The Abdus Salam
International Centre for Theoretical Physics

United Nations
Educational, Scientific and
Cultural Organization

IAEA
International Atomic Energy Agency

2155-27

International Workshop on Cutting-Edge Plasma Physics

5 - 16 July 2010

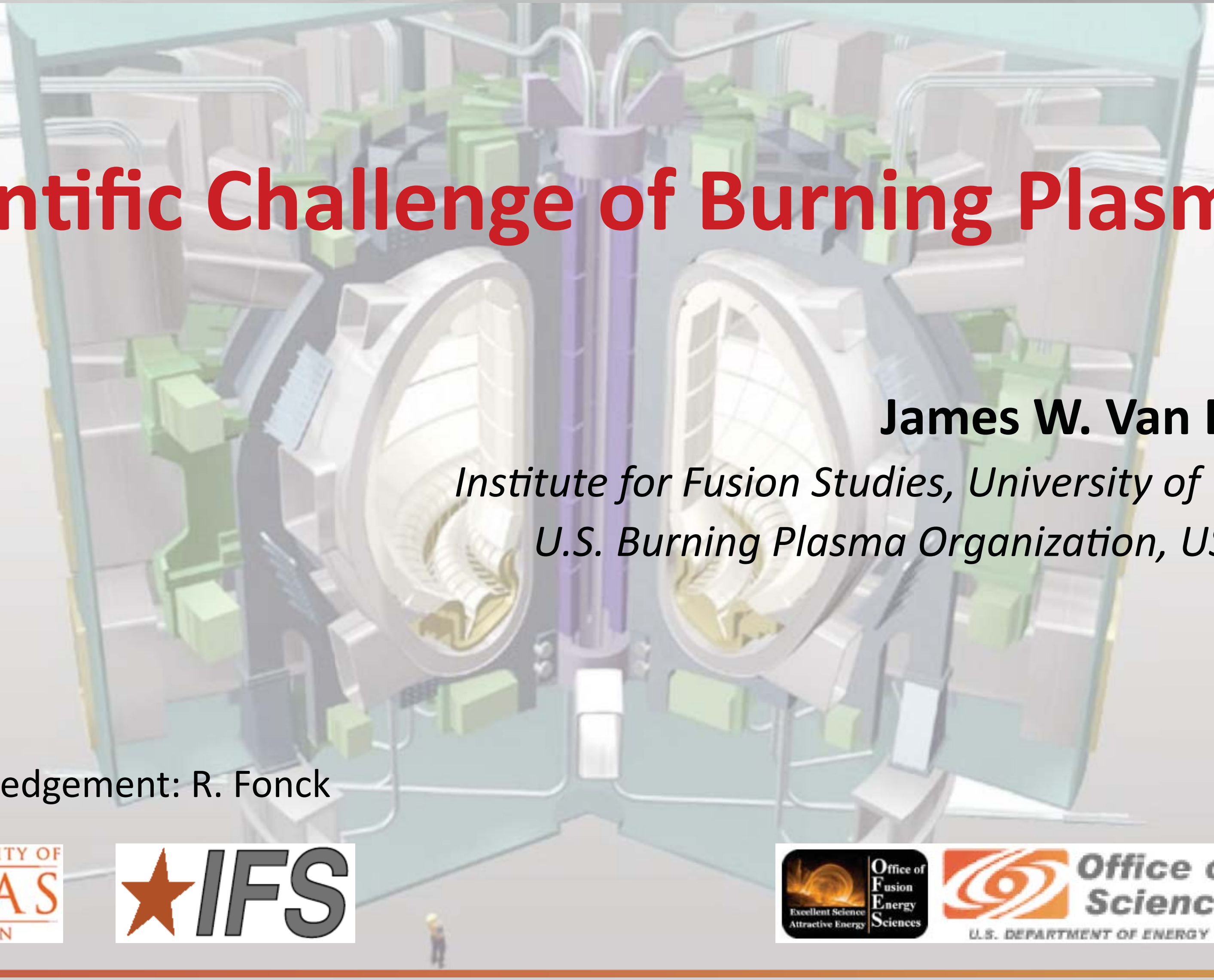
Scientific Challenge of Burning Plasmas

James W. Van Dam
Institute for Fusion Studies
University of Texas

Strada Costiera 11, 34151 Trieste, Italy - Tel.+39 040 2240 111; Fax +39 040 224 163 - sci_info@ictp.it

USBPO United States Burning Plasma Organization

Scientific Challenge of Burning Plasmas



James W. Van Dam

Institute for Fusion Studies, University of Texas

U.S. Burning Plasma Organization, USDOE

Acknowledgement: R. Fonck

THE UNIVERSITY OF TEXAS AT AUSTIN

IFS

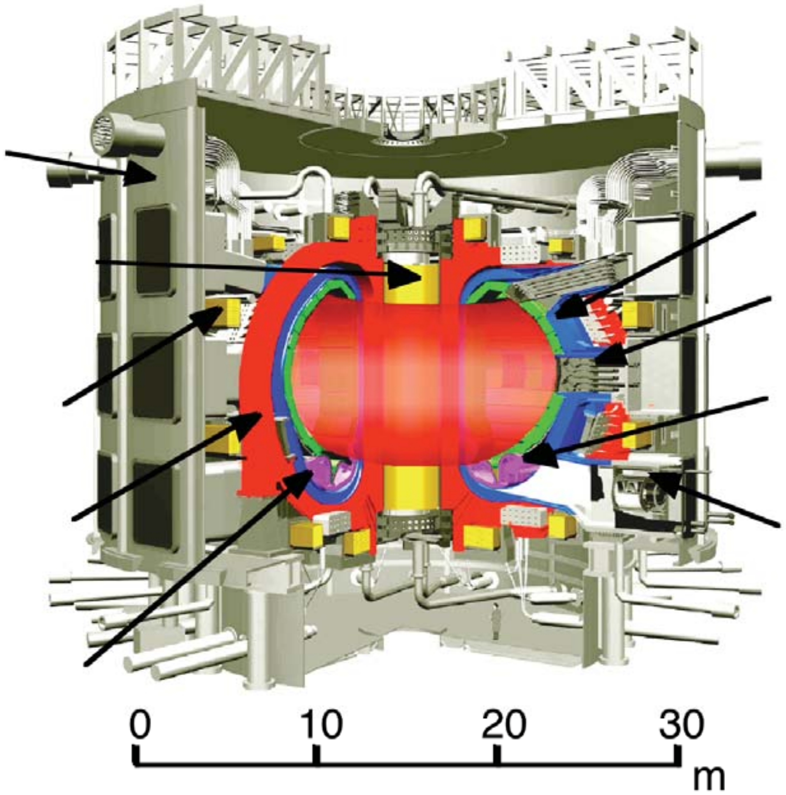
Office of Fusion Energy Sciences — Excellent Science Attractive Energy

Office of Science U.S. DEPARTMENT OF ENERGY

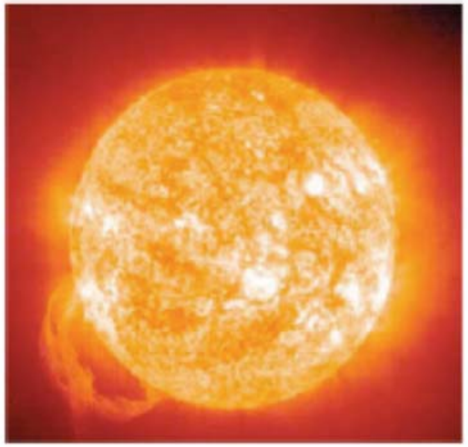
Burning plasmas: The next frontier

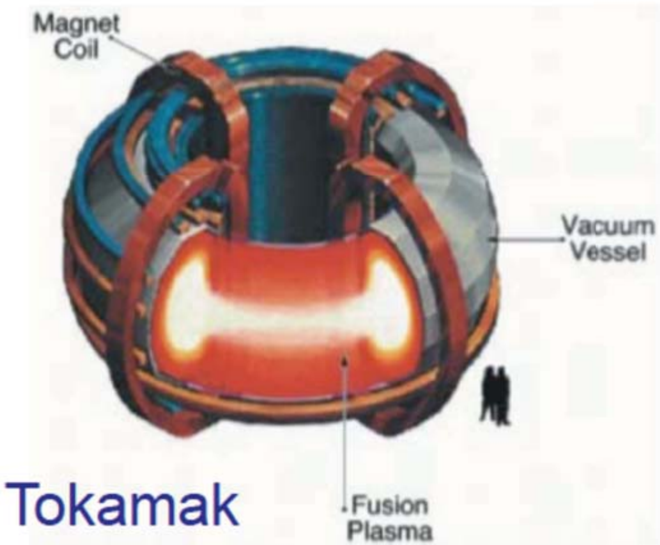
- ***Understanding the behavior of burning plasmas*** **is the challenge faced by fusion research today, as a necessary step towards the ultimate demonstration of fusion as a source of energy**
  - ITER, to be operated as an international project, will push research efforts into this new regime of burning plasma science

- **This talk with focus on** ***science issues for burning plasmas***



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





Lab fusion reaction of choice:

$$D^2 + {}_1T^3 \rightarrow {}_2He^4 + {}_0n^1$$

(3.5 MeV) (14.1 MeV)

Energy/Fusion: $\varepsilon_f = 17.6$ MeV

Fusion energy gain: $$Q \equiv \frac{P_{fusion}}{P_{heat}} = \frac{5\,P_\alpha}{P_{heat}}$$

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

Breakeven	$Q = 1$	$f_\alpha = 17\%$
Burning plasma regime	$Q = 5$	$f_\alpha = 50\%$
	$Q = 10$ (ITER)	$f_\alpha = 60\%$
	$Q = 20$	$f_\alpha = 80\%$
	$Q = \infty$ (ignition)	$f_\alpha = 100\%$

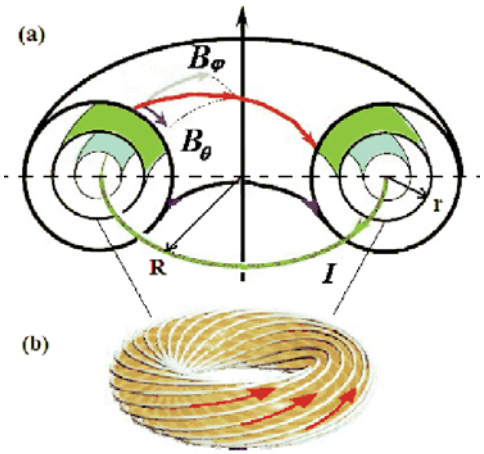
New and continuing challenges for burning plasmas

- **Many of the scientific challenges for burning plasmas are the same as those of today's experiments**
  - Plasma **equilibrium**
  - Macroscopic **stability**
  - **Transport** and confinement
  - **Supra-thermal particles** and **plasma-wave interactions**
  - **Measurement and control** tools

- **Burning plasmas also have new challenges**
  - Dynamics of exothermic medium
  - Self-heated and increasingly self-organized
  - Large plasma size
  - Large population of highly energetic alpha particles
  - Thermonuclear environment

Tokamak equilibrium is well described by ideal MHD theory

- **Equilibrium formation is governed by** $j \times B = \nabla p$
  - Uncountable number of solutions → experimental freedom



- **Tokamak equilibrium requires plasma current**

Perpendicular:

$$j_\perp = \frac{B \times \nabla p}{B^2}$$

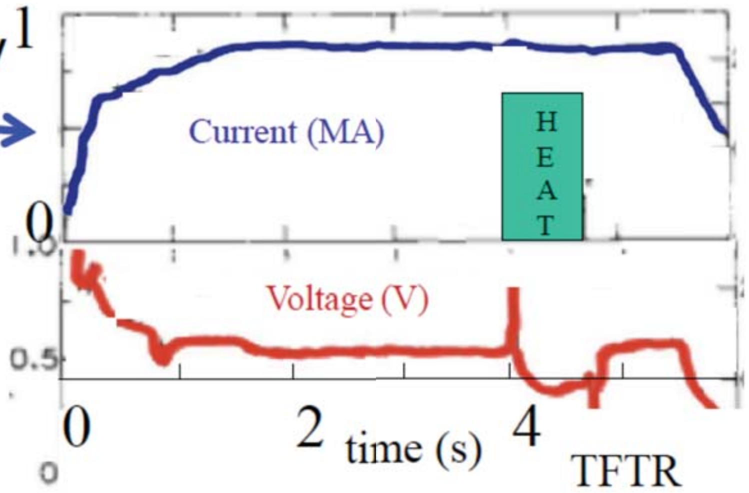
Parallel: (Ohm's law with stress tensor)

$$j_\parallel = \frac{E_\parallel}{\eta} - \frac{1}{ne\eta}(\nabla \bullet \Pi)_\parallel$$

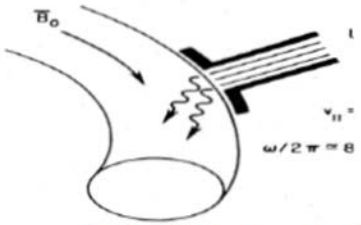
  - Viscous forces from field non-uniformity cause "bootstrap" current

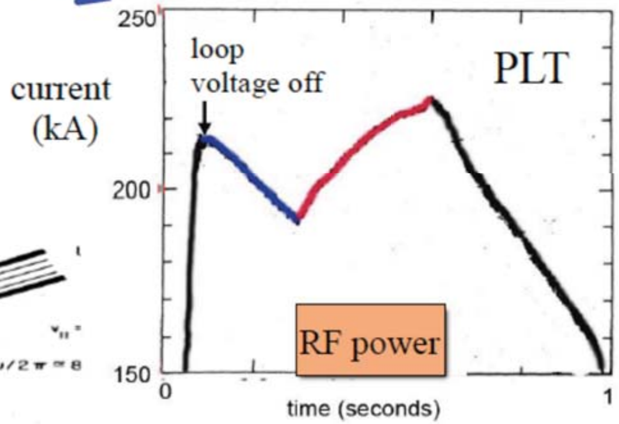
Driving current and shaping profiles are tools for feedback control

- Bootstrap current experimentally validated

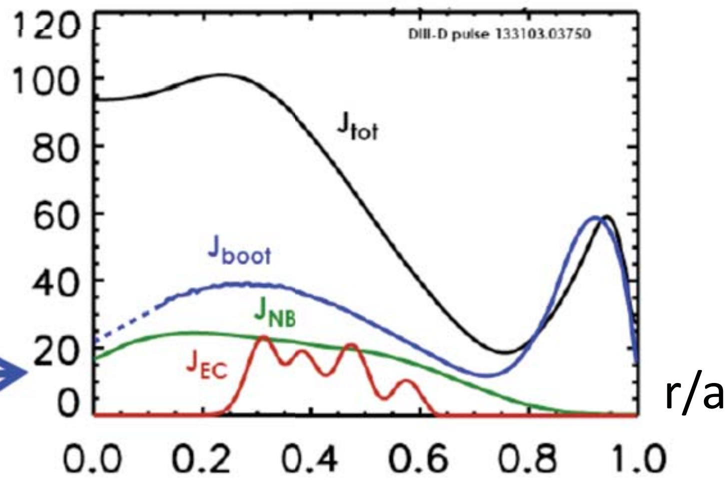


- Driven currents via Landau damping of injected wave:





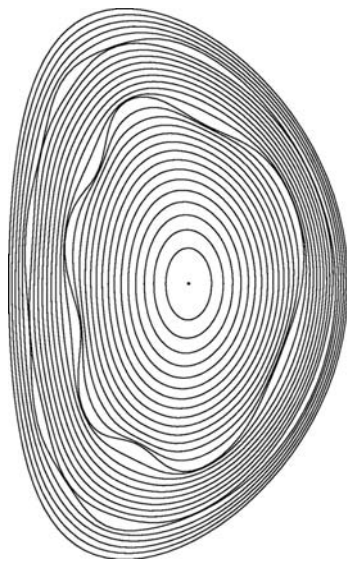
- Fully non-inductive shaped current profiles accessible
  — Continuing development



Equilibria can be MHD unstable

- **Macroscopic MHD instabilities cause large-scale (λ ~ a) perturbations of the magnetic field structure**
  - Large sawtooth (ST): possible seed for NTM
  - Resistive wall modes (RWM)
  - Edge localized modes (ELM): cause heat pulse, melting

- **Field lines can reconnect and form magnetic islands**
  - Neoclassical tearing modes (NTM): possibly lead to disruption



