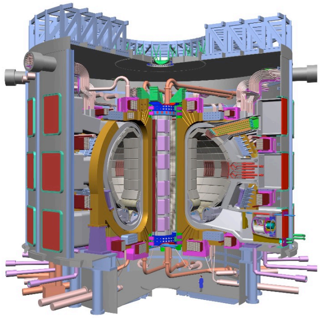
Progress in Physics Basis and its Impact on ITER



ITER

The Way to Fusion Energy

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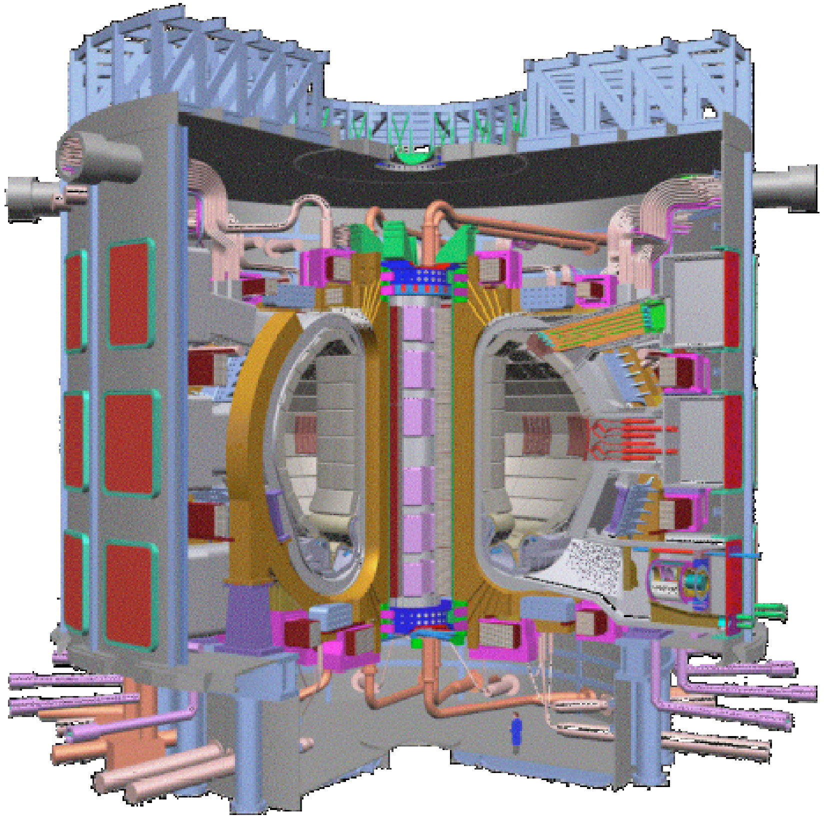


