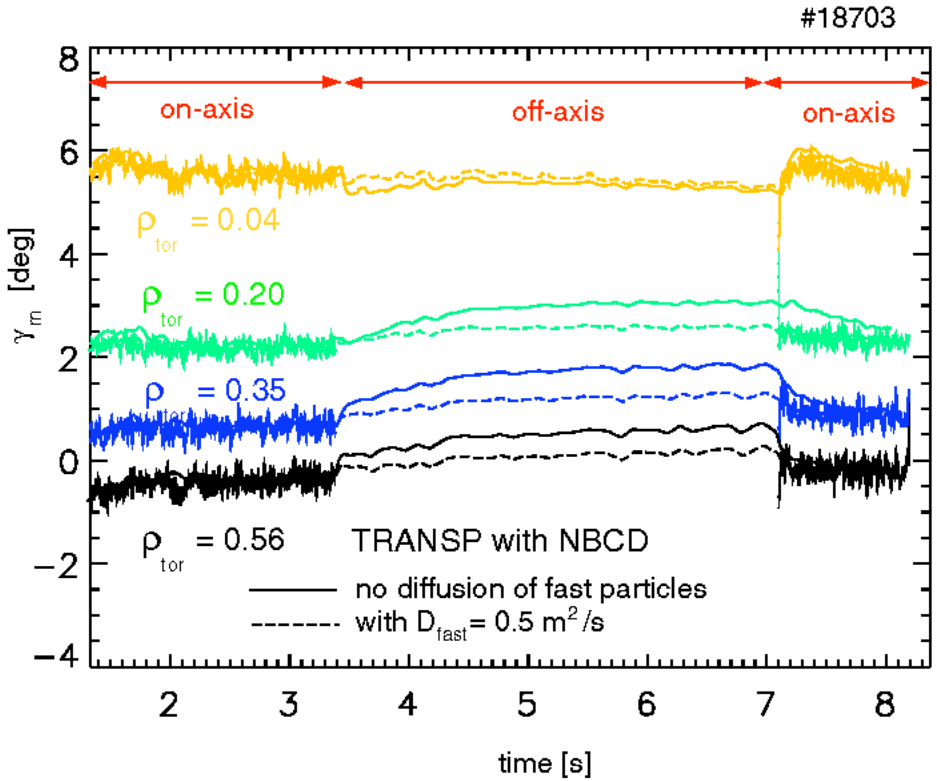

(S. Ide, IAEA (1994))

# 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

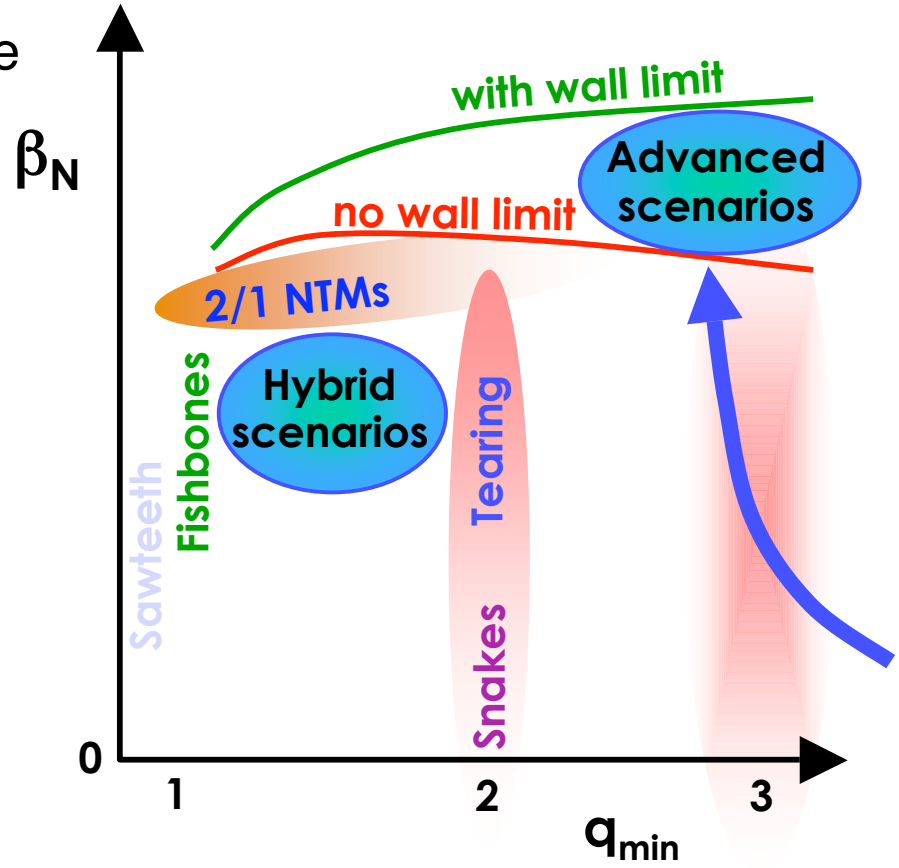
⇒ Priority to determine how generally this applies (and why)



