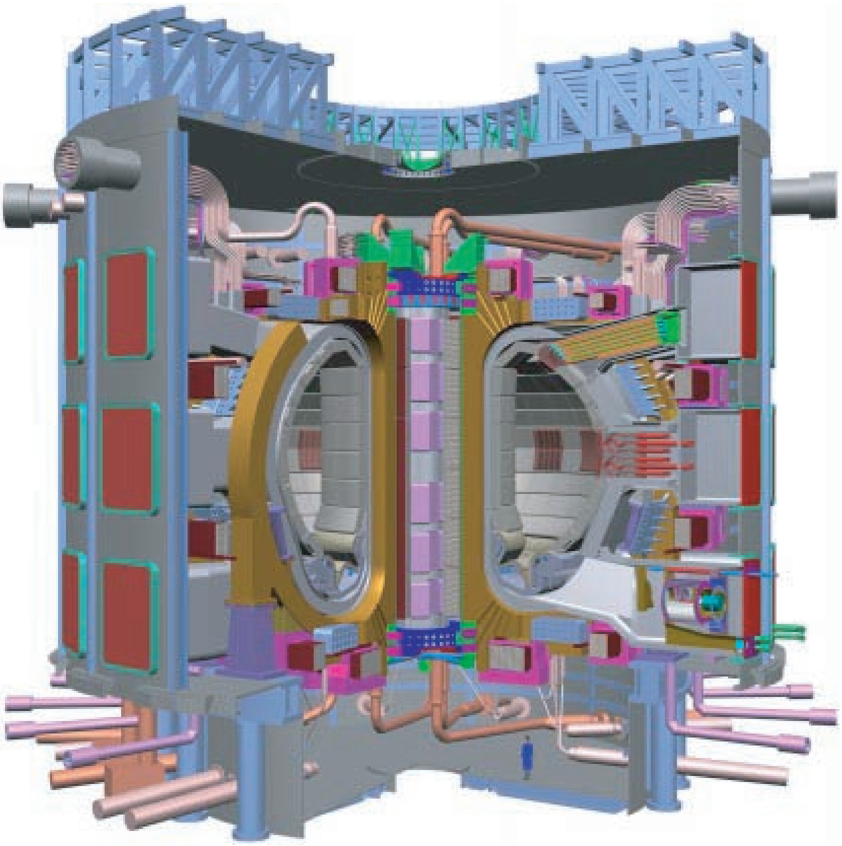


THE PHYSICS OF ITER-FEAT

presented by **D J Campbell**

EFDA, Close Support Unit - Garching

Acknowledgements:

Members of the ITER Joint Central Team
and Home Teams

42nd APS-DPP/ ICPP-2000, Québec City, 23-27 October 2000

Synopsis

- **ITER-FEAT Goals**
- **Physics design rules for ITER**
- **New ITER design**
- **Performance predictions:**
  - operating space for inductive operation
  - requirements for steady-state operation
- **Design basis and physics issues:**
  - Confinement and transport
  - MHD stability and control
  - Divertor performance
  - Alpha-particle physics
- **Conclusions**

ITER-FEAT Goals

Plasma Performance

- achieve extended burn in inductively driven plasmas with the ratio of fusion power to auxiliary heating power of at least 10:
    - for a range of operating scenarios
    - with a duration sufficient to achieve stationary conditions on the time scales characteristic of plasma processes.
- aim at demonstrating steady-state operation using non-inductive current drive with the ratio of fusion to current drive power of at least 5
- the possibility of controlled ignition should not be precluded

Technology

- demonstration of integrated operation of technologies essential for a fusion reactor
- testing of components for a fusion reactor
- testing of concepts for a tritium breeding module

Physics Design Rules

Confinement

- IPB98(y,2) ITER Physics Basis energy confinement scaling (variations of scaling have also been investigated):

$$\tau_{E,th}^{ELMy} = 0.144 \times I^{0.93} B^{0.15} P^{-0.69} n_{e,20}^{0.41} M^{0.19} R^{1.97} \varepsilon^{0.58} \kappa_{eff}^{0.78}$$

- H-mode threshold scaling with isotope correction:

$$P_{thr} = 2.84 \times M^{-1} B^{0.82} \bar{n}_{e,20}^{0.58} R^{1.0} a^{0.81}$$

MHD stability

- safety factor: $q_{95} = 3$
- elongation: triangularity: determined essentially by control requirements
- density: $\bar{n}_e \leq n_{GW}$
- beta limit: $\beta_N \leq 2.5$

Scrape-off layer/ Divertor

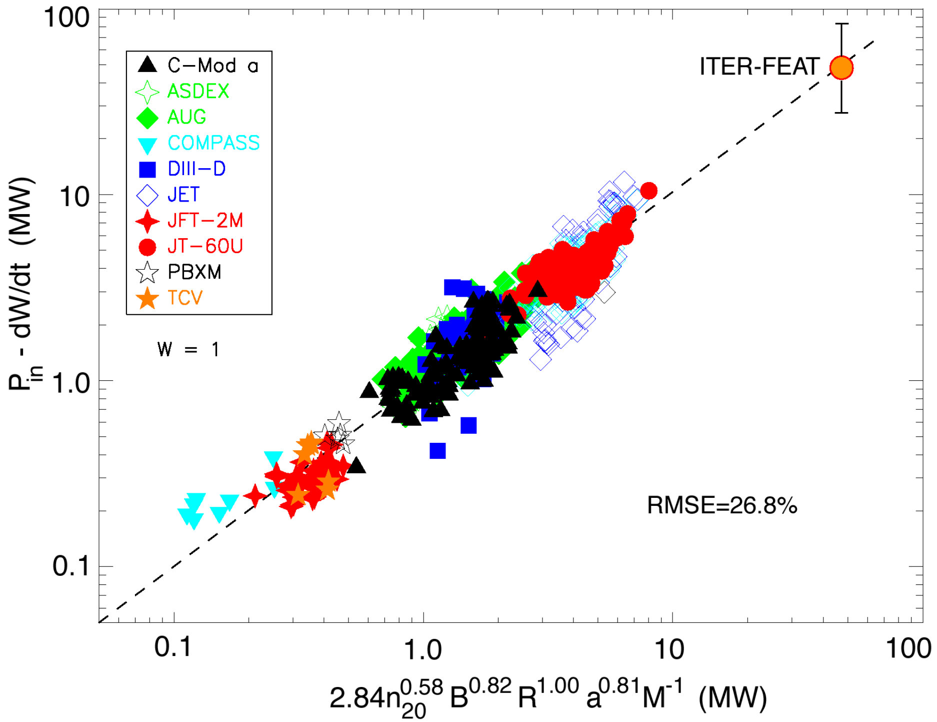
- peak target power: $\leq 10 \mathrm{MWm}^{-2}$
- helium content: simplified core/edge transport model

  or: $\tau^*_{He} / \tau_E \sim 5$
- impurity content: $\bar{n}_{Be} / \bar{n}_e = 0.02$

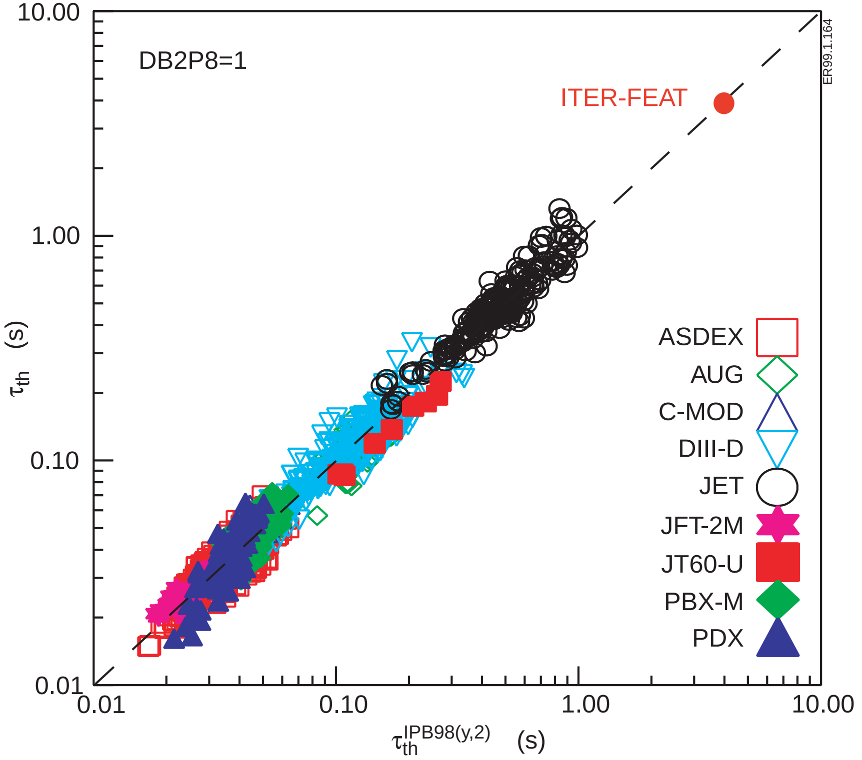
  plus contribution from sputtered carbon and seeded noble gas to limit peak target power

