ITER Design Issues and *Research Opportunities*

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by
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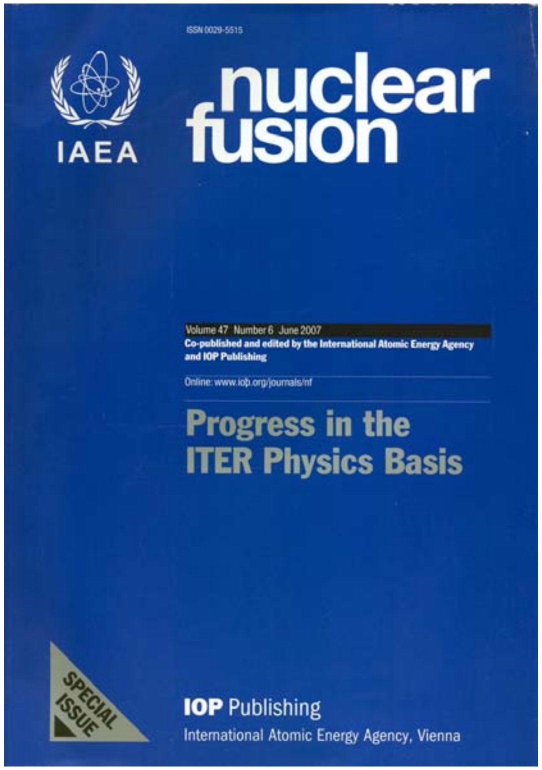
Design Review Participants: D. Campbell, G. Janeschitz, Y.Kamada, K. Lackner, G. Saibene, A. Sen, R. Stambaugh, and P. Thomas
and
EU, JA, IO and USPBPO contributors

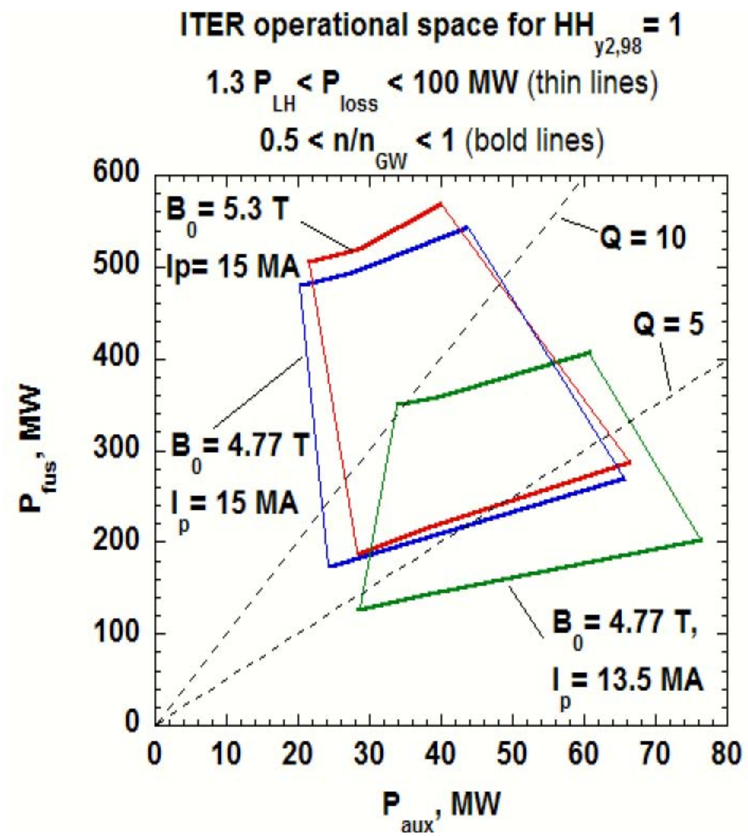
Design Review Identified Scientific Issues Requiring Near-Term Results

- **Focus of the talk is on (some) near-term research opportunities affecting design decisions in the following areas:**
  - **Confinement (sensitivity studies)**
  - **Plasma shaping and vertical stability**
  - **First wall components**
  - **Pellet pacing**
  - **ELM and RWM control coils**
  - **Disruption mitigation**