# Beta limit

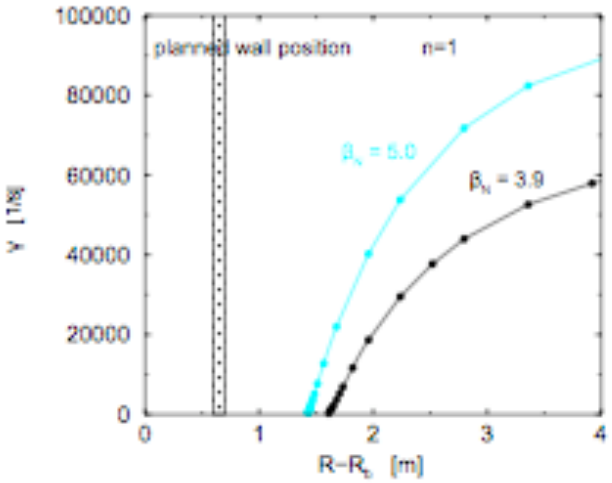
- Two high β regimes being considered:
  - 'Advanced' regimes which require strong current profile control and wall stability of ideal MHD but which hold out the hope of steady-state operation
  - Improved H-mode or 'Hybrid' regimes which require less current profile control and are limited by NTMs but which would require more external current drive to reach steady-state

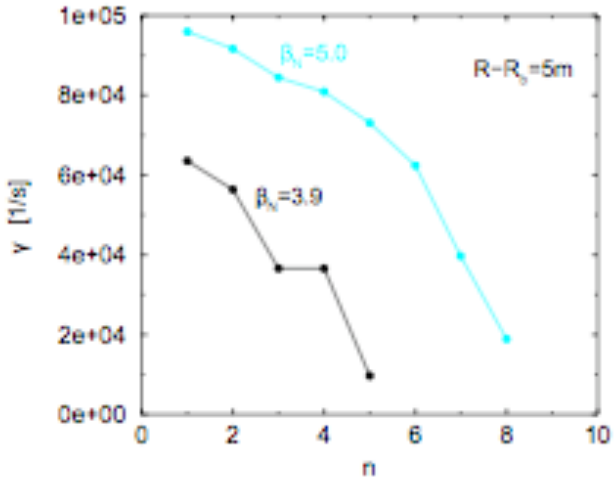
(R. Buttery, 13th EFPW)



# Beta limit

- Profiles are being tested for low-n stability in DEMO, based on the hypothesis that it is possible to place a conducting wall ~0.6 m from the plasma
- As a benchmark, profiles from the ARIES-AT study (C.E. Kessel, Fusion Eng. & Des. **80** (2006) 63) were tested and the high beta limit confirmed

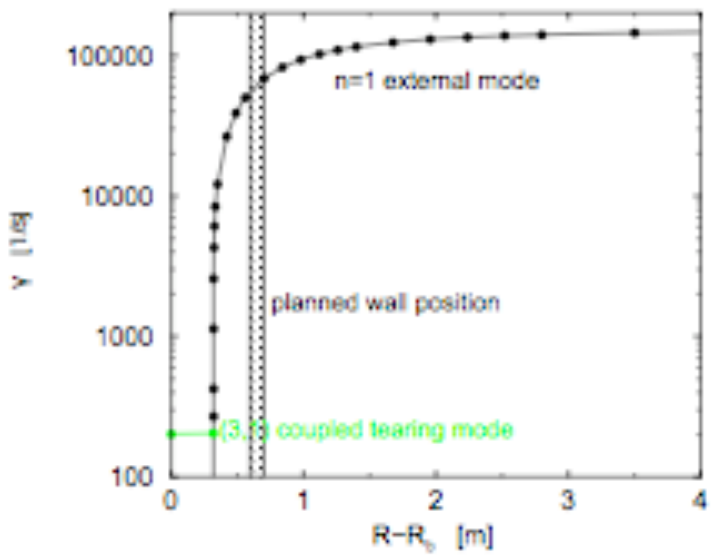


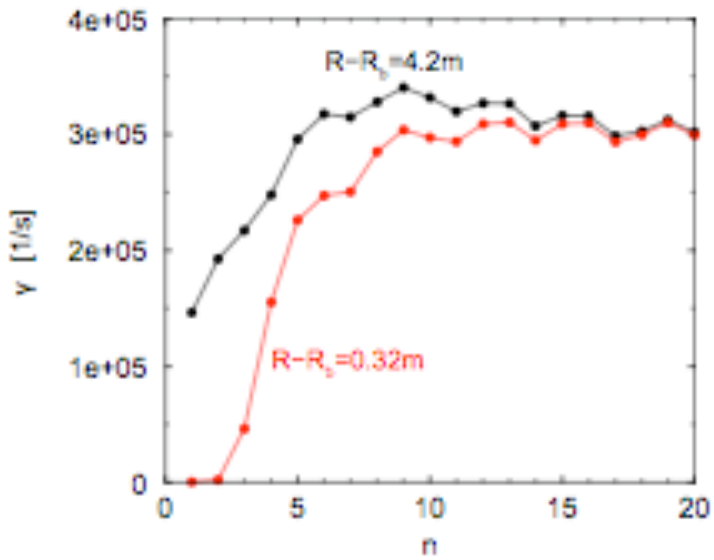




(E. Strumberger)