H-Mode Scalings

Power threshold



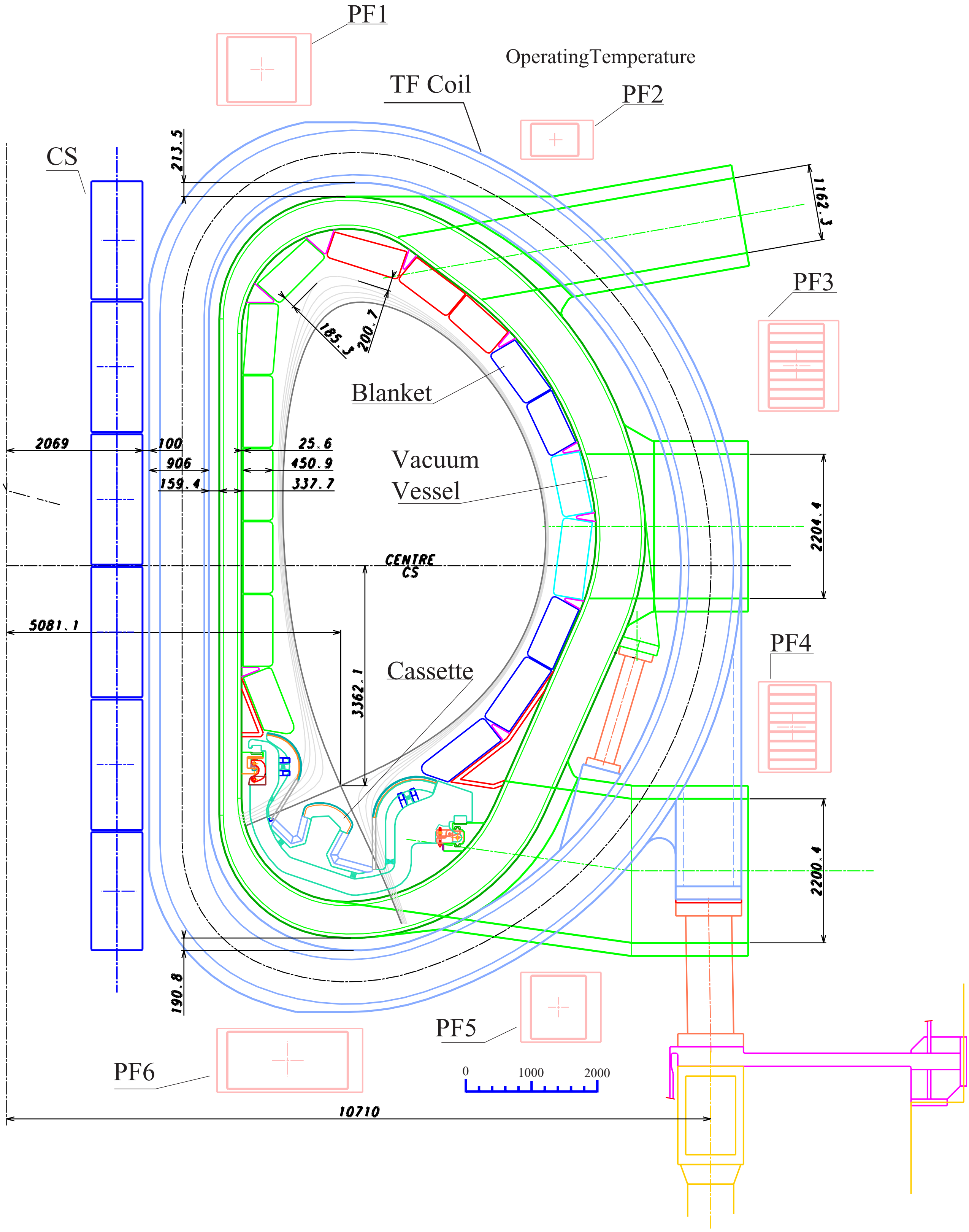
Energy Confinement



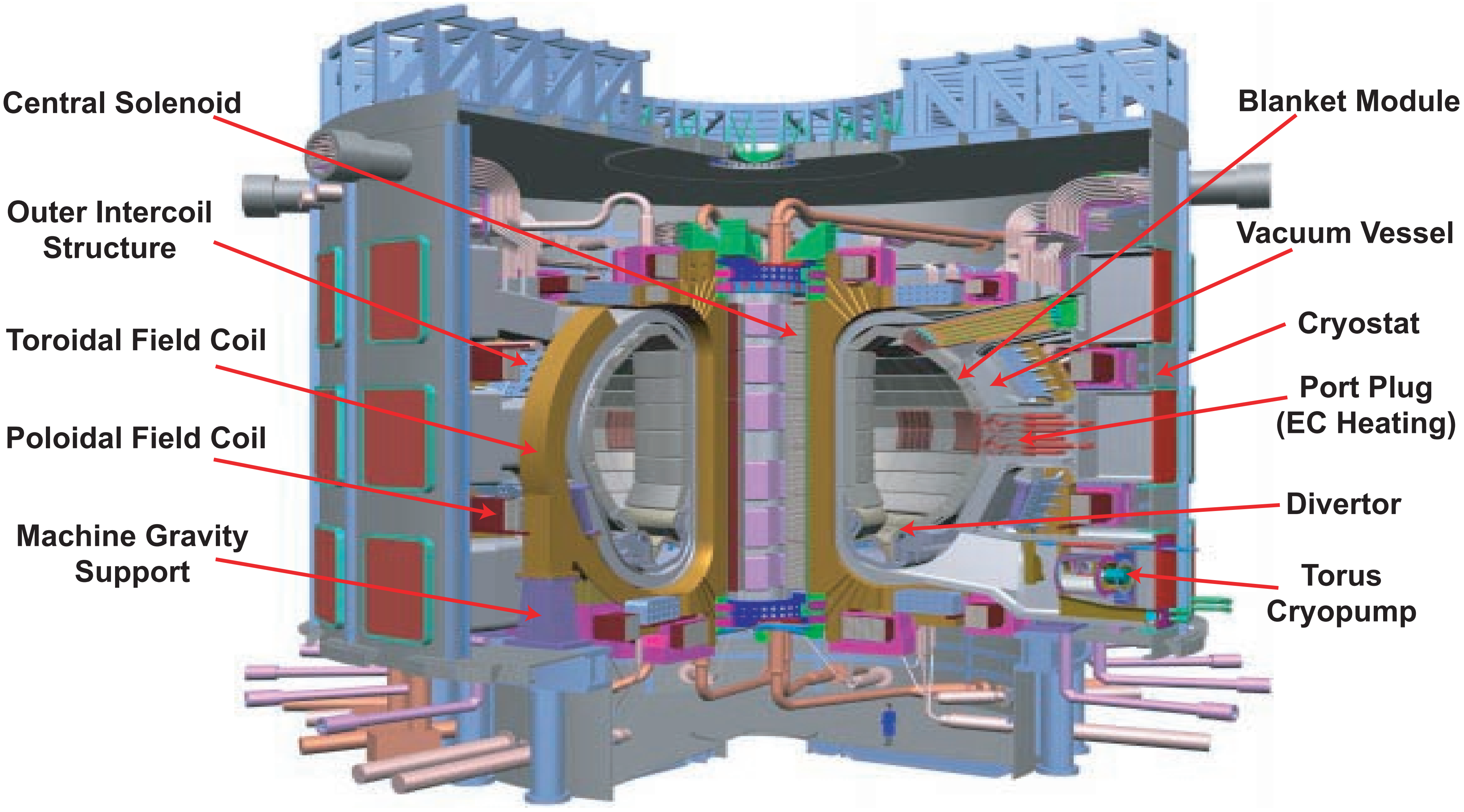
Device Parameters

Parameter	**ITER**
κ_{95}, κ_x	1.70, 1.85
δ_{95}, δ_x	0.33, 0.49
R, a (m)	6.20, 2.0
R/a	3.1
Vol (m^3)	828
B (T)	5.3
I_p (MA)	15.0
t_{burn} (s)	≥300
$\langle n\rangle/n_{GW}$	0.85
$\langle n\rangle$ ($10^{20}m^{-3}$)	1.01
$\langle T_e\rangle, \langle T_i\rangle$ (keV)	8.8, 8.0
$Z_{eff,axis}$	1.69
$n_{He,axis}/n_e$ (%)	4.3
β_N	1.8
β (%)	2.5
P_{fus} (MW)	400
L_{wall} (MWm^{-2})	0.47
Q	10