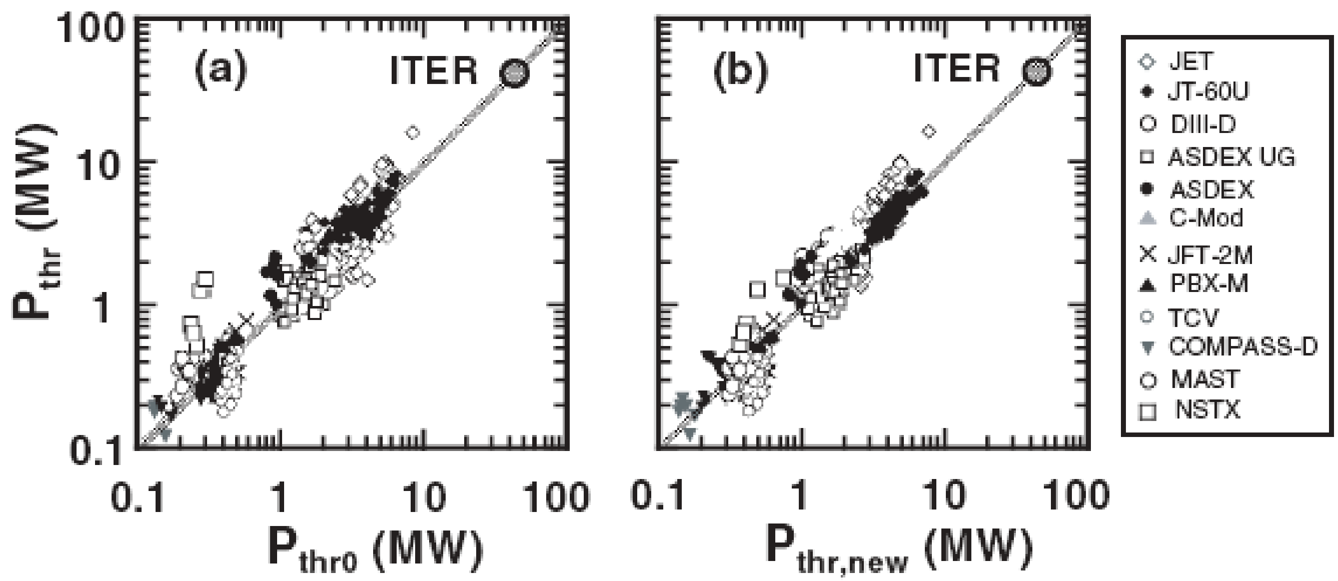


Sensitivity Studies

- **High level goals for ITER are 500 MW fusion power, Q=10, for 300-500 seconds.**
- **For the reference inductive scenario, lowering B_T and I_p by 10% reduces fusion power and Q to about 2/3 of the goals.**
- **Operating space diagrams show a healthy operating space around Q=10 shrinks to a single point at 10% less B_T and I_p.**
- **Important that ITER operate reliably at full parameters.**
- ***Research Opportunity:***
  Does low q operation provide more margin for uncertainties in confinement (17MA?) or margin for engineering issues (B_t=4.77T, I_p= 15MA)?
  Is operation at low q too prone to disruptions?



ITER Designed to Achieve H-mode in Deuterium

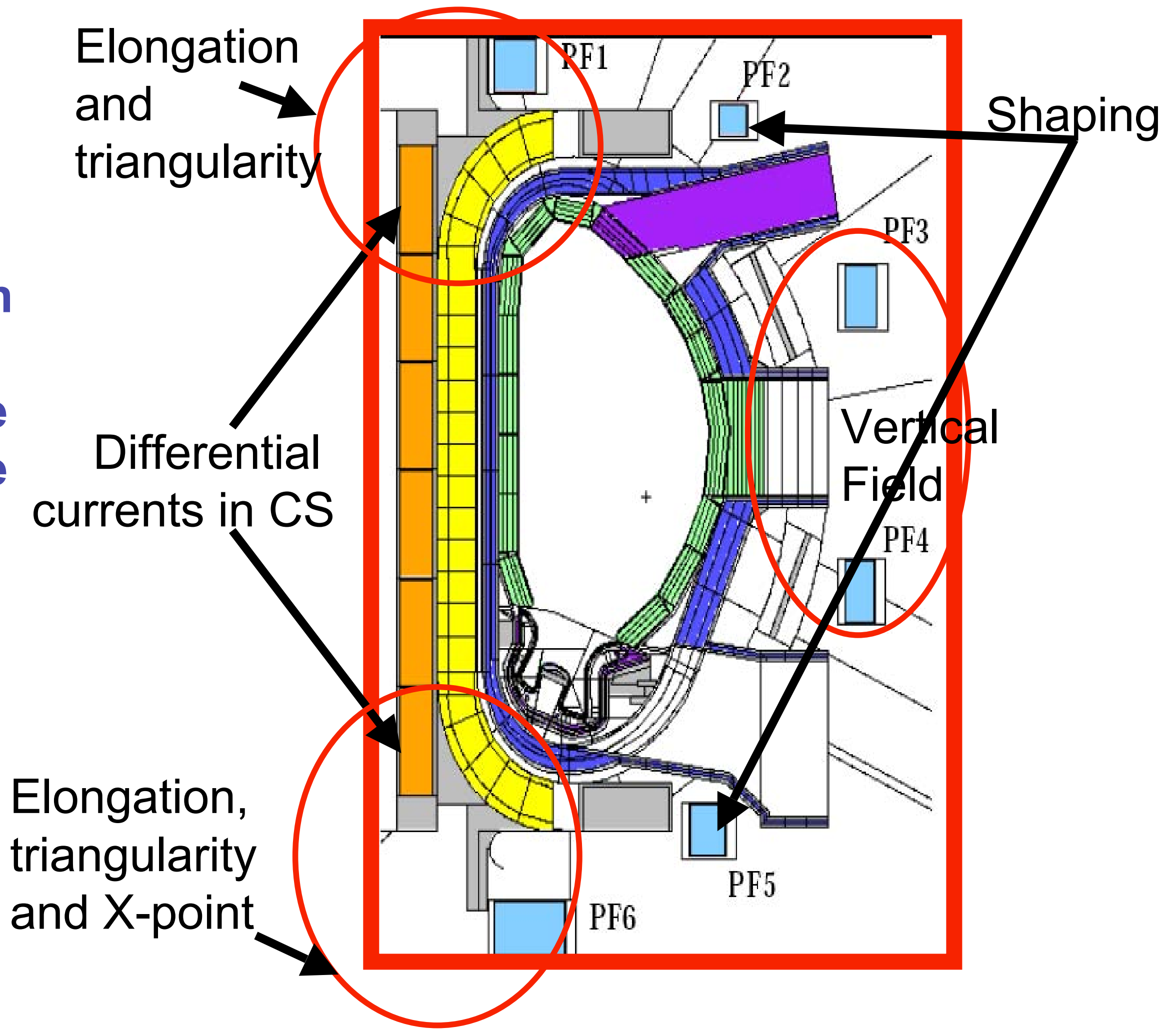


- ***Research Opportunities:***
  - What is the H-mode power threshold in hydrogen and τ_E improvement?
  - Does the threshold depend on the power to electron channel?
  - What is the threshold at low density?
  - Under what conditions is there power hysteresis?

