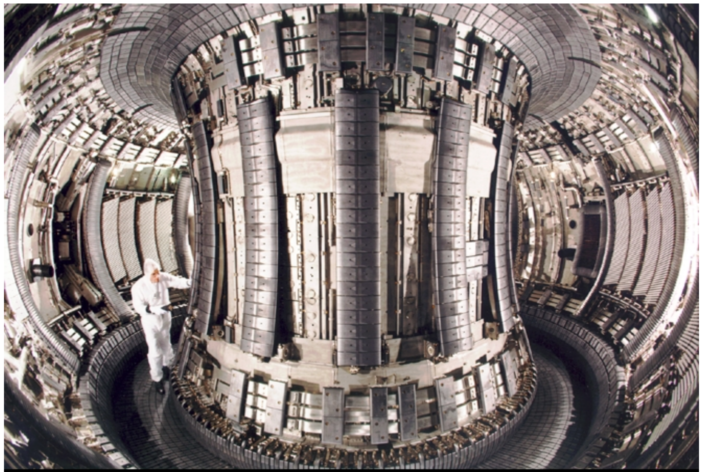
# Advances in burning plasma-related physics and technology in Magnetic Fusion

**Amanda E. Hubbard,**
*MIT Plasma Science and Fusion Center*

**AAAS 2013**
**Fusion Energy Symposium**
February 16, Boston, MA

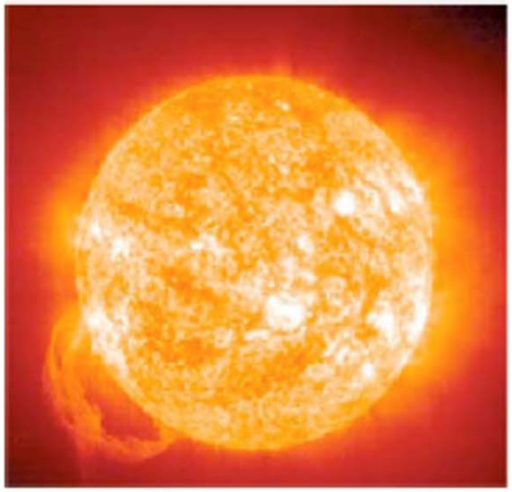

Inside the Joint European Torus (JET) vacuum vessel, JET Joint Undertaking, UK

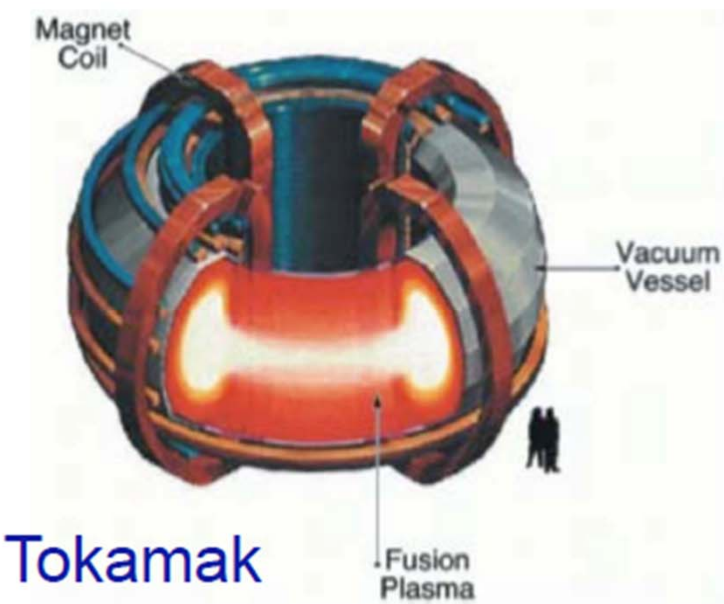
Thanks for input from many colleagues, including N. Howard, J. Hughes, B. Lipschultz, J. Minervini, A. White (MIT), A. Diallo, PPPL, K. Burrell, C. Greenfield, D. Hill, G. Staebler (GA), J. Van Dam (DOE FES), F. Romanelli (EFDA-JET), G. McKee, R. Fonck (U. Wisc), D. Meade (FIRE), R. Hawryluk (ITER), T. Eich (IPP Garching)

# OUTLINE

- **What is required to make a plasma "burn"?**
  – Key challenges in creating a burning plasma in ITER.
- **Examples of recent progress in meeting these challenges.**
  – Validation of core turbulence models.
  – Predictions of edge transport barriers.
  – Avoidance of edge transients.
  – Understanding boundary heat flux.
  – Operation with ITER wall materials.
- **Physics and technology challenges for fusion, beyond ITER.**

# Burning plasma: self-heated by fusion reactions of thermal ions






Lab fusion reaction of choice: DT

$$ {}_1D^2 + {}_1T^3 \rightarrow \underbrace{\underset{(3.5\text{ MeV})}{{}_2He^4} + \underset{(14.1\text{ MeV})}{{}_0n^1}} $$

Energy/Fusion: $\varepsilon_f = 17.6$ MeV

**Fusion energy Gain:** $Q \equiv \dfrac{P_{fusion}}{P_{heat}} = \dfrac{5\,P_\alpha}{P_{heat}}$

**Alpha heating fraction:** $f_\alpha \equiv \dfrac{P_\alpha}{P_\alpha + P_{heat}} = \dfrac{Q}{Q+5}$

| | | |
|---|---|---|
| **Breakeven** | Gain =1 (~now) | $f_\alpha$ = 17% |
| **Burning Plasma Regime** ↓ | Gain=5 | $f_\alpha$ = 50% |
| | Gain=10 (ITER) | $f_\alpha$ = 66% |
| | Gain=20(reactor) | $f_\alpha$ = 80% |
| | Gain=∞(ignition) | $f_\alpha$ =100% |

# A burning plasma requires sufficient temperature, density and confinement time

**Power balance determines requirements for fusion:**

**Lawson Criterion $n\,\tau_E\,T_i > 5\times10^{21}$ for Q=10** *Where are we?*

**$T_i$=central ion temperature**

(1 eV=11,600 K, 1 keV=$1.16\times10^7$ K)

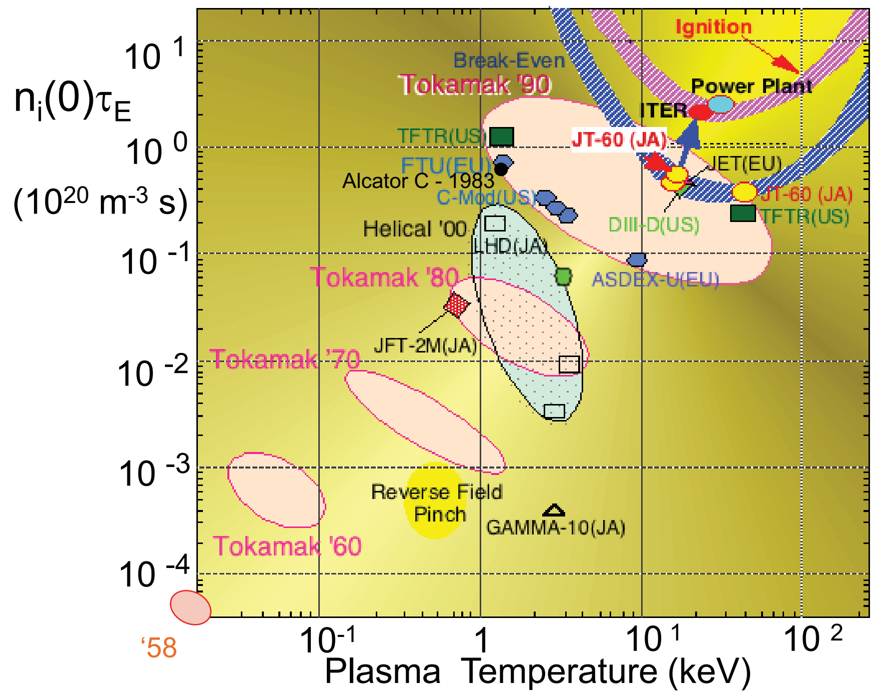
- Optimum is set by D-T cross-section. **10-20 keV ~ 116-230 million K**

✓ Has been exceeded on current large experiments (~ 45 keV on TFTR, JT60-U)

**n=ion density ($m^{-3}$)**

- Maximum stable density is set by device size and current. **For ITER ~ $10^{20}$ $m^{-3}$.**

✓ Absolute density often exceeded in smaller experiments, and density relative to limit reached.