ITER Poloidal Elevation



ITER: Main Design Features



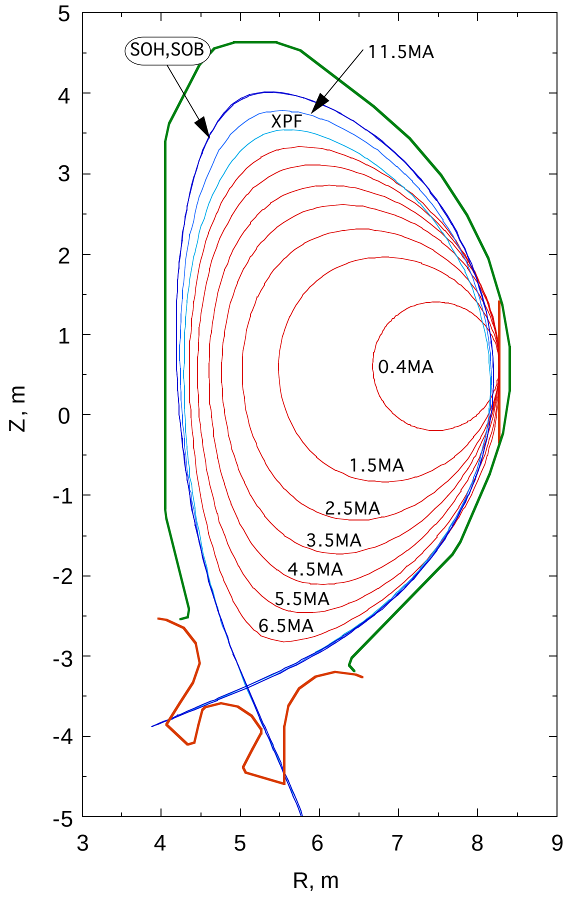
Heating and Current Drive

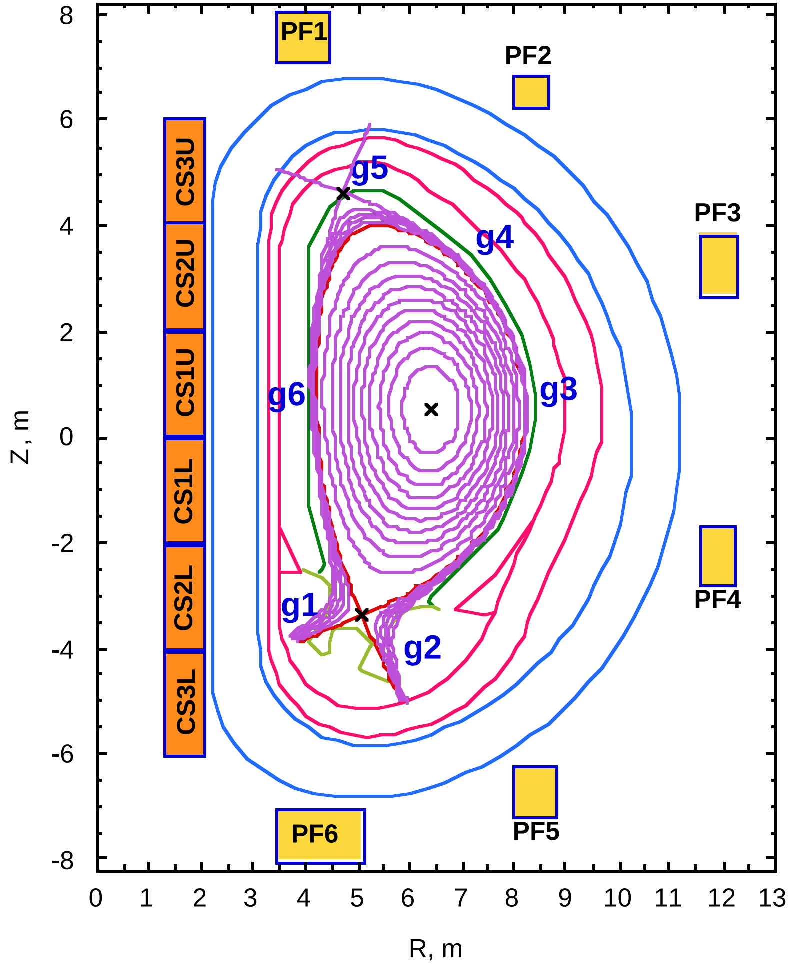
- **Heating and current drive functions:**
  - heating plasmas through H-mode transition and to burn
  - control of plasma burn point
  - current drive for hybrid/ steady state operation
  - localized current drive for mhd stability control
  - plasma start-up assist, wall conditioning

- **Proposed initial heating and current drive capability: total power = 73MW**
  - 20MW of ECRF at 170GHz
  - 20MW of ICRH in range 35-55MHz
  - 33MW of 1MeV negative ion based NBI

- **Additional capability for mhd control or steady-state current drive foreseen, totalling >100MW**
  - this could include ~20MW of LHCD at 5GHz

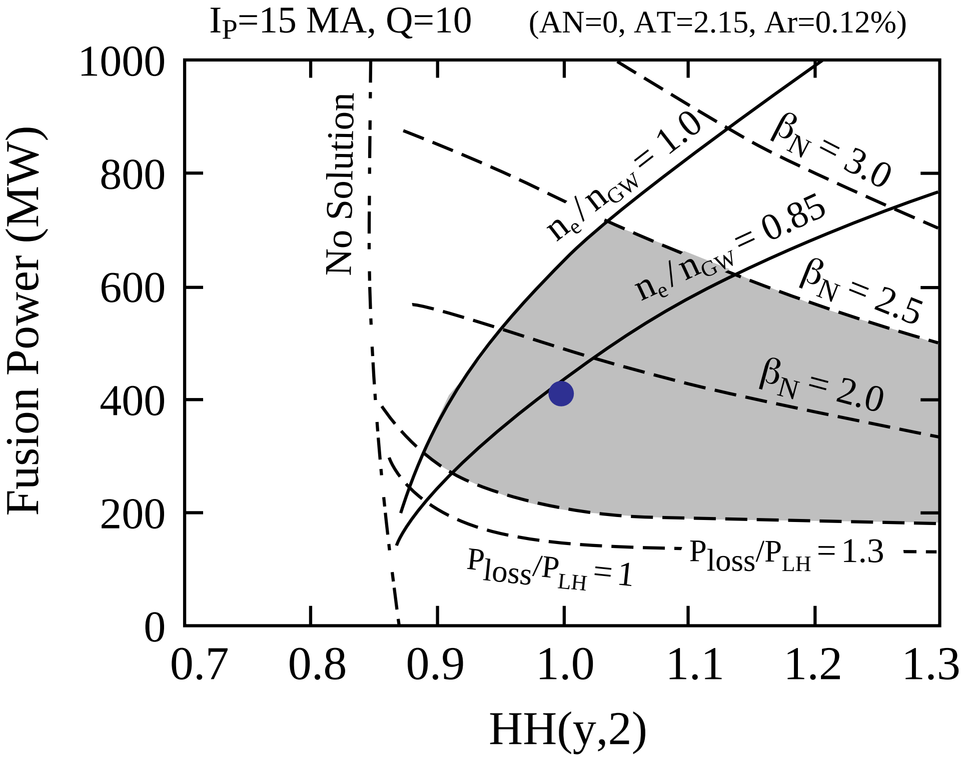
ITER Plasma Equilibria



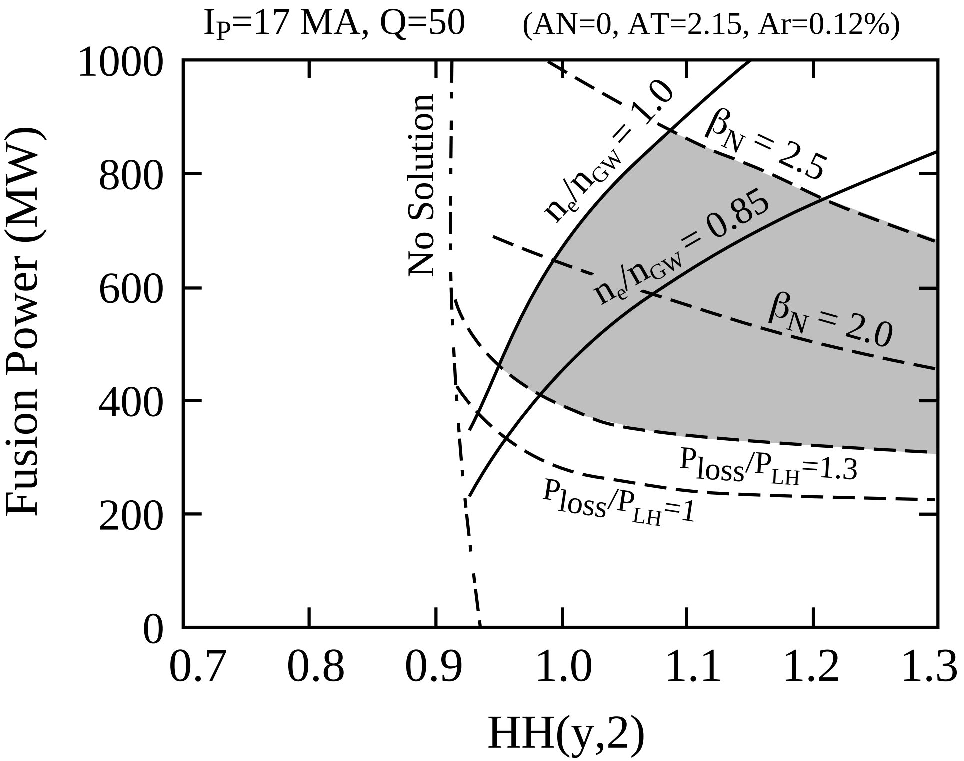


Performance in Pulsed Operation

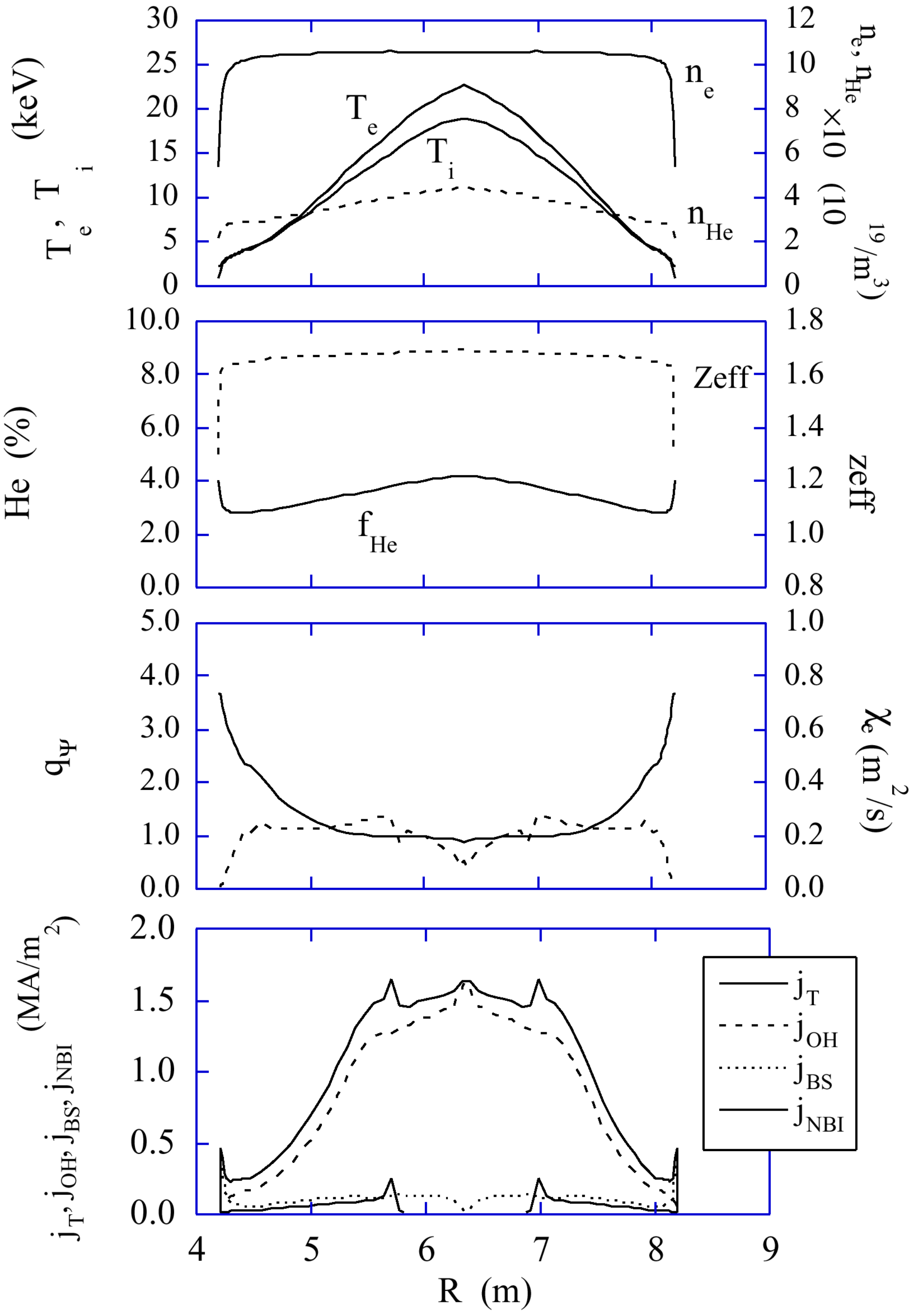
Q=10 at 15MA (q_{95}=3)



