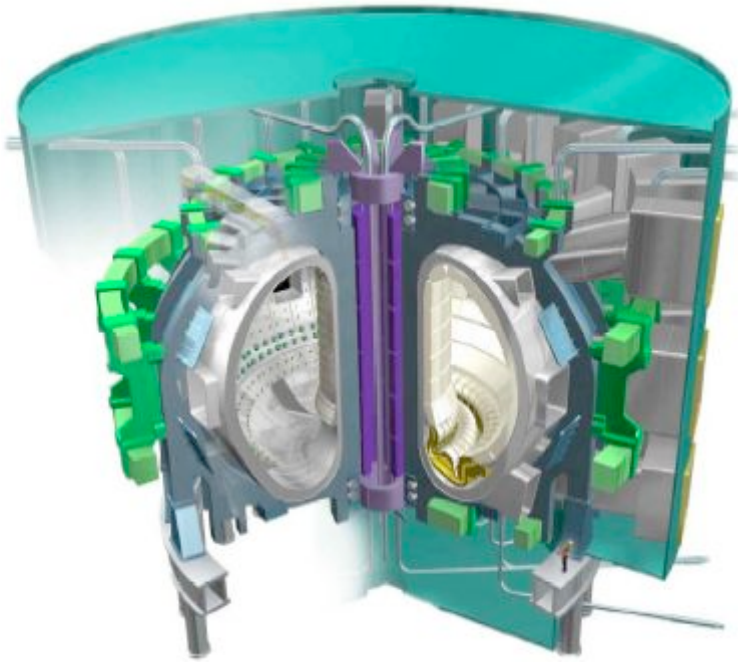
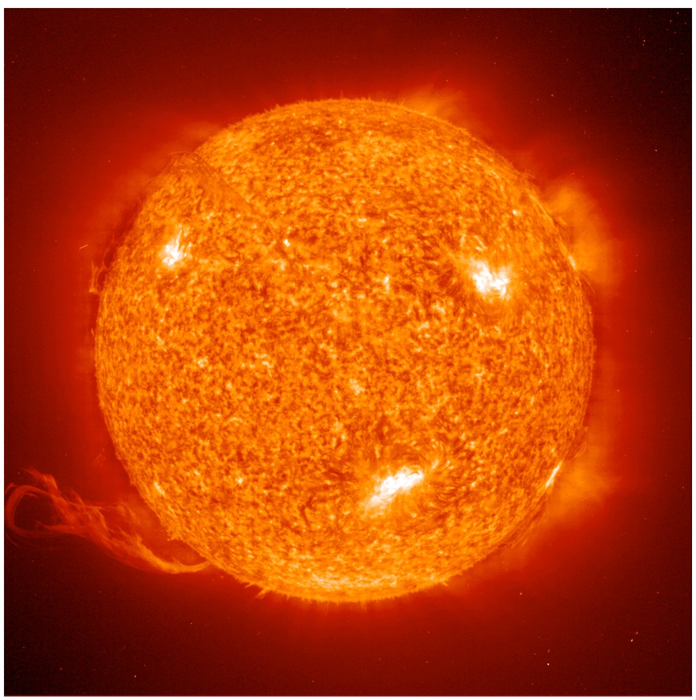


The Scientific Challenge of Burning Plasmas

— A Tutorial —



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APS-DPP Meeting, Orlando, FL
Nov 14, 2007

Supported by Office of Fusion Energy Sciences — Office of Science

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

- **Outline of this tutorial:**
  – Distinguishing features of “burning plasmas”
  – Scientific issues for burning plasmas
  – Grand challenge of burning plasmas