NTMs threaten high-pressure plasmas

- **Bootstrap current excites Neoclassical Tearing Mode instability**

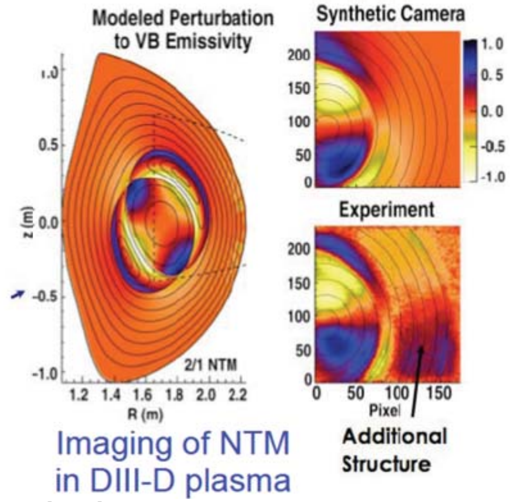
Current perturbation forms an island

↓

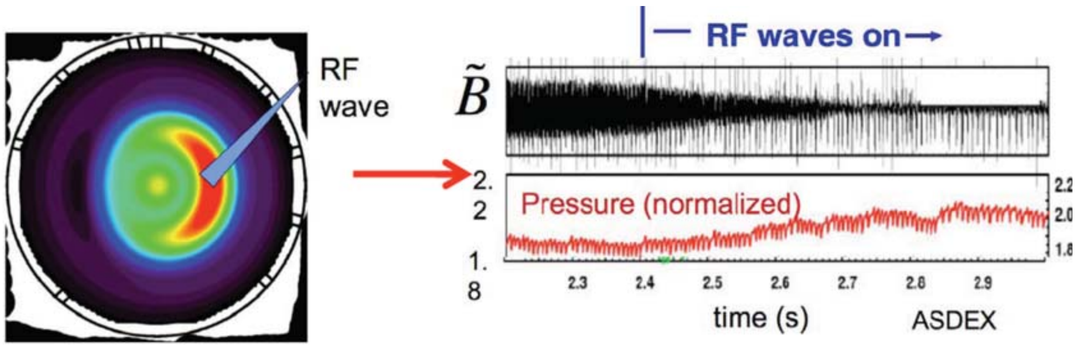
island alters pressure

↓

alters bootstrap current



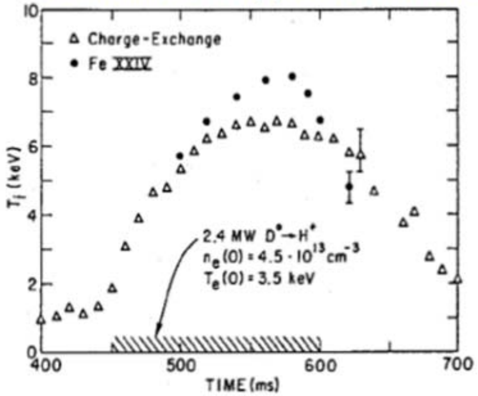
- **NTMs can be controlled by feedback stabilization to counter the perturbation to bootstrap current**



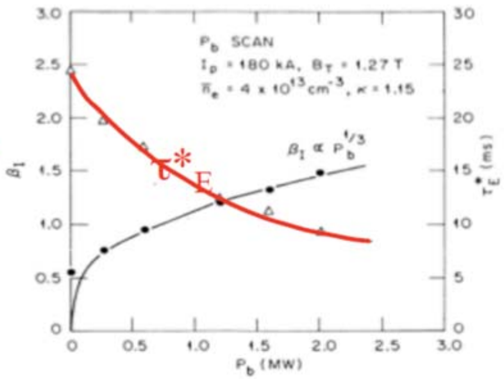
For MHD-stable plasmas, transport from micro-turbulence is dominant

- **During 1980s, transport understanding was largely empirical**

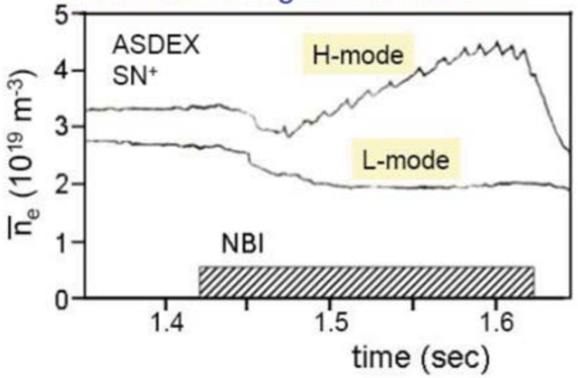
High Ti achieved despite concerns of trapped ion instability:



But, then the energy confinement was seen to degrade with T, P:



Finally, spontaneous transition to enhanced confinement regime discovered:



P_{NBI} = 2.6 MW H in D
B_o = 2.2 T
I_p = 320 kA
Configuration: SN+

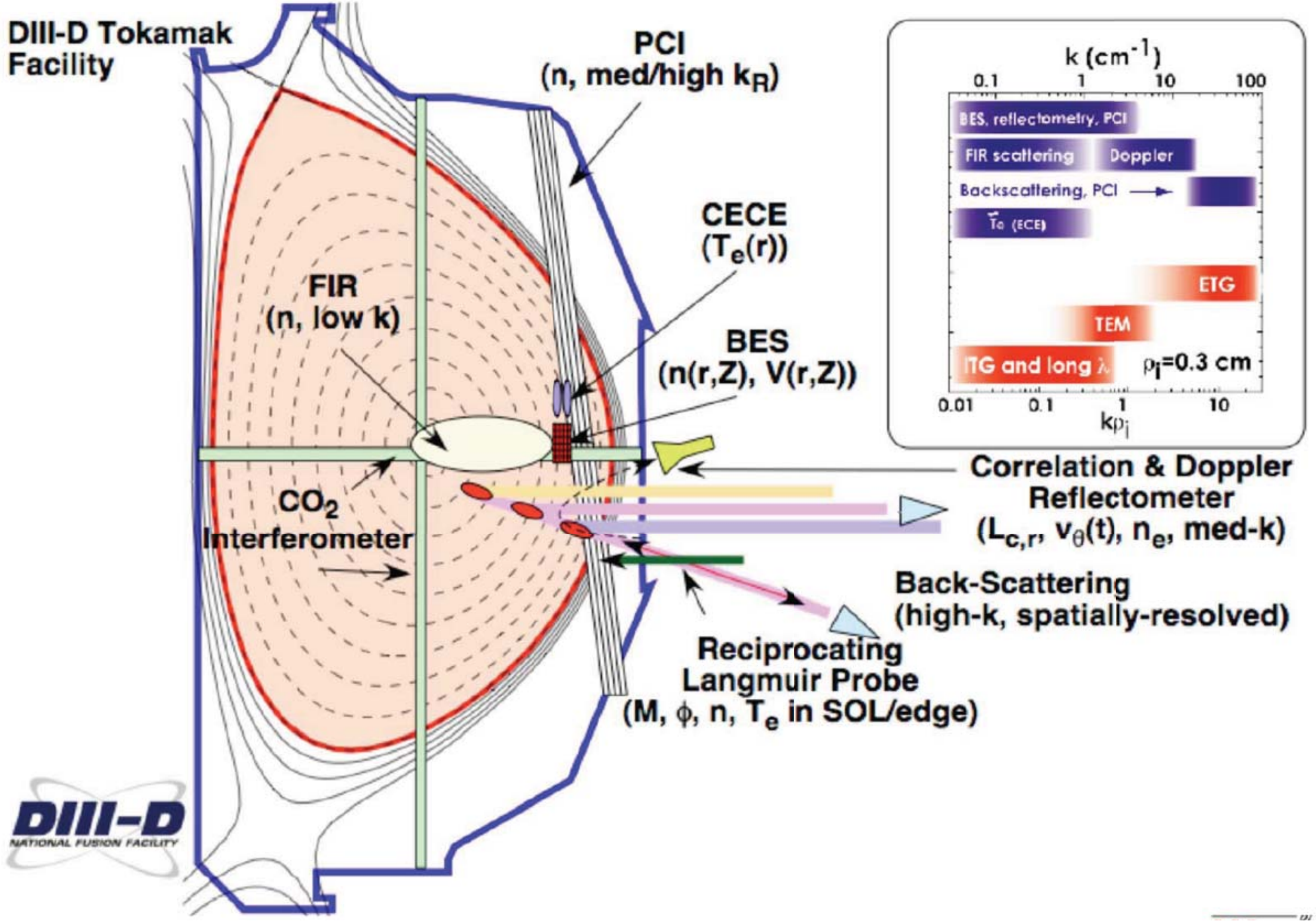
Two branches:

Type „a": L-mode
Type „b": H-mode

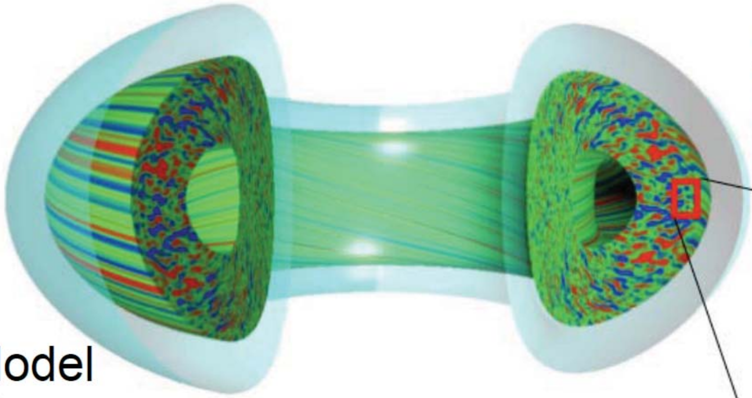
2009 - 12

~20 years ago

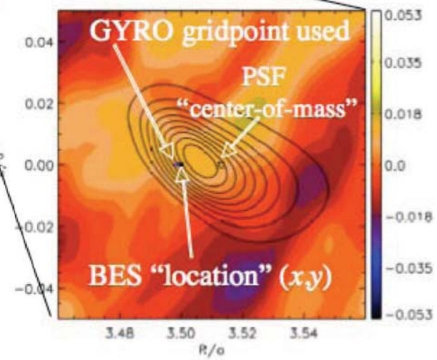
Modern transport studies use sophisticated diagnostic measurements



Transport theory and measurements have attained excellent agreement

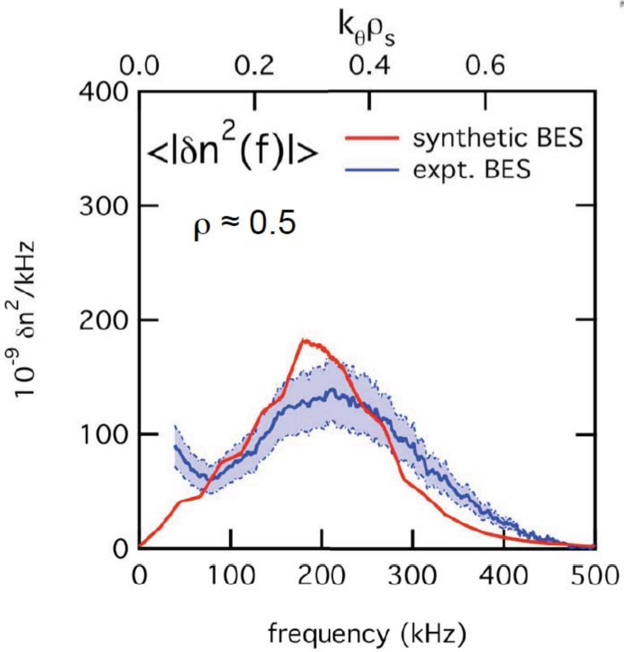


GYRO is a Eularian continuum code that simulates plasma turbulence and transport with full physics and geometry, experimental profiles



Emerging Standard Model for ion turbulence and associated transport

- Reproduces net transport rates and fluctuation spectrum at some locations in core
- But, radial variations, T_e turbulence, and nonlinear details still need work…



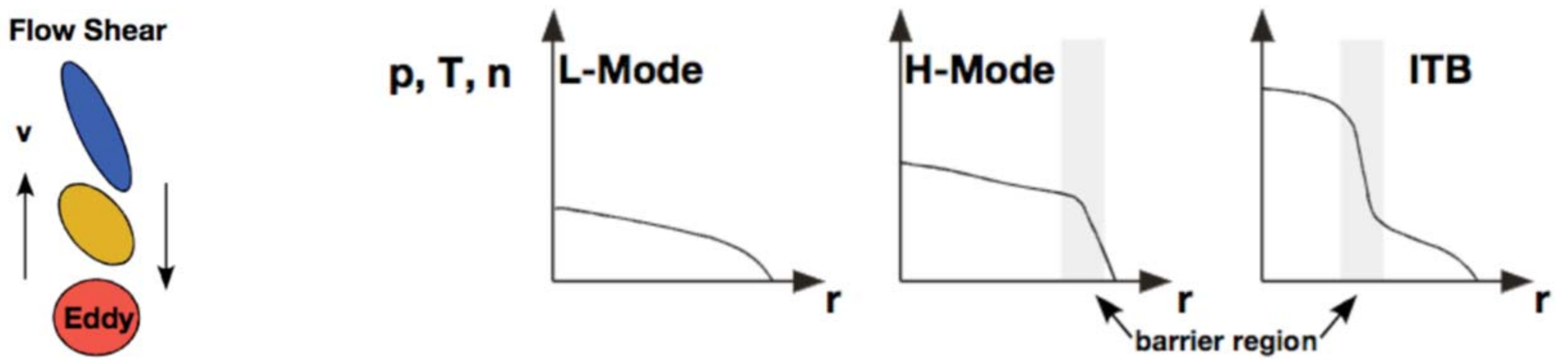
rjf APS Apr 2009 - 14

Understanding & controlling transport have led to improved confinement

- **Transport barriers: localized reduced transport in barrier region**
  - Edge transport barrier → "H mode" (high confinement)
  - Internal transport barrier (ITB) in core

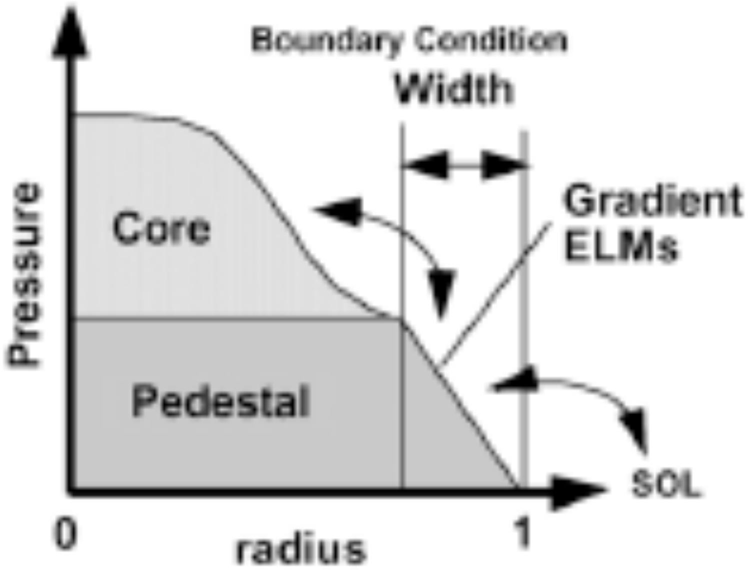
- **Reduced core transport leads to increased confinement**
  - Observed experimentally in many magnetic confinement devices

- **Transport barriers form with suppression of turbulence**
  - Suppression mechanisms: flow shear; negative magnetic shear; zonal flow

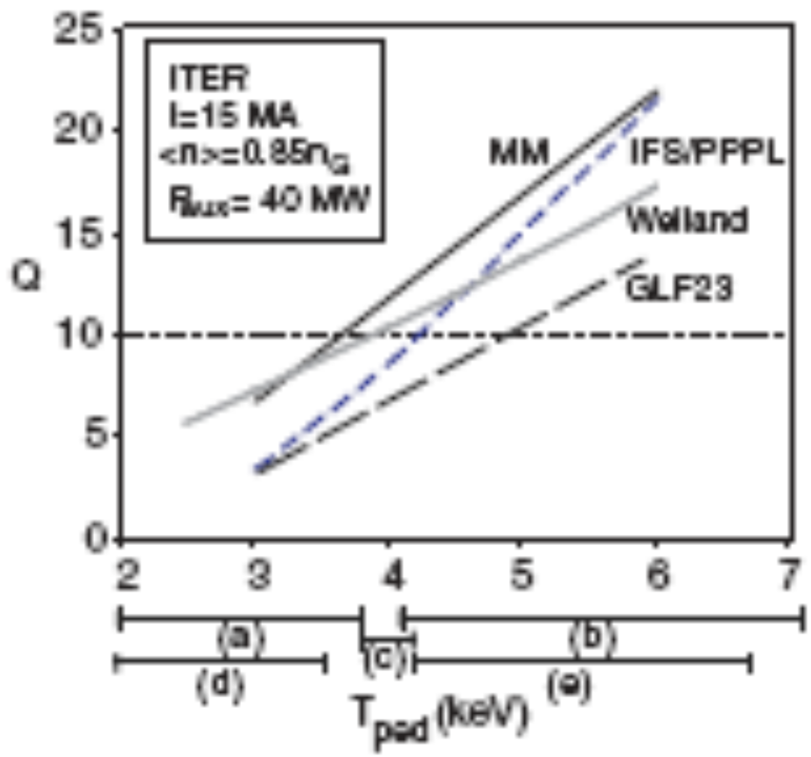


Steep edge gradients are desirable for high fusion performance

Improved confinement regimes (H mode, ITB) have steep gradients at edge

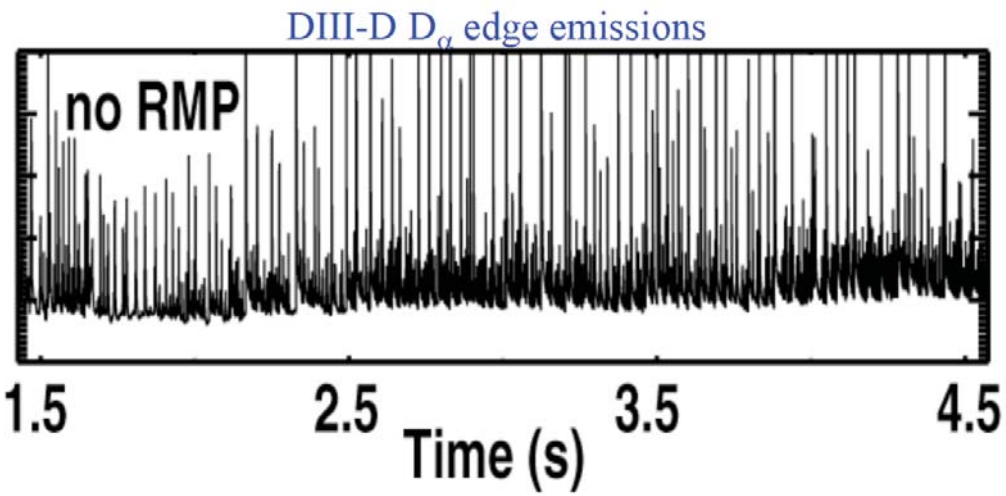


"Stiff" transport in the core means high edge T is needed for high fusion gain (Q)