Q=50 at 17MA (q_{95}=2.6)



Q=10: Plasma Profiles



- **Plasma profiles I=15MA, P_{aux}=40MW, $H_{98(y,2)}$=1**

ITER Performance

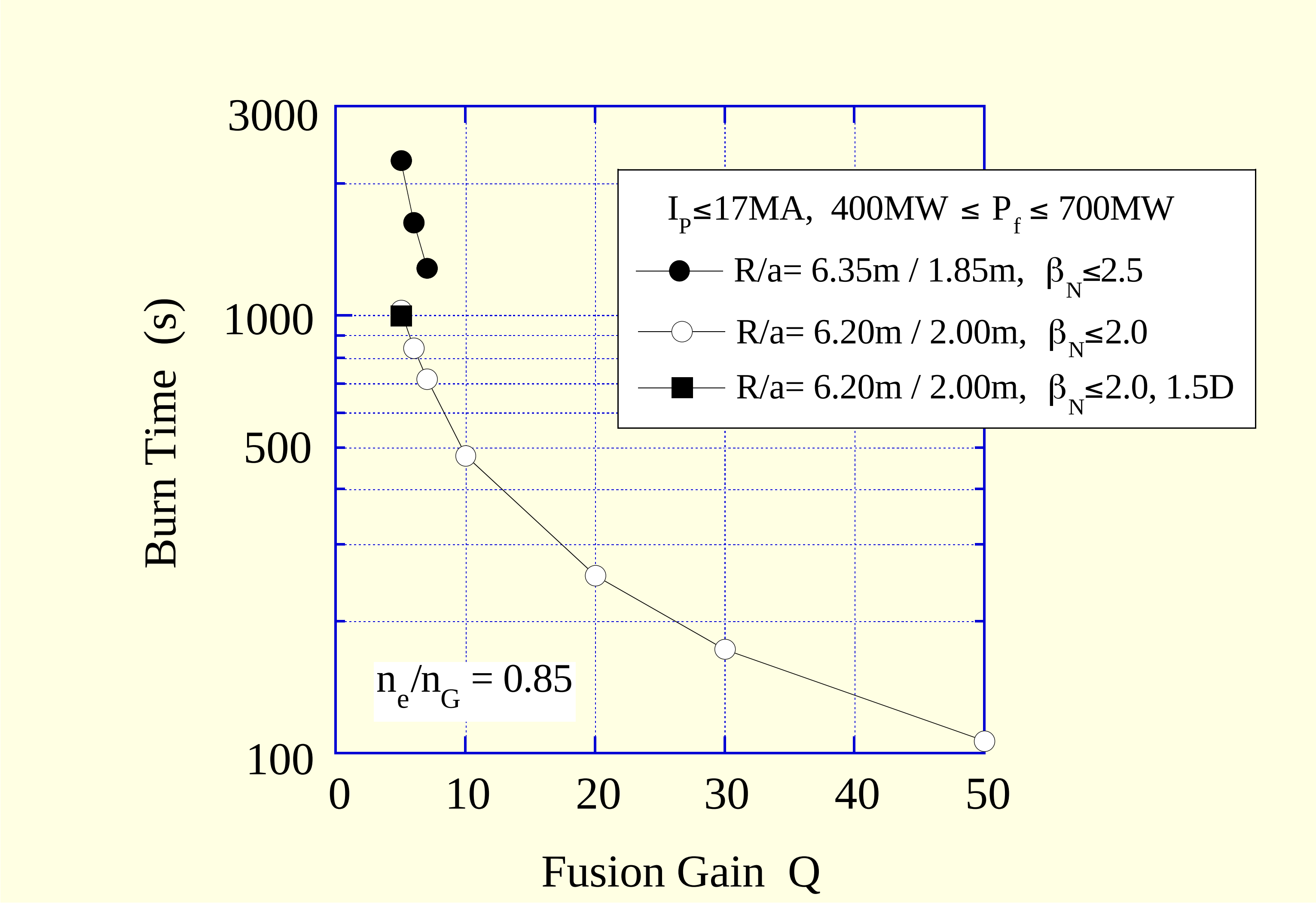
- **At Q=10, fusion power is 200-700MW at $H_{98(y,2)}$=1**

- **Neutron wall loading at $H_{98(y,2)}$=1 varies between 0.23MWm^{-2} and 0.80MWm^{-2}**
  - so there is still scope for technology studies

- **Q=10 operational space has a margin in density against the Greenwald value:**
  - at β_N=1.5, $H_{98(y,2)}$=1, Q=10 can be achieved at n/n_{GW}~0.7

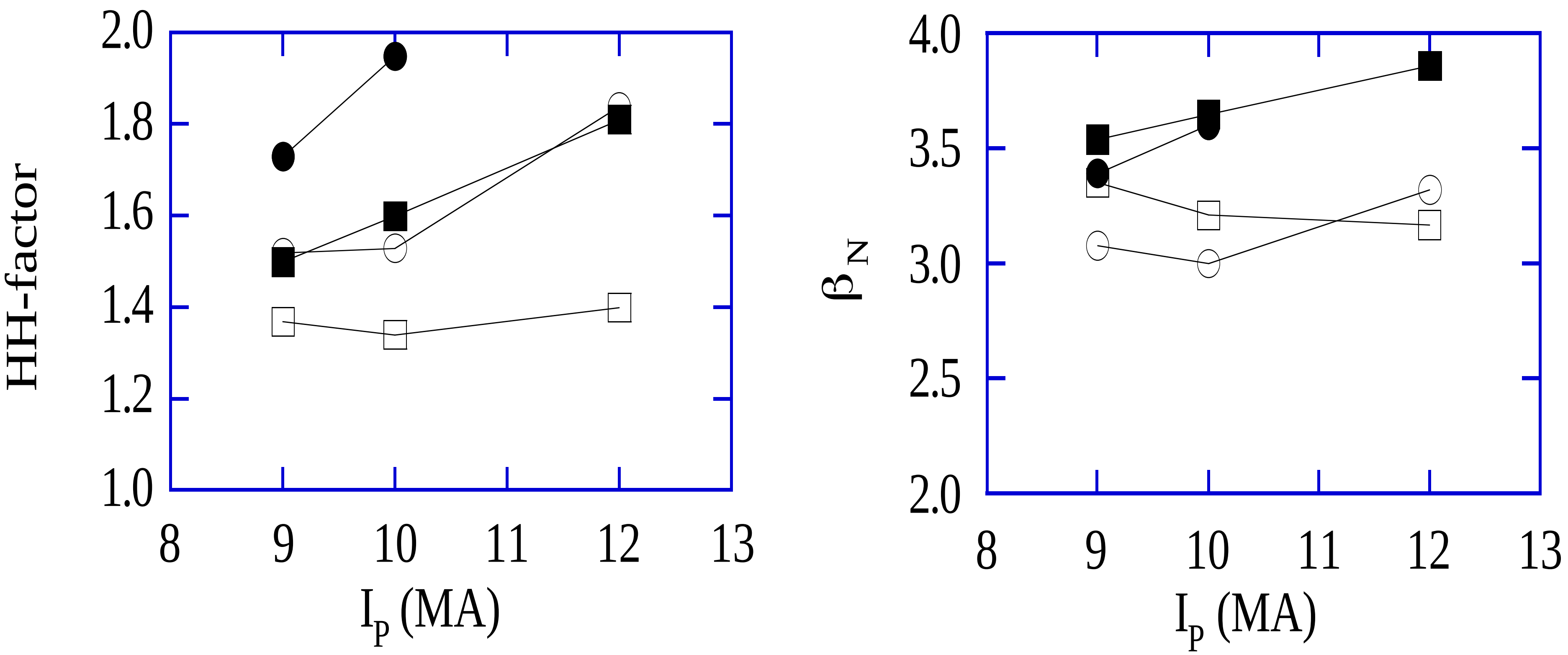
- **'Controlled ignition' (Q=50) can be attained in ITER:**
  - in an inductive advanced scenario ($H_{98(y,2)}$~1.2)
  - if operation at $n>n_{GW}$ is possible
  - if high confinement can be sustained at $q_{95}<3$