# Beta limit

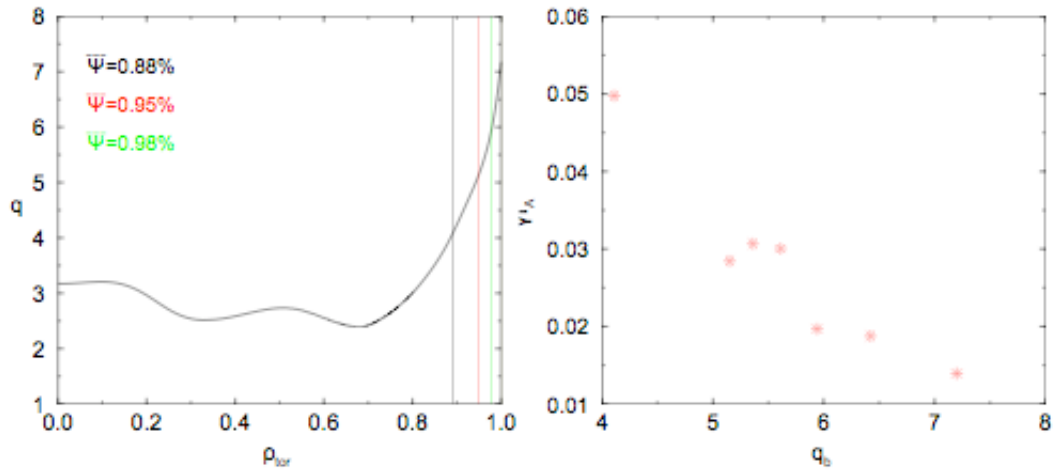
- The big question, of course, is whether or not one can generate high beta profiles which are consistent with transport models
- Here, the first iteration (at $\beta_N$=1.55) is unfavourable due to the large edge pressure gradient
- Note that resistive MHD can also be important!



# Beta limit

- In the course of this work, an important issue with these ideal MHD stability calculations was highlighted:
  - The codes can't deal with X-point geometries and the plasma must be truncated
  - This is crucial for external kink modes which rely on resonance with rational surfaces outside the (ideal) plasma

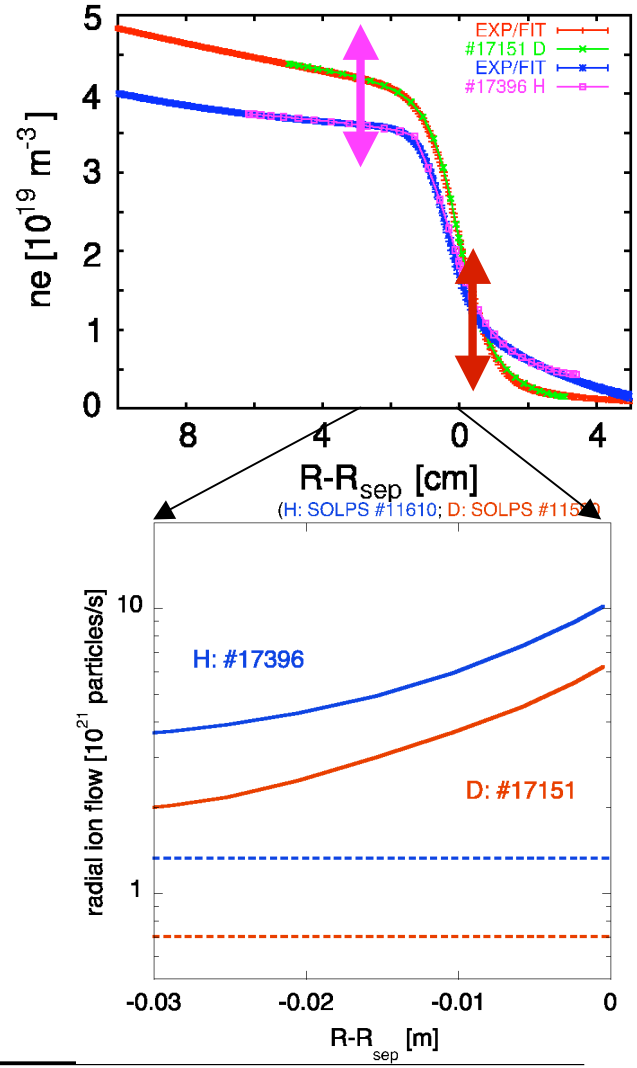


# Beta limit

- Two solutions are being considered:
  - Switching from ideal to resistive MHD: the transition from ideal (infinitely conducting) plasma to vacuum is then naturally made by the restive layer at the plasma edge
  - Cutting the plasma at the position corresponding to the skin depth of the resistive wall (when there is one)
- Tests of these ideas are subjects of the new (2007) tasks