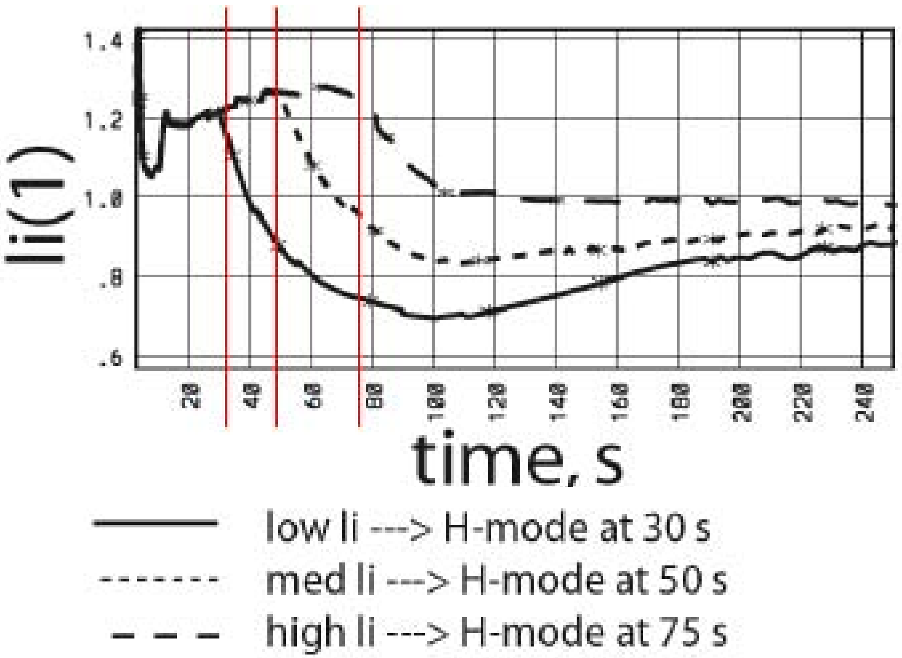
ITER PF System Has Important Ramifications for Operations

- While full discharge evolution scenarios do exist, many simulations performed of the plasma evolution show saturation of the PF currents, consequent loss of shape control and contact of the plasma with first wall PFCs for periods of seconds.

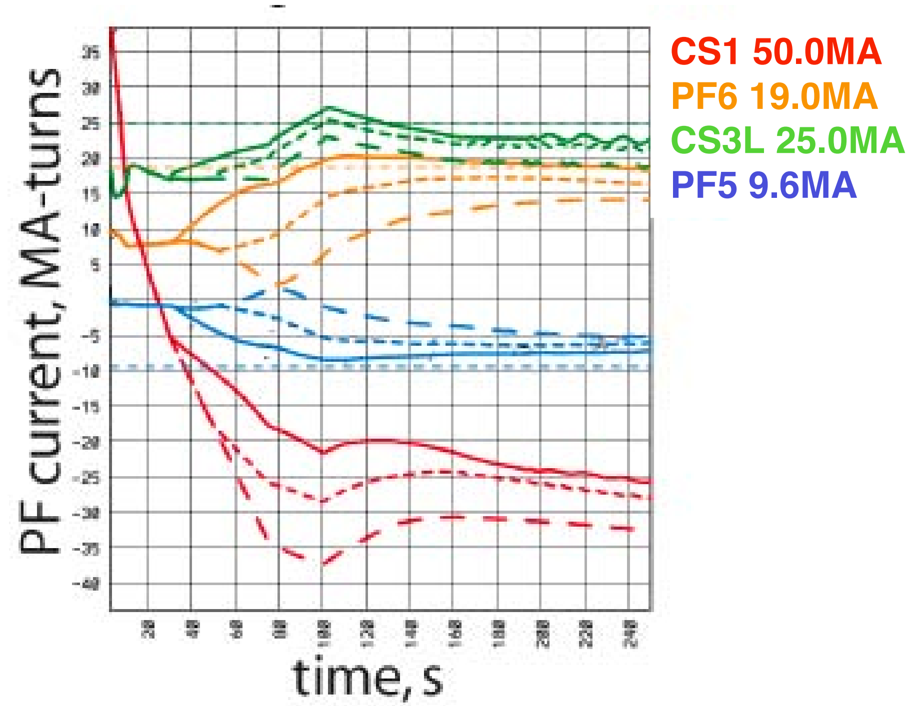
- Most usually, PF6 is the coil that saturates and, with it, PF2 and PF5. Some simulations also show saturation of PF4.