Hybrid Operation: Q=5



Steady-State Operation: Q=5

open - without impurities
closed - with impurities



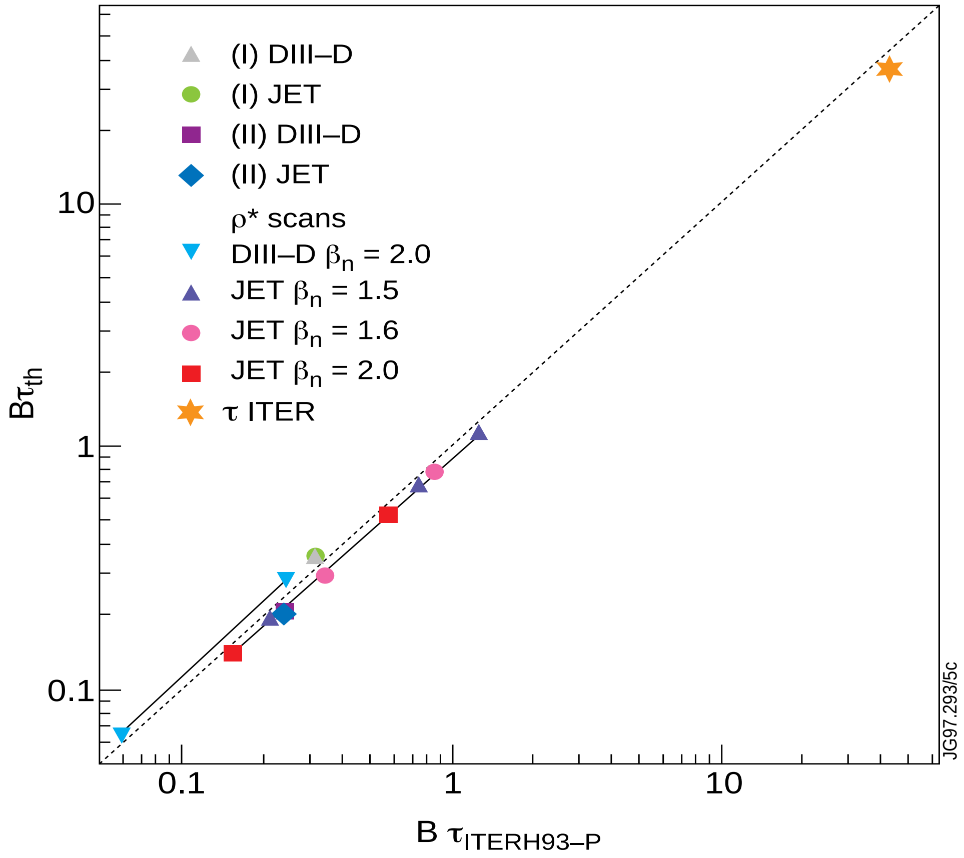
Hybrid and Steady-State Operation

- **Hybrid operation allows long pulses (~2000s) to be produced for technology testing**
  - Q=5 requires $H_{98(y,2)}$~1 and β_N=2.5
  - this mode of operation should allow true steady-state to be developed gradually
- **1.5-D analysis of steady-state operation shows that Q=5 requires:**
  - $H_{98(y,2)} \geq 1.5$, $\beta_N \geq 3.5$ for $9 \leq I_p \leq 12$ and $n/n_{GW} \leq 1$
  - I_{bs}/I_p~40-50%
- **These requirements imply that scenarios with active profile control would be required**
  - β_N values required imply that stabilization for resistive wall modes necessary

Design Basis and Physics Issues for ITER

- **Confinement and transport**
- **MHD stability and control**
- **Divertor performance**
- **Alpha-particle physics**

H-Mode Confinement: Non-Dimensional Scaling



- **JET/ DIII-D comparisons (for example) show $B\tau_E$ scaling in an almost gyro-Bohm fashion ($B\tau_E \sim \rho_*^{-3}$) - star shows ITER-1998**
    - independently derived global scaling expressions have approximately gyro-Bohm dependence
    - analysis of local transport coefficients confirms gyro-Bohm form in ELMy H-modes

J G Cordey et al, Plasma Phys Control Fusion **38** (1996) A67

Core-Edge Integration

- **At the reactor scale plasmas must simultaneously:**
  - exhibit good core confinement
  - operate at high density ($n \sim n_{GW}$)
  - possibly operate close to H-mode threshold
  - dissipate exhaust power (significant radiation)

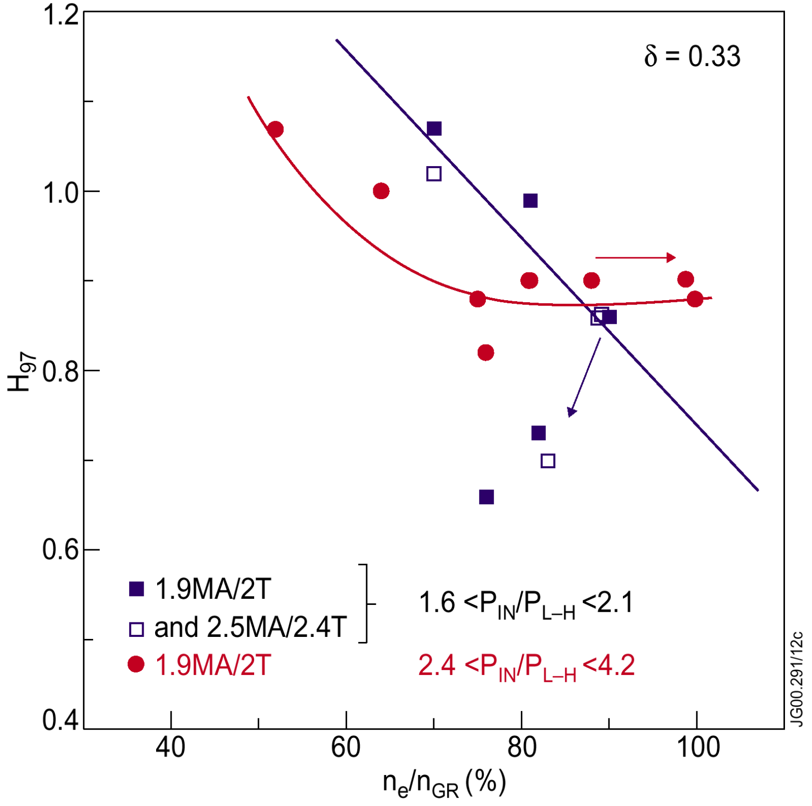
- **Core-edge integration issues**
  - core and pedestal confinement scale differently from existing experiments to ITER scale
  - current experiments matching ITER core dimensionless parameters have ‘low density’ edges, typically well above the H-mode threshold, and with low to moderate radiation
  - only an ITER-scale device can maintain reactor-relevant core parameters with reactor-relevant edge
  - operation at high density with low NBI fuelling will necessitate application of reactor relevant fuelling techniques

Triangularity Issues

- **Wedged TF construction allows segmented central solenoid, providing additional flexibility in equilibrium control ⇒ higher triangularity**
  - limit in ITER is probably set by approach to DNX configuration - require $\Delta_{sep} \geq 4$cm from divertor modelling
- **Although triangularity does not appear explicitly in confinement scaling:**
  - increased triangularity increases current capability
  - JET and ASDEX Upgrade have found high confinement can be maintained at densities closer to n_{GW} with increasing triangularity
- **In contrast, with increasing triangularity, ELM frequency decreases and heat pulses to divertor may cause increased erosion**
  - high density operation, pellet injection, or alternative access to alternative H-mode regimes may moderate ELM behaviour

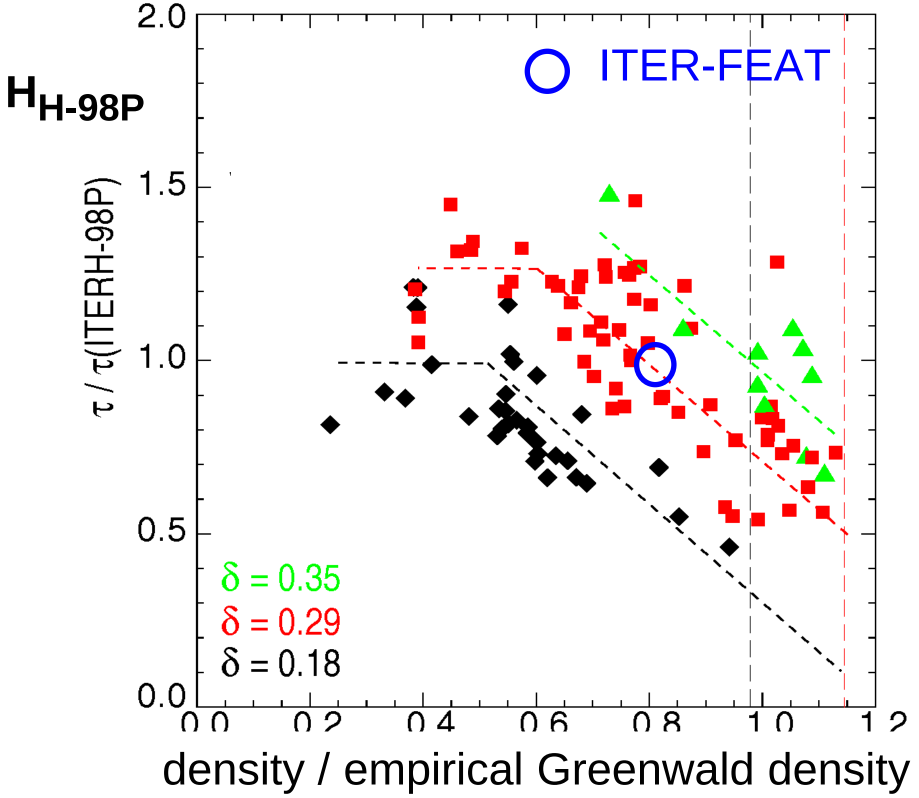
Influence of Triangularity on Confinement