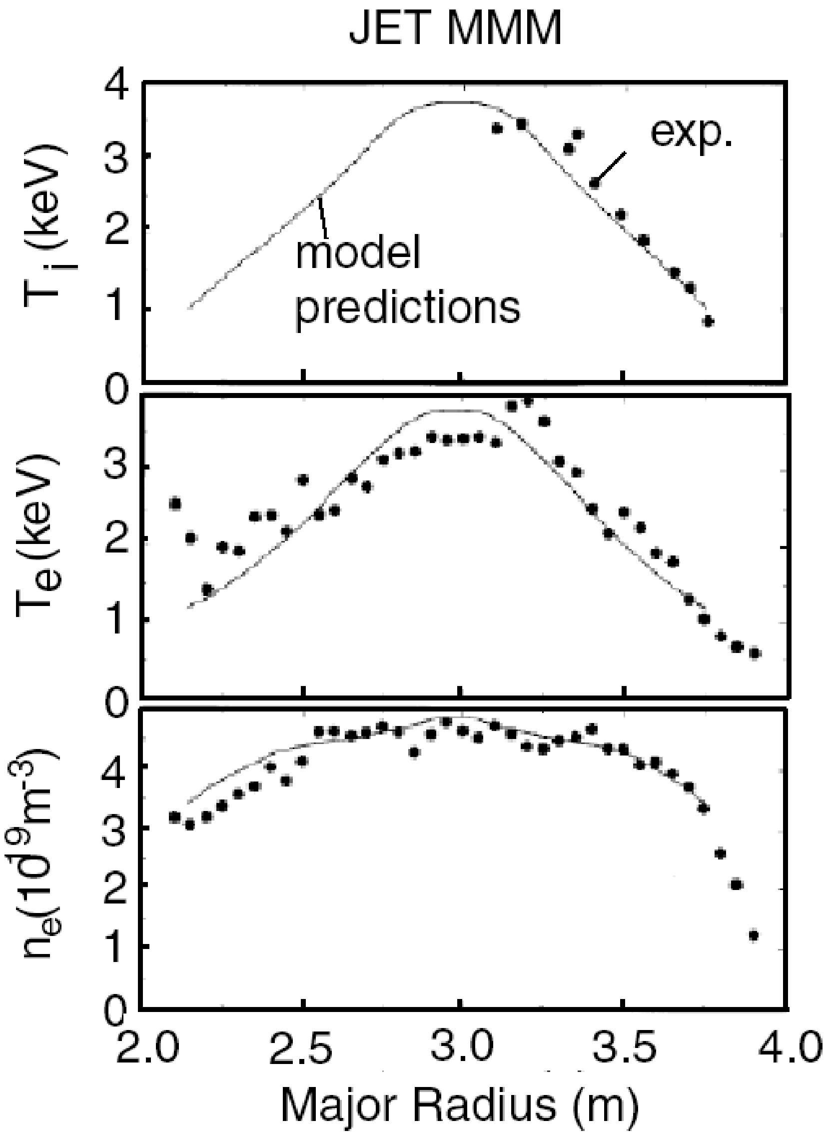
Outline

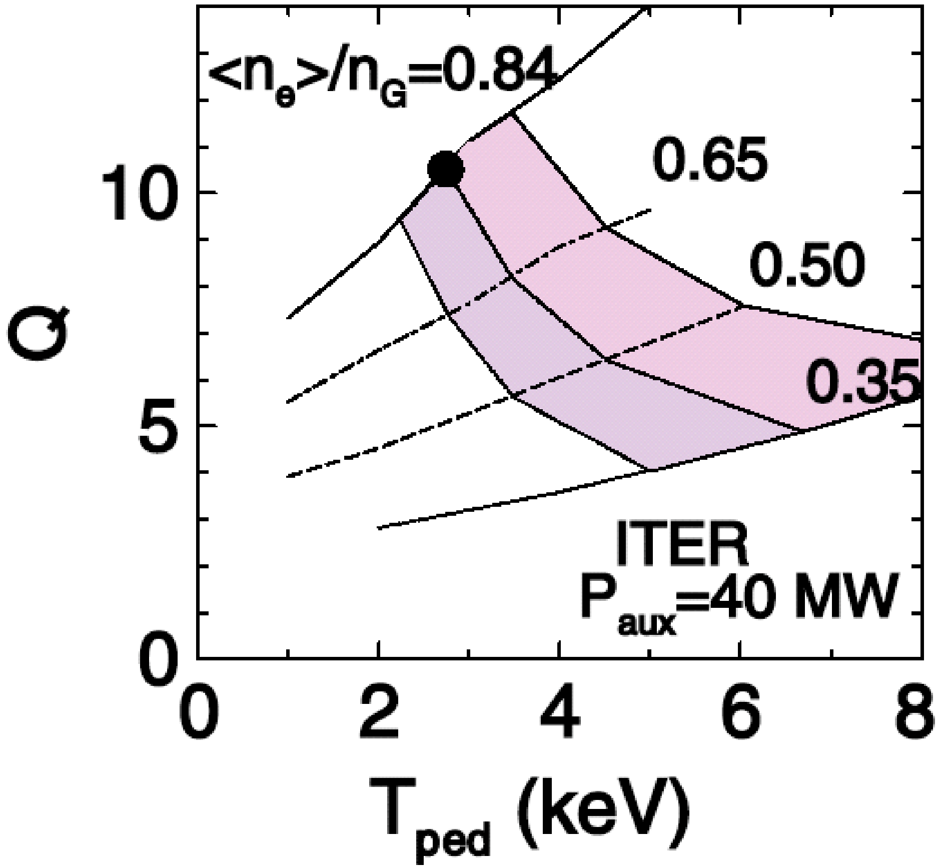
- Physics R&D through ITPA
- Areas where progress is good
  - Theory-based transport modeling
  - Edge Localised Modes (ELM)
  - Neoclassical Tearing Modes (NTM)
  - Weak Magnetic Shear Operation
  - Resistive Wall Modes (RWM)
- Areas where much more work is needed
  - Plasma-Wall Interaction (PWI)
  - Disruptions
  - Instabilities driven by Energetic Particles
- Summary

Physics R&D through the International Tokamak Physics Activity (ITPA)

- Coordinated physics R&D for ITER is undertaken to develop and improve methodologies for projection and control of ITER through the ITPA.
- All ITER Parties (RF, EU, JA, US, CN, KO) are participating.
- Significant progress has been made since the publication of the ITER Physics Basis. This has improved the confidence of ITER achieving its goals.
- A review paper of tokamak physics for burning plasmas is in preparation to be published in Nuclear Fusion.

Theory-based transport modeling in the core + empirical pedestal model predicts Q ~ 10 in ITER inductive operation (Bateman)