PF Coil Design Constrains
Plasma Startup and Evolution

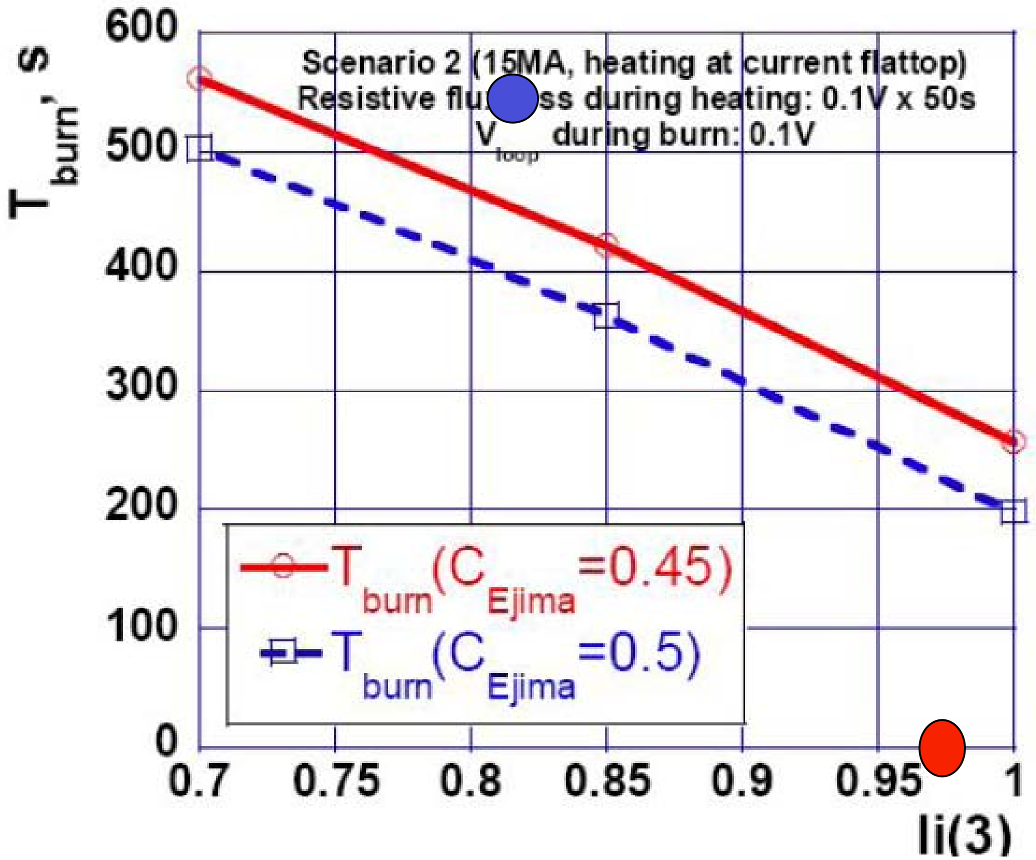


C. Kessel



- Ohmic startup with expanded aperture consumes all volt-sec during rampup. (Not shown)
- Early H-mode exceeds coil current limits (PF6, CS3L)
- TSC simulations indicate full bore startup, with intermediate to late H-mode transition and shaping change satisfies the constraints.
  - Is this sufficient experimental flexibility and are the codes accurate enough?

Pulse Duration Depends on Internal Inductance and Details of Plasma Evolution



TSC, full bore, early divert (13s), late H-mode (75s)

TSC, aperture expansion & ohmic rampup

Research Opportunity:

Verify and validate time dependent transport codes of V-sec consumption and plasma shape control.

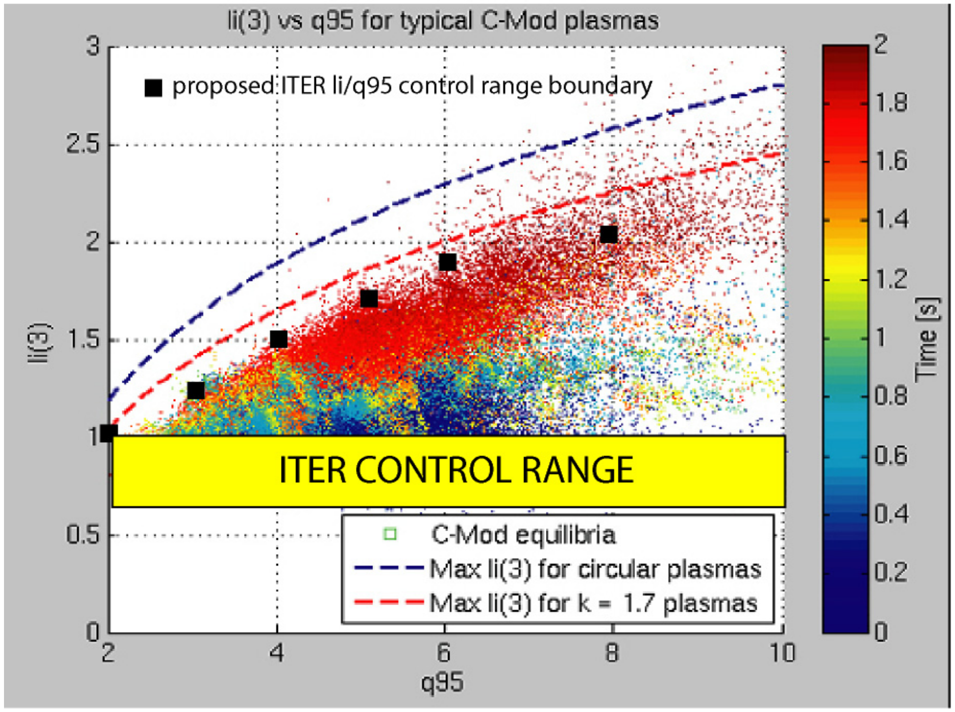
Establish routine use of transport codes to develop scenarios.