JET



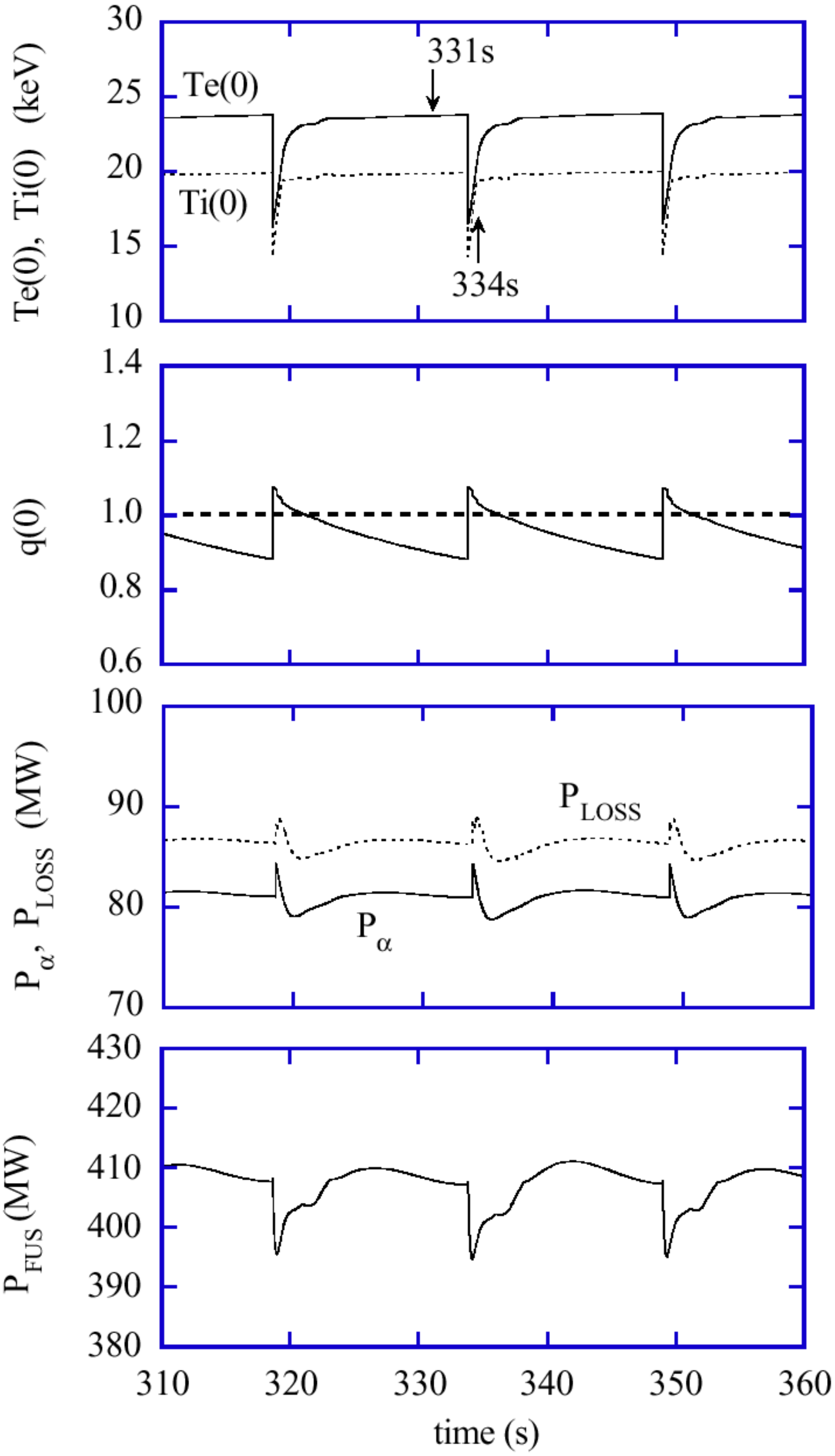
(J Paméla et al, 18th IAEA Conference, Sorrento, 2000)

ASDEX Upgrade



(O Gruber et al, 18th IAEA Conference, Sorrento, 2000)

Sawtooth Simulation in ITER



- **Sawteeth have small effect on fusion power**

(Y Murakami et al, Journal of Plasma and Fusion Research (to be published))

Disruptions

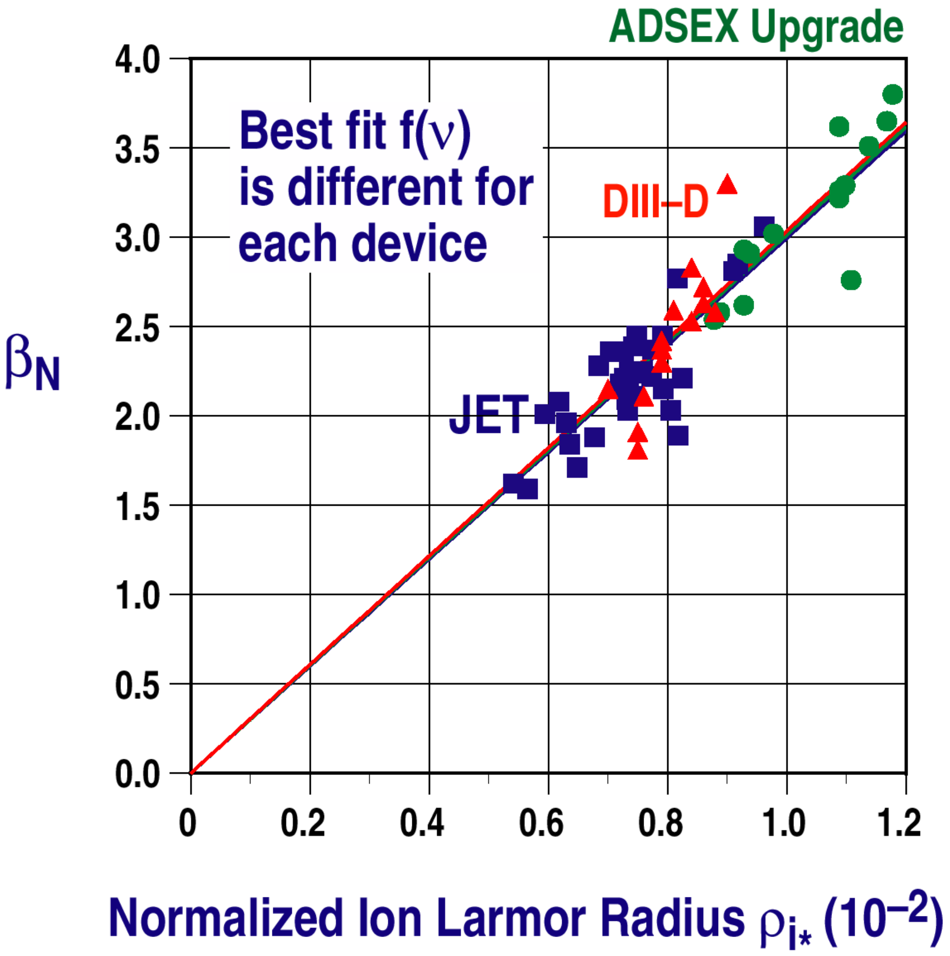
There are 3 main issues arising from disruptions and vertical displacement events:

- **Thermal quench, involving ~300-500MJ:**
    - vapour shield formation expected to mitigate thermal quench effects (energy to target<<10%)
- **Current quench/ VDE involving ~0.5GJ of energy:**
    - eddy currents and halo currents give rise to electromagnetic forces (up to ~10^4 tonnes)
- **Runaway electrons might be produced by avalanche effect in cold, impure post-disruption plasma:**
    - calculations for the new ITER design indicate that the total energy involved could be limited to ~20MJ

β-Limit - Neoclassical Modes

- **Evidence from many tokamaks shows that most severe constraint on β is the growth of neoclassical tearing modes:**
  - such modes are often observed in the region β_N~1.5-3
  - extensive experimental evidence that critical β_N depends on $(\rho^*)^\mu$, with $0.7 \leq \mu \leq 1$
- **Experimentally (3,2) and (2,1) modes are most common:**
  - (3,2) modes lead to degradation of confinement
  - (2,1) modes often cause disruption
- **Theory of such modes is well-developed:**
  - however, predictive capability limited by need for a ‘seed-island’ to trigger mode growth
- **Expected mode growth time in ITER in range 10-100s, allowing time for counter-measures:**
  - ECCD stabilization experiments now underway