FEATURES OF BURNING PLASMAS

Our focus: magnetically confined plasmas

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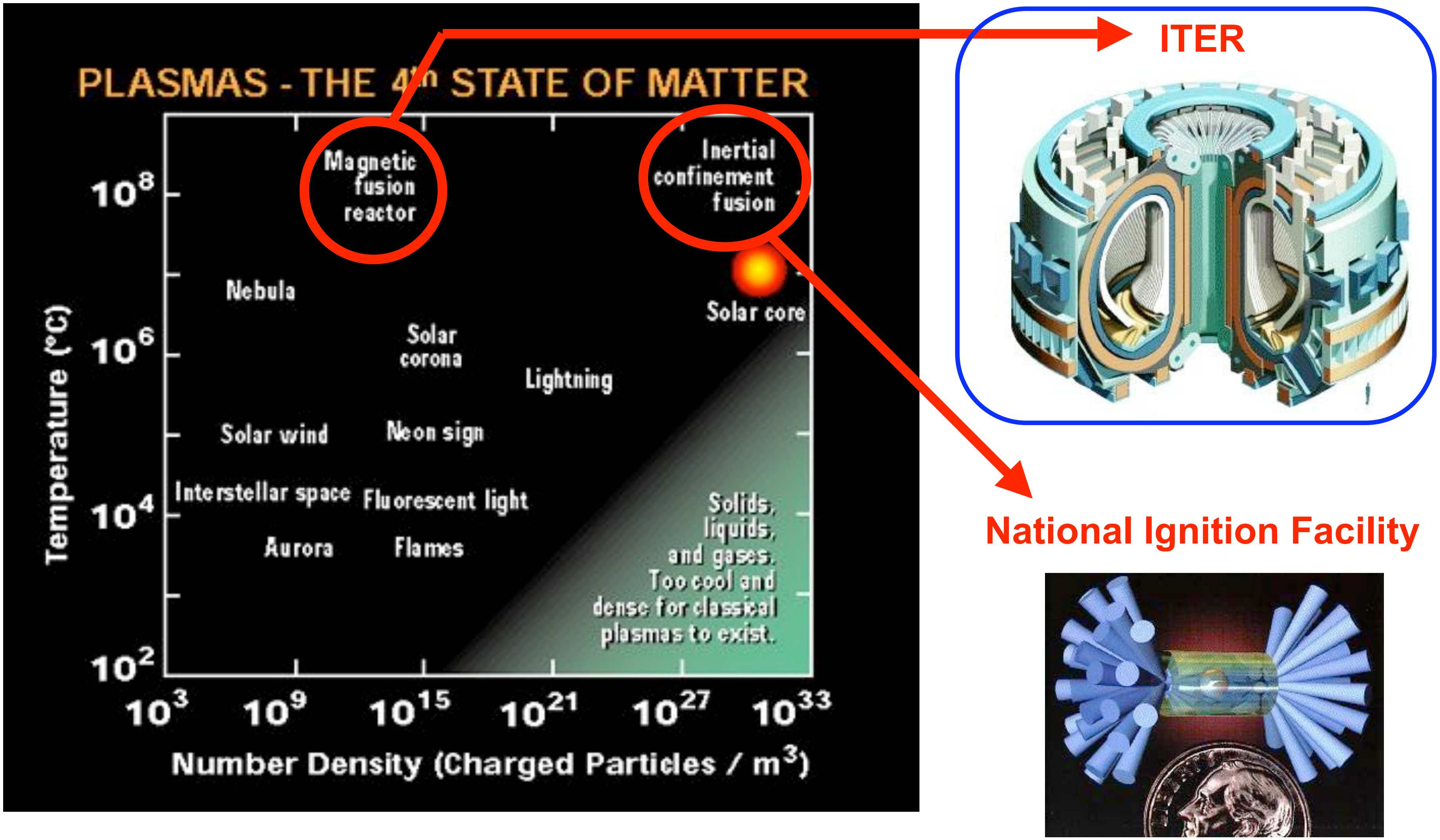

What is a "burning" plasma?

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- **"Burning" plasma** = dominantly ***self-heated*** by fusion products (e.g., alpha particles) from thermonuclear reactions in the plasma

- **Reactions of interest for laboratory fusion power:**

$$D^{+} + D^{+} \longrightarrow {}^{3}He^{++}\ (0.82\ \text{Mev}) + n^{0}\ (2.5\ \text{MeV})$$

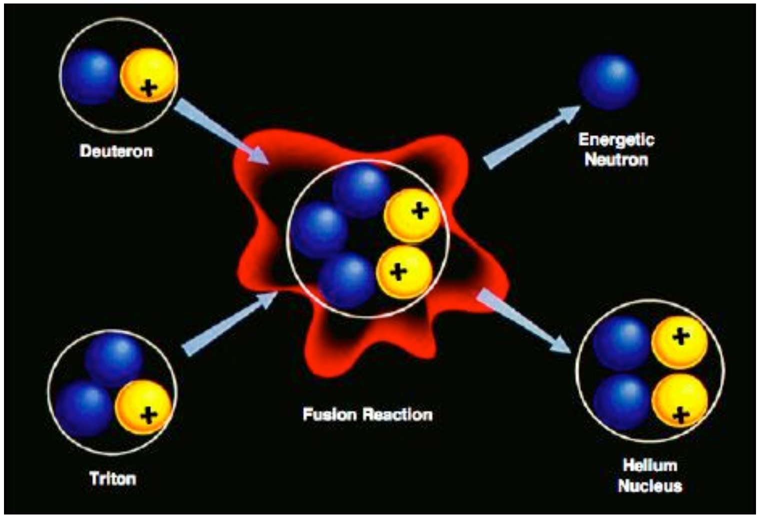
$$\longrightarrow T^{+}\ (1\ \text{MeV}) + p^{+}\ (3\ \text{MeV})$$

$$D^{+} + {}^{3}He^{++} \longrightarrow {}^{4}He^{++}\ (3.6\ \text{MeV}) + p^{+}\ (14.7\ \text{MeV})$$