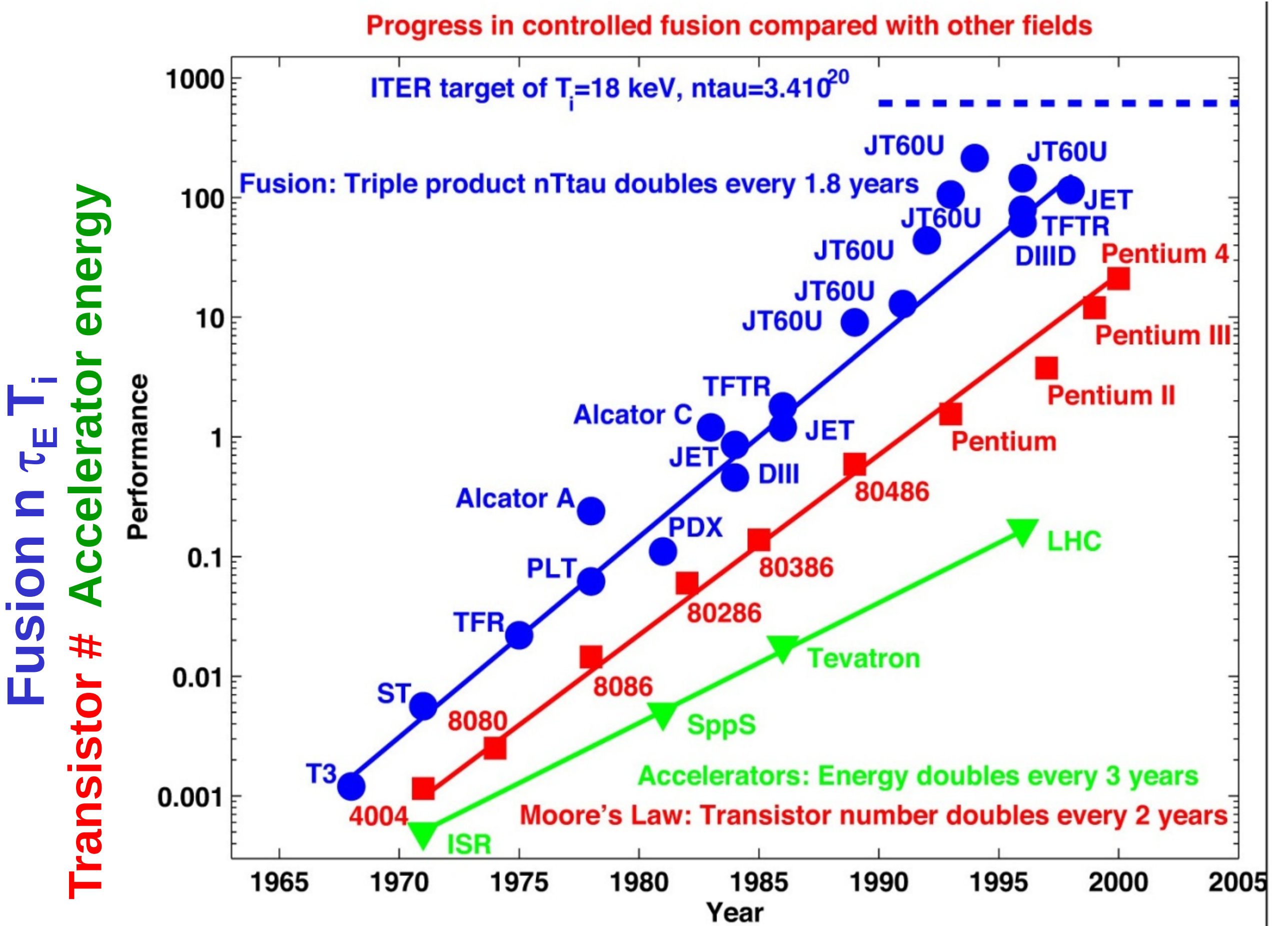



**$\tau_E$ = "confinement time (s)= Stored Energy/input power**

**=>Need $\tau_E$ ~ 3-4 sec.**

X Up to 1 sec in present largest tokamaks. $\tau_E \sim R^2 I_p$. **Size matters!** Sets parameters of ITER.

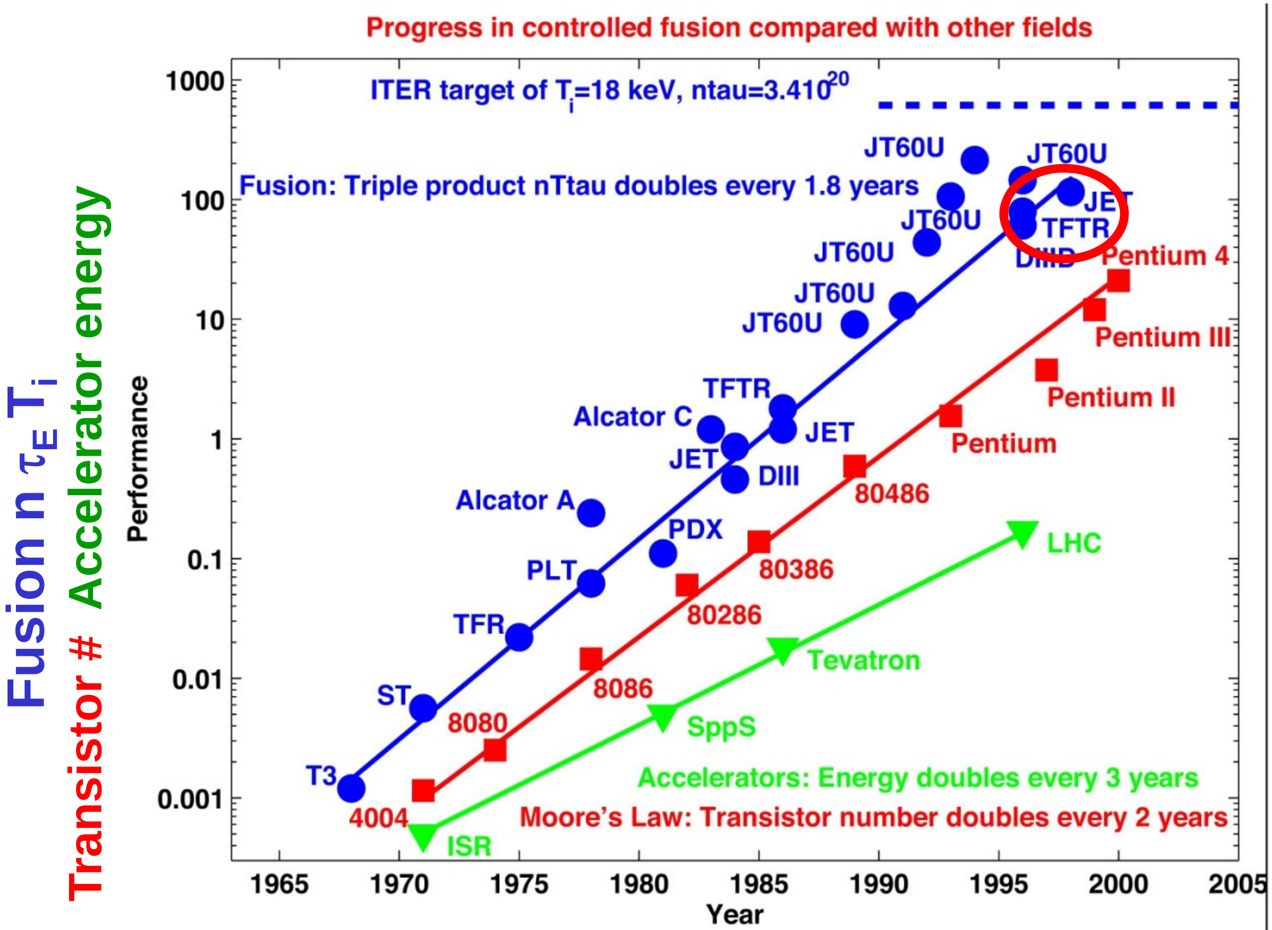
# Worldwide progress in fusion performance has been dramatic




- **Progress in magnetic fusion has increased $n\,\tau_E\,T_i$ by>5 orders of magnitude, doubling every 1.8 years.**
- Remaining step is modest (but is requiring a big investment).

ITER Newsline
Oct 2008

# Worldwide progress in fusion performance has been dramatic




ITER Newsline
Oct 2008

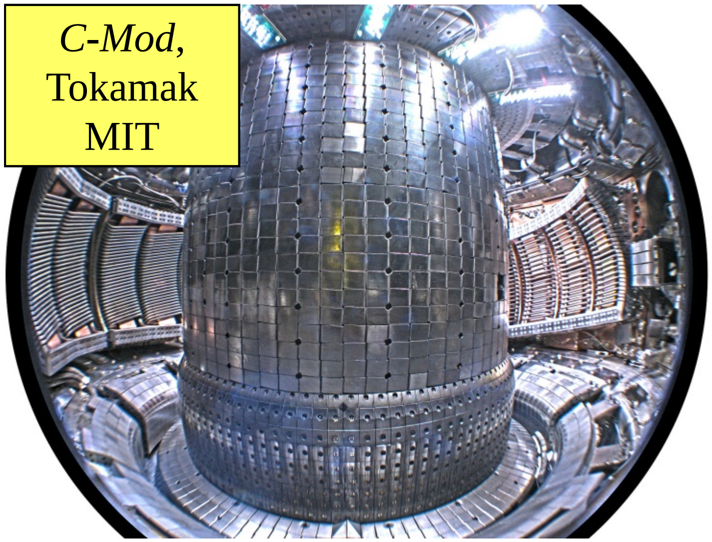
- **Progress in magnetic fusion has increased n $\tau_E$ $T_i$ by>5 orders of magnitude, doubling every 1.8 years.**
- Remaining step is modest (but is requiring a big investment).
- JET and TFTR used D-T fuel, **producing actual fusion power, up to 16 MW and 20 MJ per pulse**.