Vertical Position Control Must be Robust & Reliable in ITER

- **Loss of vertical plasma position control in ITER will cause thermal loads on PFC of 30-60 MJ/m^2 for ~0.1s.**
  - **PFCs cannot be designed to sustain (repetitive) thermal loads like those quoted above.**

- **VDE also generates the highest electromagnetic loads**
  - **A recent extrapolation of horizontal forces from worst JET cases implies horizontal loads ~70MN (~3 times larger than previous estimate) on ITER vacuum vessel.**

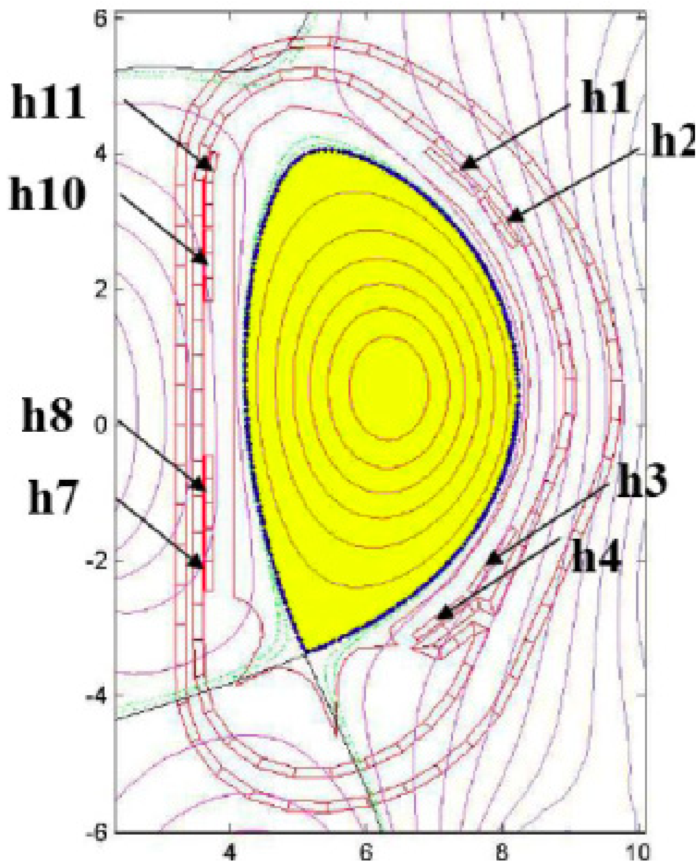
Is this correct? Substantial design implications.



Can we ensure that we will operate within the control range?

Possibly Connect Toroidal Rings of Blanket Shield Modules to improve Vertical Stability

- **Increasing PF voltage requirements may decrease reliability of coil insulation.**
- **Toroidal rings would permit ~2.5x increased vertical displacement and enable control.**



<u>Research Opportunities:</u>

- ***Verify and validate analysis used by IO to estimate vertical stability response.***
- ***Evaluate disruption loads on vessel and toroidal rings due to VDEs.***
- ***Evaluate impact on plasma startup. Where and if will breakdown occur?***
- ***Analyze equilibrium and control implications.***

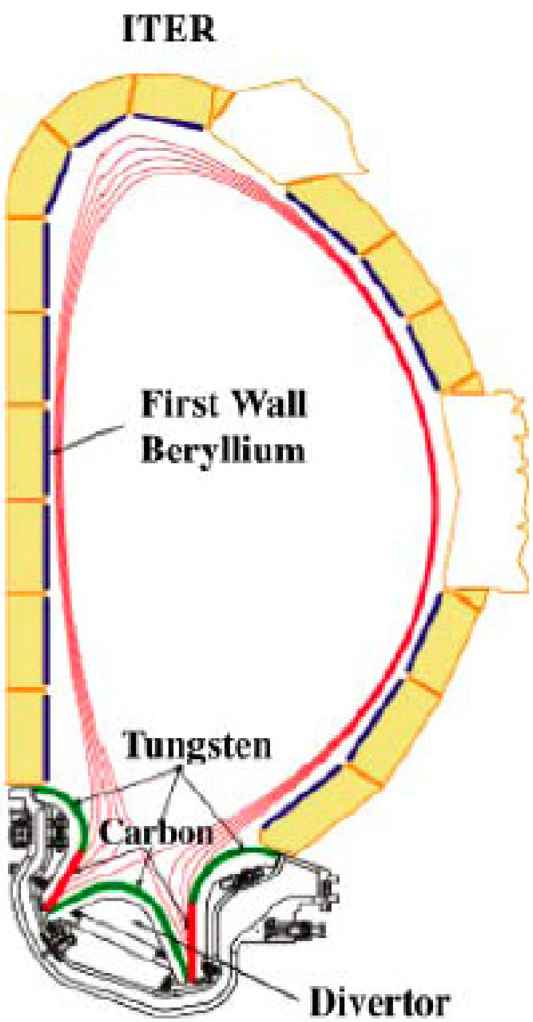
Choice of First Wall and Divertor Materials is Arguably the Most Contentious Issue

Carbon at Divertor
- Better able to handle transient heat loads (ELMS and disruptions.)
- Demonstrated tritium retention problem.