Plasma $$D^{+} + T^{+} \longrightarrow {}^{4}He^{++}\ (3.5\ \text{MeV}) + n^{0}\ (14.1\ \text{MeV})$$

Solid $$Li^{6} + n \longrightarrow {}^{4}He\ (2.1\ \text{MeV}) + T\ (2.7\ \text{Mev})$$

D-T fusion

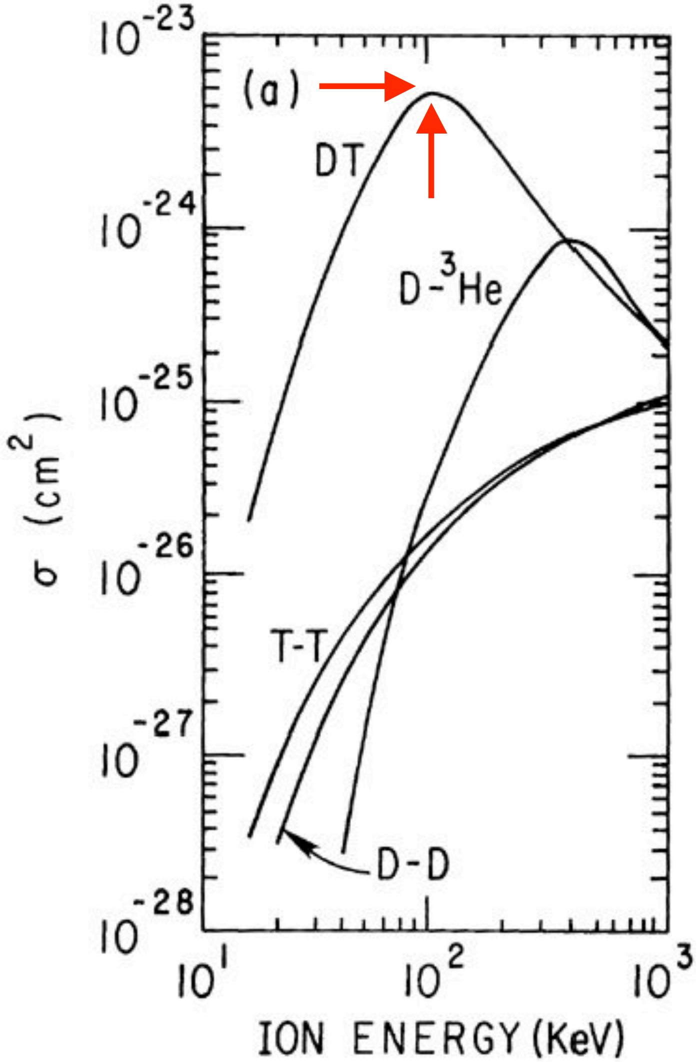


- The “easiest” fusion reaction uses hydrogen isotopes: deuterium (D) & tritium (T)

$${}_1D^2 + {}_1T^3 \rightarrow {}_2He^4 + {}_0n^1$$

(3.5 MeV) (14.1 MeV)