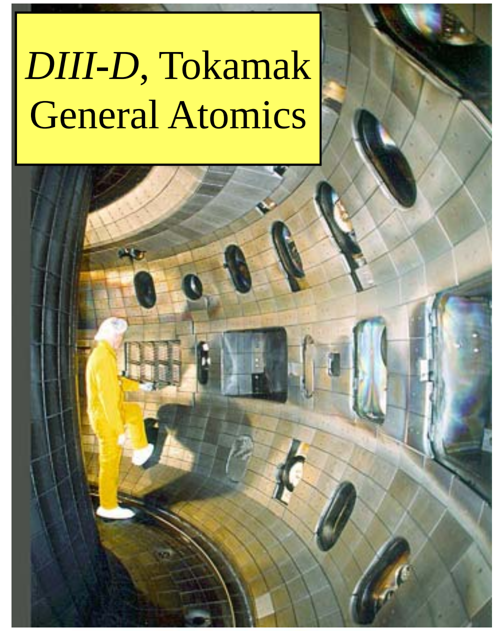
# Large size and stored plasma energy bring new challenges for fusion

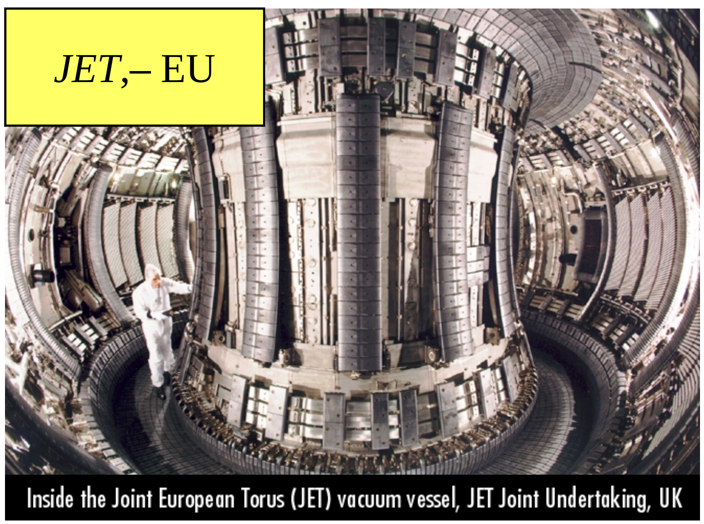
- Empirically and theoretically, $\tau_E$ increases with major radius. **ITER R is > twice largest present tokamak,** about the size of a fusion power plant.
- Volume increases by $R^3$ (x 10), Surface area only by $R^2$.
- **Stored energy is >20 x higher than max today.**
- This means that the potential for damage if stored energy is released is much higher; *need to avoid transients.*
- Size is also larger compared to natural plasma scales such as gyroradius. *Affects on confinement and stability are quite well understood.*

| | **C-Mod (small) US** | **DIII-D (med) US** | **JET (large) EU** | **ITER** |
|---|---|---|---|---|
| R (m) | 0.68 | 1.75 | 2.96 | **6.2** |
| $I_p$ (MA) | 1.4 | 1.5 | 5 | **15** |
| B (T) | 5-8 | 2.1 | 3.5 | **5.3** |
| Vol ($m^3$) | 1.0 | 22 | 100 | **830** |
| S ($m^2$) | 7 | 60 | 200 | **680** |
| Heating Power (MW) | 7 | 24 | 40 | **50 in 150 out** |
| Energy $W_{th}$ (MJ) | 0.25 | 4 | 14 | **320** |
| Energy/S (MJ/$m^2$) | 0.035 | 0.07 | 0.07 | **0.47** |

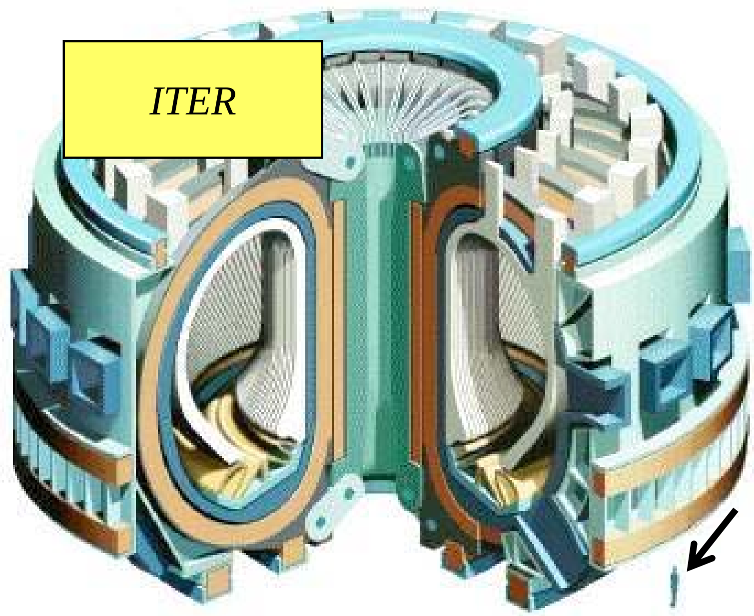
# Many tokamaks worldwide are addressing these challenges together



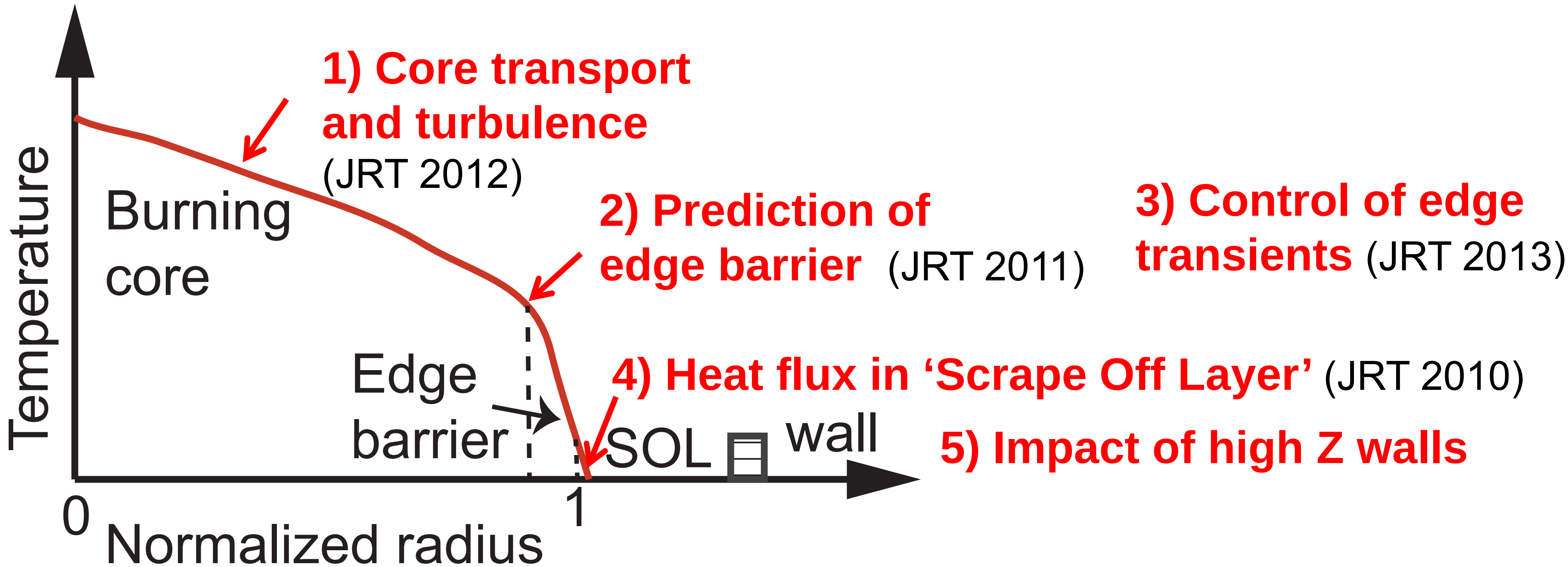



Inside the Joint European Torus (JET) vacuum vessel, JET Joint Undertaking, UK



# Issues for ITER are being addressed by a coordinated R&D program

**In this talk, I will cover:**

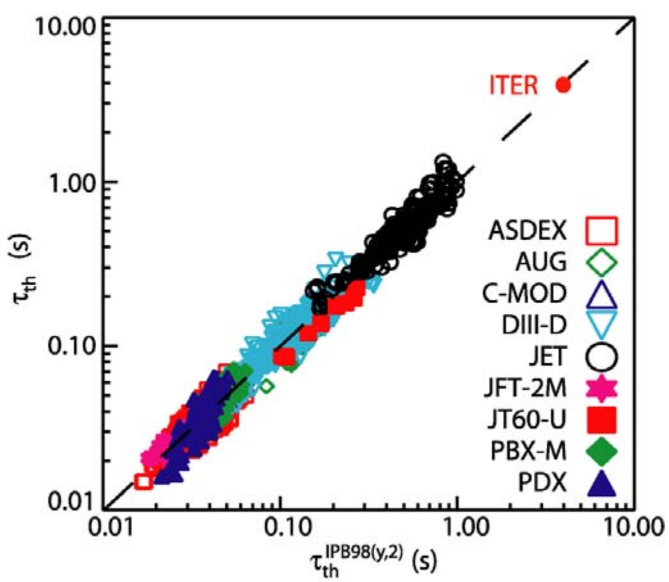



- Several of these topics were the subjects of US "Joint Research Targets", in which coordinated experiments on multiple facilities, combined with theory and simulation, yielded major advances in understanding and prediction.