# 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

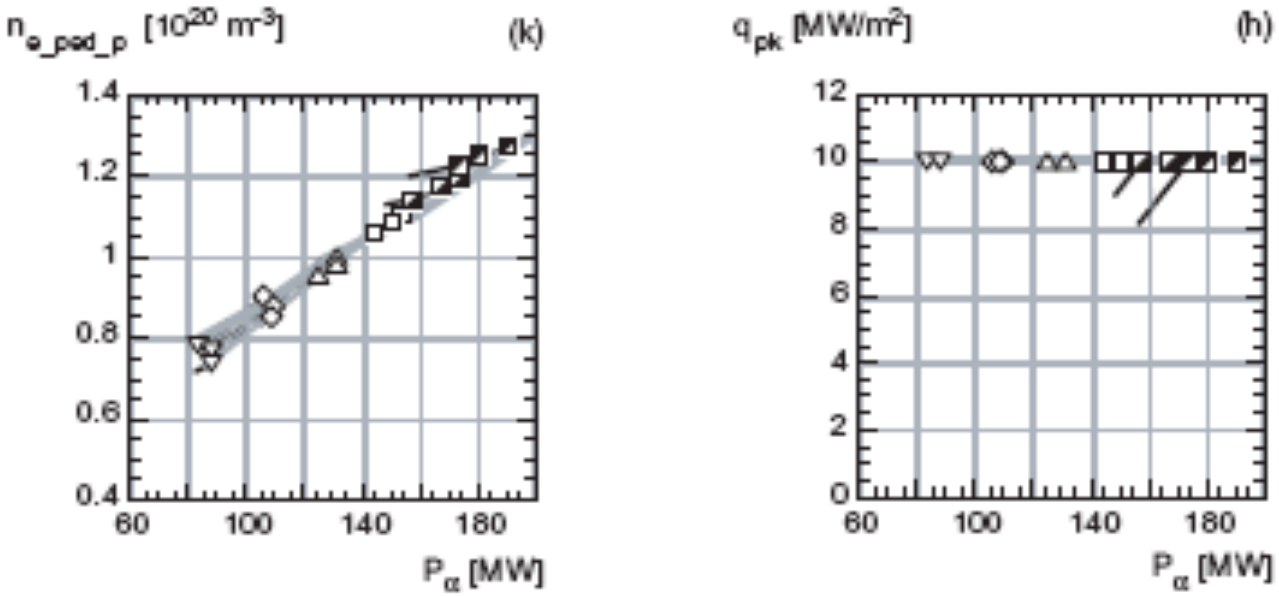



(Horton et al., NF **45** (2005) 856)

# Density & Radiation Limits

- In ITER (and DEMO), 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

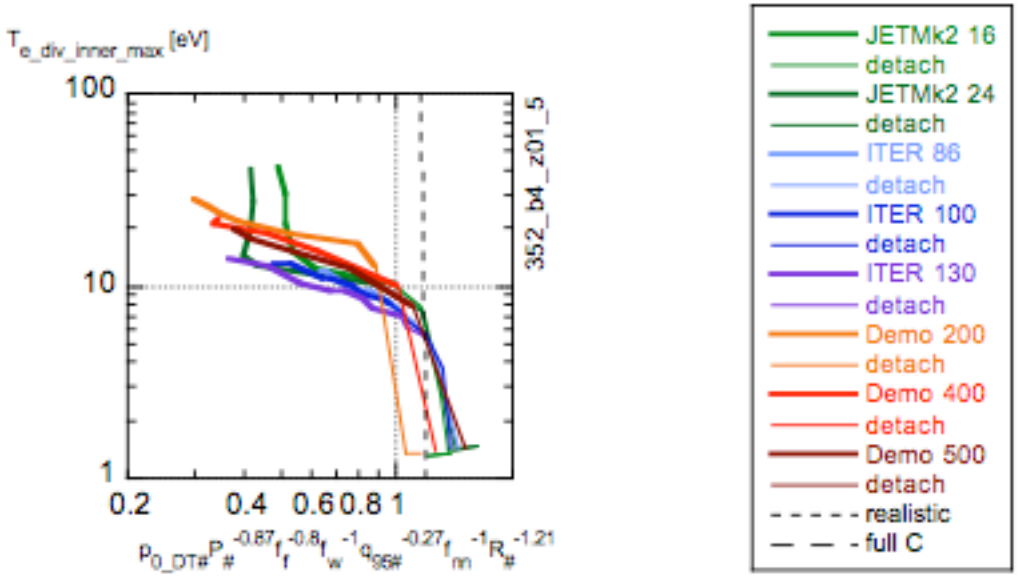
⇒ Can we test this idea with pellets in JET at the highest currents?




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

# Density & Radiation Limits

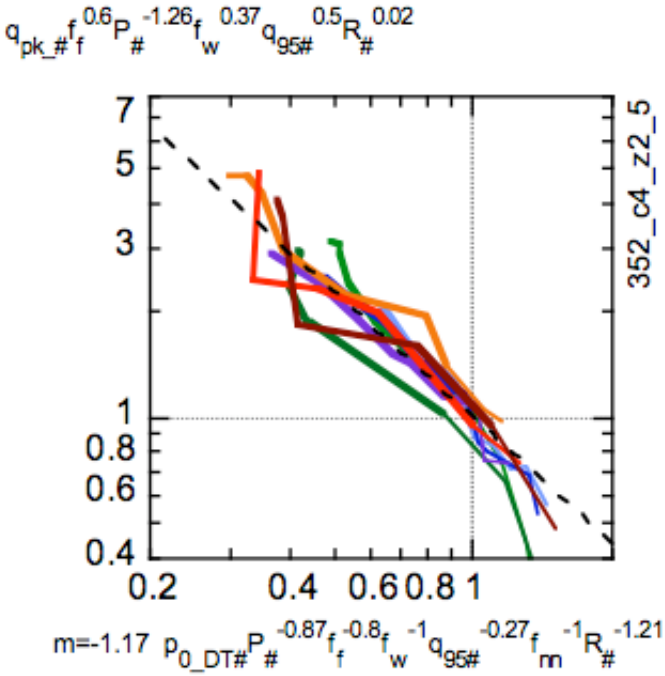
- Parametrising the edge detachment limit requires computationally intensive scans of the 2D edge code.
- With appropriate parameter normalisation, it is possible to the ITER results for DEMO - this is because ITER is already in the regime of little direct neutral fuelling