Energy/Fusion: $\varepsilon_f = 17.6$ MeV



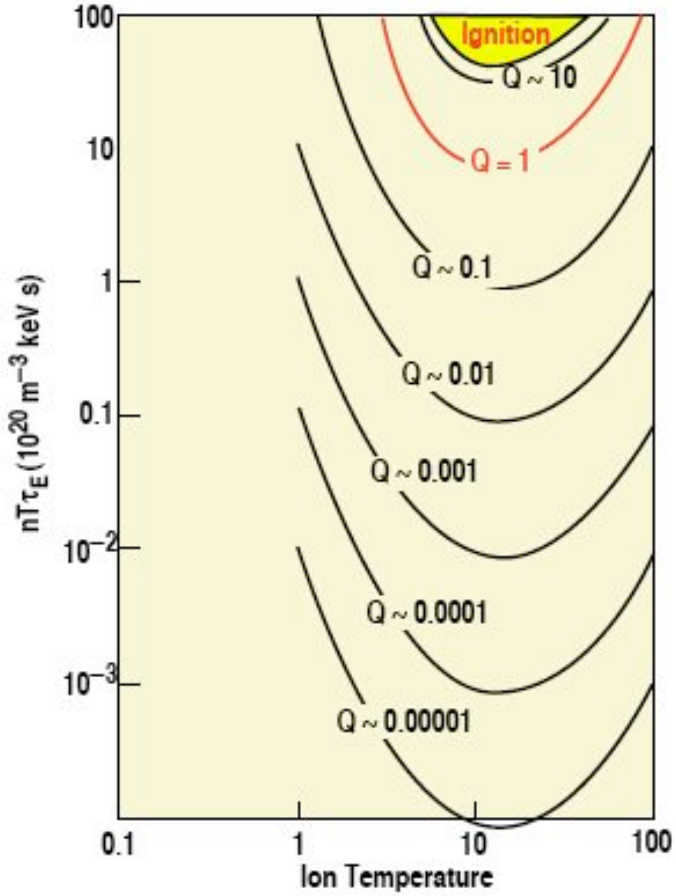
Nuclear cross sections

Better definition of “burning”

$$\frac{dW}{dt} \to 0 \implies P_\alpha + P_{heat} = \frac{W}{\tau_E}$$

Define fusion energy gain, $Q \equiv \dfrac{P_{fusion}}{P_{heat}} = \dfrac{5\,P_\alpha}{P_{heat}}$

Define α-heating fraction, $f_\alpha \equiv \dfrac{P_\alpha}{P_\alpha + P_{heat}} = \dfrac{Q}{Q+5}$



Breakeven	Q = 1	f_α = 17%
Burning plasma regime	Q = 5	f_α = 50%
	Q = 10 (ITER)	f_α = 60%
	Q = 20	f_α = 80%
	Q = ∞ (ignition)	f_α = 100%

SCIENCE ISSUES FOR BURNING PLASMAS

Many of the same challenges as today

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- **Confinement**
  - H mode, internal transport barriers, electron thermal transport, momentum transport, …
- **MHD macrostability**
  - Resistive wall modes, neoclassical tearing modes, pressure-driven instabilities, ELMs, disruptions, sawteeth, fast-ion instabilities, …
- **Power and particle control**
  - Impurities, plasma-facing component materials, divertor design, …
- **Long-pulse operation**
  - Heating and current drive, profile control, hybrid scenarios, …
- **Diagnostics**
  - High time/space resolution, velocity distribution measurements, …
- **Plasma control**
  - Start-up, real-time feedback and control, …

New burning plasma challenges

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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 PFCs
- ***Nuclear environment***
  - Radiation, tritium retention, dust, tritium breeding

Integration of nonlinearly coupled elements

1. Alpha particles

- Characteristic properties
- Dynamics of alphas
- Ripple loss
- Effect on MHD modes
- Toroidal Alfvén Eigenmodes
- Internal plasma diagnostic

Alpha particle characteristics

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- **Plasma ions and electrons:**
  - $T_{i,e}$ ~ 10-20 keV
  - "Frozen-in" behavior to lowest order (MHD description)
  - Thermodynamic equilibrium (Maxwellian distribution)

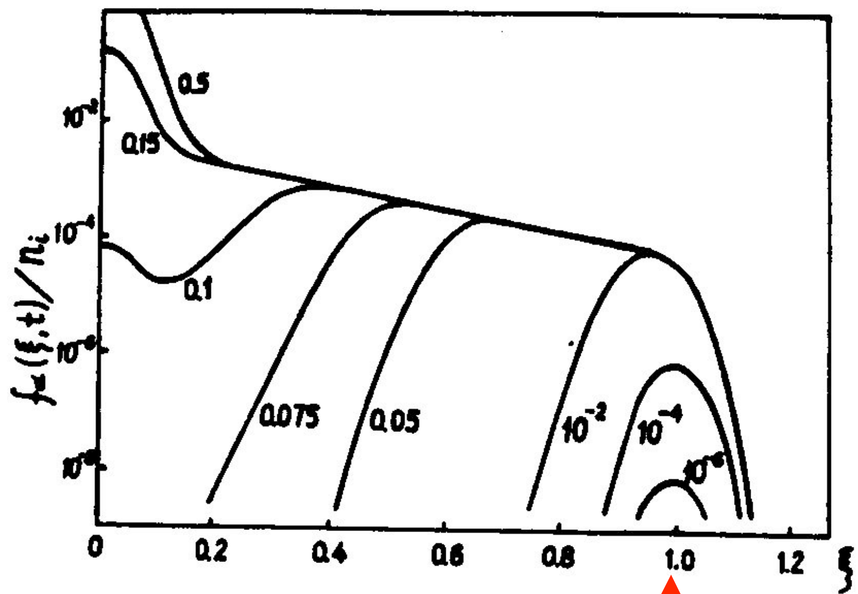
- **Alpha particles:**
  - High energy: $T_{\alpha,birth}^{DT}$ = 3.5 MeV
  - Not "frozen" to B-field lines (require kinetic description)
  - Low density ($n_\alpha < n_{i,e}$), but comparable pressure ($p_\alpha \sim p_{i,e}$)
  - Non-Maxwellian "slowing down" distribution
  - Centrally peaked profile
    $$\left|\nabla p_\alpha / p_\alpha\right|^{-1} \leq a/2$$