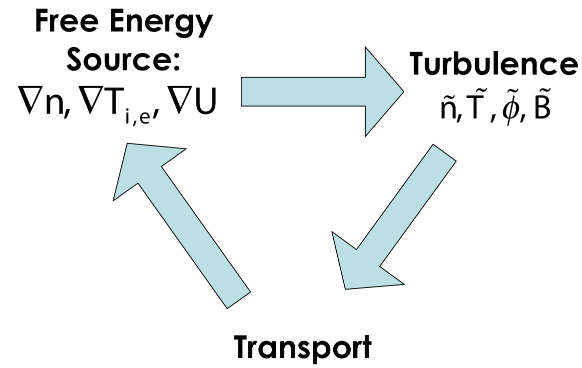
- Research is also coordinated via the International Tokamak Physics Activity and US Burning Plasma Organization.

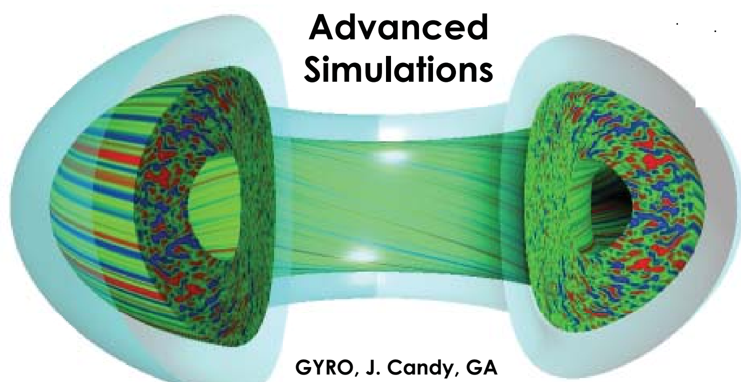
# First-principles models of core transport are being validated with detailed turbulence measurements

- In 1980-90's, fusion relied on empirical scaling of global $\tau_E$.
- Did not reveal underlying physics, separate transport channels.
  *Could regime change at large size? With electron vs ion heating?*

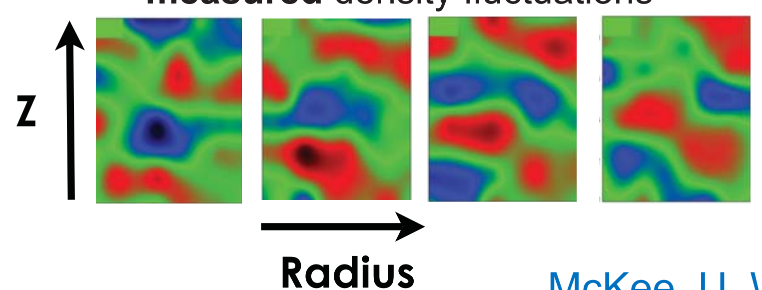



- **Plasma transport is mainly due to turbulence.**
- Low turbulence
  ⇨ Low transport
  ⇨ High confinement $\tau_E$




**measured** density fluctuations

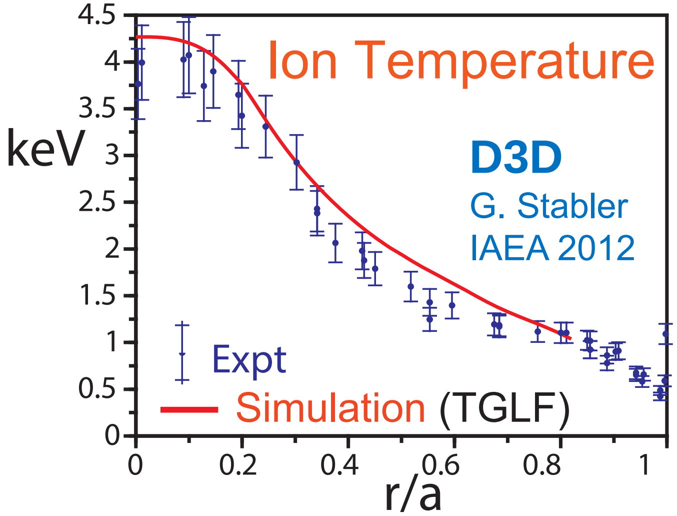


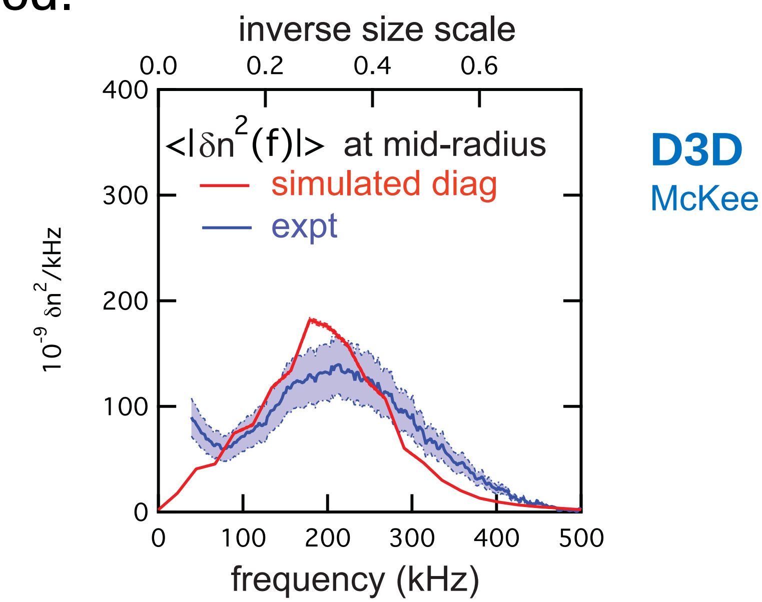

We now have **first-principles models**, and excellent **diagnostics** of turbulence of many parameters (n, T etc) and size scales (cm to sub-mm)

McKee, U. Wisc, APS review

# Core transport comparisons are revealing strengths and weaknesses of turbulence models.

- Predictions of **heat transport via ION channel** in the hot core and of larger scale turbulence are generally good.



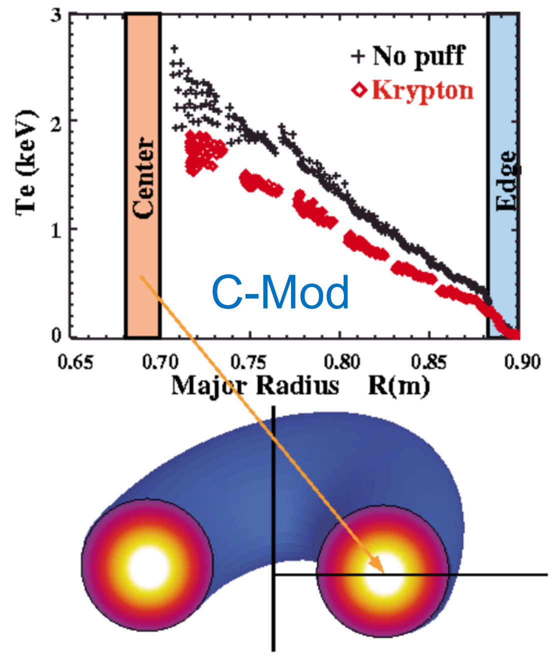




- **Heat transport via ELECTRON channel**, and due to smaller-scale turbulence, are often less accurately predicted.
- For the first time, can also predict and measure **particle transport** (diffusion and convection of main fuel ions and impurities). Good agreement so far.
- And, we are **learning to control, reduce transport.**

# Prediction of edge barrier or 'pedestal' is critical

- Core turbulence models do NOT predict the barrier region of the edge where turbulence is suppressed, and gradients steepen, improving confinement.

- The top of this barrier forms a boundary condition to core turbulence, and affects the gradient of the whole profile.