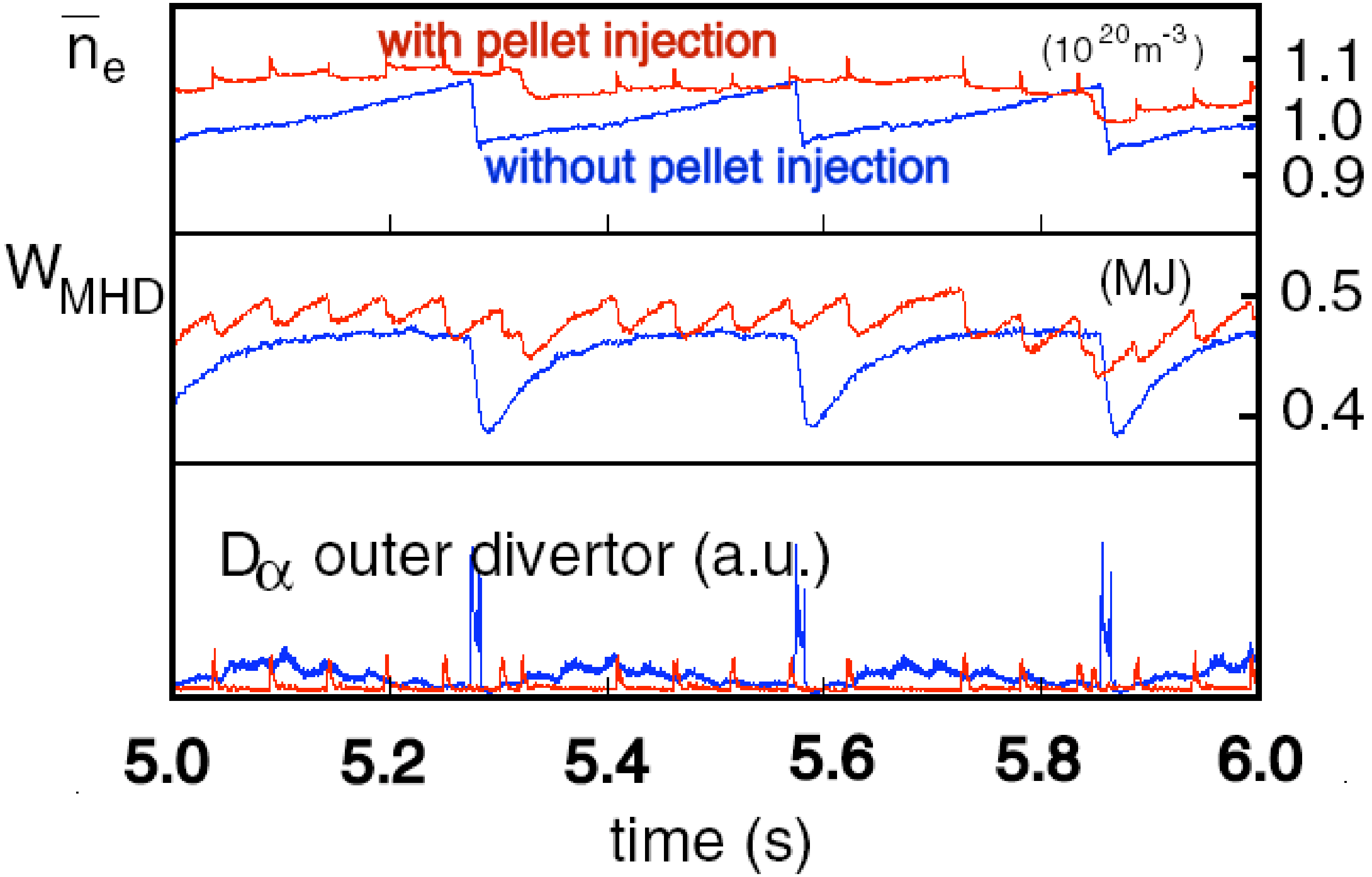




Z_{eff} ~ 1.3 is assumed

Edge Localised Modes (ELM)

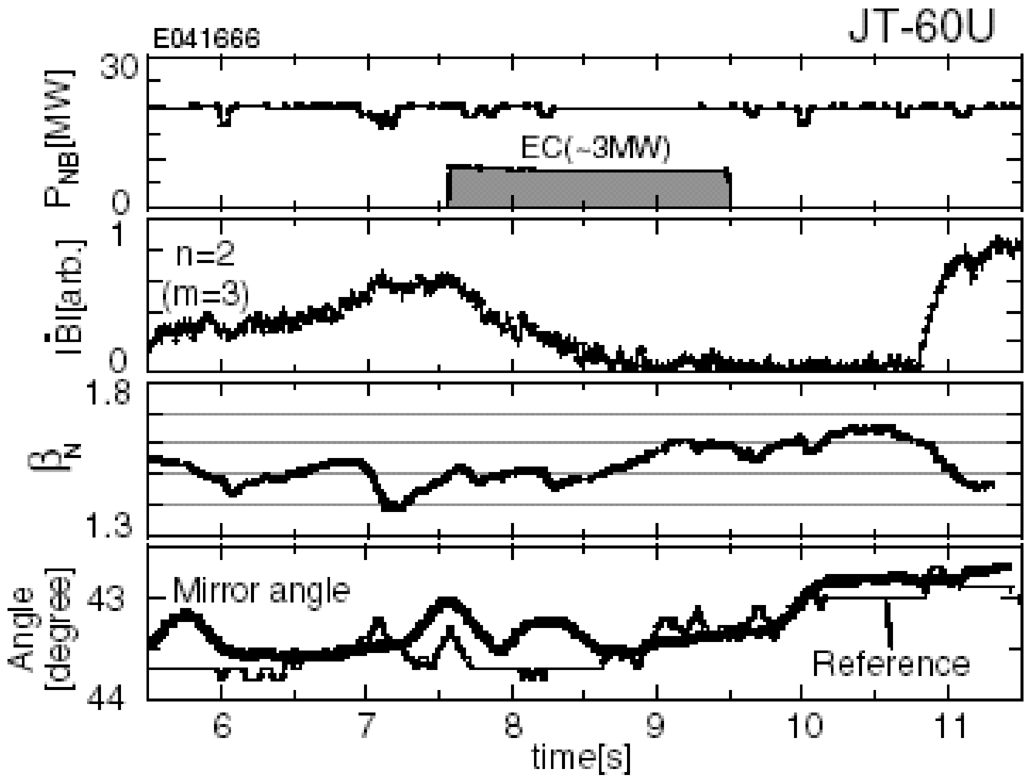
The amplitude of ELMs can be reduced by inducing frequent ELMs by pellet injection (ASDEX Upgrade) or by edge ergodisation (DIII-D)



With pellet injection, a small confinement deterioration (~10%) is observed.

ASDEX Upgrade

Neoclassical Tearing Modes (NTM) Suppression by ECCD



Suppression of NTM has been demonstrated for 2/1 and 3/2 modes (ASDEX Upgrade, DIII-D, JT-60U).