Tungsten in lower heat flux divertor zones
- Low erosion in a reactor.
- Melting and cracking
- Plasma radiation due to tungsten impurities.

Beryllium first wall
- Low Z - lowest plasma radiation.
- May melt even as a result of disruption mitigation.

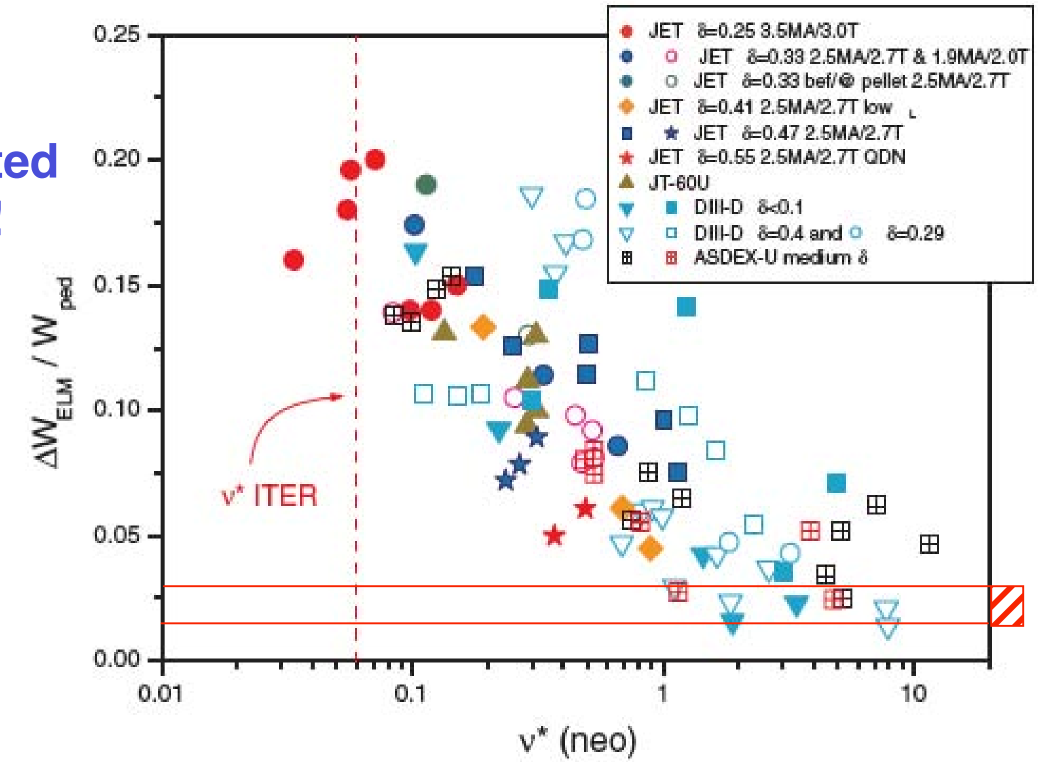
Research Opportunities:
- *Behavior of mixed materials.*
- *In-situ measurement, retention and removal of tritium.*
- *Wall conditioning techniques*
- *Heat load requirements*



Control of Type 1 ELMs Is a Pressing Issue for ITER

Loarte et al., Nuclear Fusion, ITER Physics Basis,Chapter 4

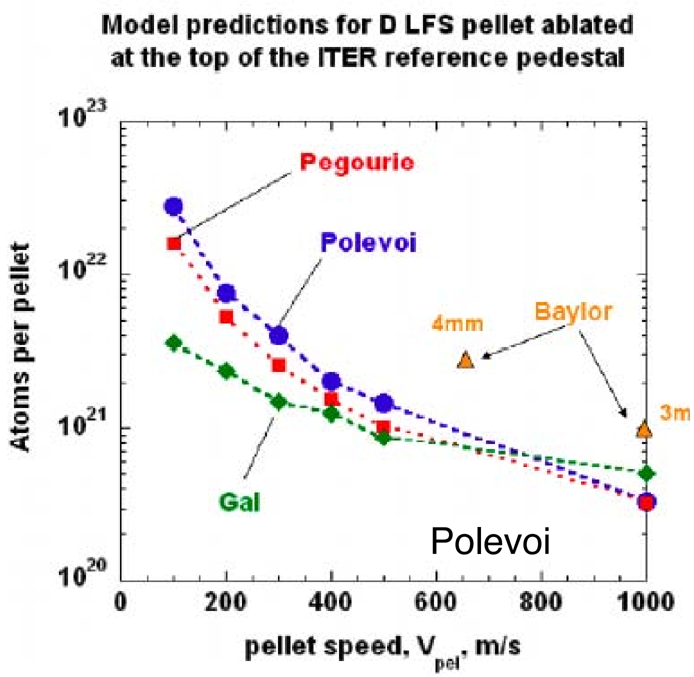
Projected ~20MJ!