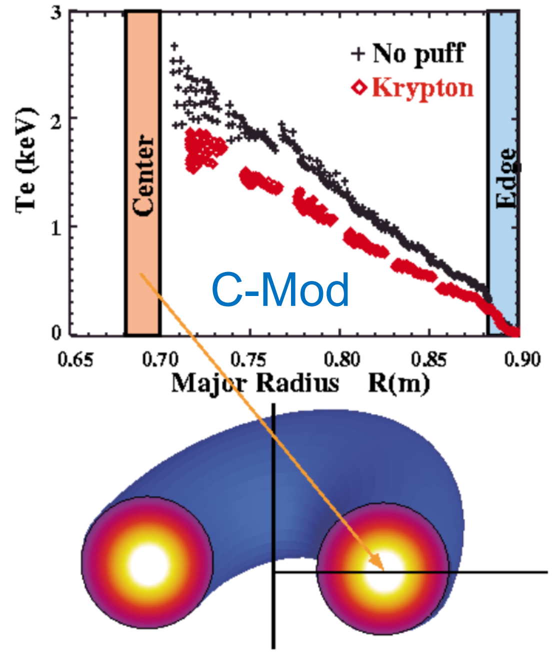


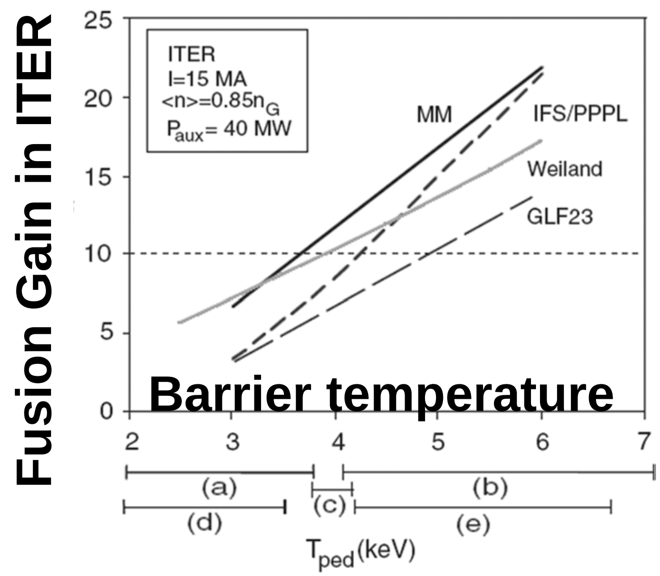
# Prediction of edge barrier or 'pedestal' is critical

- Core turbulence models do NOT predict the barrier region of the edge where turbulence is suppressed, and gradients steepen, improving confinement.

- The top of this barrier forms a boundary condition to core turbulence, and affects the gradient of the whole profile.

- Until a few years ago, predictions varied widely ($T_{ped}$ ~2-7 keV), and were largest source of uncertainty in predictions for ITER.



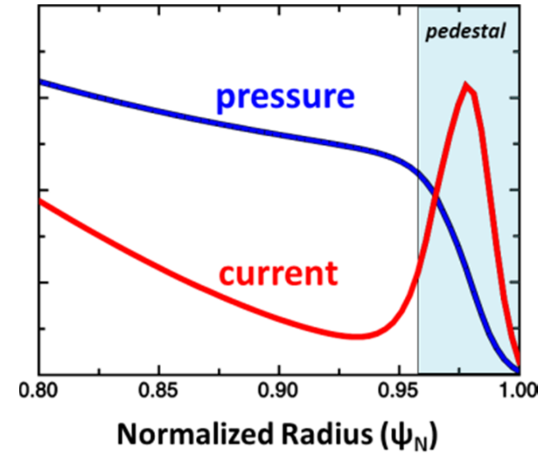

Progress in ITER Physics Basis (2007)

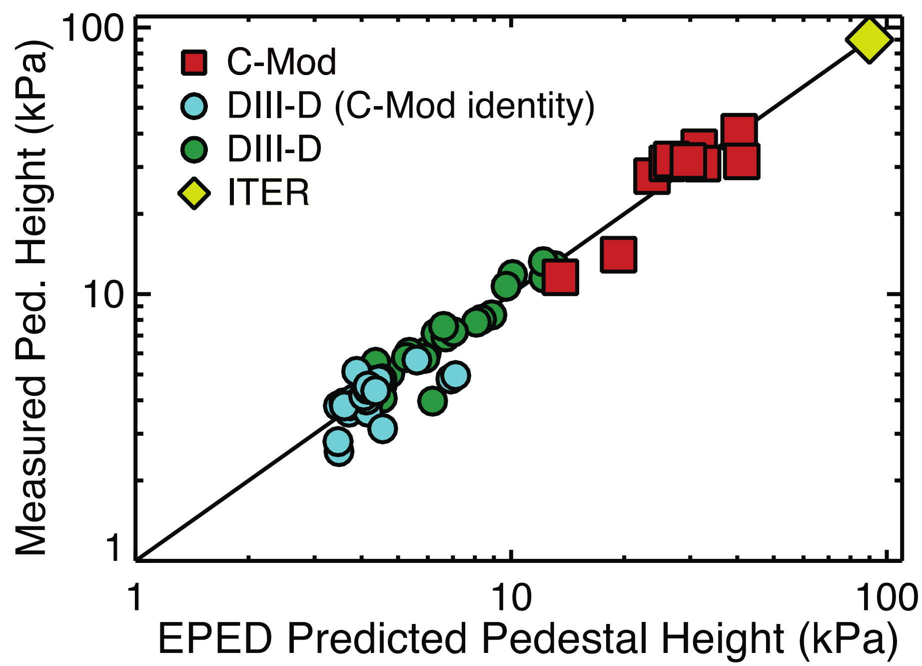
# New model predicts barrier pressure via stability calculations

- In region of steep pressure and current gradients, profiles are limited by large-scale 'Peeling-Ballooning modes', and smaller scale 'kinetic ballooning modes'.

- Combining their thresholds gives a prediction for barrier width and pressure.
  P. Snyder, GA (EPED model)

- **Model agrees well with current experiments, allowing much more confident projection to ITER**



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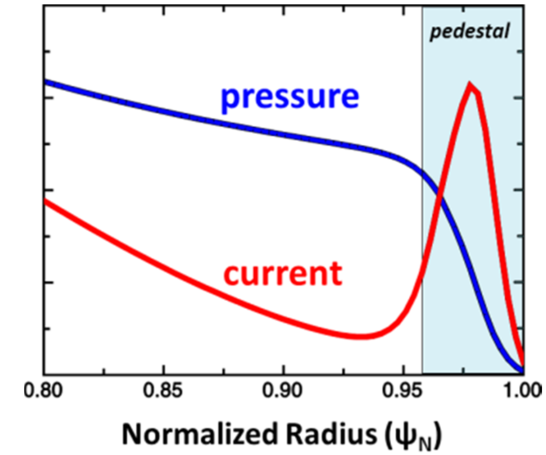
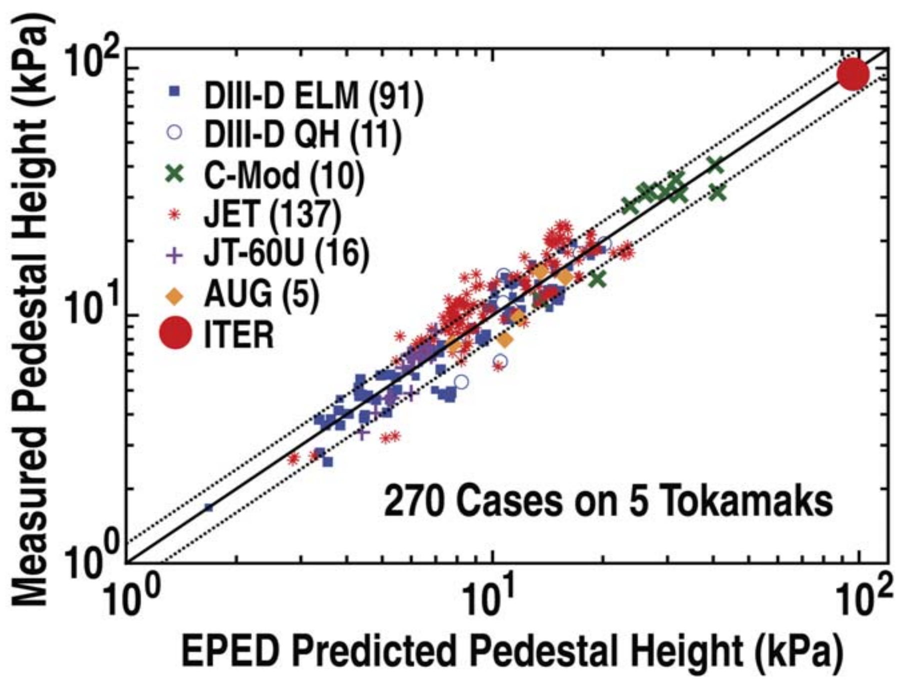



- Combining their thresholds gives a prediction for barrier width and pressure.
  P. Snyder, GA (EPED model)

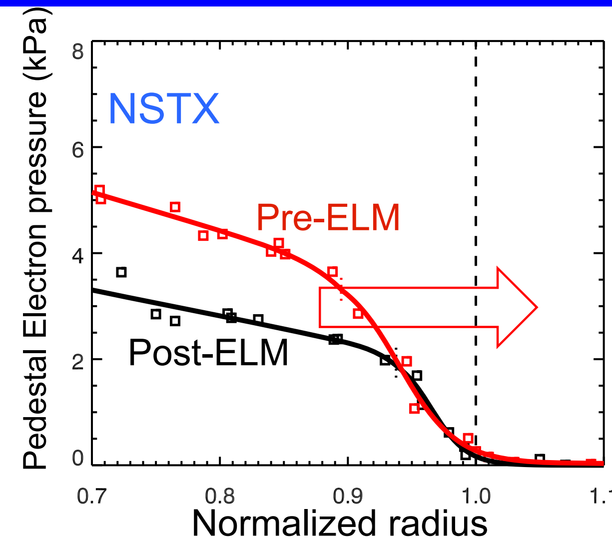
- **Model agrees well with current experiments, allowing much more confident projection to ITER**

  for $n_{ped} \sim 7 \times 10^{19} m^{-3}$
  **$T_{ped}$ ~ 4.5 keV => Q $\geq$ 10**