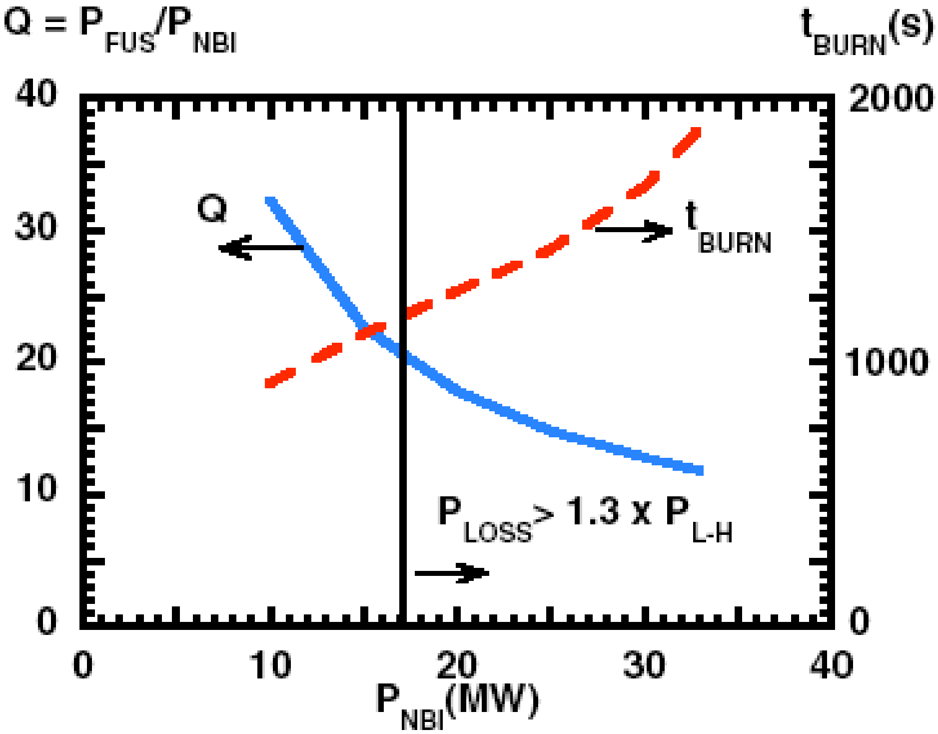
The magnetic island is tracked real-time and early injection has reduced the required power (JT-60U).

The required power in ITER is estimated to be 10-30 MW

Good confinement is observed in the presence of n=2 or 3 tearing modes

Weak Magnetic Shear Operation (1)

Weak magnetic shear (high β_p, “hybrid”, $q(0) = 1\text{-}1.5$) discharges show improved confinement and high β. (e.g. $H_{98(y,2)} \sim 1.2$ at $n/n_G = 0.85$) In ITER, fusion powers of ~ 350 MW, Q~ 20 and $t_{burn} > 1000$ s would be expected at $\beta_N \leq 2.2$ ($< \beta_{no\ wall}$). This would make an attractive scenario with high Q, long pulse and small ELMs.



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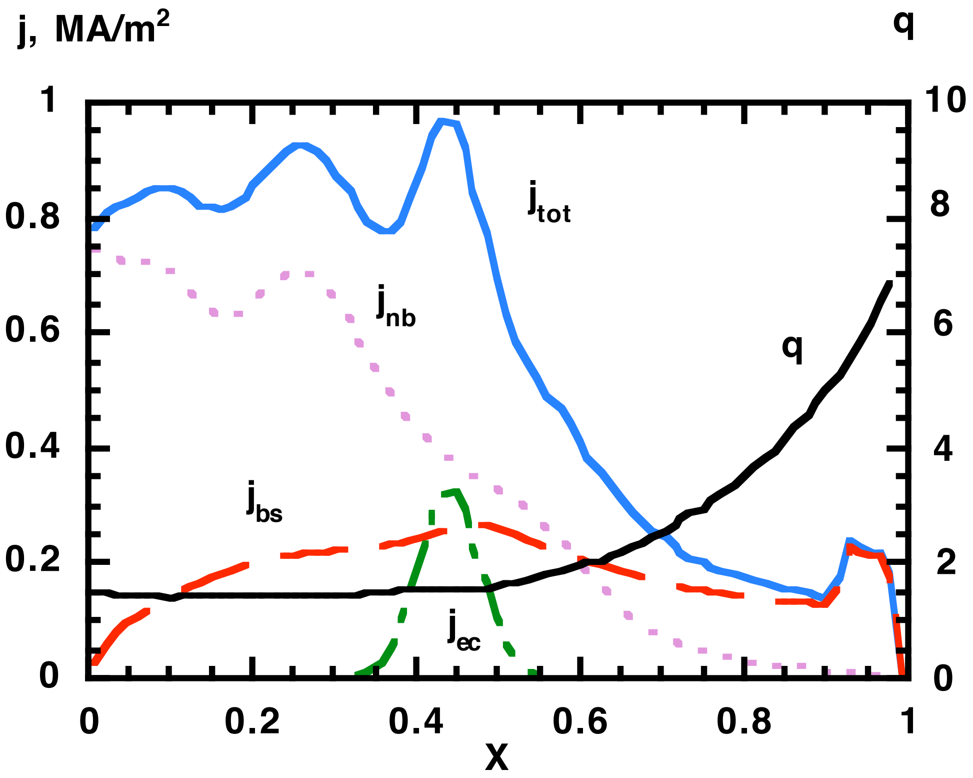
Weak Magnetic Shear Operation (2)



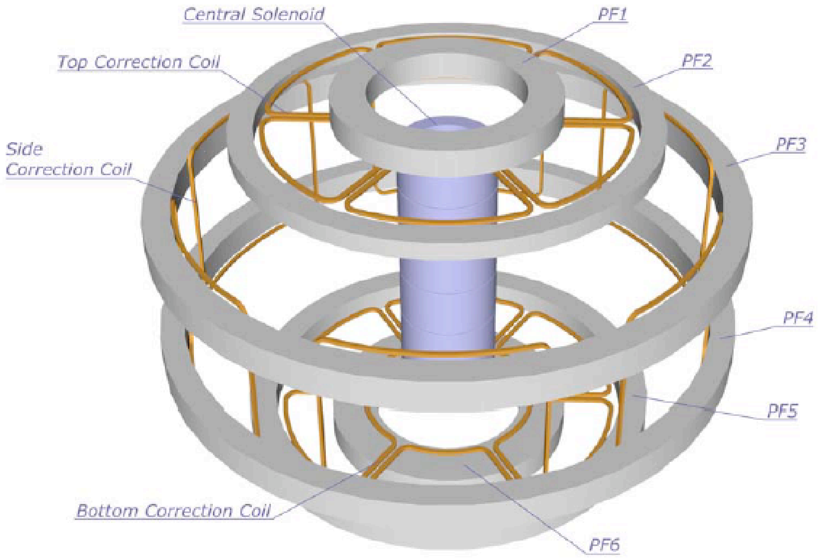
A weak shear steady state scenario of ITER with the current drive systems of the initial operation, i.e. 33 MW NB and 20 MW EC