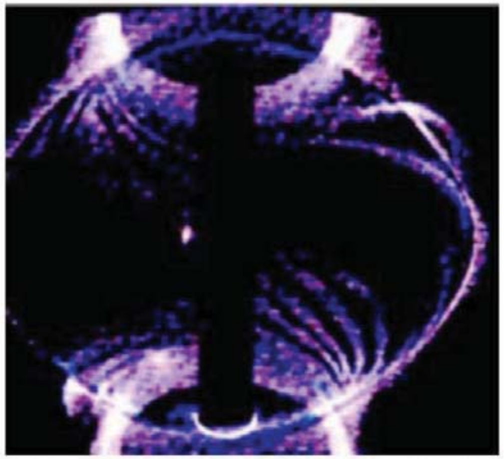


But steep edge gradients can be explosively unstable (ELMs)

- **High-confinement (H mode) plasmas experience short, sharp expulsions of heat and current at edge (Edge Localized Mode)**
  - Cause surface melting & erosion

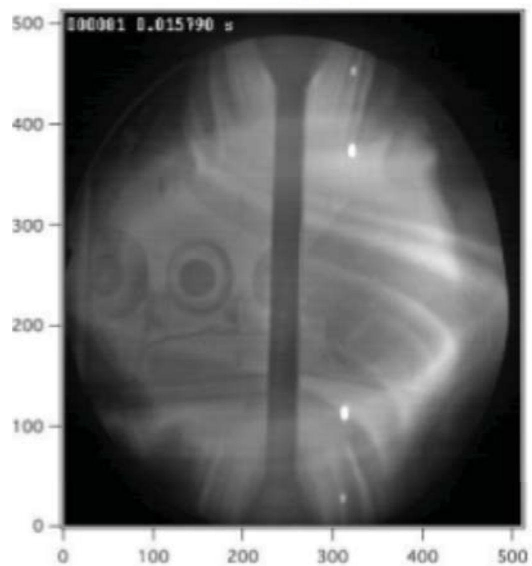


  - Each D_α spike is correlated with large, coherent filamentary instability at edge



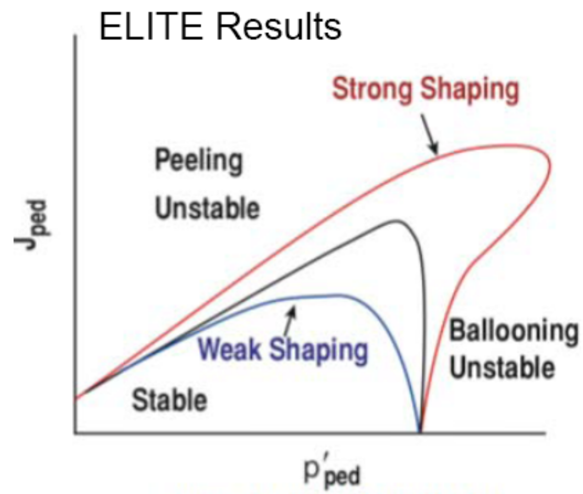
Kirk, 2004 Proc. 20th Int. Conf. on Fusion Energy 2004

MAST

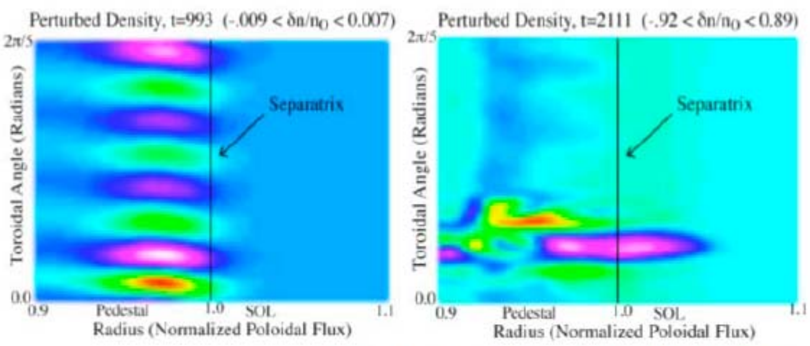


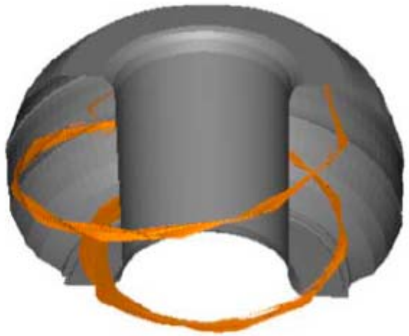
Edge Localized Modes are well described by peeling-ballooning theory

- **High edge current (peeling) and high pressure (ballooning) drive ELMs to relax unstable gradients**
- **Peeling-ballooning mode theory reproduces stability threshold and observed mode structure**

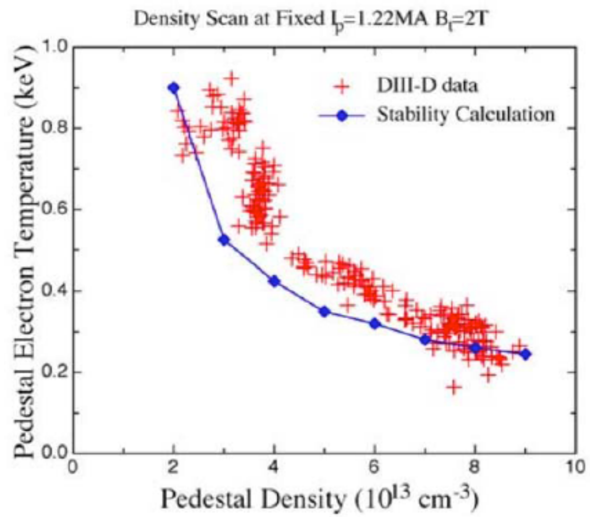


Snyder, Phys. Plasmas **12**, 056115, 2005





P.B. Snyder et al, Phys. Plasmas **12** *056115 (2005).*



New science issues for burning plasmas

USBPO
U.S. BURNING PLASMA ORGANIZATION

Uniquely BP issues

- ***Alpha particles***
  - Large population of supra-thermal ions
- ***Self-heating***
  - "Autonomous" system (self-organized profiles)
  - Thermal stability

Reactor-scale BP issues

- ***Scaling with size & B field***
- ***High performance***
  - Operational limits, heat flux on plasma-facing components
- ***Nuclear environment***
  - Radiation, tritium retention, dust, tritium breeding

All issues are strongly coupled/integrated

NEW CHALLENGES FOR BURNING PLASMAS

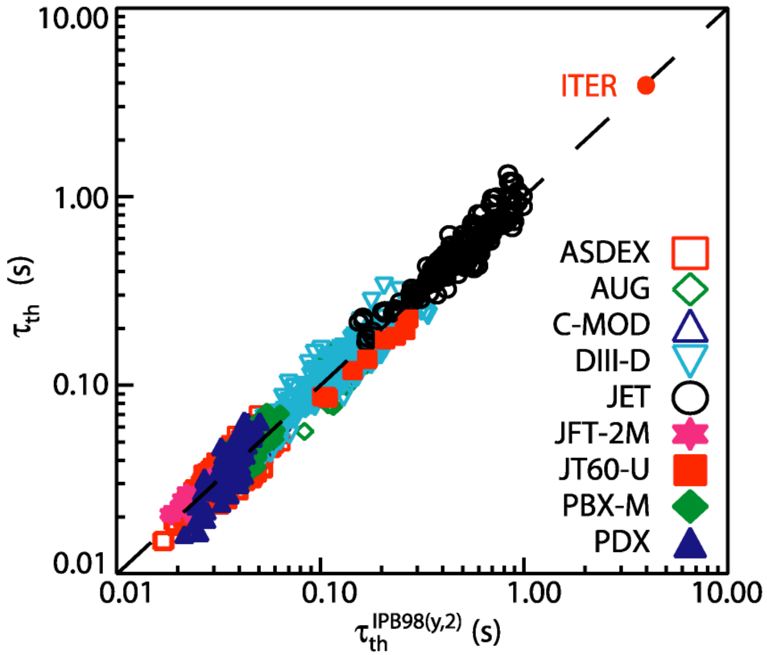
1. Size and magnetic field scaling
2. Self-heating
3. High performance requirements
4. Thermonuclear environment
5. Strongly coupled physics
6. Alpha particles

1. Size and magnetic field scaling

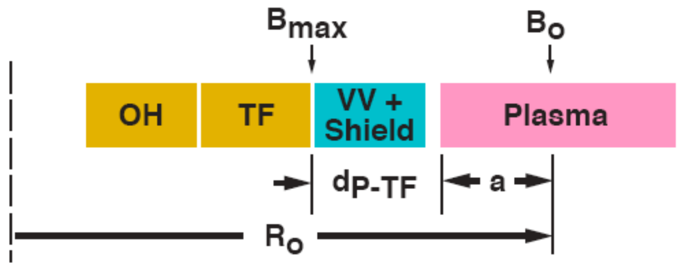
- Normalized gyro-radius scaling
- Impact on auxiliary heating methods

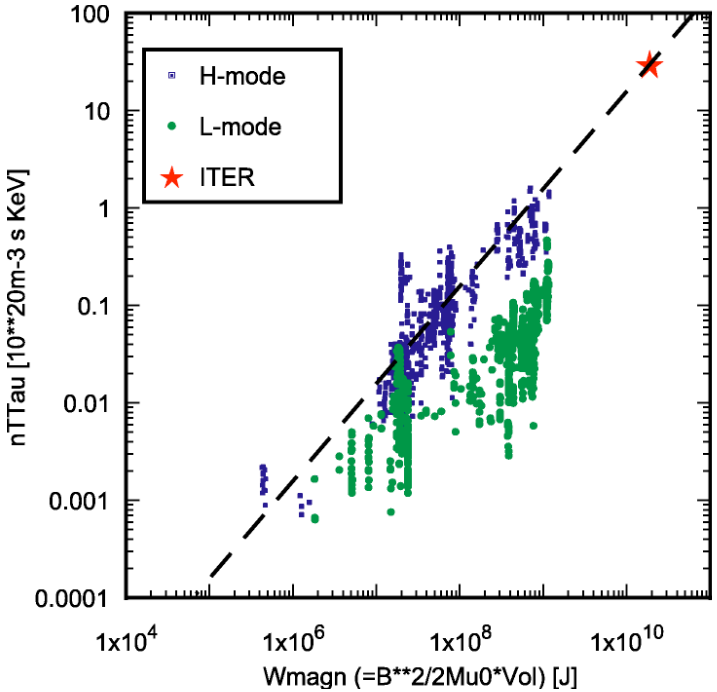
Determining size of a burning plasma

- **Large size determined by:**
  - Need for sufficient confinement
  - High power density (materials)
  - Radiation shielding of SC magnets



Scaling prediction for energy confinement time τ_{th}



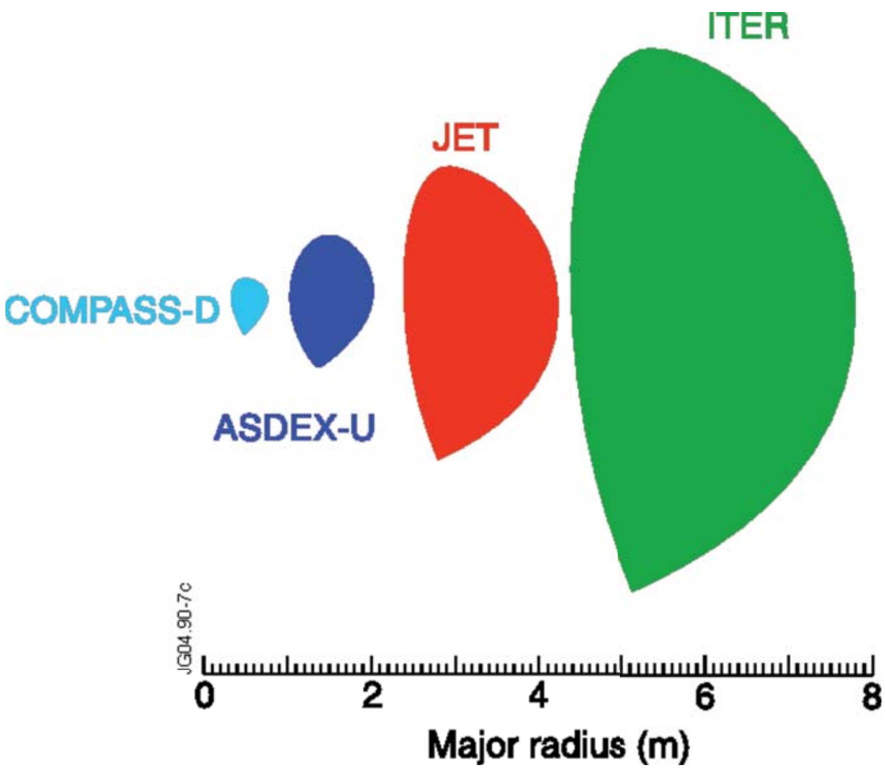


Confinement scaling for fusion triple product $nT\tau_E$

Size scaling

- **Significant difference**
  – Current tokamaks have $\rho_i^* = \rho_i/a \sim 0.5\text{-}1.5 \times 10^{-2}$, whereas burning plasmas (ITER) have $\rho_i^* \sim 1\text{-}2 \times 10^{-3}$

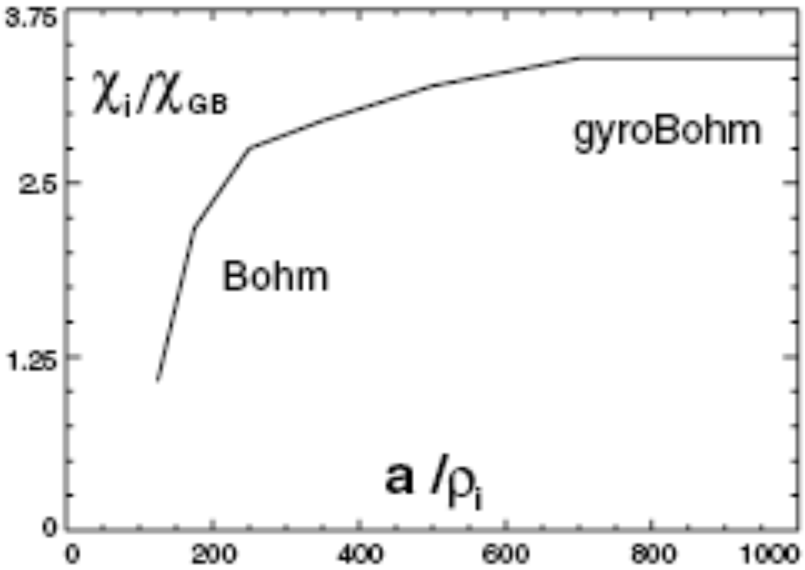
- **Issues for very small ρ^***
  – ITB formation
  – Hybrid regimes
  – Confinement scaling
  – NTM threshold beta
  – Alfvén eigenmode spectrum



Cross sections of present-day EU divertor tokamaks compared to the cross section of ITER