# But, large edge instabilities need to be avoided for ITER

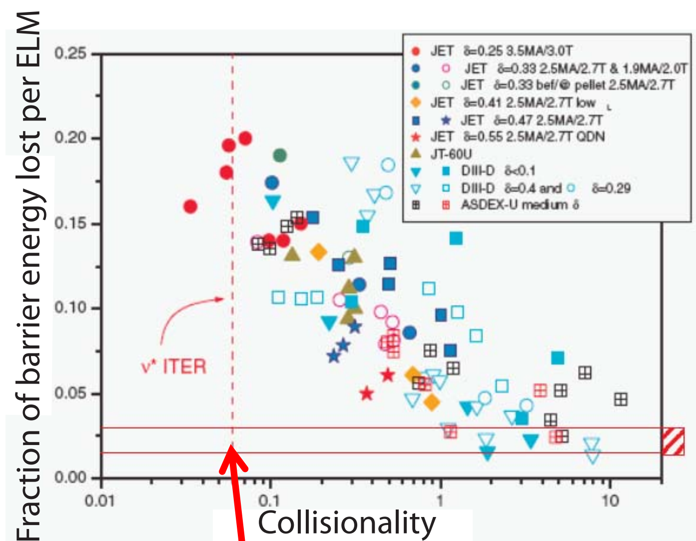
- Most high confinement experiments to date are in regime with **Edge Localized Modes (ELMs),** where the barrier periodically reaches pressure limits, then relaxes.
  - A small fraction of the plasma energy is lost, travels to material 'divertor'.




A. Diallo, PPPL. Nucl. Fus. 2011

- For ITER, due to much larger energy, these heat pulses would erode and damage the material.

- **Need to greatly reduce energy of, or avoid, Edge Localized Modes!**



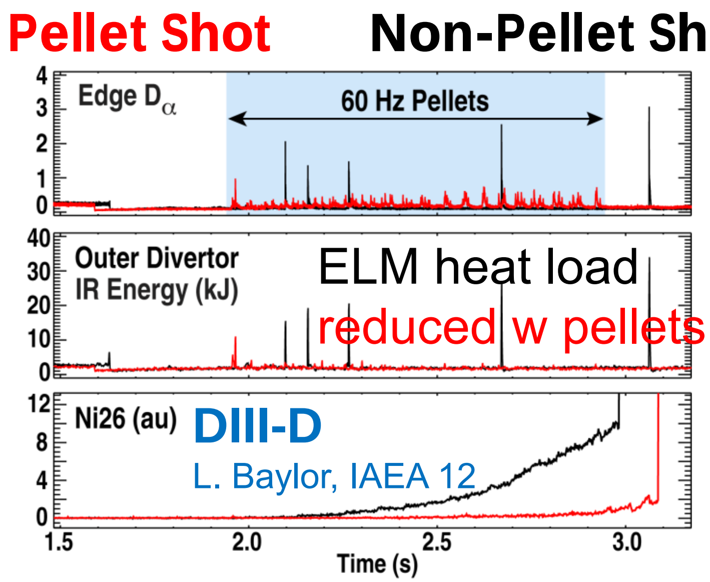

**Acceptable Value ~1MJ**

W after tests simulating 5 'Large ELMs.'

Klimov PSI 2008

# Means of actively suppressing or mitigating ELMs have been developed

- Firing small **pellets** into the pedestal triggers more frequent (and smaller) ELMs.



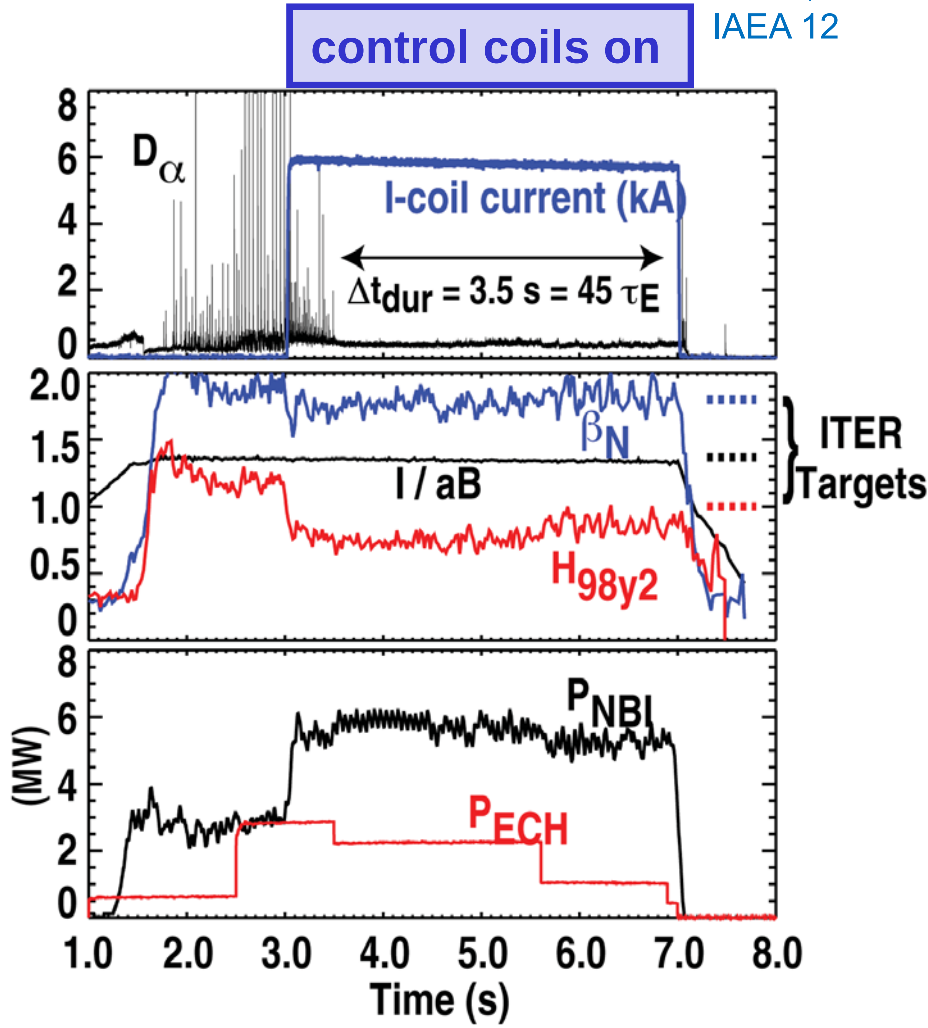
# Means of actively suppressing or mitigating ELMs have been developed

- Firing small **pellets** into the pedestal triggers more frequent (and smaller) ELMs.

- Adding **Magnetic Perturbations** via external coils modifies transport and profiles, suppressing ELMs in some conditions.

- Both techniques are recently developed on current experiments, and have led to plans for hardware additions on ITER.
  - A number of issues still remain, including prediction of pedestals and performance *without* large ELMs.

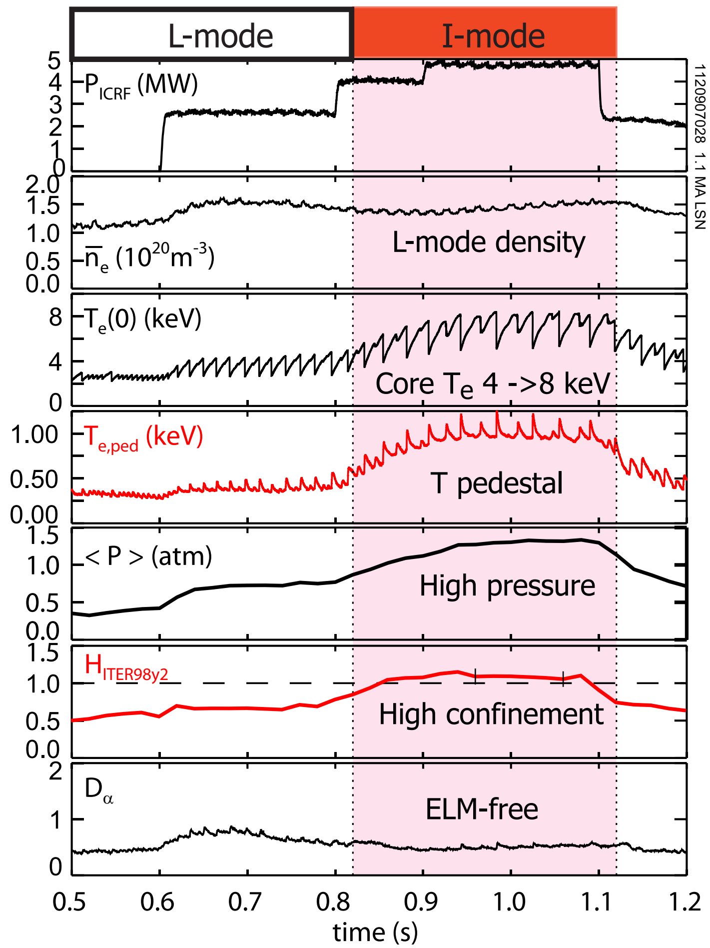
**DIII-D, n=3 RMP**
D. Hill, IAEA 12



# New high confinement regimes naturally free of instabilities are being explored

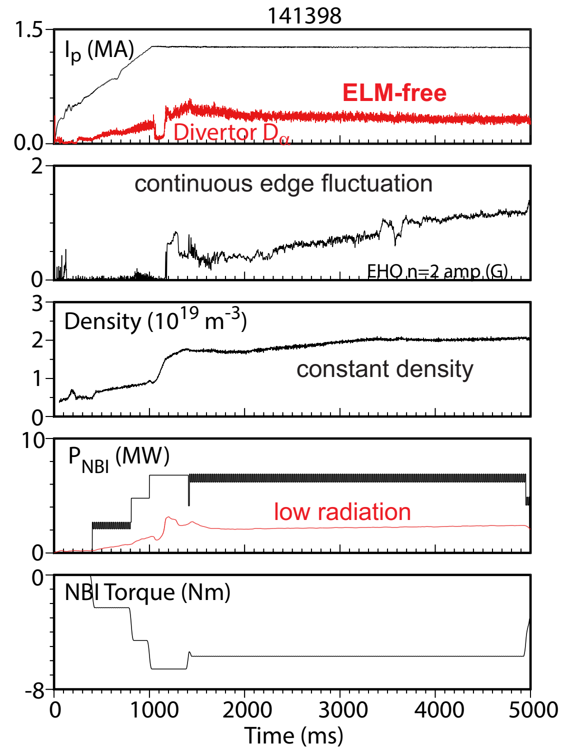
- **I-mode features an energy barrier *without* a particle barrier, reducing impurities.**.