β_N^{SS}=2.76, $\beta_N^{no\ wall}$=3.0, l_i=0.87, $H_{H98(y,2)}$ = 1.7, $q_0 / q_{min} / q_{95}$=1.72/1.54/5.74

Advantage: free of Resistive Wall Mode (Polevoi, IT/P3-28)

Resistive Wall Modes (RWM)

DIII-D experiments demonstrate that RWM can be suppressed by a combination of plasma rotation and feedback control with external coils. An analysis shows that RWM control is possible up to $C_\beta \sim 0.8$ ($C_\beta = (\beta - \beta_{\text{no wall}})/(\beta_{\text{ideal wall}} - \beta_{\text{no wall}})$) in ITER. (Liu and Bondeson, TH/2-1, Gribov and Kavin, IT/P3-22)



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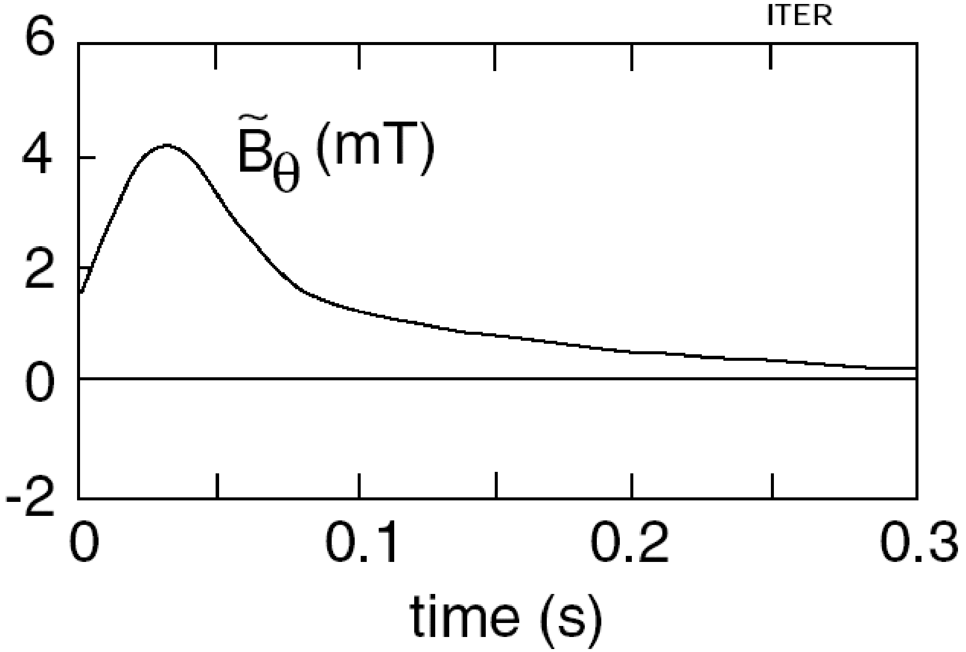
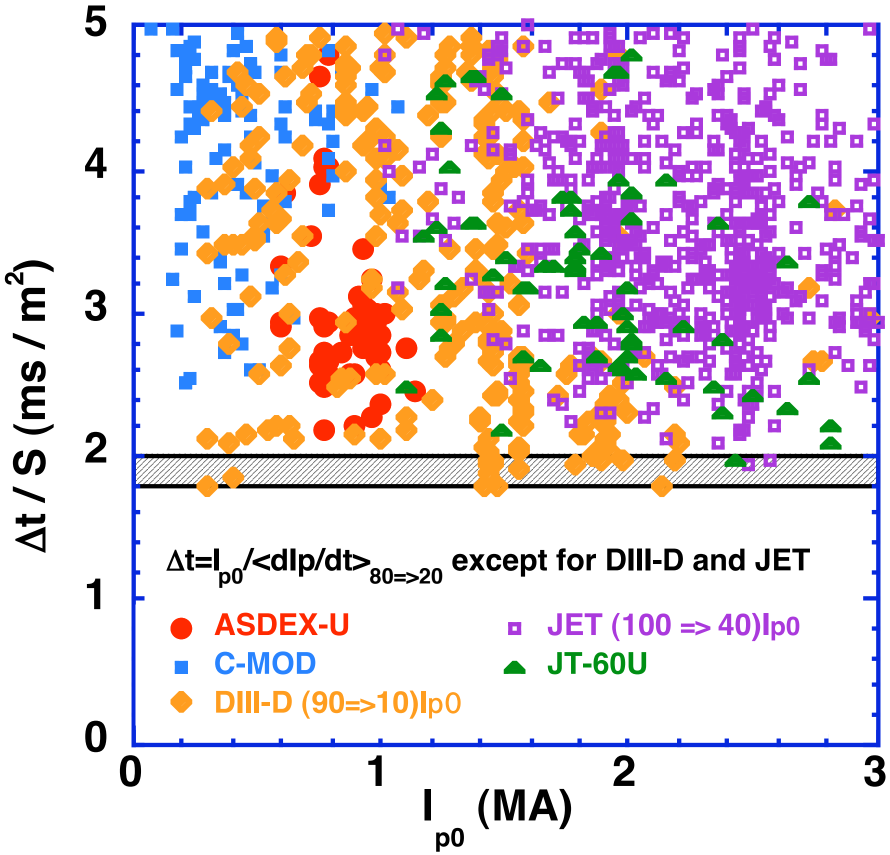
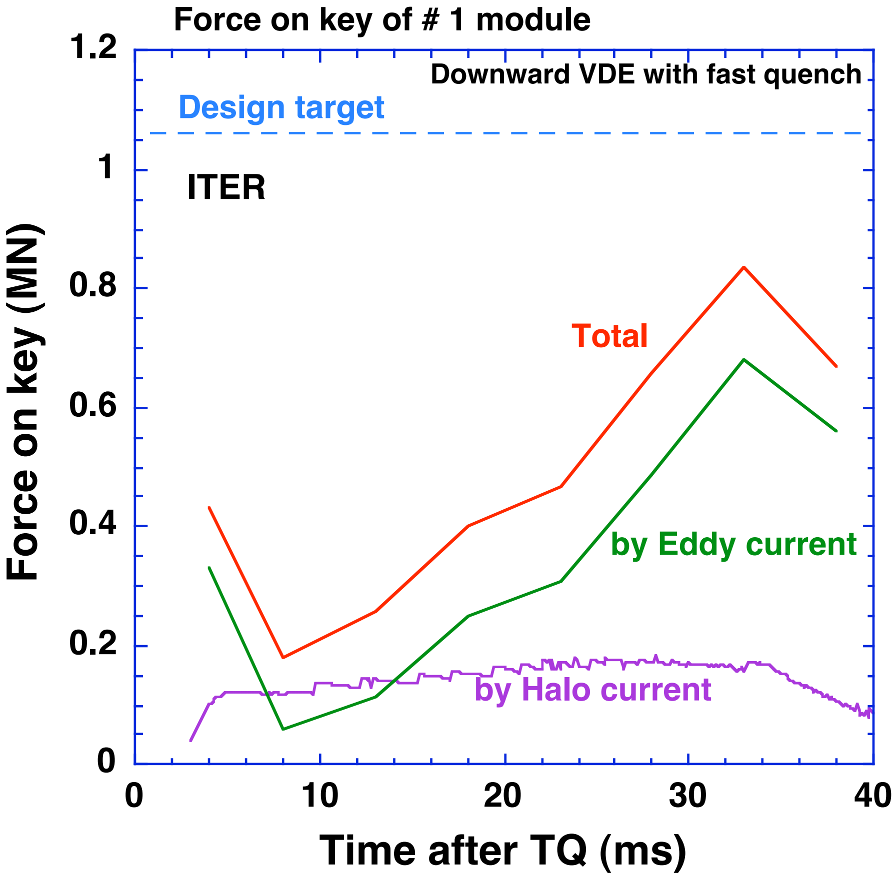