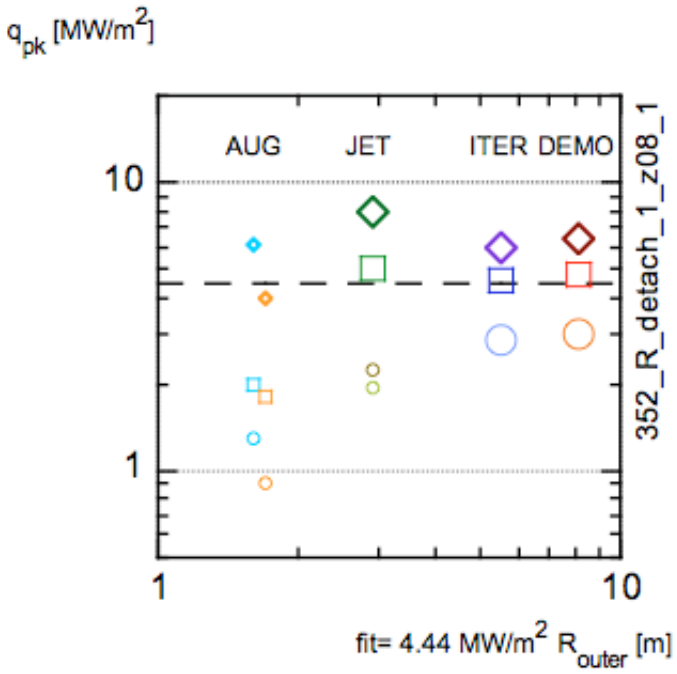



(G. Janeschitz)

# Density & Radiation Limits

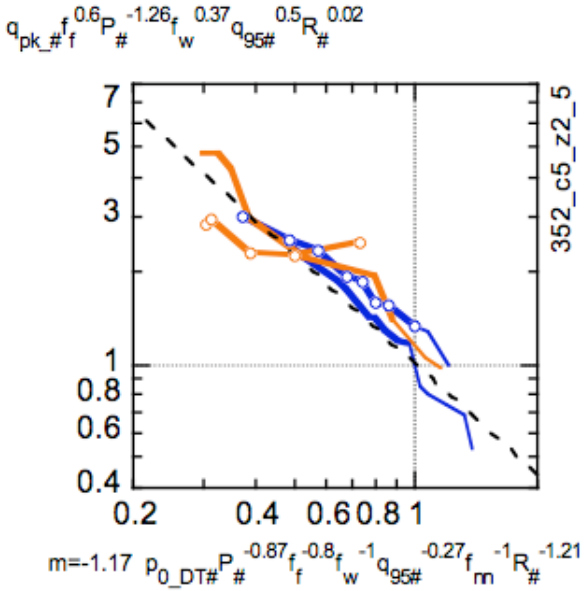
- The peak power to the divertor target at the onset of divertor detachment (taken as the highest SOL density compatible with high core confinement) scales as well
- The absolute values remain in the technologically acceptable range