**C-Mod**
Hubbard
IAEA 2012




- **Quiescent H-mode Strong edge rotational shear helps establish a stable barrier.**

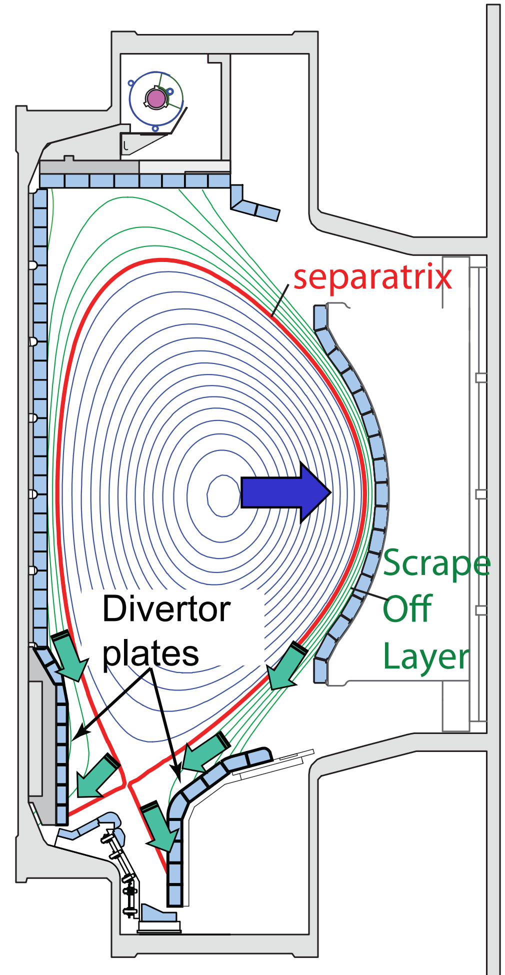
**DIII-D**
Burrell
APS 2011

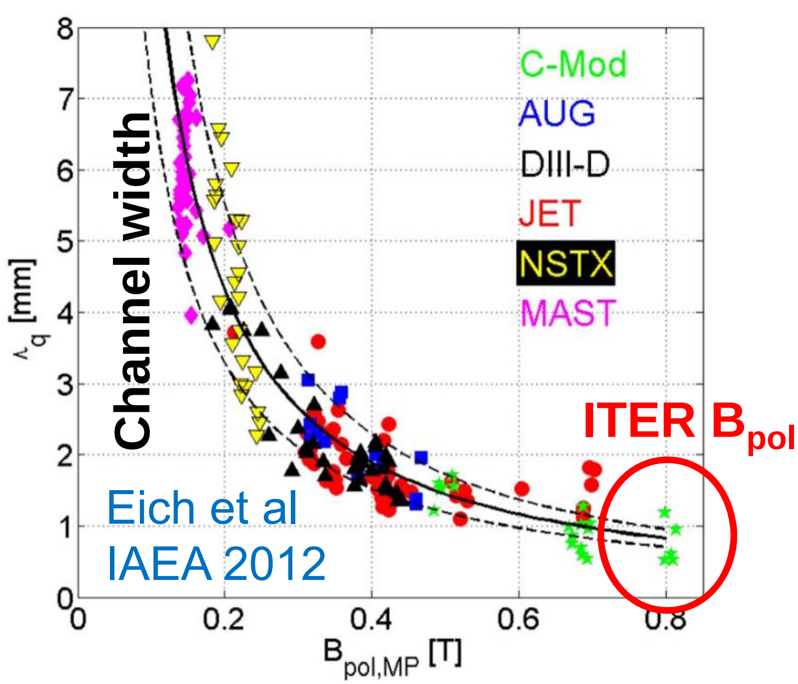



In both cases, continuous fluctuations provide needed transport, replace large ELMs. Focus of current US research.
***Can we reliably access these regimes on ITER?***

# Plasma heat flux to materials will be a challenge

- All the heat input to, or produced by, a burning plasma reaches the edge. Most then flows along field lines in the 'scrape off layer' to a robust 'divertor'.
  - The channel width $\lambda_q$ determines the heat concentration.
- Surprising new result shows $\lambda_q$ does not increase with machine size, varies with $B_{pol} \sim I_p$/size. Scaling implies only 1 mm on ITER – same as C-Mod!




- Other interpretations suggest $\lambda_q$ is related to gradient in barrier, would be wider on ITER.
  - **Need improved physics basis!**

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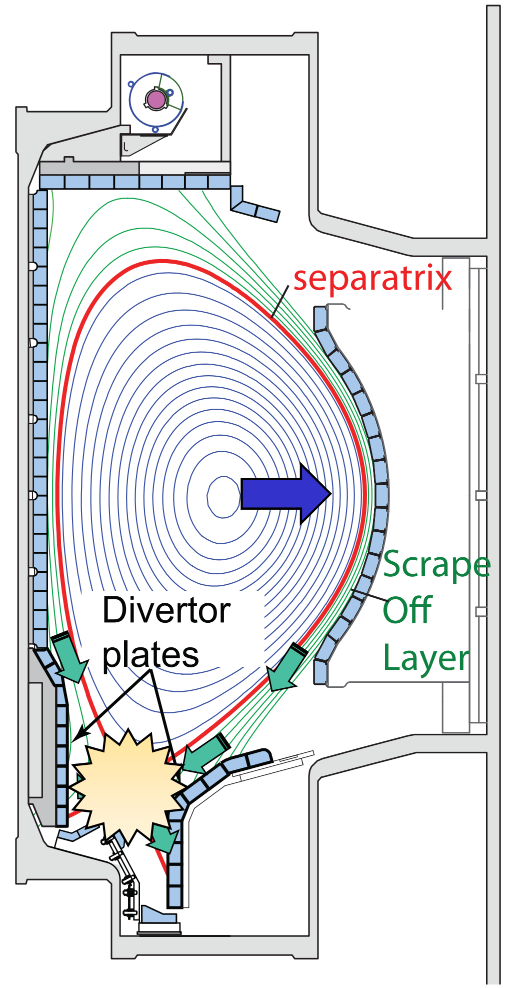
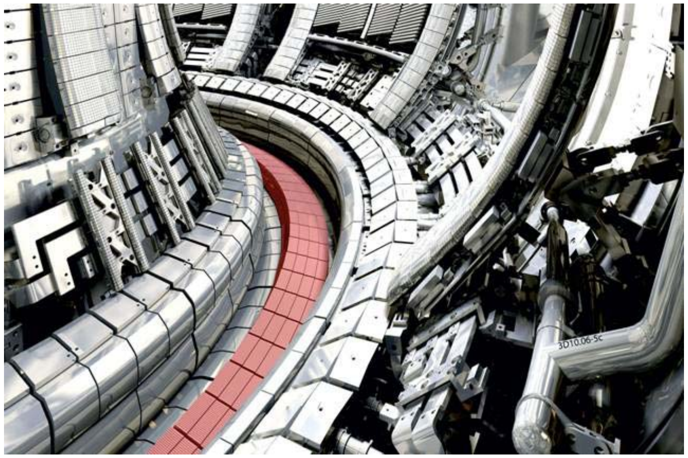
- Surprising new result shows $\lambda_q$ does not increase with machine size, varies with $B_{pol} \sim I_p$/size.
  Scaling implies only 1 mm on ITER – same as C-Mod!

- **In any case, ITER needs to radiate much of the heat in the divertor, without contaminating the burning core.**
  This has been demonstrated in current experiments.