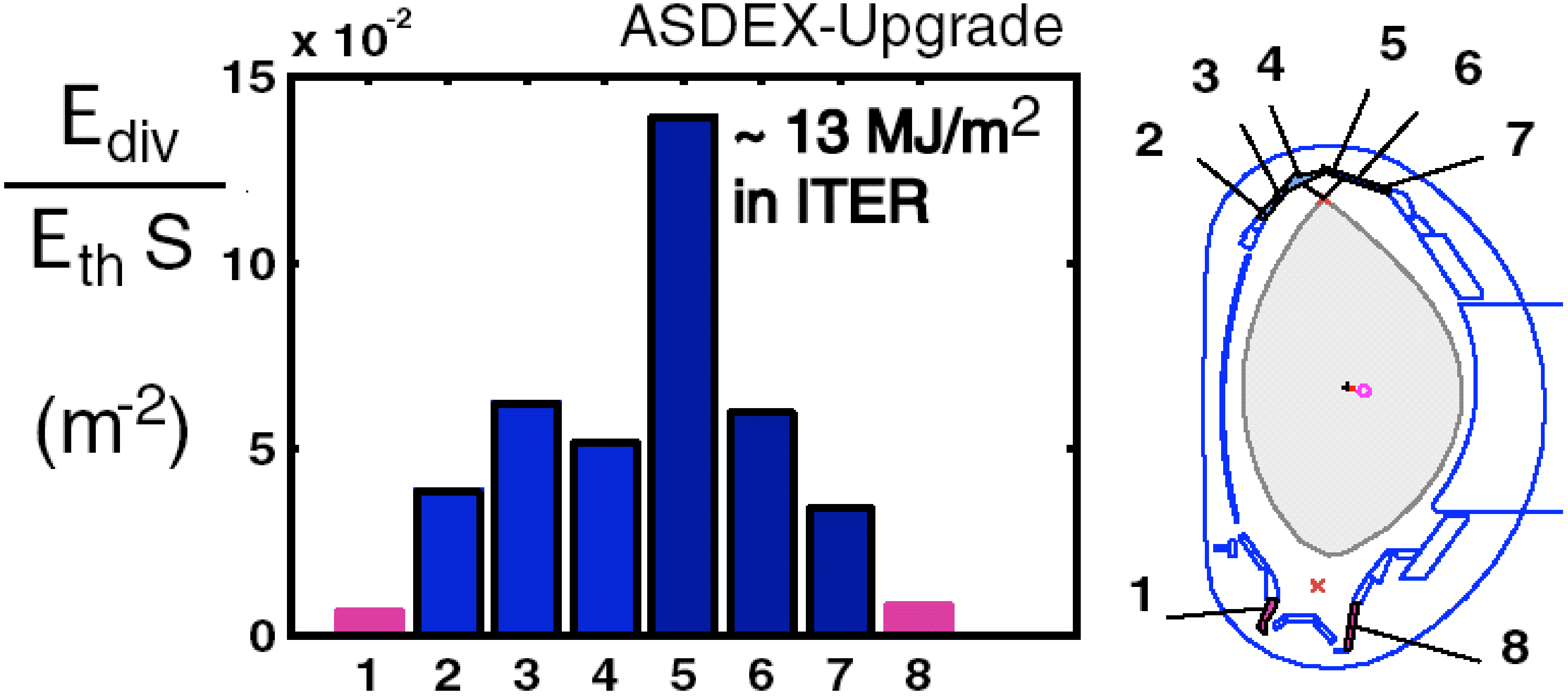
Disruptions (Electromagnetic load)





EM load has been analysed on the basis of current quench time and halo current (TPF x $I_{halo}/I_{p0} \leq 0.7$) derived from experiments. With conservative assumptions, there is a moderate margin. Mitigation system is under development (Sugihara, IT/P3-29)

Disruptions (energy load) (Loarte, IT/P3-34)



The thermal quench causes a heavy energy load on the divertor targets (30-100 % of stored energy in AUG, < 50 % in JET, 50-100 % in DIII-D), indicating that high-Z material would melt if used for ITER divertor targets. Rough surfaces would melt during normal operation

Plasma-Facing Components (initial phase)

Graphite CFC Divertor Target:

No Melting under transient Power Loads

Compatibility with wide Range of Plasma Regimes

Because of T retention, the use of CFC should be minimized.