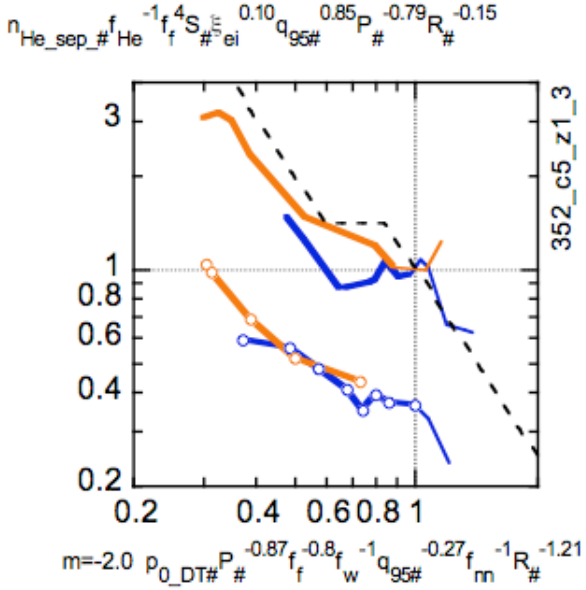


# Density & Radiation Limits

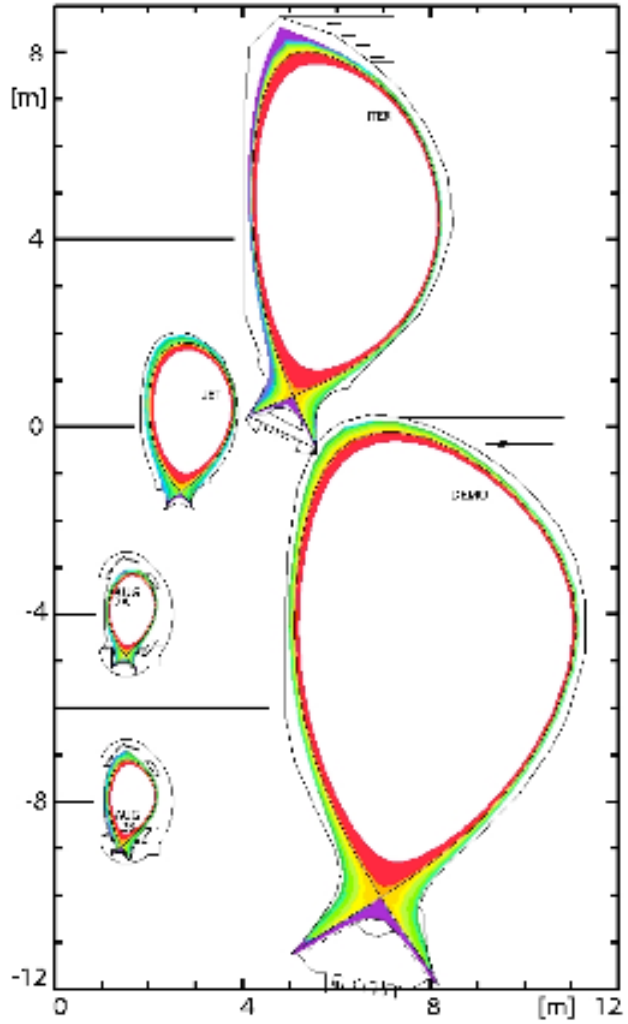
- Since the time of the scaling studies for ITER, progress has been made in the physics included in the 2D modelling, e.g. neutral-neutral collisions & molecular dynamics, including molecular-assisted recombination and molecule-ion elastic collisions
- Initial simulations show this additional physics is helpful, e.g. higher He exhaust, at similar divertor power loads