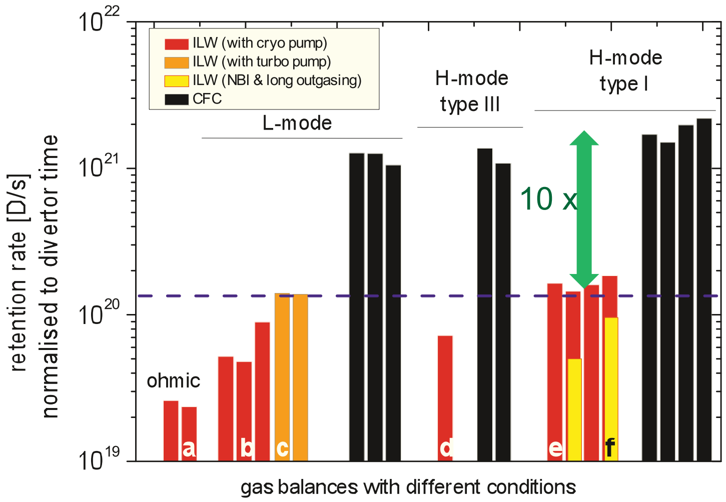


# JET is testing ITER wall materials

- Most current tokamaks, until recently, used carbon walls.
- But, for ITER, long pulses would erode too fast, and retention of Tritium would exceed safety limits – plan to use W in divertor, Be elsewhere.
- JET in UK replaced its plasma facing components to test this combination "ITER-Like Wall".



- **Good news:** T retention is 10 x lower w **ILW** than **C** (as had been expected)




F. Romanelli, IAEA FEC 2012.

- **Mixed news:** Changed several aspects of plasma operation and behavior, in unexpected ways.
  - Eg breakdown, disruptions, barrier access and height, core impurities and energy confinement.
  - **The walls matter!**

# Many other important topics are being studied worldwide for ITER

A partial list:

- **MHD stability**, and control of instabilities. Neoclassical tearing modes, resistive wall modes...
- **Disruptions** (fast loss of plasma current) and their mitigation.
- **Heating and current drive** via neutral beams and RF waves, at high field and density.
- **Energetic particles** and their instabilities, which will be important in a self-heated burning plasma.
- Demonstrating **integrated operating scenarios** (inductive and steady state) for ITER.

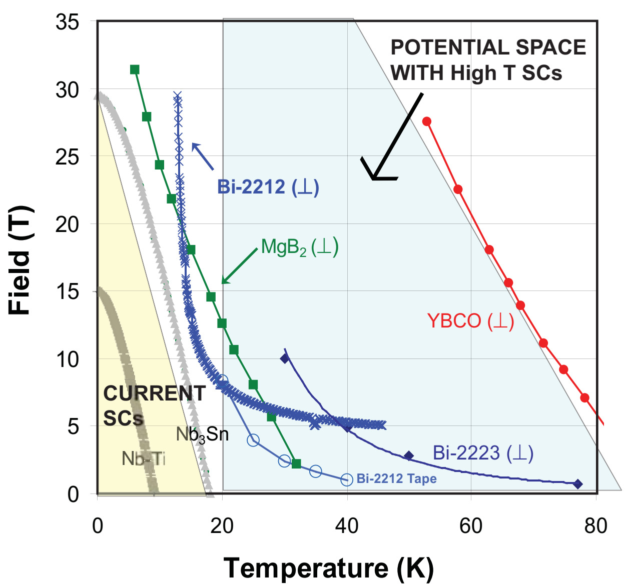
Topical groups in the International Tokamak Physics Activity, and US Burning Plasma Organization, are engaged in each of these topics, and others.

# Physics and technology challenges for fusion, beyond ITER.

# Practical fusion energy requires meeting other technical and physics challenges

- **Steady state**: Sustaining plasma for long durations (months), without large transients. For tokamak, non-inductive current, mainly self-driven. Stellarator is inherently steady-state.
- **Power handling solutions** with even higher heat fluxes and durations, at **high wall temperatures** (700 C) for high Carnot efficiency.
- Structural and PFC materials capable of handling high **nuclear fluence**.
- **Fusion power extraction and Tritium breeding.**
- **Superconducting (SC) magnets**.

**New superconducting tokamaks EAST (China) and KSTAR (Korea)** will focus on steady state.
EAST already has 1 min discharges with RF current drive, 30 s H-modes.




**Demountable High Temp SCs** could enable higher field, compact fusion reactors, improve availability.
Minervini, MIT

Research is getting underway on present confinement and test facilities. The world community is planning an R&D program in parallel with, and beyond, ITER. Talk this session by Hutch Neilsen.

# Magnetic Fusion program is making major advances towards burning plasmas

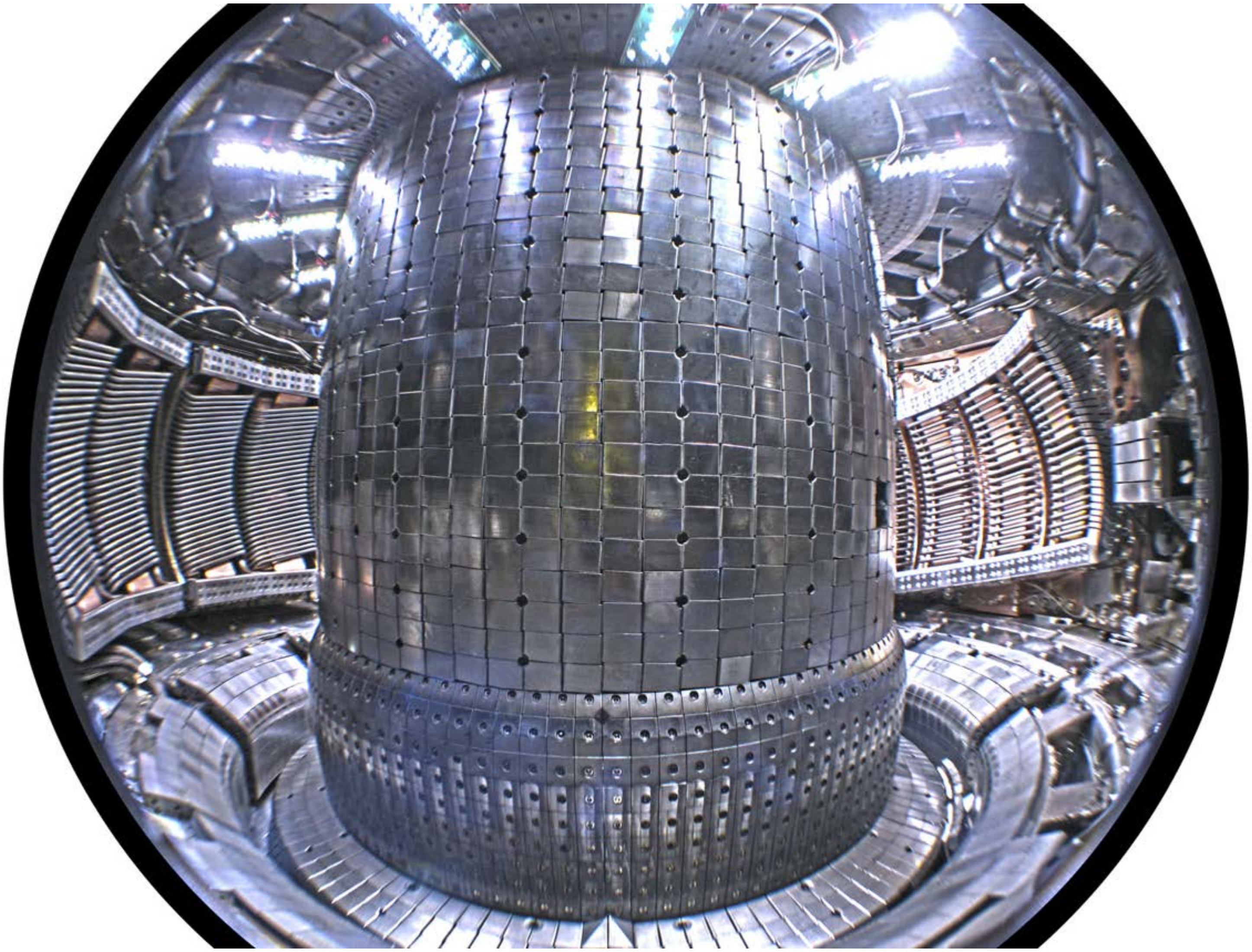
- ITER is a priority for the international fusion program, which has focused attention on the critical issues for fusion-scale plasmas.

- **Examples of recent progress include:**
  - Simulations of core turbulence and transport, validated by detailed measurements.
  - Prediction of the edge transport barrier.
  - Developing means to control or avoid large edge instabilities.

**Accurate prediction of confinement**

- **In each case, progress has been enabled by a coordinated research effort including experiments on multiple facilities, theory and simulation.**
  It will be important to continue such strong efforts to address remaining issues, and new ones as they arise, for ITER and for a demonstration fusion reactor (DEMO).

# Tour the MIT Plasma Science and Fusion Center



## Saturday, February 16
## 12PM – after the Fusion Symposium
## Including Pizza Lunch

**RSVP: CENSABEL@MIT.EDU**

Tour includes:

- Alcator C-Mod Tokamak
- Levitated Dipole Experiment (LDX)
- VTF Magnetic Reconnection Plasma Experiment
- Superconducting Magnet R&D Program
- Inertial Fusion Confinement Diagnostic Lab

**Depart Hynes Convention Center by bus: 12:00 pm**
Boylston Street Entrance

**Depart MIT: 3:30 pm**, arriving back at Hynes at 3:45PM

**Limited to 50 people, first come first served.**

Sign up through Friday, February 15
by emailing Valerie Censabella: censabel@mit.edu

or by sign-up sheet at the Fusion Symposium (February16)