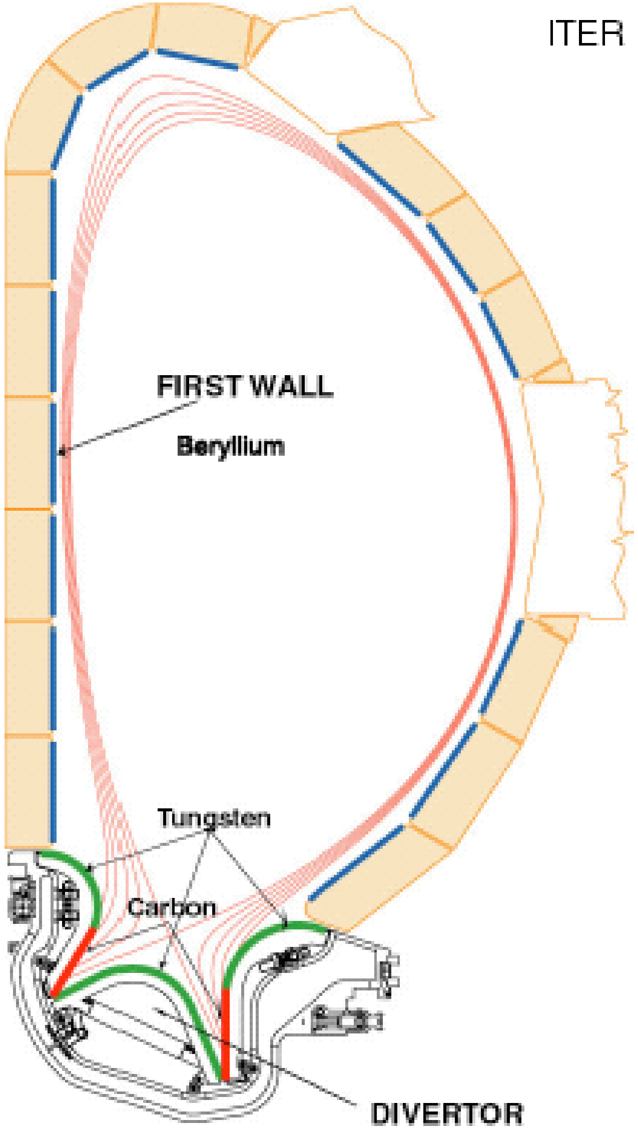
4 changeovers of divertor targets

W Baffle/Dome: low Erosion, long Lifetime

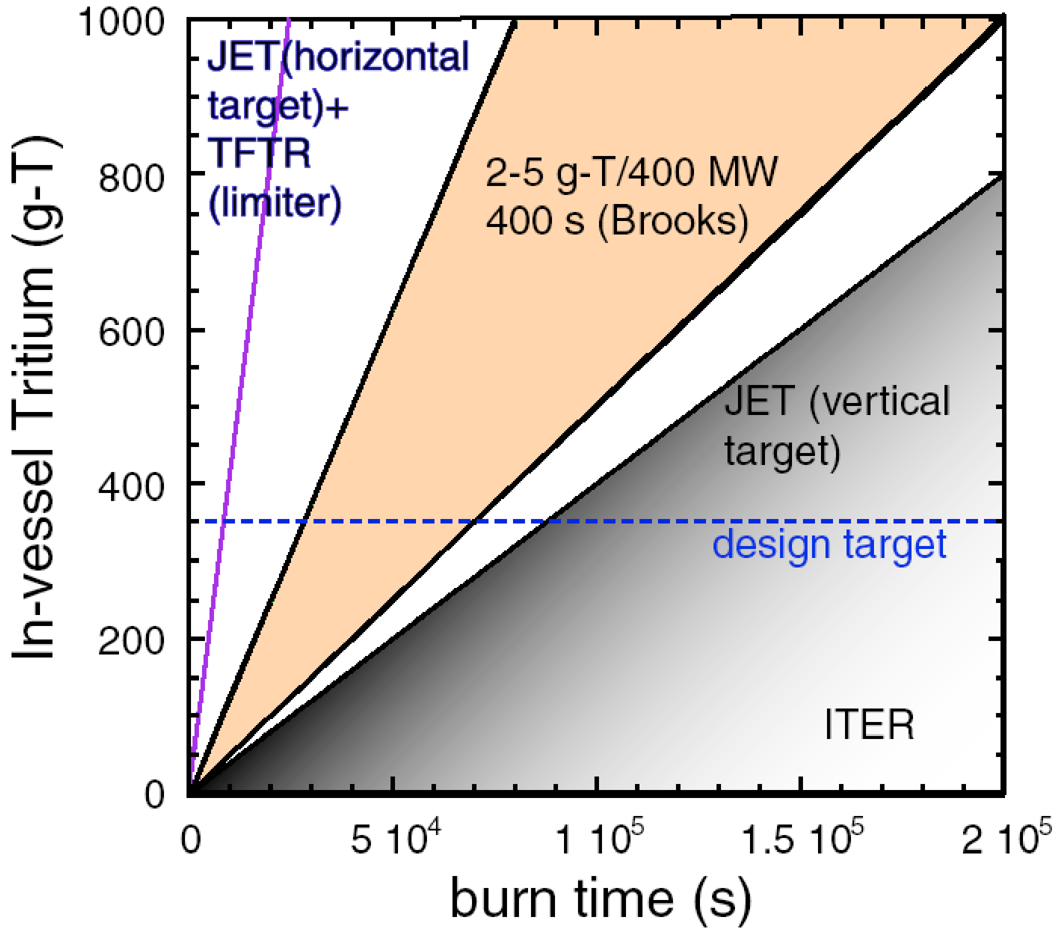
Be first wall & limiter: low Z + O_2 getter