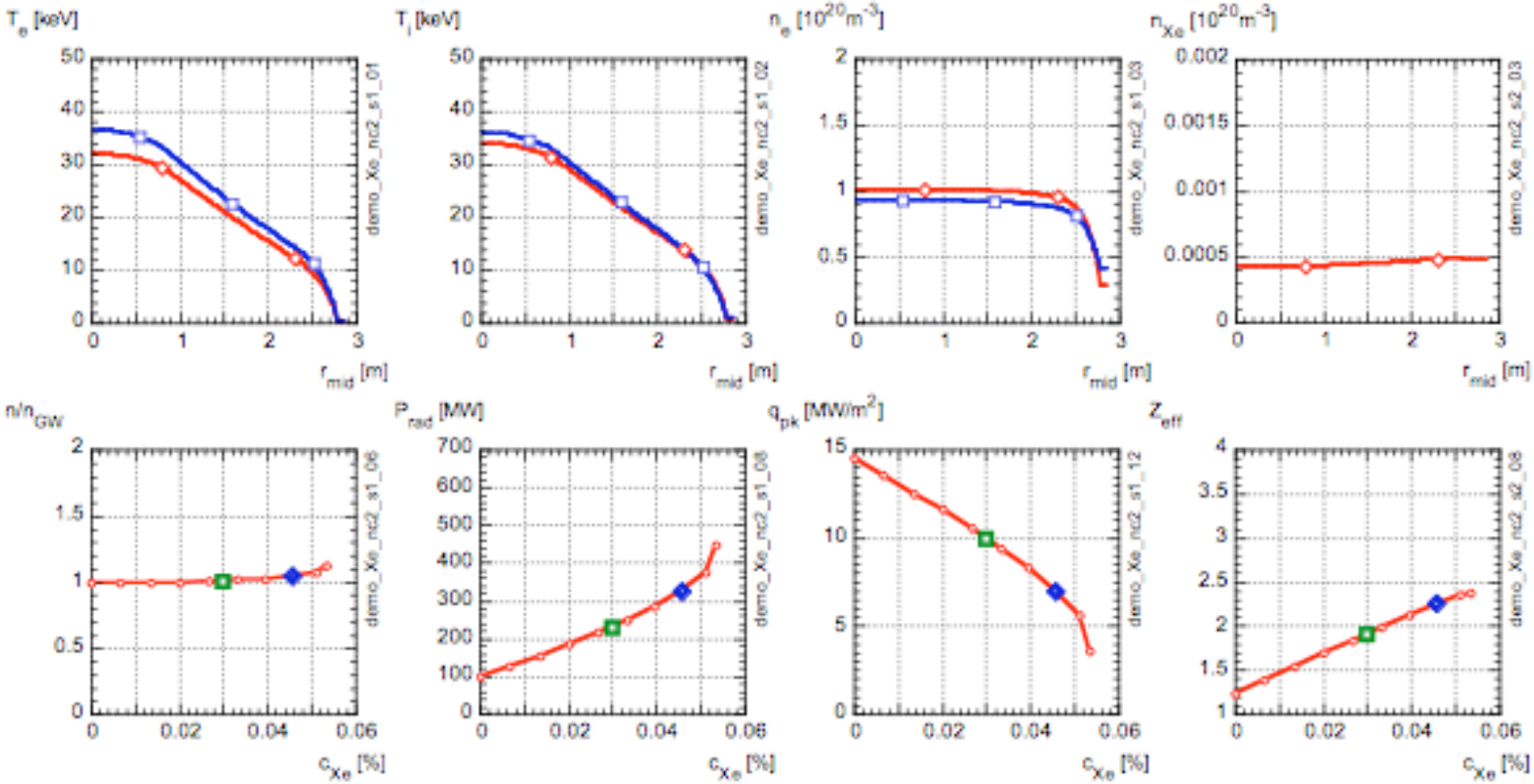



# Density & Radiation Limits

- One can use the 2D parameter scan as boundary conditions for a 1D core model and thus study the coupling between core and edge
- With the core transport model chosen in this study, DEMO solutions are found which are near ignition (Q~150) over the entire range of transport assumptions considered
- No internal transport barrier is required



# Density & Radiation Limits



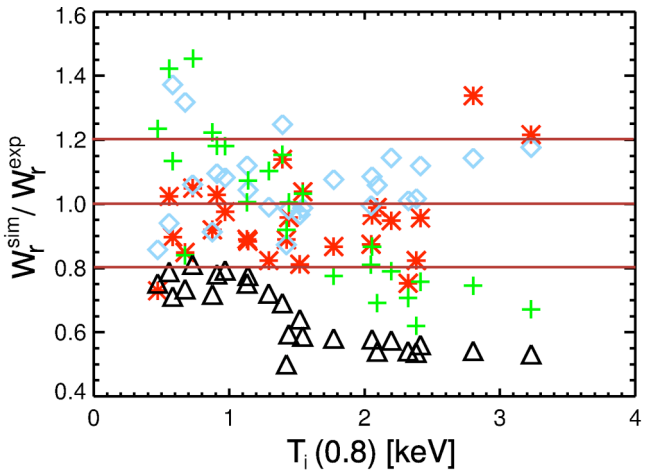
# Core confinement

- The difference in the predictions is in the confinement models being used
- It is generally agreed that the transport across the core plasma can be explained by drift wave turbulence
- To be tractable, even in 1D transport codes, the fundamental turbulence calculations must be parametrised
- Depending on how this is done, different physics is captured in the models and their range of applicability may vary

⇒ Extrapolation is dangerous!

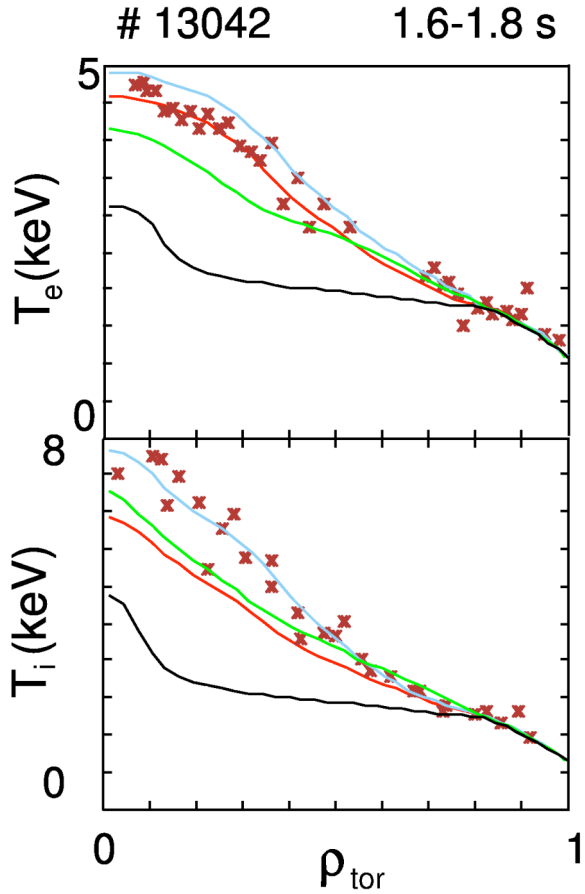
# Core confinement

- I'll take AUG as an example:
- Energy confinement is well reproduced in steady-state plasmas with no internal transport barrier (when the edge barrier is specified)
- The less stiff Weiland model is better (for this dataset)