β-Limit - Neoclassical Modes

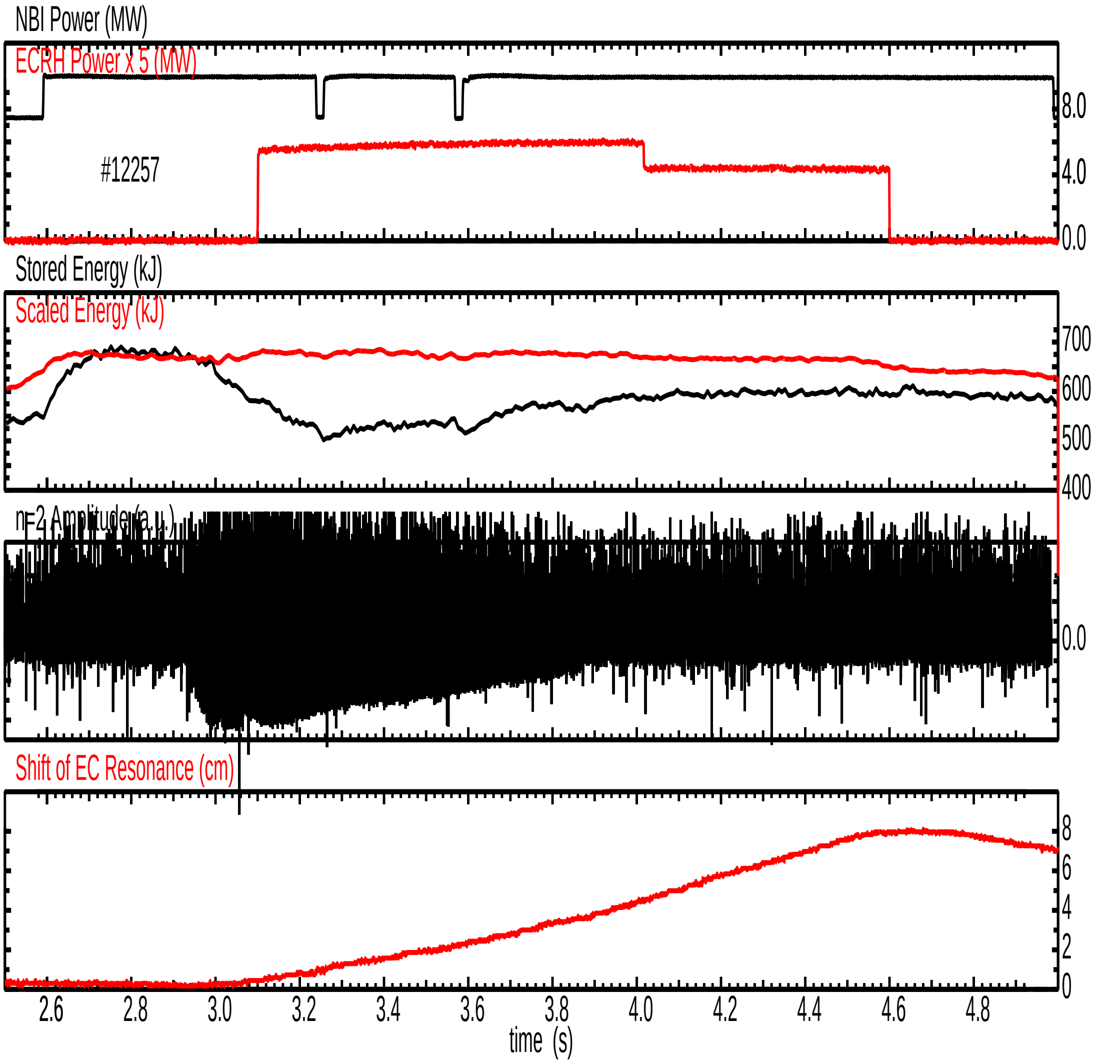


- **Analysis of the critical β_N for the onset of (3,2) NTMs has been carried out across several devices:**
  - $\beta_N \propto \rho^* f(\nu)$ is consistent with theory based on (stabilizing) 'polarization current' theory

- **Indicates neoclassical modes could be expected in ITER operating region**

R J LaHaye et al, Phys Plasmas **7** 3349 (2000)

Stabilization of NTMs



- **Experiments with modulated ECCD in ASDEX Upgrade have successfully suppressed NTMs**
  - success achieved on several tokamaks
  - recovery of initial β remains a key issue
  - calculations predict that ~20-30MW of ECRF power required for stabilization in ITER

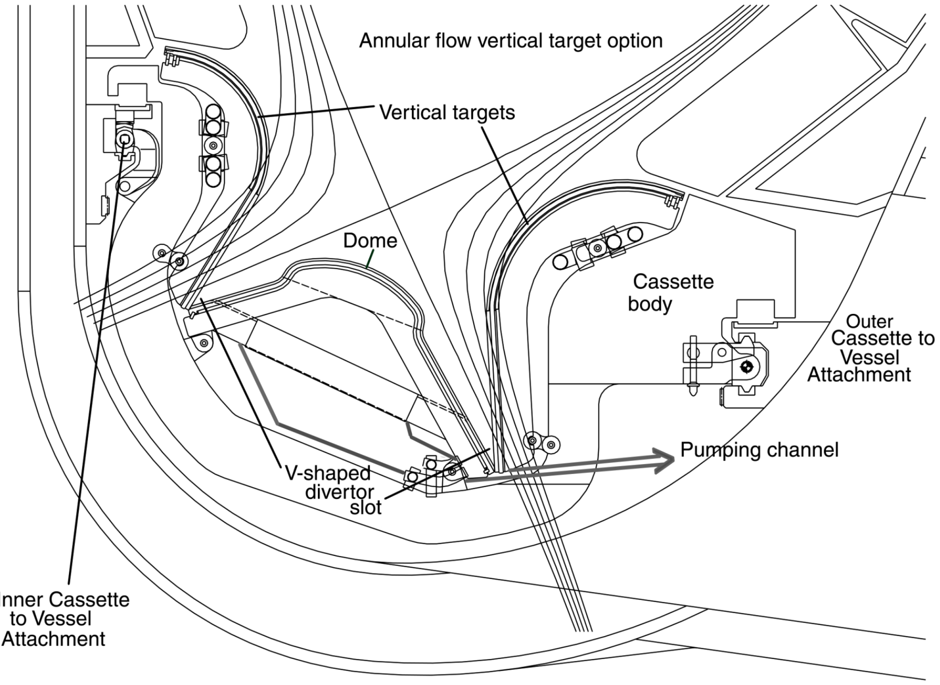
G Gantenbein et al, Phys Rev Lett **85** 1242 (2000)

MHD Stability

- **Main influence of sawteeth is likely to be via generation of seed islands for neoclassical tearing modes (NTMs)**
    - however, test of m=1 theory is required at reactor scale to address role of α-particles in sawtooth stabilization and fishbones
- **Disruption thermal loads, forces, and halo currents will allow investigation of reactor-relevant phenomena**
- **ITER will operate in range β_N~1.5-2.5, where NTMs might occur**
    - stabilization of NTMs by ECCD/ LHCD has been successfully demonstrated on several devices - such a system is foreseen for ITER
- **In steady-state scenarios, resistive wall modes are likely to determine β-limit - if theoretical limit can be reached**
    - a system of external stabilization coils for low-m, n=1 RWMs is in under design
    - coil set also used for error field correction

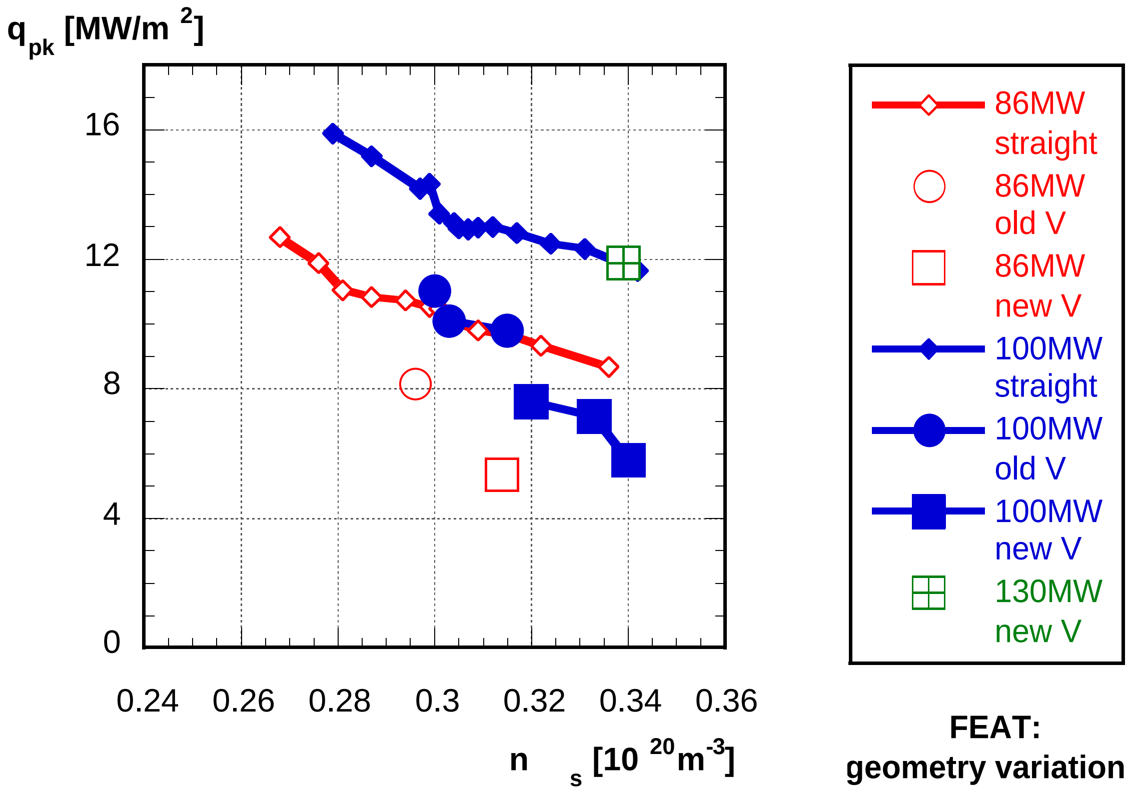
Divertor Issues

- **Long pulse capability of ITER makes divertor performance critical - main issues:**
  - peak power load
  - helium fraction
  - control of density and fuel mixture
  - impurity content
  - transient power loads - ELMs, disruptions