A changeover of FW is possible in ~ 1 yr

(4 In-vessel vehicles, possibly partial replacement)



Tritium Inventory Control



A large uncertainty exists in the T build-up rate. Recent JET results show fuel retention rates of ~ 3 % or lower. This means >88,000 s available for 400 MW burn before reaching 350 gT in ITER. (Safety analysis: 1000 gT)

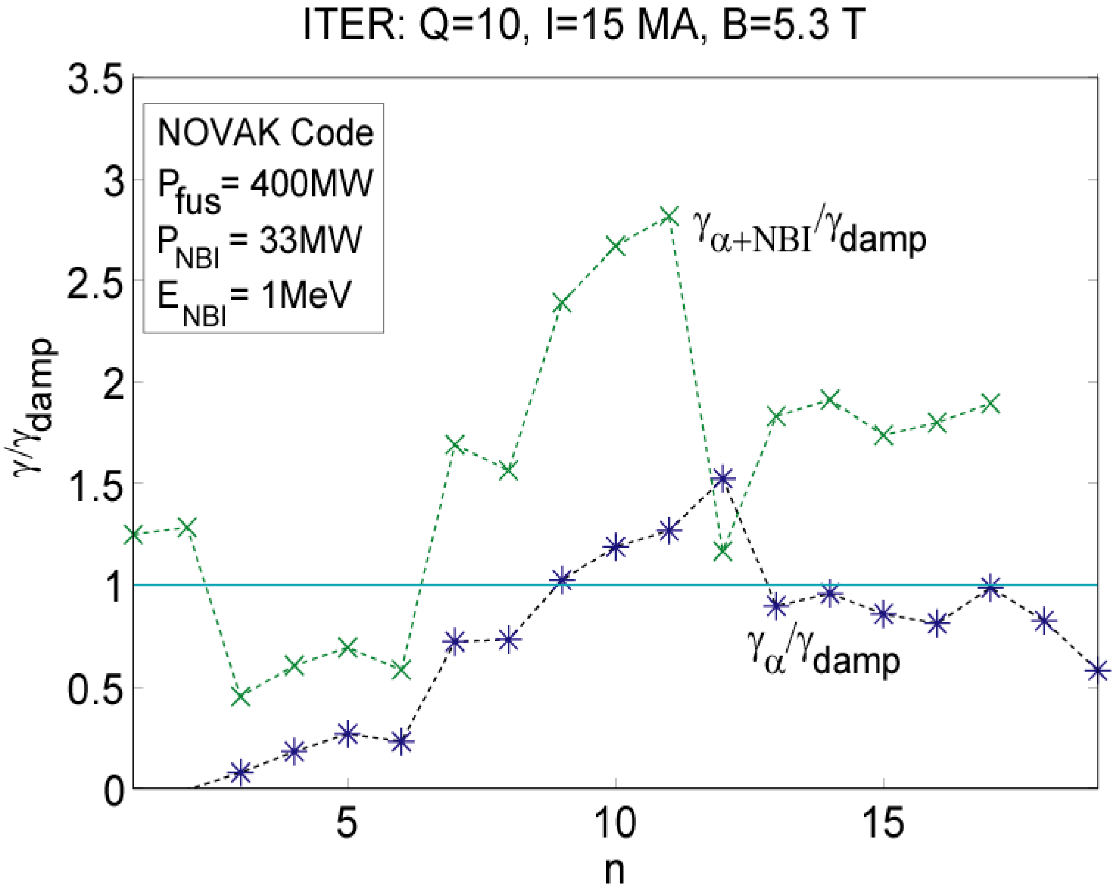
Be coverage of CFC greatly reduces T build-up (PISCES).

Development of methods to remove tritium esp. from the shadow is a high priority (e.g. Ion Cyclotron wall conditioning could remove 350 gT in ~10 days(Tore-SUPRA), but not from the shadow).

These suggest T retention is manageable during very low duty cycle experimental phase.

It is desirable to remove C targets before high duty operation.
Schemes for disruption control and impurity control should be established by then.

Instabilities driven by Energetic Particles



NOVAK analysis of Alfvén Eigenmode shows that n = 10-12 are unstable and injection of 1 MeV neutral beam would make n = 7-17 unstable in the ITER nominal inductive scenario [Gorelenkov].

In configurations with reversed shear, drift-kinetic Alfven Eigenmodes and Energetic Particles Modes could be made unstable [Briguglio, Jaun], which could set an upper limit to the minimum q-value in ITER.

Summary

- Validation of core transport models has progressed and analysis with ITER parameters confirms that the achievement of $Q > 10$ in the inductive operation is feasible.

- Improved confinement and beta have been observed with low shear (=high β_p="hybrid") operation scenarios in many tokamaks. If similar normalized parameters were achieved in ITER, it would provide an attractive scenario with high Q (>10), long pulse (>1000 s) operation with beta < no wall limit and benign ELMs.

- For improved physics understanding, more work remains in the areas of transport of momentum and particle and transport and stability in the pedestal and TAE modes. For reliable and high duty operation, further work is important to develop the control schemes of ELM, impurity, NTM, RWM, disruption and tritium retention.