**CDBM** GLF23 IFS/PPPL Weiland

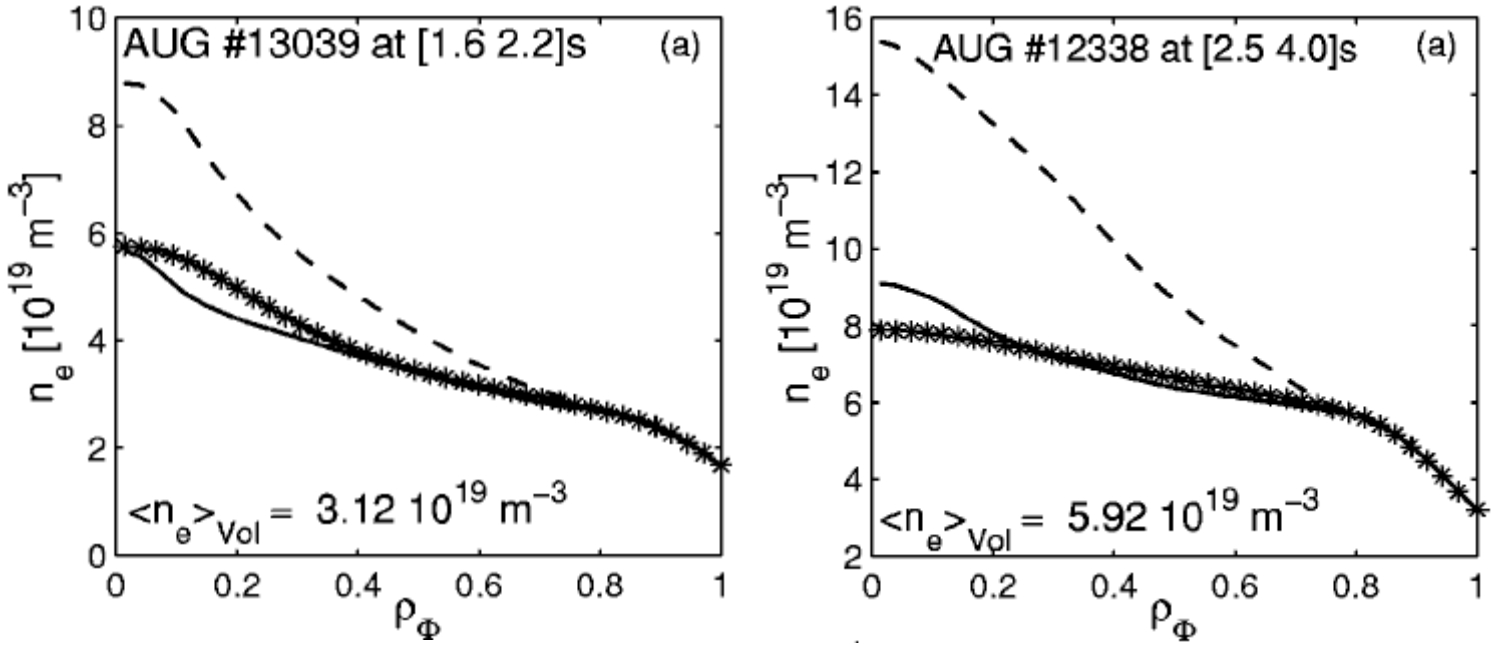
σ = 0.144 σ = 0.137
σ = 0.228 σ = 0.366




(G. Tardini, NF **42** (2002) 258)

# Core confinement

- Same dataset:
- Particle confinement, in particular density peaking, is best fit with the GLF23 model (solid curves) - the Weiland model (dashed curves) doesn't include the necessary collisional physics




(C. Angioni, PoP **10** (2003) 3225)

# Core confinement

- To date, the different modellers have dealt with this situation with different prescriptions: some use GLF23, some Weiland with an ad hoc correction to the particle transport

⇒ Further benchmarking is necessary (and is underway under the auspices of the ITPA)

⇒ Note that the situation with transport barrier (internal and external) is even more challenging

# Updated Systems Studies

- Following the physics studies and further discussion in the DEMO Working Group, a set of provisional parameters has been defined as a starting point of the technology tasks which have now begun
- PPCS Model AB technology (He-cooled lithium lead blanket, He-cooled divertor) and hybrid physics was assumed
- Note that these numbers are already being revised due to changes in the inboard build to reflect neutron shielding issues

| Parameter | DEMO Provisional Parameters |
|---|---|
| Unit Size [$GW_e$] | 1.0 |
| Fusion Power [GW] | 2.4 |
| Major Radius [m] | 7.5 |
| TF on axis [T] | 6.2 |
| Plasma Current [MA] | 17.0 |
| $\beta_N$ (thermal, total) | 3.0, 3.6 |
| $H_H$ (IPB98y2) | 1.3 |
| $P_{add}$ [MW] | 134+40 |
| Divertor Peak Load [$MW/m^2$] | 10 |

(D. Ward)

# Summary

- A main goal of the EU DEMO studies is to identify and address the critical physics issues: confinement, current drive efficiency, beta limits and density limits.
- Key issues in the new physics tasks are:
  - Reactor fusion performance, in particular of the hybrid scenario;
  - Analysis of current drive efficiency and its implications for current profile control;
  - Development of an improved radiation model;
  - Improved MHD stability analysis using a more realistic treatment of the plasma edge-vacuum transition.

# Summary

- In addition, items have been identified which must be addressed in the fusion programme more generally and in ITER:
  - Develop a physics-based model for transport barriers;
  - Demonstrate stable operation with an internal transport barrier and at high beta;
  - Demonstrate high (off-axis) current drive efficiency in DEMO-relevant (high Te) conditions;
  - Demonstrate reliable operation above the no-wall stability limit;
  - Demonstrate separate control of the pedestal-top and the separatrix density in conditions of low fuelling from recycling neutrals;

# Summary

- The results from this physics analysis are being fed back into the conceptual engineering design of DEMO. The goal is to establish a working dialogue between physicists and engineers.
- Rather than trying to develop a definitive picture of DEMO, the goal is to identify key issues as input when setting priorities in the EU fusion research programme.