Consequences of size scaling

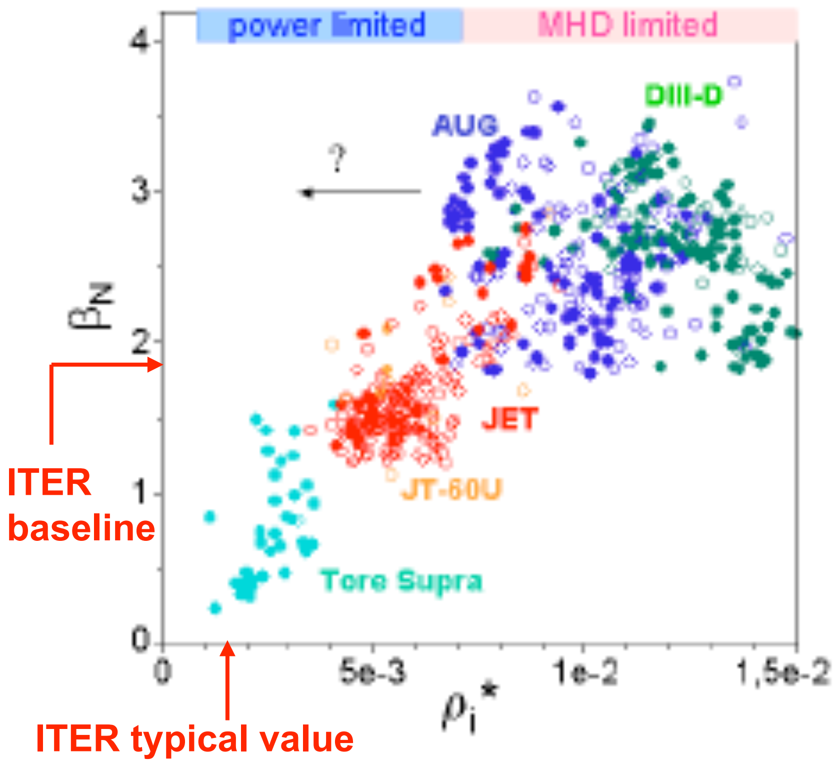
Transport scaling



Example of simulations that show transition in ion thermal conductivity as the minor radius increases (1/ρ_i^*)
— Accurate size scaling of transport is critical for design of fusion reactor

Z. Lin (PRL 2002)

Stability for NTM



ITER could exceed beta threshold for NTM stability at low ρ_i*

G. Sips et al. (IAEA 2004)

Beam heating in burning plasmas

- **D, T neutral beams can heat & drive current in burning plasmas**
  - To penetrate dense/hot burning plasma, require neutral beam energies of several 100 keV to 1 MeV (>> typical 120 keV in current-day tokamaks)
  - Efficient production of such high-energy hydrogen atoms requires use of negative ion-based neutral beams (N-NBI)

- **Status of N-NBI development**
  - **JT-60U:** injection power 5.8 MW at energy 400 keV; continuous injection of 2.6 MW at 355 keV
  - **LHD:** achieved 10.3 MW (in total) and 4.4 MW (per injector) at 180 keV

- **Ancillary issues**
  - N-NBI fast ions can be affected by TAE instabilities, sawteeth, fishbones, and tearing modes, which would degrade current drive efficiency

Wave heating in burning plasmas

- **Electron cyclotron heating (ECH)**
  - Because electron cyclotron frequency waves propagate in vacuum and couple efficiently to edge plasma, the wave launcher can be distant from plasma, advantageous in a burning plasma

- **Lower hybrid (LH)**
  - In a burning plasma, well suited for non-inductively sustaining and modifying off-axis current profile (r/a > 0.65) → lower hybrid current drive
  - No particle trapping or parasitic absorption on alphas because LH waves damp at high parallel velocities

- **Ion cyclotron resonant heating (ICRH)**
  - Capable to heat D-T plasma to the burning plasma regime (e.g., TFTR, JET)
  - ICRF discharge conditioning can remove hydrogen isotopes from vessel walls
  - Creates high-energy ions that could affect stability and heating
  - 1st/2nd harmonic ICRH heating of D likely affected by parasitic absorption by fusion alphas and beryllium impurities

2. Self-heating

- Equilibrated ion & electron temperatures
- Low rotation
- Self-organized profiles
- Density control
- Burn control and thermal stability

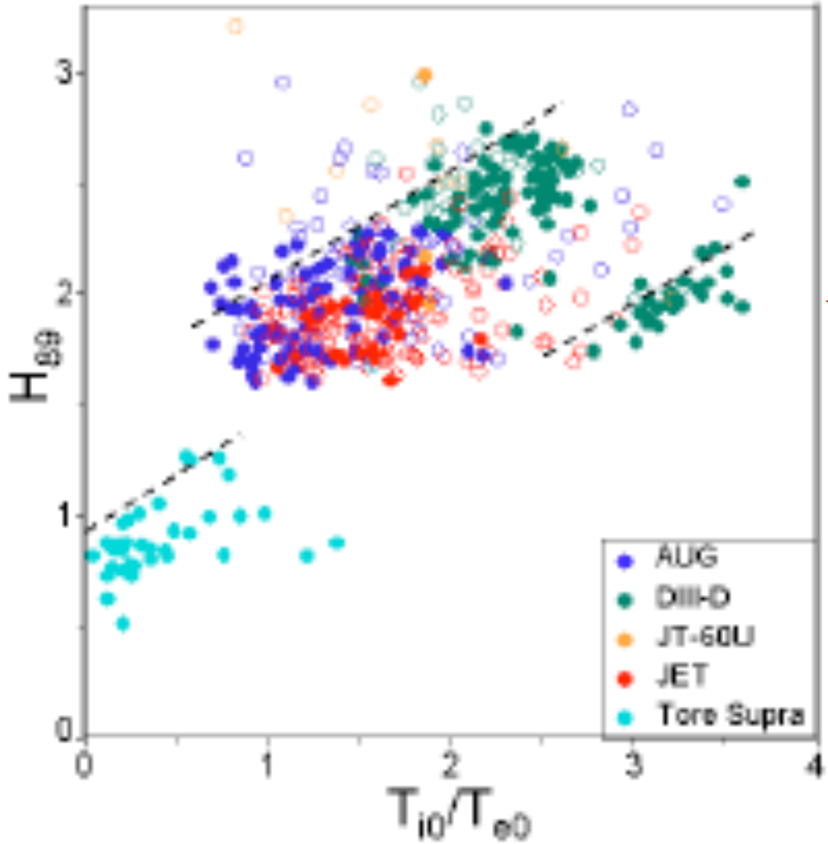
Equilibrated temperatures ($T_i = T_e$)

- **Dominant electron heating**
  - In burning plasmas, fusion alphas will dominantly heat electrons, leading to centrally peaked electron heating and weaker ion heating
  - Negative-ion neutral beams (MeV range) and ICRF/ECH auxiliary heating for burning plasmas also predominantly heat electrons
  - Weak ion-electron coupling is compensated by large size of burning plasma device and the long energy confinement time, so electrons and ions are weakly coupled in core plasma but increasingly coupled toward the edge

- **Temperature equilibration**
  - Electron-ion equilibration time (~0.5 s) is shorter than energy confinement time (~6 s) in burning plasma reactor-scale device.
  - Thus, energy transfer from electrons to ions will lead to $T_i \sim T_e$ in burning plasmas
  - Contrast to present-day ~100 keV neutral beam-heated plasmas that have $T_i >> T_e$

Impact on thermal transport

- **Possible degradation of confinement**
  - Question whether good ITG confinement with $T_i >> T_e$ (e.g., hot ion mode, supershot mode) will extrapolate to burning plasma with $T_i \sim T_e$



ITER baseline

Confinement enhancement factor H_{89} versus ratio of central ion and electron temperatures, for hybrid and reversed-shear advanced scenarios (open circles = transient, closed circles = stationary)

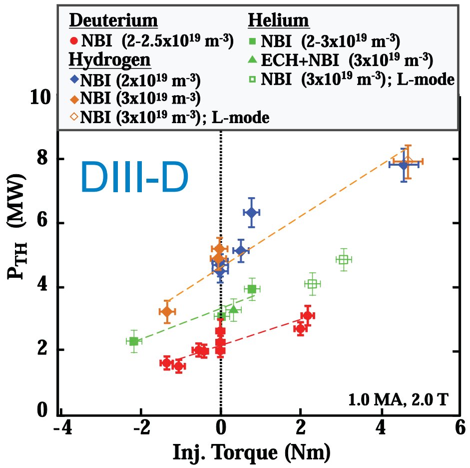
Sips et al. (2004 IAEA)

Low rotation in burning plasmas

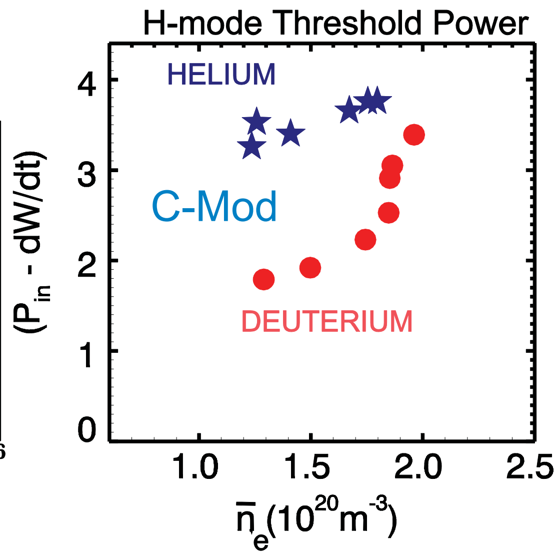
- **Toroidal rotation and ExB velocity shear are important in current-day tokamaks for confinement and stabilization**
  - Stabilize ion temperature gradient (ITG) and resistive wall mode (RWM) instabilities
  - Suppress turbulent transport and help internal transport barrier formation
- **Neutral beams may be insufficient to create rotation in reactor-grade plasmas**
  - Short penetration depth
  - Requires high injection energy E, hence imparted momentum $\propto P_{inj} / E^{1/2}$ is modest
- **Hence, expect low rotation in burning plasmas**
  - Also, isotropic fusion alphas lead to little toroidal momentum input

Access to high confinement (H-mode)

- **Issue**
  - ITER plans to operate in “high confinement” H-mode with edge transport barrier. Desirable to achieve this in pre-nuclear operation phase (H or He) to test ELM physics and divertor hardware. What is the L-mode to H-mode power threshold?
- **Experimental results**
  - ITPA joint expts in C-Mod, DIII-D, and NSTX (+ EU tokamaks)
  - L-H power threshold higher in He than D (C-Mod 20-80%, DIII-D 30-50%). Still higher in H.
  - Smaller difference (up to 20%) between He, D found in NSTX



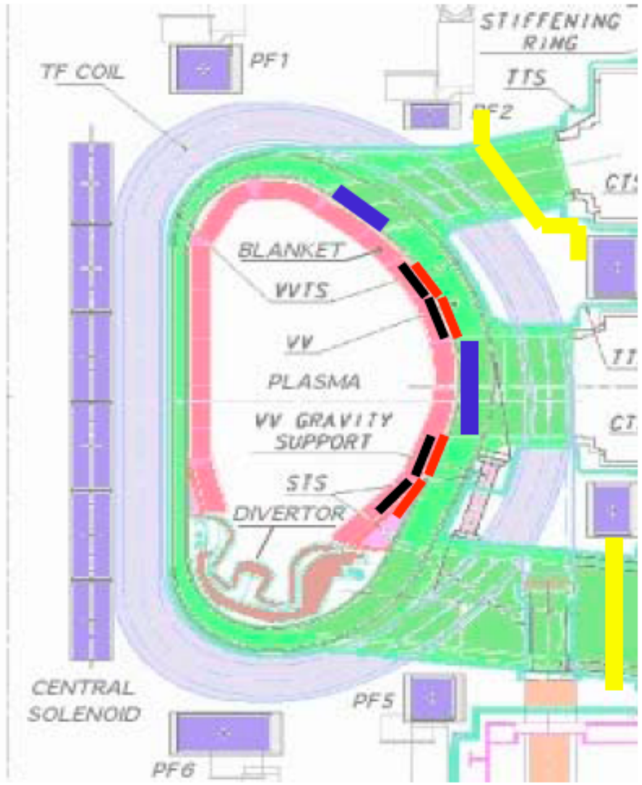
P. Gohil et al., 12th international workshop on “H-mode physics



- **Direction**
  - Given variation in L-H thresholds, prudent for ITER to plan for higher power thresholds for H-modes in pre-nuclear phase
  - ITPA will further study physics mechanisms and H-mode, ELM regimes in helium

Resistive Wall Mode control coils

- **RWM control: enables high β_N operation, for required fluence**
  - Rotation in ITER may be too low for stabilization; hence may need active control of RWM instability by means of internal coils



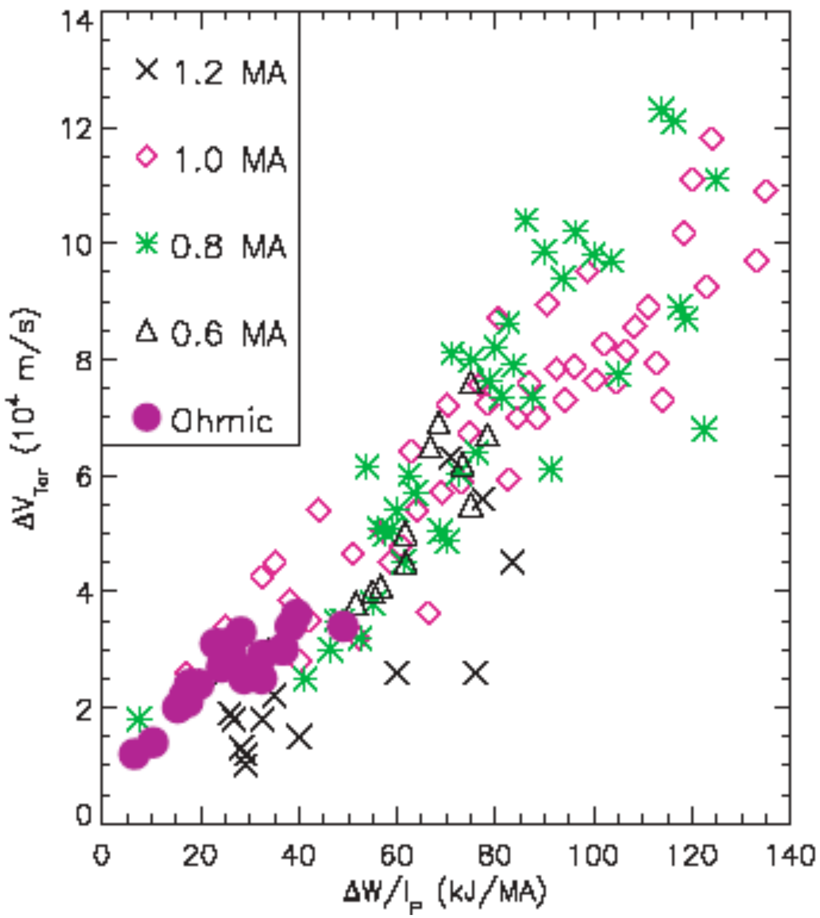
1. Coils around blanket modules
2. Coils at blanket/wall interface
3. Upper+mid-plane port-plug coils
4. 36 external coils outside TF

Hawryluk, ITER Design Review

“Spontaneous” toroidal rotation

Rice et al., Nucl Fusion (2001)

- **Considerable recent interest in “intrinsic” toroidal rotation**
  - Observed to be spontaneously generated, without externally applied torque (i.e, no NBI), in tokamaks with Ohmic and cyclotron frequency (IC/EC) heating, especially in H-mode
  - Experimentally, found to be proportional to plasma stored energy (or pressure) and inverse to current



- **Several explanations**
  - Orbit losses at edge; neoclassical toroidal viscosity in core; turbulence-driven momentum transport

- **Intrinsic rotation is ~2% of Alfvén speed**
  - Possibly strong enough to stabilize MHD modes in ITER

Less external control because profiles are self-organized

- **Present-day tokamaks have developed techniques to externally control profiles of current, pressure, momentum**
  - Neutral ion beam injection and RF waves for heating and current drive
  - Pellet injection for density control