- **Divertor design developed from experience in current tokamaks**

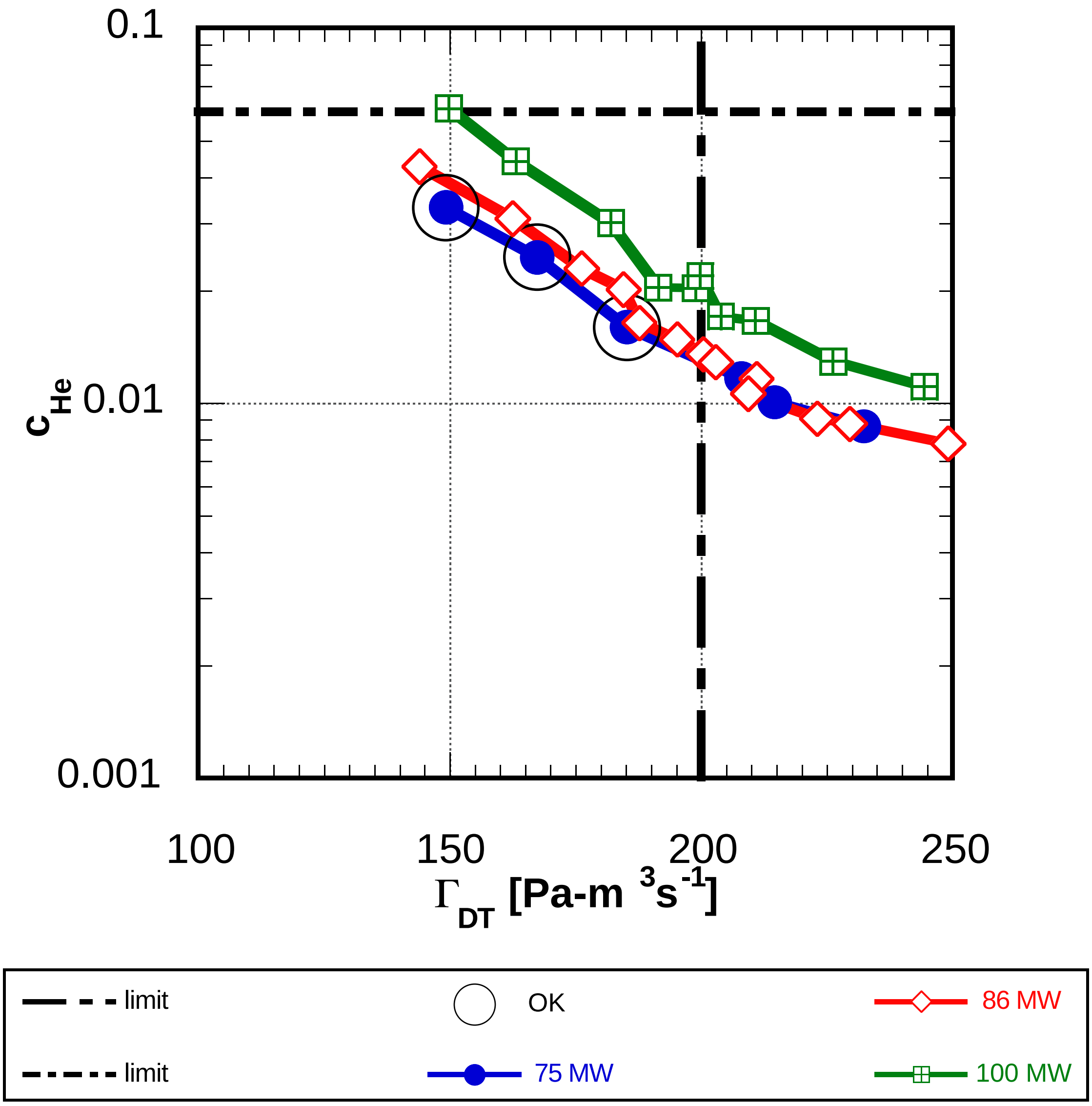
Divertor Modelling



FEAT:
geometry variation

- **Modelling using B2-EIRENE for ITER shows that under partially detached conditions, peak power load on outer divertor remains below 10MWm^{-2} over a range of separatrix densities**
  - V-shaped geometry used in target region favours development of partial detachment
  - influence of impurity seeding investigated
  - core Z_{eff} lies below 1.6

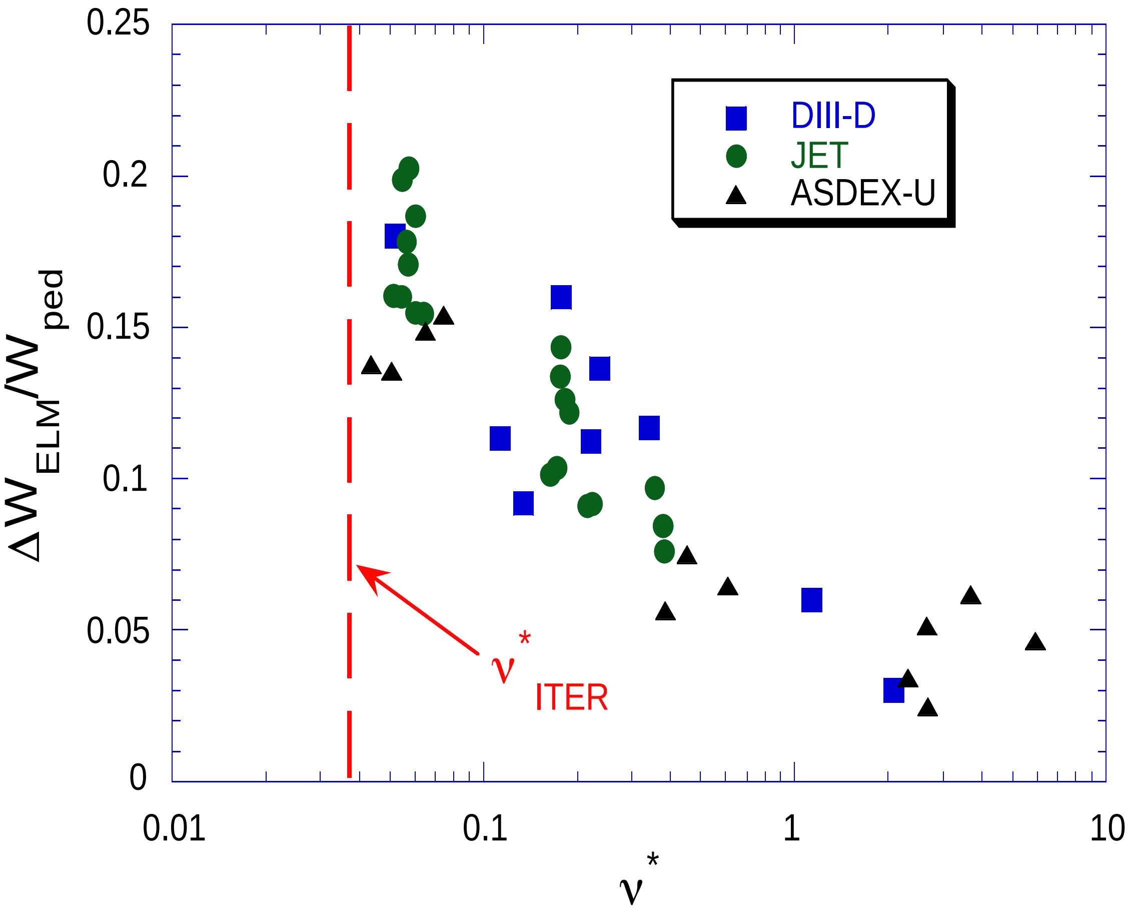
Helium Exhaust - Modelling



FEAT: Power Variation (Straight, S_p=75, C)

- **Predictions of core helium concentration as a function of fuel throughput, Γ_{DT}, for ITER**
  - an installed fuelling capacity of 200Pam^{3}s^{-1} should ensure that the core helium concentration can be held below 6%.

ELM Power Loading



- **Recent analysis of ELM energy loss indicates that pedestal collisionality and parallel transport time in the SOL are important**
  - extrapolation to ITER would imply type I ELM amplitude of ~10MJ
  - this would pose problems for the divertor lifetime
  - alternative H-mode operational regimes would be desirable (eg type II ELMs, EDA)

A Loarte et al, 18th IAEA Conference, Sorrento 2000

Divertor Performance

- **Detailed modelling underway:**
    - steady-state peak power load on outer divertor can be kept below 10MWm^{-2} design limit
    - core helium concentration can be kept below 6%, as required
    - $\Delta_{sep} \geq 4$cm required to limit power load in vicinity of upper null to that of first wall generally
- **Transient power loads due to ELMs and disruptions might prove the most severe limit on target lifetime**
- **Use of inside pellet launch and high triangularity plasmas can provide tools for achieving high confinement at high density**
- **Co-deposition and retention of tritium must be addressed by development of appropriate conditioning techniques**

Alpha Particle Physics

- **Key issue is that α-particles should slow down classically and provide efficient heating**
  - extensive experience in experiments with energetic particle populations produced by auxiliary power systems
  - TFTR and JET DT experiments confirm α-heating as expected (within uncertainties)
- **TF ripple losses must be within first wall power loading constraints:**
  - theory well validated by experiments in several tokamaks
  - acceptable TF ripple losses in steady-state conditions will require ferromagnetic inserts
- **ITER will permit models of interaction with mhd instabilities to be tested:**
  - formalism exists for analyzing interaction with sawteeth, fishbones, kinetic ballooning modes, localized interchange modes
  - interaction with NTMs and ELMs conjectural

- **Alfvén eigenmodes:**
  - extensive validation of numerical codes against experimental observations
  - ITER-1998 expected to differ from present experiments in that many modes with n>10 could be excited
  - many of critical parameters in ITER ($\beta_\alpha(0)$, v_α/v_A, $R\nabla\beta_\alpha$) differ little from ITER-1998 (~20%)
  - certain parameters (ρ_α/a) differ by up to a factor of 1.5

- **Analysis of α-particle behaviour for ITER plasma conditions is now being initiated**
  - it is expected that unless unstable modes overlap and extend to wall, non-linear redistribution of α-particles may simply results in profile broadening
  - complications arising from 1MeV beam ions will have to be addressed in parallel

Conclusions

- **The new ITER design has been derived from:**
  - the ITER Physics Basis, which has been validated in the experimental tokamak programme
  - engineering methodologies and guidelines which have been established during the ITER EDA
- **The design can fulfil the requirements of the ITER programme:**
  - a significant margin for Q=10 inductive operation
  - long pulse inductive operation appropriate for study of mhd stability and divertor operation (including helium exhaust)
  - capability for studying steady-state scenarios at Q=5
  - possibility of achieving ‘controlled ignition’ under favourable conditions
  - physics processes, including α-particle physics, will be characteristic of reactor scale plasmas

- **Major physics issues:**
  - maintenance of high confinement at high density
  - control of NTMs and their impact on the β-limit
  - impact of ELMs on divertor target lifetime
  - tritium inventory control
  - development of steady-state scenarios