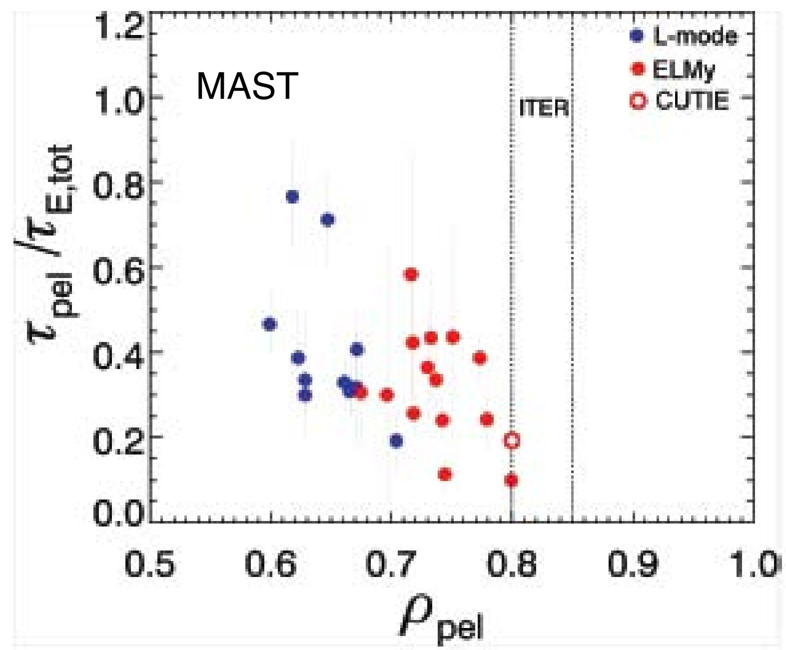


Acceptable Value ~1MJ

Recent results reduced the acceptable energy loss from ELMs. Reducing the energy loss to <1MJ using pellet pacing is challenging. DIII-D experiments have stabilized ELMs by Resonant Magnetic Perturbation (RMP) coils.

Is Pellet Pacing Consistent with the Fueling and Pumping Requirements for ITER?





- Pellet pacing is planned to control ELMs.
  - For <1MJ ELMs, estimate 40 Hz compared with ~4Hz in current design at the top of the pedestal.
- Implies 4 10 ^{22} to 1.2 10 ^{23} atoms/s, ignoring loss in flight tube at 500m/s.
- According to Valovic the MAST data extrapolates to 3.7 10^{22} atoms/s for core fueling.
  - Major extrapolation from MAST to ITER.

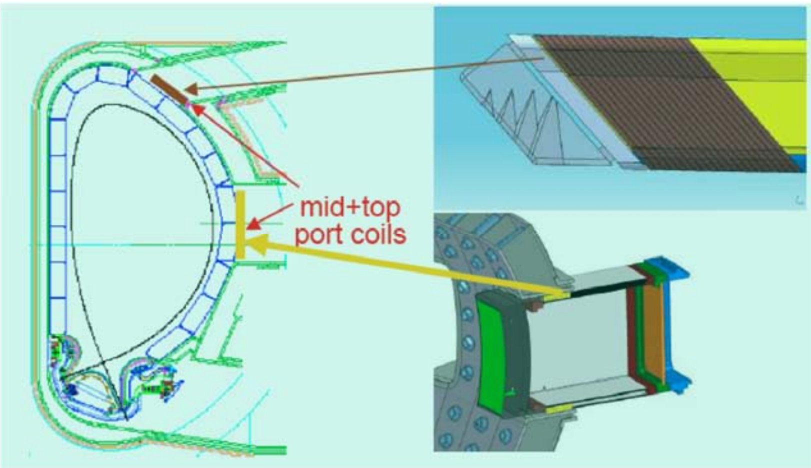
A Design Change Request (DCR) on Pellet Pacing was Submitted

- **The fueling rate was increased last week to 200 Pa•m^{3}s^{-1}.**
  - **Decision on increasing the number of pellet injectors was deferred.**

- ***Research Opportunities:***
  - **Depth of pellet penetration required**
  - **Mass retained (drifts/redistribution) and convected power**
  - **Particle transport coefficients.**
  - **Recycling and divertor behavior.**
  - **Need for a consistent edge-core simulation.**

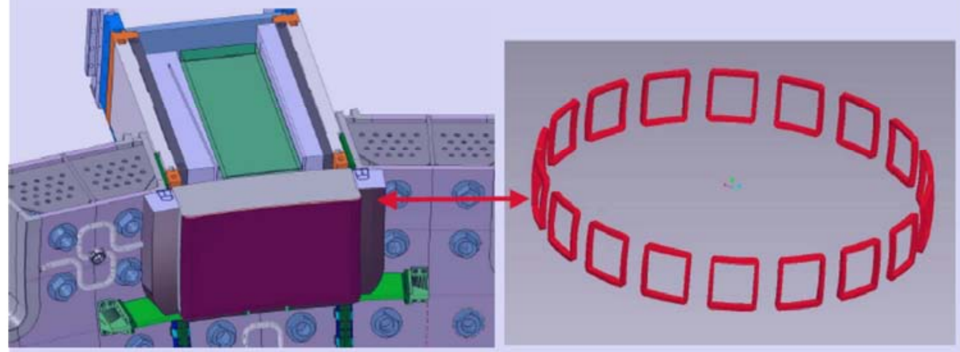
  - ***Impact on edge pedestal parameters when pellet repetition time corresponds to 1% of $\tau_{E.}$***
  - ***Can we preserve good H-modes?***