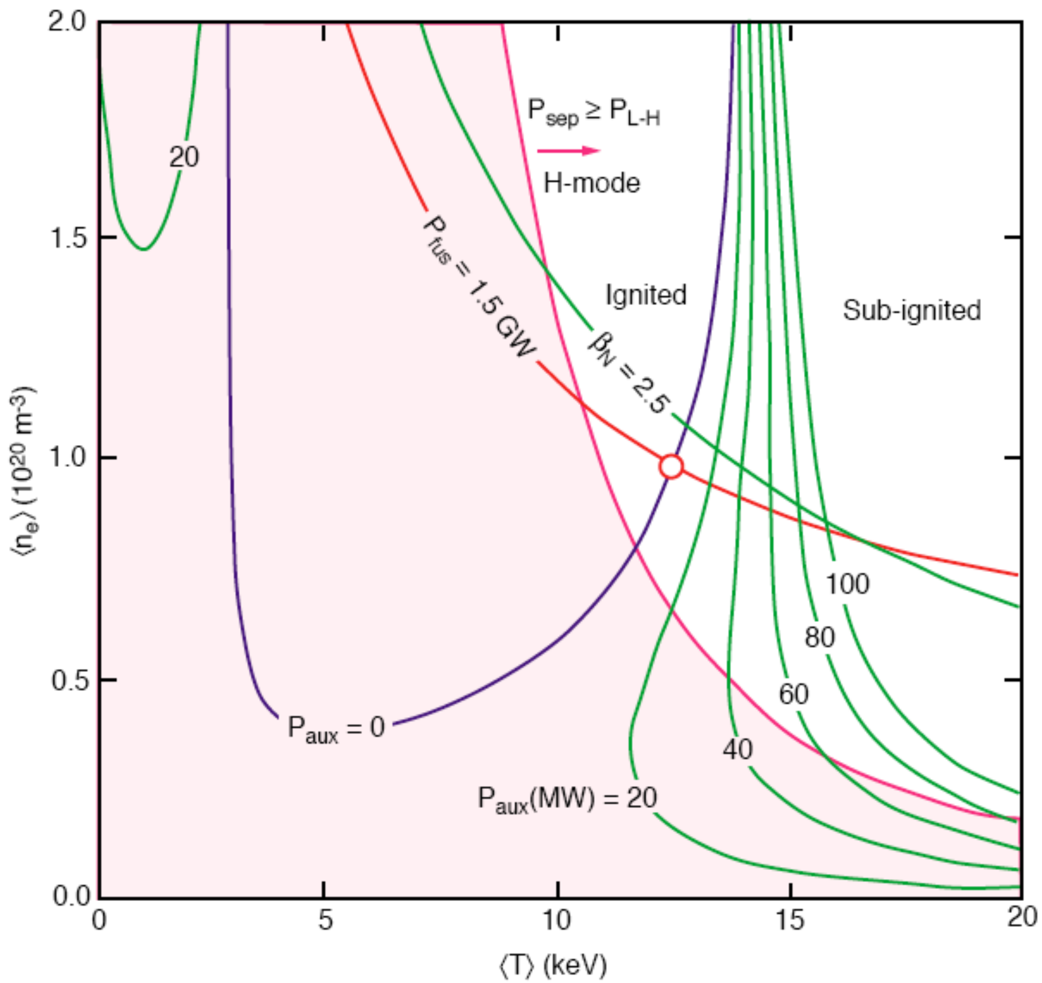
- **Burning plasma has an "autonomous" plasma state**
  - With dominant self-heating from fusion reactions, a burning plasma determines its own profiles (current, pressure, impurities)
  - Hence, much less flexibility than in present-day experiments to control current, pressure, and rotation profiles by means of heating & current drive from externally applied RF waves and neutral beams

Density fueling

- **In present-day tokamaks:**
  - Fueling is provided by gas injection, pellets, and neutral beams
  - Penetration (and hence core fueling) are possible

- **In burning plasmas:**
  - Central particle fueling is low, due to penetration difficulties (hence ITER often assumes a flat density profile)
  - An inward pinch (predicted by transport simulations) could be important, since it would yield a peaked core density profile even with edge fueling, thus achieving higher fusion gain
  - Recent results see $n_e(r)$ peaking at low collisionality (ν^*)
  - Too strongly peaked density profile is undesirable since it could cause early onset of neoclassical tearing modes or central accumulation of impurities
  - Work is also being done on new fueling schemes: e.g., high-speed DT pellet injection from inner wall (high-magnetic-field side)

Burn control and thermal stability



(representative contours)

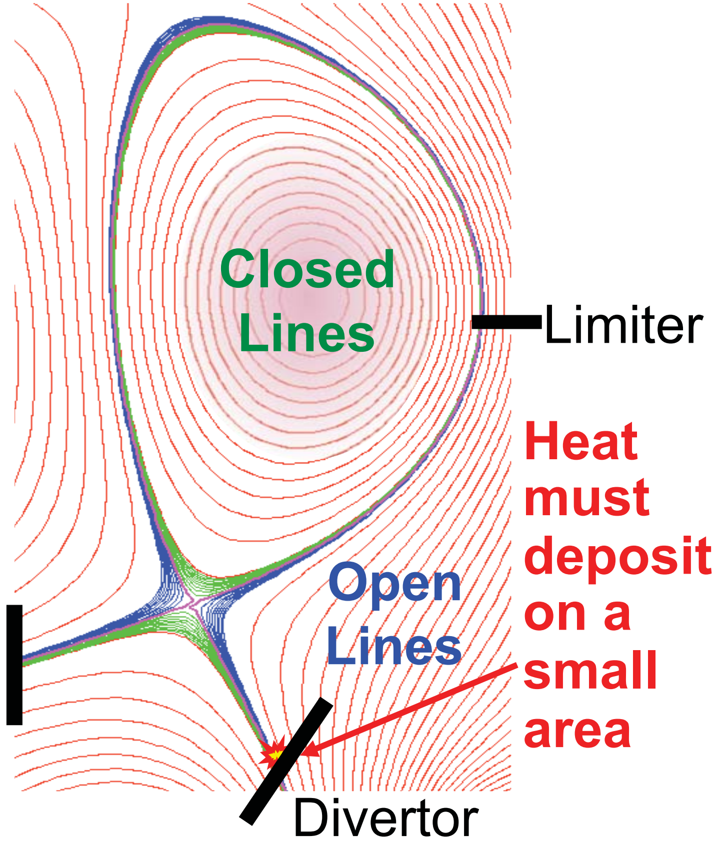
- **Plasma operation contour (POpCon)**
  - Sustained, thermally stable fusion is possible for ignition (P_{aux} = 0) and finite-Q (P_{aux} > 0) contours in the H-mode domain ($P_{sep} \geq P_{L\text{-}H}$) and below the beta limit
  - Plasma burn in ITER will be stable since it operates near the stable (right) branch of the ignition curve where power loss increases faster with temperature than the fusion power

3. High performance

- Heat loads
- Transient thermal events (disruptions, ELMs)
- Impurity accumulation
- Choice of PFC material
- Steady-state operation

High heat loads

- **Burning plasma will have large steady power fluxes and longer pulses**
  - Hence larger erosion of these components, during steady-state plasma conditions and especially during off-normal events (disruptions, ELMs)
  - High fraction of power must be radiated before divertor plate contact
- **ITER**:
  - P_{fusion} = 400 MW fusion
  - P_{heat} = 120 MW
  - $f_{rad} = P_{rad}/P_{heat}$ ~ 70%
- **DEMO fusion reactor**:
  - P_{fusion} = 2000-3500 MW fusion
  - P_{heat} = 500-1000 MW
  - f_{rad} ~ 95%



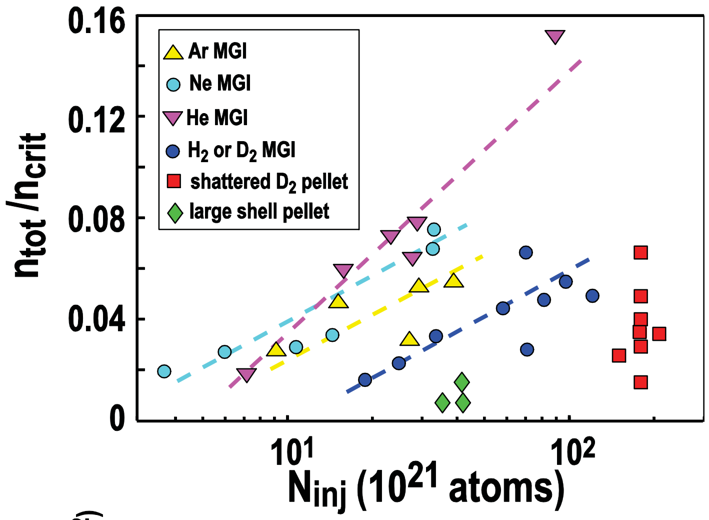
Kotschenreuther et al. (PoP 2007)

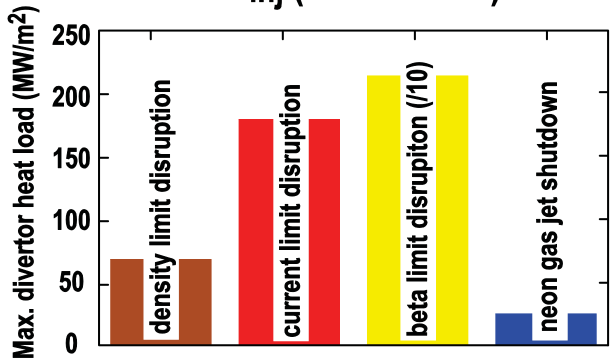
Disruptions

- **Off-normal operational event**
  - Cause large heat and electromagnetic loads, plus conversion of thermal plasma current to relativistic (~10 MeV) suprathermal "runaway" electrons
- **Particularly dangerous for burning plasmas**
  - Because of high plasma stored energy, generated by fusion reactions
  - Disruptions are less frequent than ELMs (1-10% of ITER discharges expected to disrupt), but energy fluxes are 10X larger
  - Repetitive disruptions can shorten PFC lifetime and cause wall conditions to deteriorate (localized melting, vaporization)
- **Disruption mitigation methods**
  - Massive gas injection (to dissipate the plasma energy through radiation over the entire chamber before it reaches the divertor)
  - Pellet injection (multi-pellet, hyper-velocity pellets)
  - High-density liquid jet injection

Disruption mitigation

- **Issue:**
  - Need highly reliable method for mitigating disruptions (fast I_p quench) to avoid machine damage by I x B forces, thermal heat loads, and runaway electrons
- **DIII-D:**
  - Assessing Massive Gas Injection (MGI), shattered pellets, and shell pellets [Hollman, APS 09]
- **C-Mod:**
  - Testing MGI with mixed gases; using LH current drive to generate fast electron "seed" [Whyte, APS 09]
- **Both DIII-D and C-Mod** show good mitigation of heat loads, vessel currents, and resulting forces with Massive Gas Injection

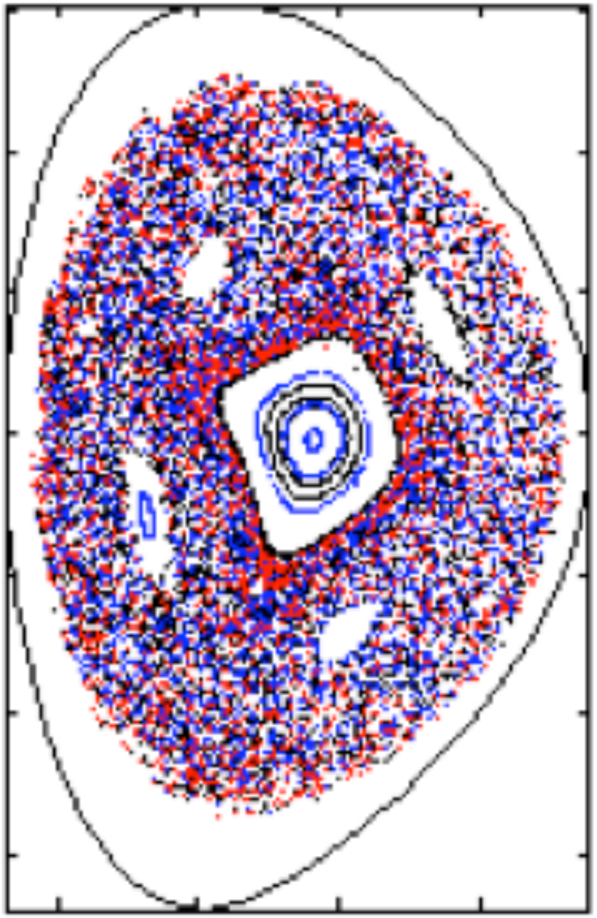




Disruption mitigation: runaways

- **Key open issue:**
  - What density is needed to suppress high-energy runaway electron "avalanche"
  - Suppression purely by collisions would require a critical density (several hundred grams) that is difficult to attain in ITER and that would impose large gas load on pumping system

- **Recent 3D resistive MHD modeling of MGI**
  - Finds that stochastic fields triggered by edge cooling can cause rapid loss of both thermal and non-thermal (runaway) particles, consistent with experiments [Izzo, APS 09]
  - This additional loss mechanism implies it may not be necessary to attain Connor-Hastie-Rosenbluth collisional limit to suppress runaways



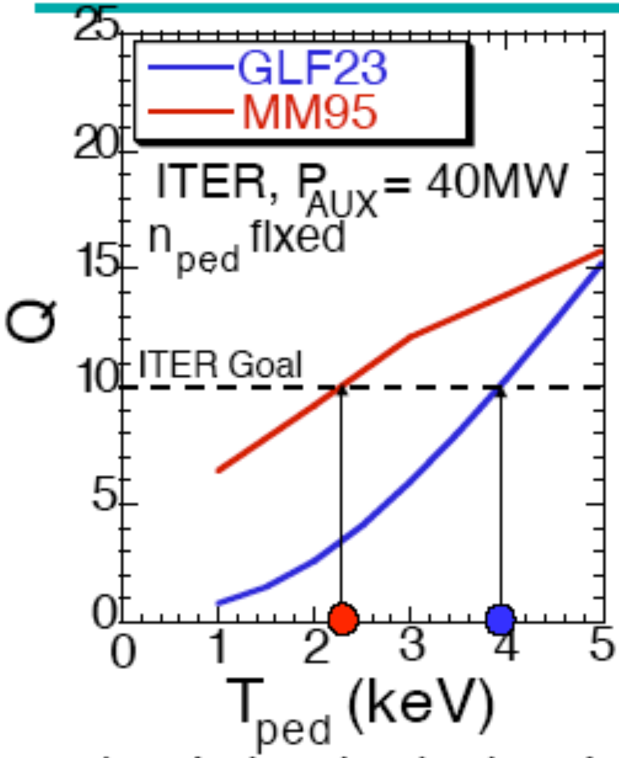
NIMROD simulation of C-Mod

Edge Localized Modes (ELMs)

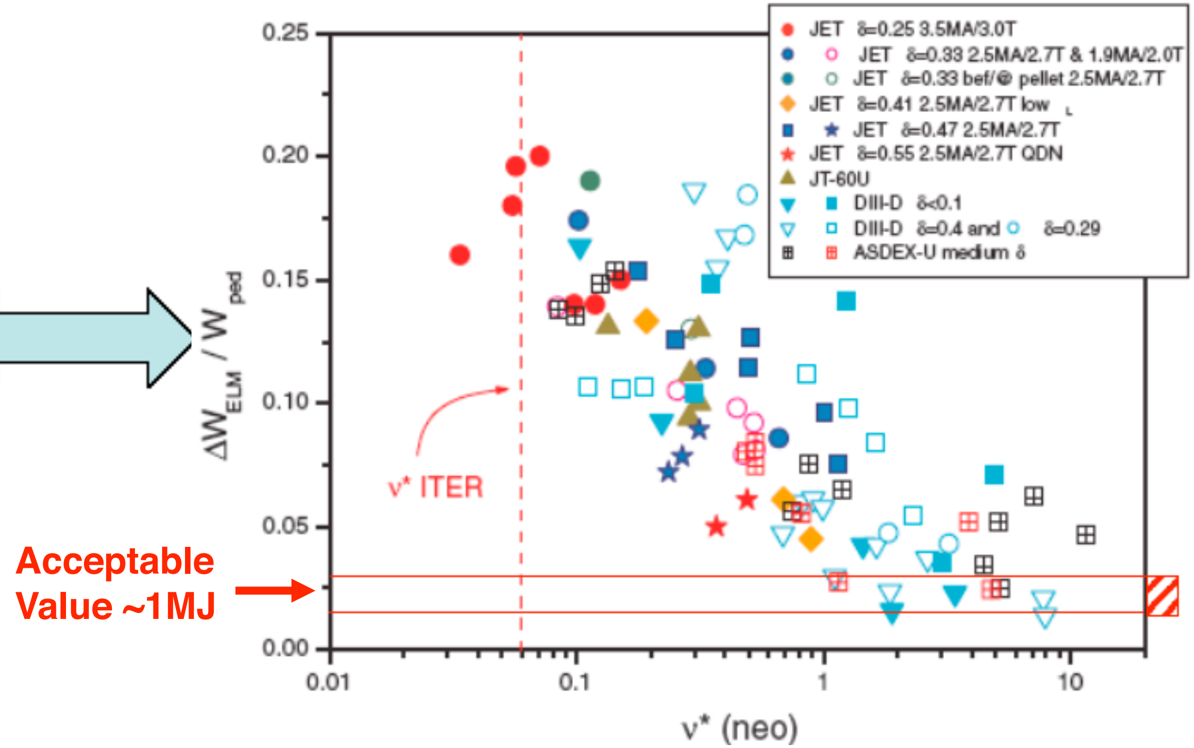
- **H-mode tokamaks are susceptible to ELMs**
  - Can cause significant heat loading on divertor, erosion of PFCs, and loss of internal transport barrier (ITB)
  - Will already be a concern for ITER with HH and DD operation

- **Even more dangerous for burning plasmas (DT)**
  - Because of high plasma stored energy, generated by fusion reactions
  - Also because heating power produced in burning plasma eventually needs to be exhausted at the edge (prefer peak target power density < 10 MW/m^2)
  - For ITER, since many (several 100) ELMs occur during each discharge, important that surface temperature rise due to an ELM remain below threshold for sublimation (carbon) or melting (metals)
  - Burning plasma requires H mode to attain high Q; pedestal temperature determines Q, but pedestal pressure is limited by transport and ELMs

The Pedestal Requirement: High Pressure with Small ELMs



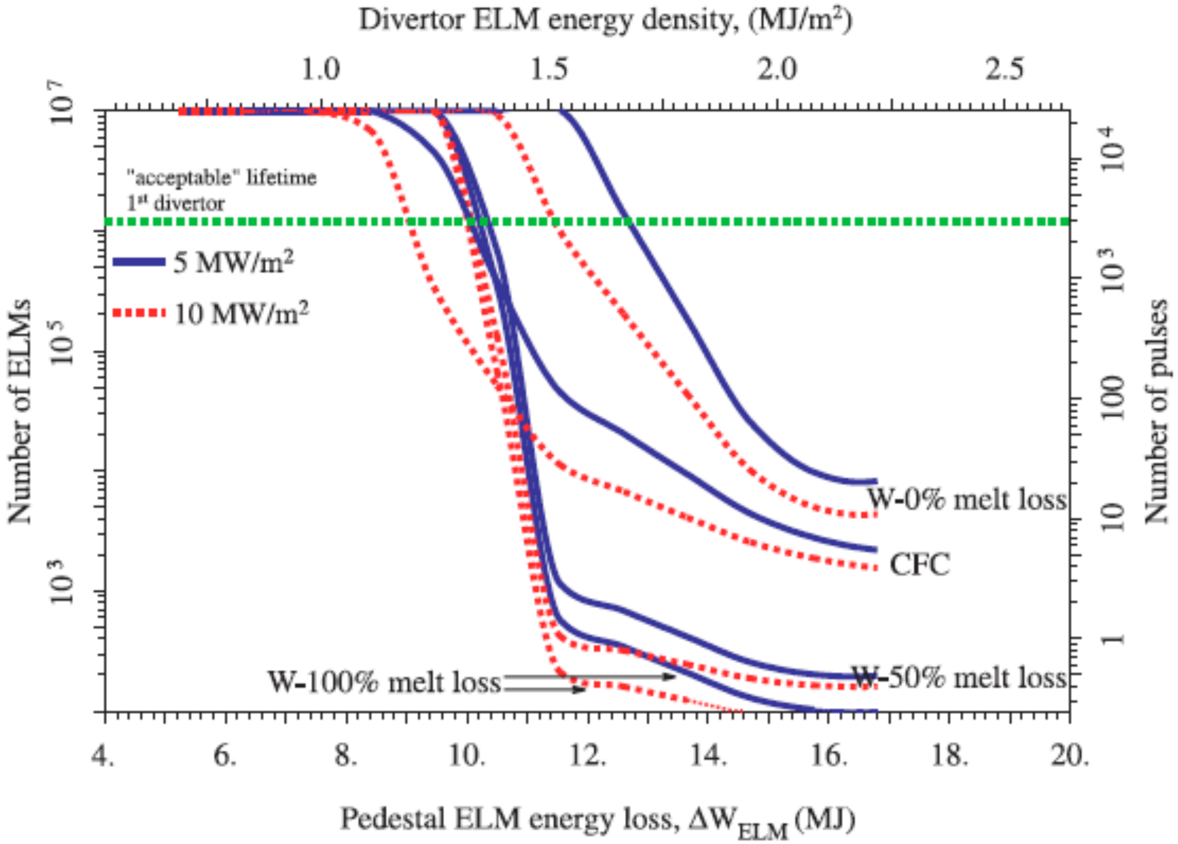
J. Kinsey (Fusion Sci. and Tech 2003)



- Burning plasma performance dependence on pedestal pressure varies with stiffness of the core transport model
- Low collisionality pedestals in current devices usually result in large ELMs that are incompatible with a burning plasma first wall

Large ELMs cannot be tolerated

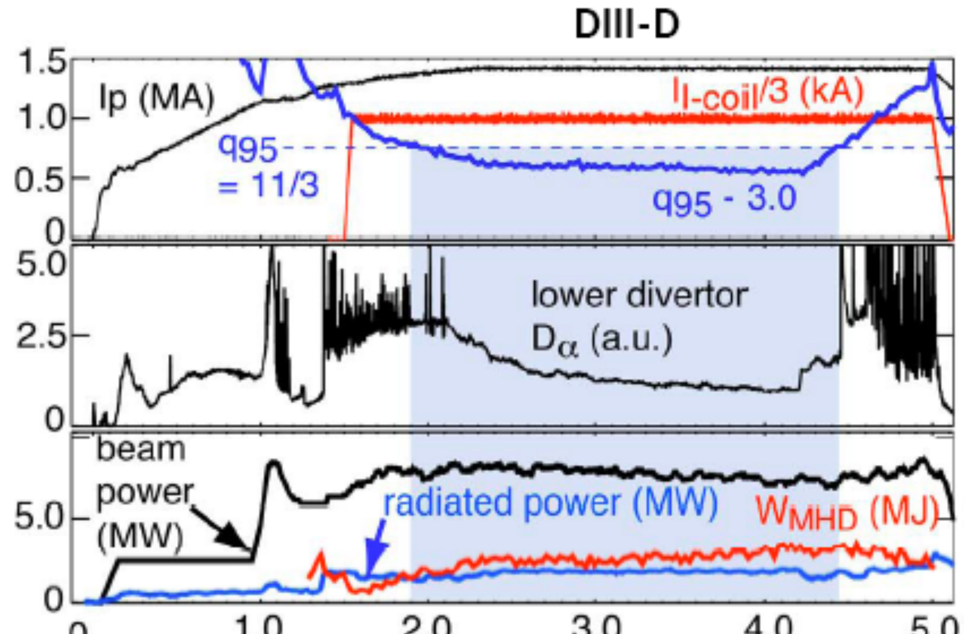
- **Large Type I ELMs will likely damage ITER divertor structure**



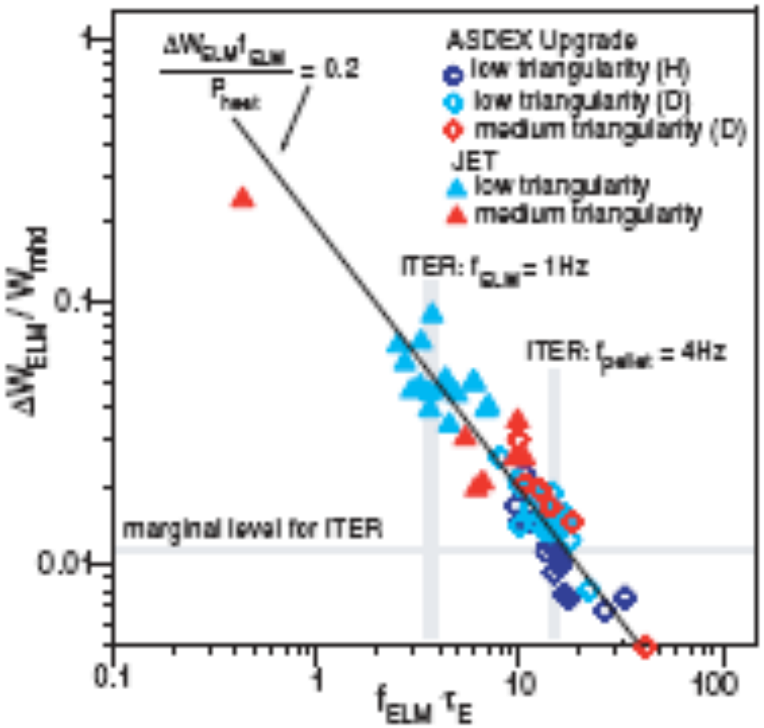
G. Federici (PPCF 2003)

Erosion lifetime in number of ELMs (left) or ITER full-power pulses (right) of a W target (10 mm thick) and CFC target (20 mm) as a function of ELM energy loss from the pedestal, for inter-ELM heat loads of 5 MW/m^2 (—) and 10 MW/m^2 (…) and for different tungsten melt loss fractions

ELM control methods



T. Evans (APS 2005)



- **Edge ergodization (Resonant Magnetic Perturbation coils)**
  - Being explored for ITER
  - Issues: distance from plasma; compatibility with other hardware

- **Pellet-triggered ELM pacing**
  - Being explored for ITER
  - Issues: minimum pellet size and pedestal penetration; compatibility with fueling requirements

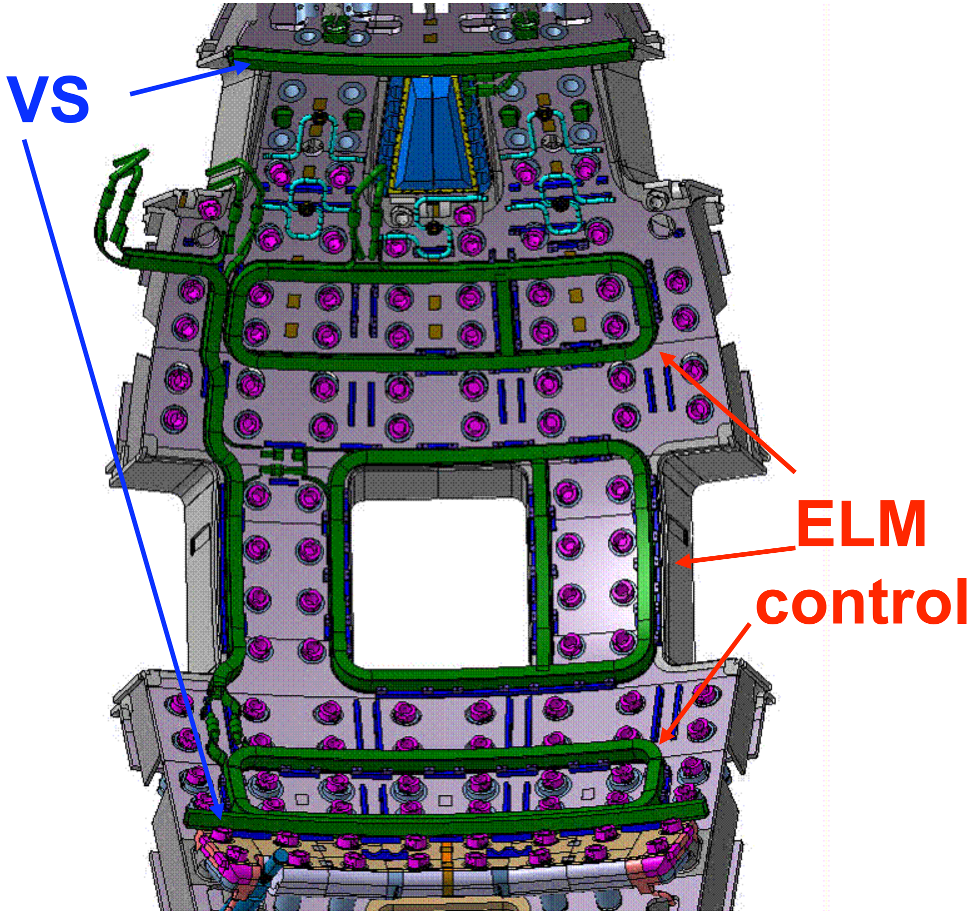
Mukhovatov (PPCF 2003)

ELM control by RMP coils in ITER

USBPO U.S. BURNING PLASMA ORGANIZATION

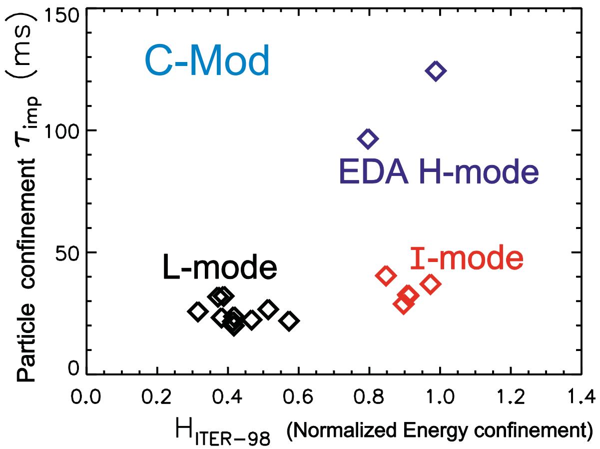
- **A set of resonant magnetic perturbation coils is under design**
  - Consists of 9 toroidal X 3 poloidal array on internal vessel wall

- **Current physics issues**
  - ELM suppression criteria; effect of RMP on particle and energy confinement

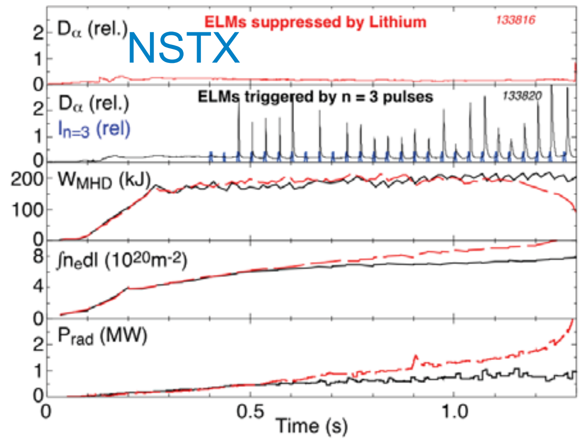


Regimes without large ELMs

- **Issue**
  - Some regimes with continuous, benign relaxation mechanism have been found in US (and other) tokamaks: extrapolation to ITER?
- **C-Mod:**
  - Enhanced D_α H-mode, without ELMs
  - "Improved L-mode" (I-mode) with energy barrier but no particle barrier [Marmar APS 09]



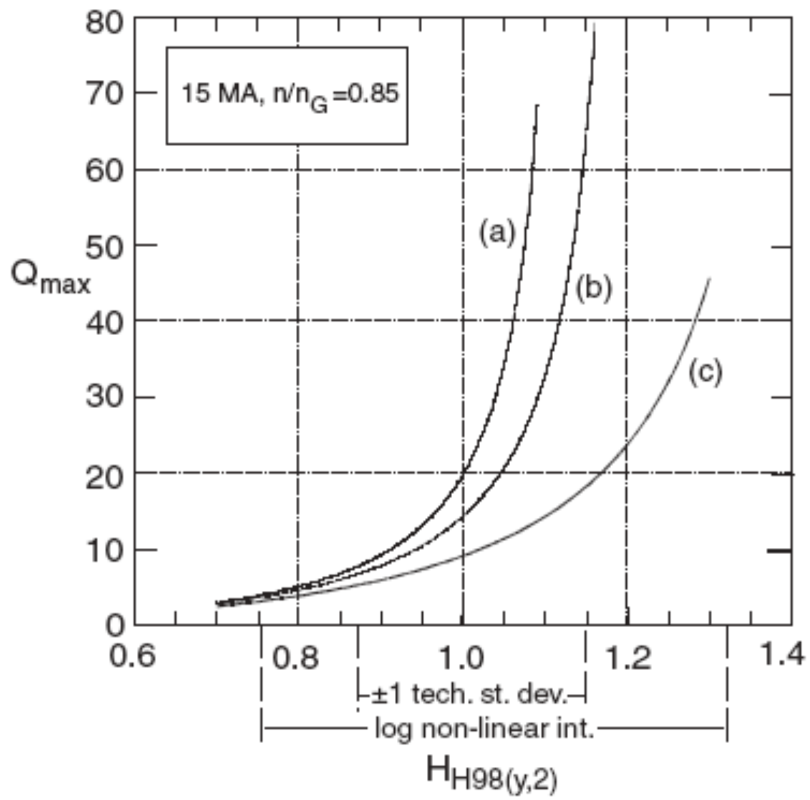
- **NSTX:**
  - Small ELM regimes
  - ELMs suppressed with liquid Li walls
  - Controlled ELMs trigged with pulsed 3D fields and vertical jogs [Maingi PRL 09]



- **DIII-D:**
  - Quiescent H-mode (no ELMs): recently extended to co-NBI and low-torque regimes, higher pedestal pressure [Burrell 09]

Impurity accumulation

- **Consequences of impurities**
  - Radiative cooling in the core
  - Dilution of the fusion fuel (by helium “ash”)
- **Sub-ignition DT experiments (TFTR and JET)**
  - Studied tritium particle transport coefficients
  - Also studied helium ash transport coefficients



- Fusion Q versus confinement H_{H98} for various He content
  - (a) f_{He} = 1.6%, τ_{He}^*/τ_E = 2.5
  - (b) f_{He} = 3.2%, τ_{He}^*/τ_E = 5.0
  - (c) f_{He} = 5.8%, τ_{He}^*/τ_E = 10.0

Mukhovatov (PPCF 2003)

Choice of plasma-facing components

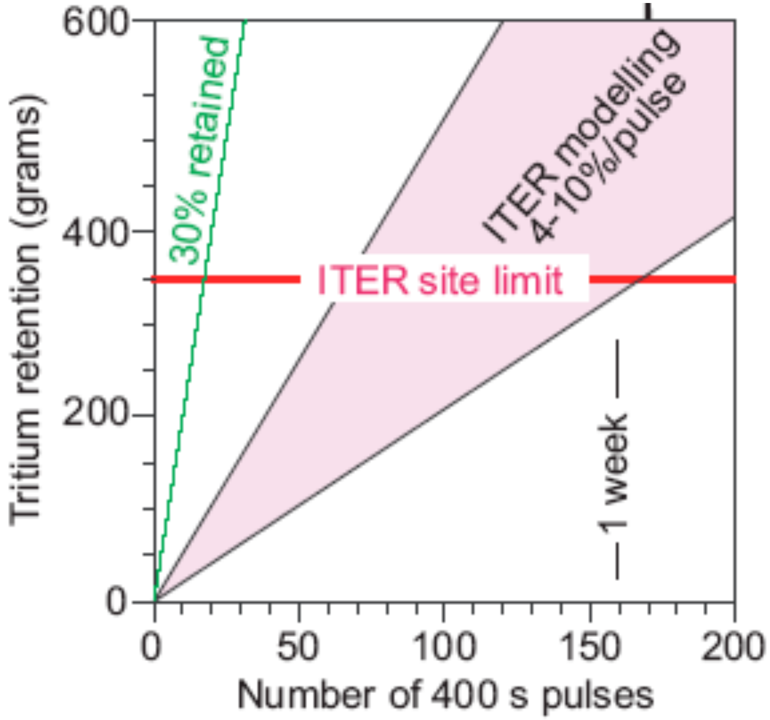
- **Plasma performance-related limitations on PFC materials:**
  - Plasma contamination
  - PFC surface lifetime and viability
    - Energy density and energy throughput (discharge length) are very high in burning plasma
    - Ablation or melting caused by uncontrolled transient surface heat loading (disruptions, ELMs, runaway electrons)