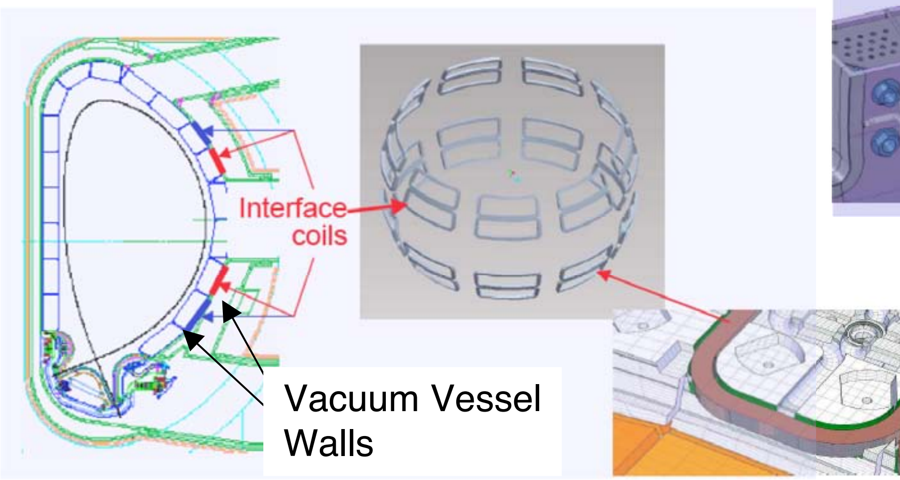
Resonant Magnetic Perturbation (RMP) Coils to Suppress ELMs Proposed for ITER



14 Outer Midplane Port Plug Coils
300 kAt required

18 Outer Midplane Port Frame Coils
100 kAt required





(4 rows x 9 toroidal) Blanket-Vessel Interface Coils
55 kAt required

D. Loesser and J. Smith

Minimum island overlap region width requirement based on DIII-D data used to estimate current requirements.

Implications of Recent Physics Analysis for ITER RMP Coils

- Upper port plugs do not provide sufficient benefit for RMP.

- The depth of penetration of the perturbed field is minimized for the blanket-vessel interface coils.
  - Less likely to lock the plasma or destabilize NTMs

- The non-resonant braking associated with the equatorial and picture frame coils is substantially higher than from the blanket-vessel interface coils.
  - Further analysis required to take into account different plasma parameters including collisionality.

- Midplane coils on DIII-D, JET, NSTX, and MAST did not stabilize ELMs
  - Only successful coil configuration to date for ELM suppression has been the DIII-D I-coils, two rows of off mid-plane coils.

- Best option for ELM control is blanket-vessel interface coils.
  - Concluded that we do not have an experimental or theoretical basis for equatorial (or equatorial plus upper) coils to suppress ELMs.

Recent Developments on RMP Coils for ITER

- Project decided to focus effort on port-plug coil.
  - Main reason was to avoid delaying the vessel procurement.
  - Remote maintenance of coils behind the blanket shield modules.

- ITER Scientific and Technical Advisory Committee met and recommended that coils located between the vessel walls be examined.
  - Vacuum vessel coils are now being explored.

- *Research Opportunities:*
  - What determines the operating window to stabilize ELMs?
  - What is the impact of RMP coils on toroidal rotation, plasma braking and locked modes?
  - Compatibility with pellet fueling.
  - Can port plug coils work?

- US and EU made major technical contributions during the past several months.
  - Now we need to bring this effort to closure.

USBPO Has Led the Effort on Analyzing Resistive Wall Mode (RWM) Stabilization

- **RWM stabilization is required to explore ITER steady state operating modes when the no-wall limit is exceeded.**

- **Most capable system would be a combination of 7 dedicated midplane and 9 upper coils dedicated to RWM stabilization.**
  - β_N **<3.8**
  - **upper coils may counteract effects of mode non-rigidity observed on NSTX.**
  - ***Need further effort to determine need for upper coils.***

- ***Need to analyze the option of using the coils between the vessel walls.***

Massive Gas Injection Has Been Used to Successfully Mitigate Disruptions

- Experiments on C-Mod and DIII-D have used massive gas injection to mitigate disruptions.
  - Accompanied by short current decay time and radiative loss of plasma and poloidal magnetic energy.
  - Detection of "control-issue" disruptions (e.g. VDE) should be reliable, and mitigation possible, due to long ITER timescales.
  - Necessary part of PFC/FW protection.
- The current and major radius of ITER is a substantial extrapolation from existing machines.
  - Analysis by Wesley and Whyte has been incorporated into the ITER Physics Guidelines for gas load requirements.
  - Large impact on vacuum and tritium systems needs to be addressed.

- ***Research Opportunity***
  - Are the runaways well confined, as assumed in the Rosenbluth-Wesley estimate?
  - Exact current quench rates (halo currents)
  - What fraction of the injected gas is "assimilated" into the plasma?
  - What is the optimal gas or gas mixture? Should pellets be used?

Design Review Has Identified Important Research Opportunities

- Design review process has been valuable in not only identifying issues but also engaging the international community.

- Project is interested in getting best technical input.
  - Pushback on incorporating new systems is to be expected.
  - Raises the threshold for a compelling case.

- Changes to ITER requirements need international support and IO support.
  - Need to work closely with IO.
  - Challenge to incorporate cutting edge results when an international consensus has not been achieved.

- USBPO has been effective in providing input to IO
  - Need an ongoing long-term mechanism to incorporate into the ITER design and research plans our best understanding and make timely assessments.