- **Regulatory-related limitations on PFC materials:**
  - Dust production
  - Tritium inventory control (retention in plasma-deposited films)
    - Minimize tritium retention and/or allow co-deposited tritium to be recovered

- **For PFC materials, carbon, beryllium, and high-Z (molybdenum and tungsten) all have advantages and disadvantages**
  - Research on alternative PFC materials (e.g., liquid lithium)

Tritium retention and removal

- **Estimates of T retention in burning plasma are uncertain**
  - DT experiments in TFTR and JET showed that T retention was ~30% of that injected, and reduced to ~15% after "cleaning"
  - Implies that T cleaning will be required after not many discharges in a burning plasma
- **ITER will require higher T removal rates than have been demonstrated**
  - Oxygen bake, RF conditioning, disruptive-radiative heating, grit-blast, replace tiles



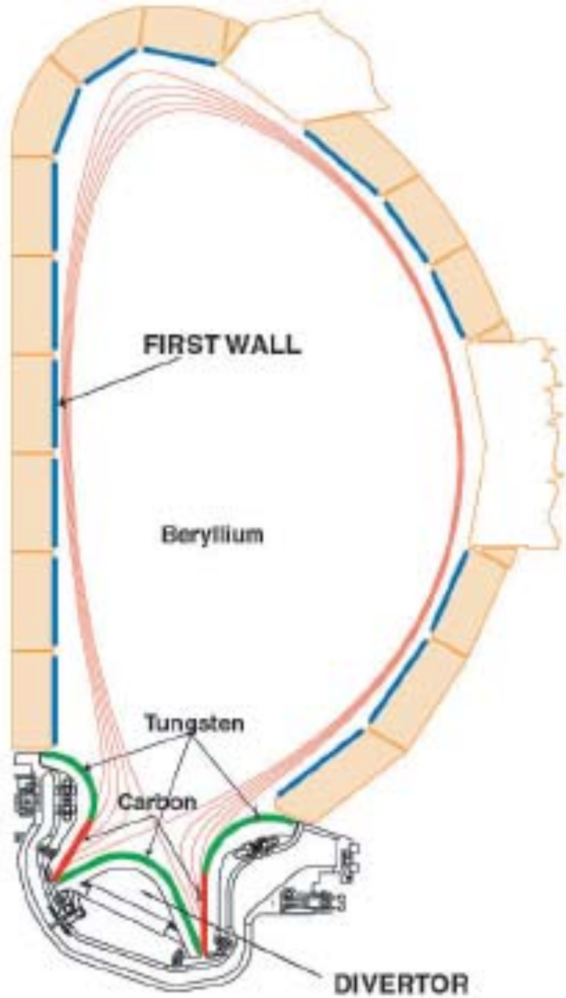
Parameter	TFTR experience	JET experience	ITER requirement
Time devoted to T removal	1.5 months	3 months	5-14 hours
Fraction of T removed	50%	50%	~100%
Tritium removal rate	~ .0014 g/hr	~ .0028 g/hr	~25-70 g/hr

Factor of 10^4 increase needed

B. Lipschultz (BP Workshop 2005)

PFCs in ITER

- **ITER PFCs for initial operation**
  - ***Carbon-fiber-composite (CFC) for divertor targets (strike point area)*** — widely used in present-day devices, due to compatibility with wide range of plasma parameters (resilience to high quiescent heat flux after "accidents")
  - ***Tungsten at dome and baffle (upper target) regions*** — due to erosion resistance (low yield of physical sputtering by neutral particles)
  - ***Beryllium for first wall*** — for small impact on plasma performance and high oxygen gettering

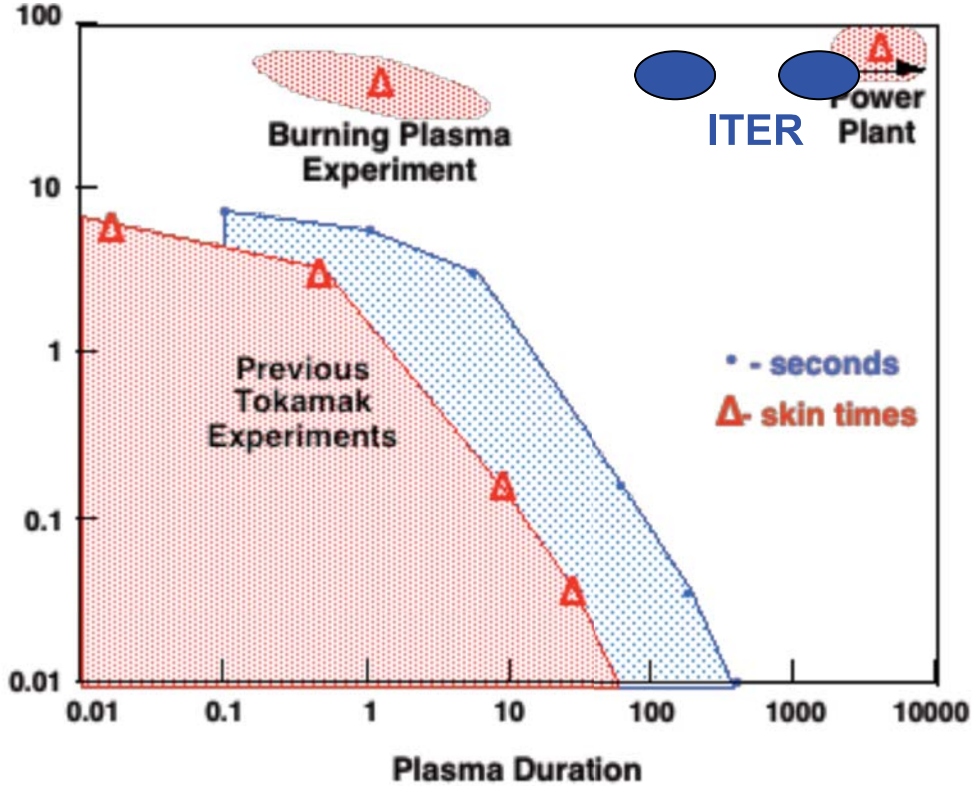


Layout of PFCs in ITER with different armor materials

G. Federici (PPCF 2003)

Long-pulse operation

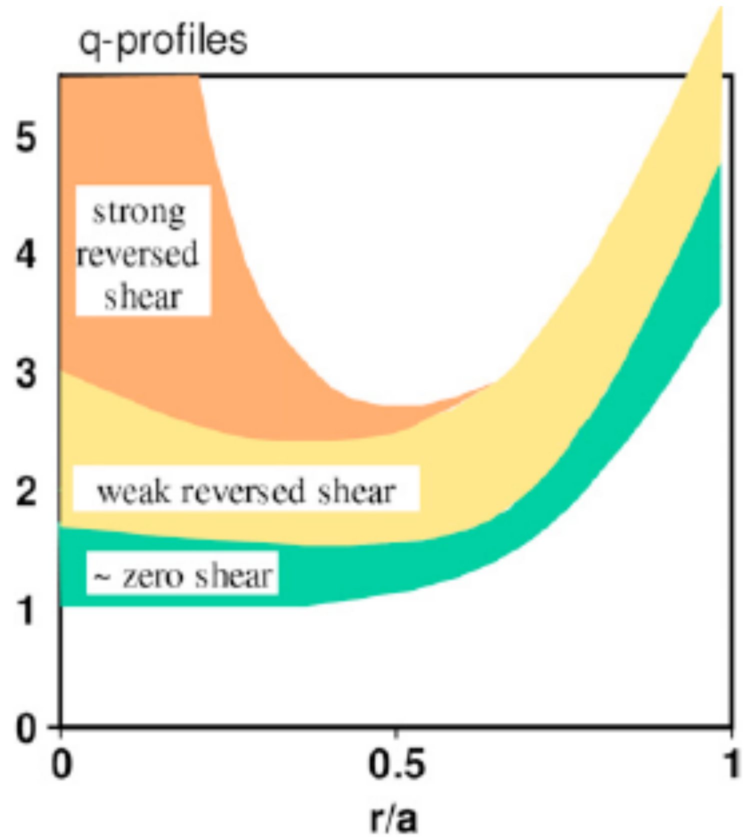
- **Time scales**:
  - energy loss rate of background plasma (τ_E)
  - energy transfer rate from alphas to plasma (τ_{sd})
  - particle accumulation rate of cooled-down alphas (τ_{ash})
  - current redistribution time (τ_{CR})
- **Why long pulse?**
  - Investigation of resistively equilibrated J(r) and p(r) profiles with strong α heating requires long burning plasma pulse ($\tau_{pulse} >> \tau_{CR}$)
  - In ITER, magnetic flux diffusion time τ_{CR} ~ 300 s
- **ITER aims for:**
  - 400 s with Q=10
  - 3000 s steady state (Q~5)



Steady-state scenarios

- **Reactor-scale steady state operation for tokamaks requires:**
  – Lower current operation: to minimize need for non-inductive current
  – High confinement: to maximize fusion production
  – High beta operation: to maximize the bootstrap current fraction

- **Active research area**
  – Design scenarios for start-up (while maintaining vertical stability) to access advanced operation
  – Maintain and control such operation (e.g., non-inductive current drive)



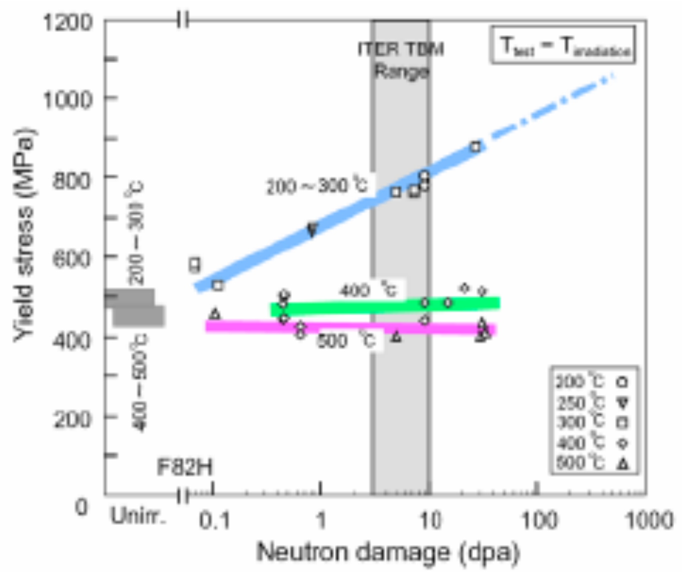
Classification of advanced scenarios for steady state operation, according to type of q-profile

4. Thermonuclear environment

- Neutron radiation
- Tritium breeding
- Burning plasma diagnostics

Neutron radiation damage

- **Radiation damage will affect all fusion materials**
  - Structural materials
  - Breeding & neutron multiplying media
  - Diagnostic & electronic materials
  - Insulators

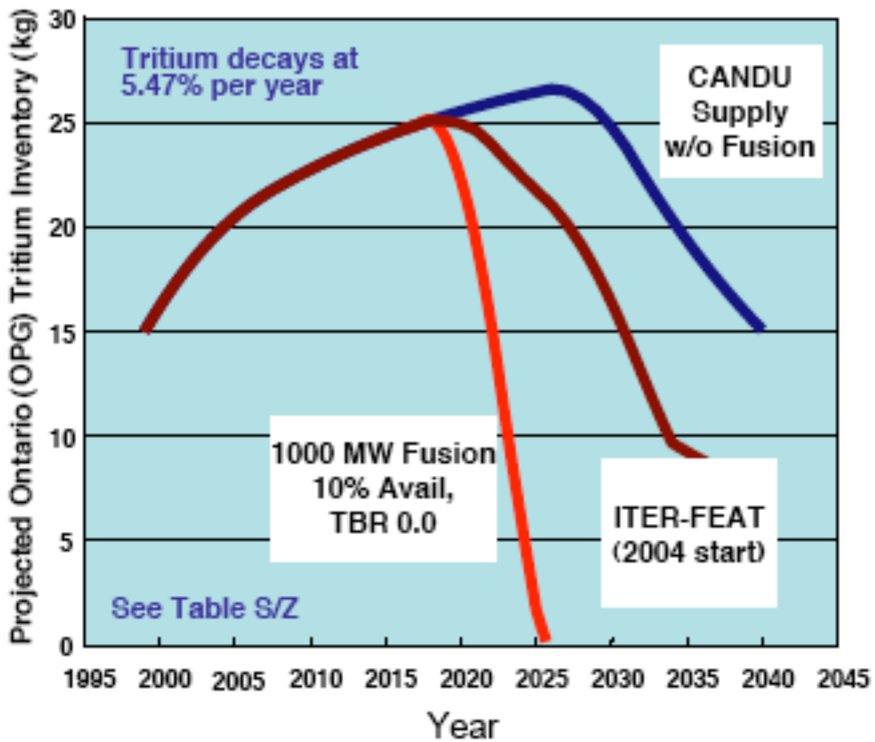


- **Typical degradation processes**
  - Hardening
  - Embrittlement
  - Phase instabilities
  - Segregation
  - Precipitation
  - Irradiation creep
  - Volumetric swelling
  - Helium embrittlement
  - Radiation-induced changes in thermal and electrical properties

N. Morley (TBM Workshop 2007)

Tritium supply

- **Large consumption of tritium during fusion**
  - 55.8 kg per 1000 MW of fusion power per year
- **Production and cost**
  - CANDU reactors: 27 kg over 40 years, $30M/kg currently
  - Other fission reactors: 2-3 kg/yr @ $84-130M/kg

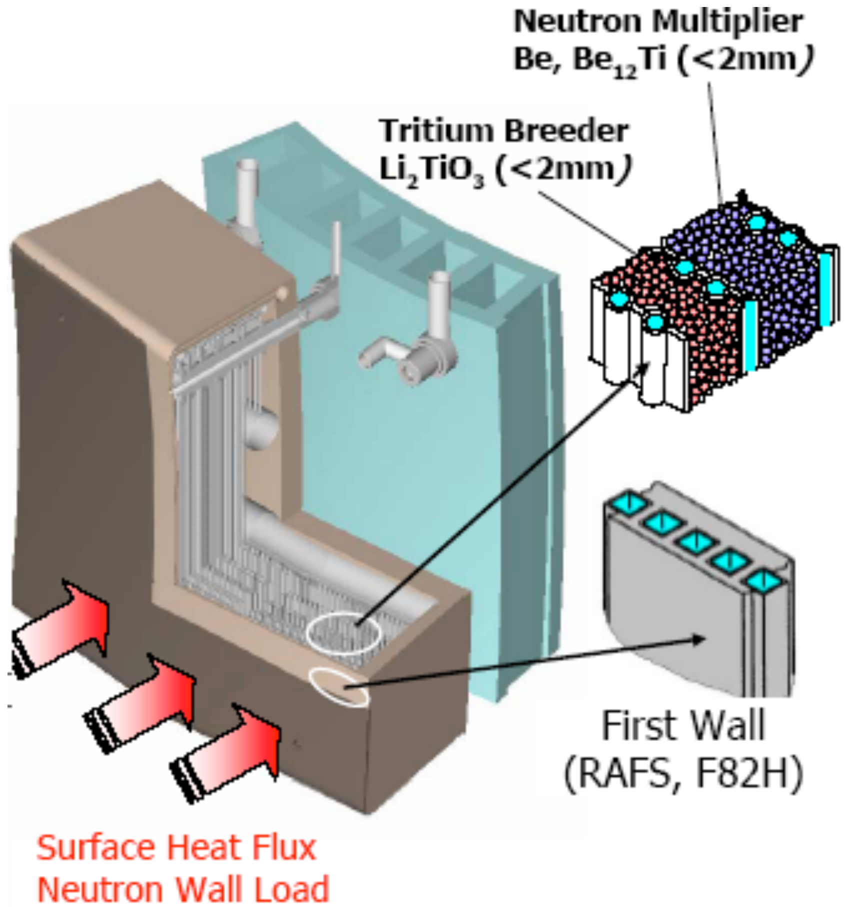


- **Tritium breeding for self-sufficiency**
  - World supply of tritium is sufficient for 20 years of ITER operation (will need ~17.5 kg, leaving ~5 kg)
  - Tritium breeding technology will be required for DEMO and reactors

M. Abdou (TBM Workshop 2007)

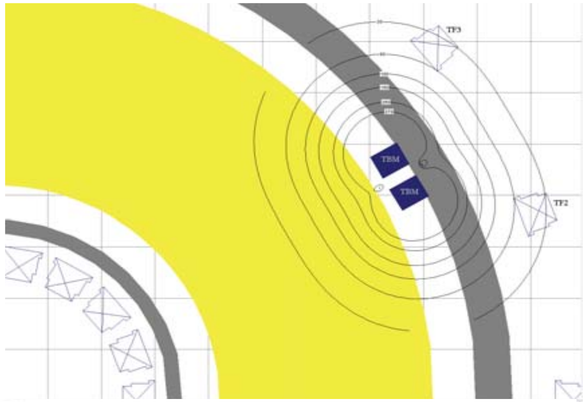
Test Blanket Modules (TBM)

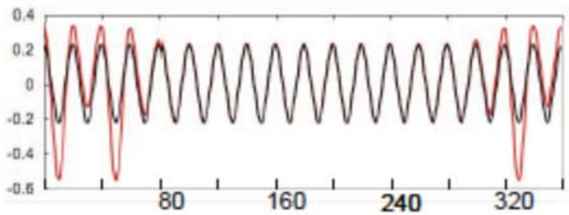
- **TBMs on ITER**
  - Sometime during ITER research program, Test Blanket Modules will be installed to investigate breeding of tritium (fusion nuclear technology)
  - ITER has 3 ports for blanket testing, and 2 TBMs can be installed in each port
  - Issues:
    - Will the neutron fluence be high enough?
    - Will TBM ferromagnetic content lead to large magnetic field ripple?
- **Other methods to test breeding**
  - Fission reactors, accelerator-based point neutron sources, non-neutron test stands



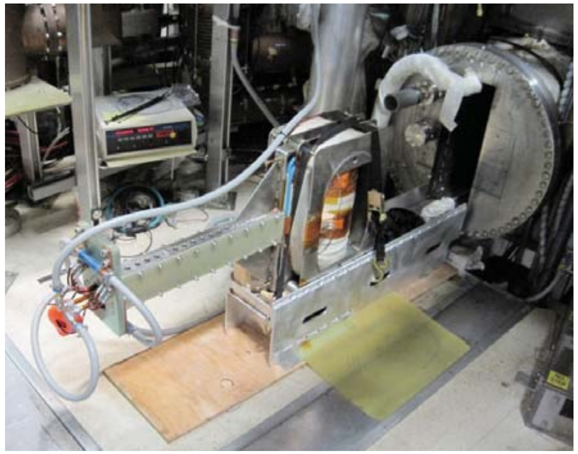
TBM error field experiments

- **Issue**
  - ITER plans to test 6 tritium-breeding Test Blanket Modules (@ ~ 1 ton ferromagnetic steel): cause localized, non-axisymmetric error field that is larger than background TF ripple (0.4%)
  - Effects on H-mode confinement, rotation, ELMs, alpha particle loss, etc.?





- **DIII-D simulation experiments**
  - Fabricated and installed a mockup coil to approximate error field of 2 TBMs in one port (ARRA funding)
  - Expts conducted Nov 2009 by international team, with scientists from ITER and 5 Members
  - Analysis underway: should help set limits on allowable B-field ripple



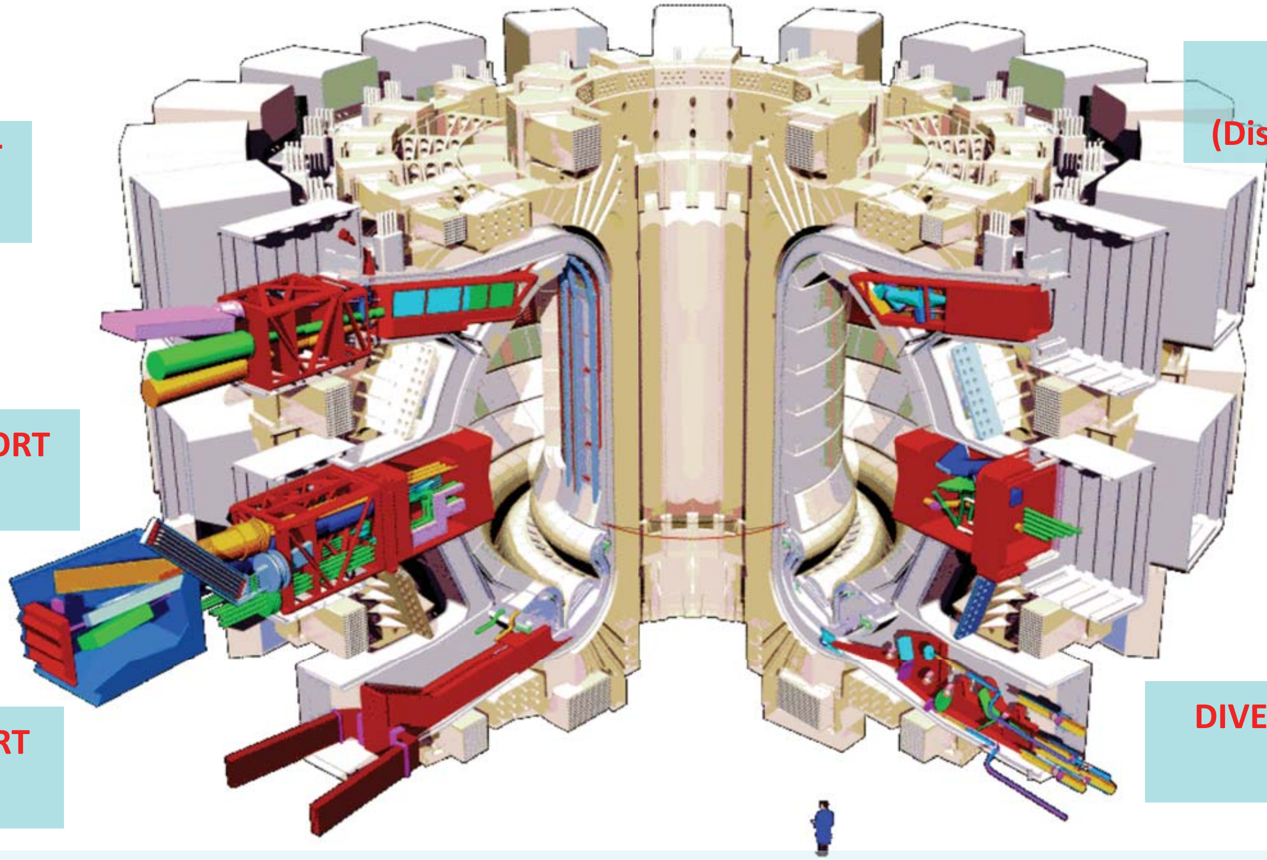
Measurements in burning plasmas

- **Essential for operation**
  - Plasma and first wall measurements will be critical in burning plasma for (1) machine protection, (2) plasma control, and (3) physics evaluations

- **Harsh radiation environment presents new challenges**
  - High neutron/gamma/plasma heat flux, particle bombardment
  - Radiation-induced conductivity & EMF in vacuum vessel magnetic sensors
  - Enhanced erosion of diagnostic first mirrors by fast particle bombardment
  - Enhanced absorption and photo-luminescence in windows and optical fibers

- **Other stringent conditions**
  - Limited installation space (number/size of ports, shielding): port plugs new concept
  - Limited access: reliability; remote handling maintainability/repair
  - Engineering requirements: maintain tritium containment and vacuum integrity; withstand high transient pressures; minimize activation
  - For very high burning plasma temperature (T_e > 40 keV), diagnostics must account for relativistic effects (Thomson scattering, ECE, reflectometry)

Plasma diagnostics on ITER



- **About 40 large scale diagnostic systems are foreseen for ITER:**
  - Diagnostics required for protection, control and physics studies
  - Measurements from DC to γ-rays, neutrons, α-particles, plasma species
  - Diagnostic Neutral Beam for active spectroscopy (CXRS, MSE ….)

5. Strongly coupled physics

- Integrated performance
- Control and data acquisition

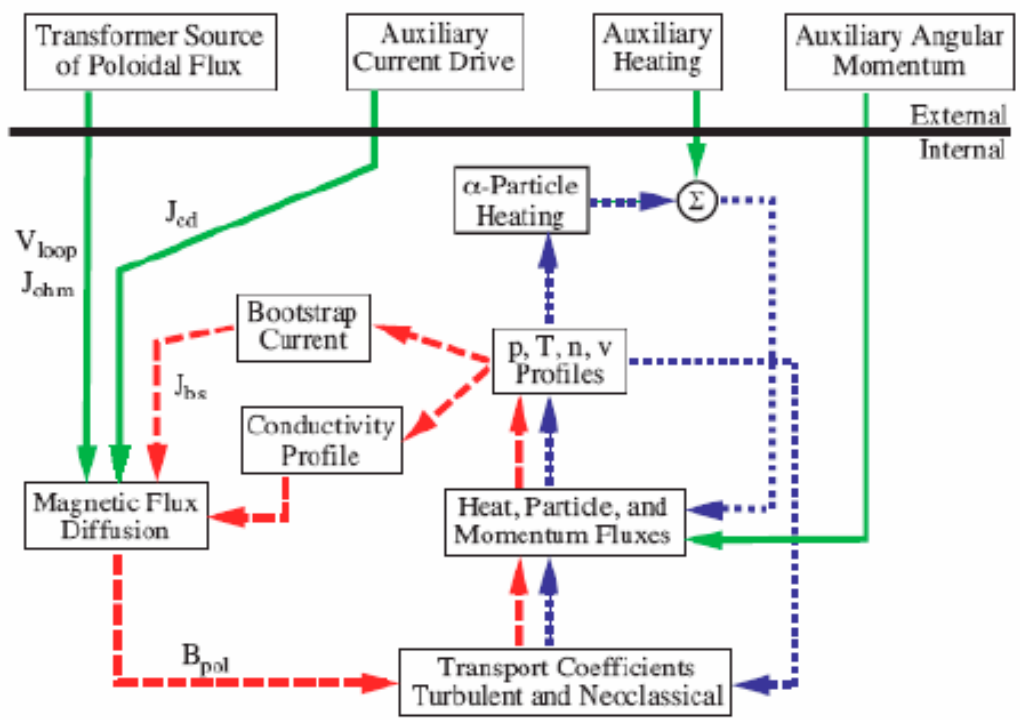
Integrated performance

- **Nonlinear coupling of burning plasma behavior**
  - The critical elements in the areas of transport, stability, boundary physics, energetic particles, heating, etc., will be strongly coupled nonlinearly in a burning plasma due to the fusion self-heating
  - New phenomena arise from full nonlinear interplay of alpha particle heating with transport, stability, and current/pressure control, as well as their compatibility with a divertor and plasma-facing materials in steady-state conditions
  - Multi-physics, multi-scale integrated behavior, which cannot always be anticipated from tests and simulations of separate effects

Example of nonlinearly coupled physics

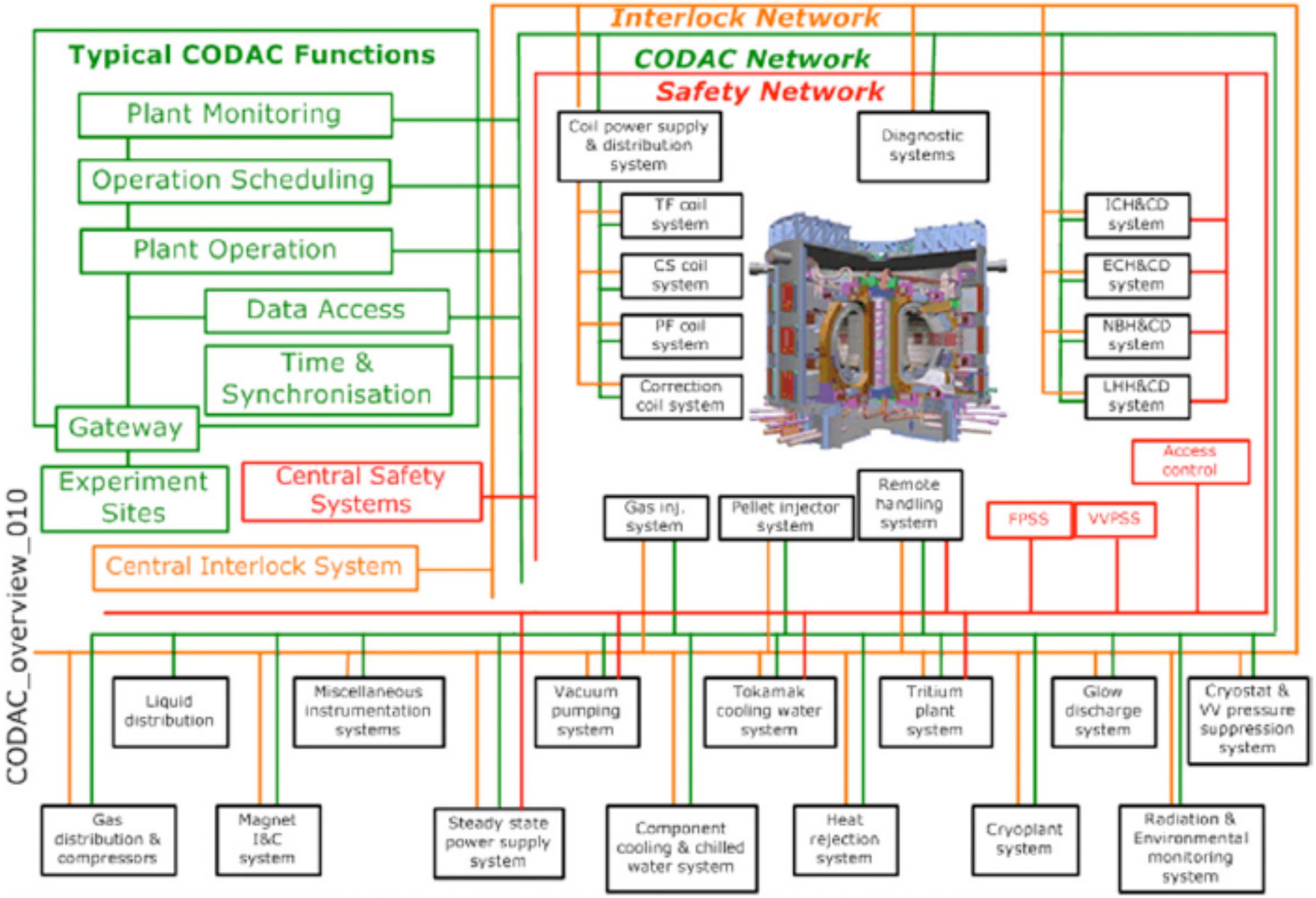
- **Nonlinear feedback loops and couplings govern transport, especially in a burning plasma with alpha heating**

- **Integrated scenarios**
  - Strong nonlinear coupling of current profile, pressure gradient, bootstrap current, and fusion power, as they evolve in time
  - Successful operation of burning plasma requires not just optimization of individual parameters
  - Must demonstrate that all essential requirements can be simultaneously satisfied in an integrated scenario



Control & data acquisition (CODAC)

- **ITER plant control system**



6. Alpha particles

Presence of energetic third ion species

- **Core burning plasma (thermal) will have D and T ions**

- **D-T fusion reactions create He ions ("alpha particles")**
  - Different behavior due to supra-thermal energy and non-Maxwellian slowing-down distribution
  - Can excite various types of Alfvén instabilities
  - Can be redistributed or lost → lead to reduction in fusion self-heating, increase in wall heat loading

- **Physics of alpha particles and Alfvén instabilities to be covered in lecture #3**

Scientific progress to burning plasmas

- **Burning plasma studies on ITER open up a new regime of plasma physics of an exothermic medium**
  - A "grand challenge" problem

- **Dramatic scientific progress in last two decades has laid the foundation for burning plasma experiments**
  - Coordinated efforts of Experiments, Diagnostics, Theory, and Simulations to create validated predictive models of relevant plasma behaviors
  - More research is needed, specifically for burning plasma operation in ITER and next-generation experiments (DEMO)

- **Construction has begun of long-awaited first burning plasma experiment: ITER**
  - Many exciting research issues in burning plasma science

References: Burning Plasmas

USBPO
U.S. BURNING PLASMA ORGANIZATION

- *Final Report–Workshop on Burning Plasma Science: Exploring the Fusion Science Frontier* (2000) http://fire.pppl.gov/ufa_bp_wkshp.html
- *Review of Burning Plasma Physics* (Fusion Energy Sciences Advisory Committee, 2001) http://fire.ofes.fusion.doe.gov/More_html/FESAC/Austinfinalfull.pdf
- *Burning Plasma: Bringing a Star to Earth* (National Academy of Science, 2004)
- R. Hawryluk, Results from Deuterium-Tritium Tokamak Confinement Experiments, Reviews of Modern Physics v. 70, p. 537 (1998)
- Presentations at USBPO Burning Plasma Workshop 2005 www.burningplasma.org/reference.html
- ITER Physics Basis, Nuclear Fusion (1999); *Progress in the ITER Physics Basis*, Nuclear Fusion (2007)
- R. J. Fonck, Scientific Developments in the Journey to a Burning Plasma, invited talk at 2009 APS Spring Meeting (http://burningplasma.org/reference.html)