- **Other energetic particles:**
  - Supra-thermal ions from NBI and ICRH
    - Can simulate α particle effects without reactivity (although NBI/ICRH ions are anisotropic in pitch angle, whereas alphas are isotropic)
    - Also present in burning plasmas with auxiliary heating
  - Run-away electrons associated with disruptions

Birth, life, and death of alpha particles

- **DT alphas are born in peaked distribution at 3.5 MeV at rate $\partial n_a / \partial t = n_D n_T \langle \sigma v \rangle$**
  - During time τ_s, they are slowed down by collisions with electrons to smoother distribution at ~ 1 MeV
  - After time τ_M, they thermalize against both electrons and ions to the plasma temperature ($T_e \sim T_i \sim 10$ keV)
  - Alphas are confined for time τ_α. In steady-state there are two alpha populations: slowing-down α's (n_s) and cool Maxwellian α's (n_M)

- **Typically $\tau_\alpha \sim 10\, \tau_M \sim 10^3\, \tau_s$: hence α's have time to thermalize**
  - Since $n_s / n_\alpha \sim \tau_s / \tau_\alpha \sim 10^{-3}$, then $n_M \sim n_\alpha \sim n_e$ (for reactors); hence "ash" (slow α's) is a problem in reactors, because it will "poison" the plasma



Birth velocity:

$$v_{\alpha 0}^{D-T} = 1.3 \times 10^{9}\, cm / s$$

$$P_{fus} \propto n^2 \langle \sigma v \rangle \sim n^2 T^2 \propto p^2$$

Parameter comparison

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Fast ion parameters in contemporary experiments compared with projected ITER values.

Tokamak	TFTR	JET	JT-60U	JET	ITER
Fast ion Source	Alpha Fusion	Alpha Fusion	Deuterium Co NBI	Alpha ICRF tail	Alpha Fusion
Reference	[3]	[3]	[34]	[20, 52]	[52]
τ_S (s)	0.5	1.0	0.085	0.4	0.8
δ/a^{a}	0.3	0.36	0.34	0.35	$\boxed{0.05}$
$P_f(0)$ (MW m^{-3})	0.28	0.12	0.12	0.5	$\boxed{0.55}$
$n_f(0)/n_e(0)$ (%)	0.3	0.44	2	1.5	0.85
$\beta_f(0)$ (%)	0.26	0.7	0.6	3	$\boxed{1.2}$
$\langle\beta_f\rangle$ (%)	0.03	0.12	0.15	0.3	$\boxed{0.3}$
max $\lvert R\nabla\beta_f\rvert$ (%)	2.0	3.5	6	5	3.8
$v_f(0)/v_A(0)$	1.6	1.6	1.9	1.3	1.9

- **Differences for fast ("f") ion physics in ITER:**
  - Orbit size δ/a in ITER is much smaller
  - Most of the other parameters (especially dimensionless) are comparable
  - No external control of alphas, in contrast to NBI and ICRH fast ions

Progress in ITER Physics Basis (2007)

Broad impacts of α particles

- **Energetic particles *per se*:**
  - Single-particle loss due to TF ripple
  - Excitation of various Alfvén-type instabilities (lead to anomalous transport)
  - Redistribution and loss (reduces alpha particle heating efficiency; causes heat loading and damage to plasma-facing components)

- **Integrated with overall plasma behavior:**
  - Macro-stability (e.g., fishbones & monster sawteeth; ballooning modes; disruptions and runaway electrons)
  - Transport (e.g., profile modification; rotation generation)
  - Heating and current drive (e.g., dominant nonlinear self-heating)
  - Edge physics (e.g., resistive wall mode stabilization)
  - Burn dynamics (e.g., thermal burn stability, fuel dilution by helium ash)

TF ripple loss of alphas

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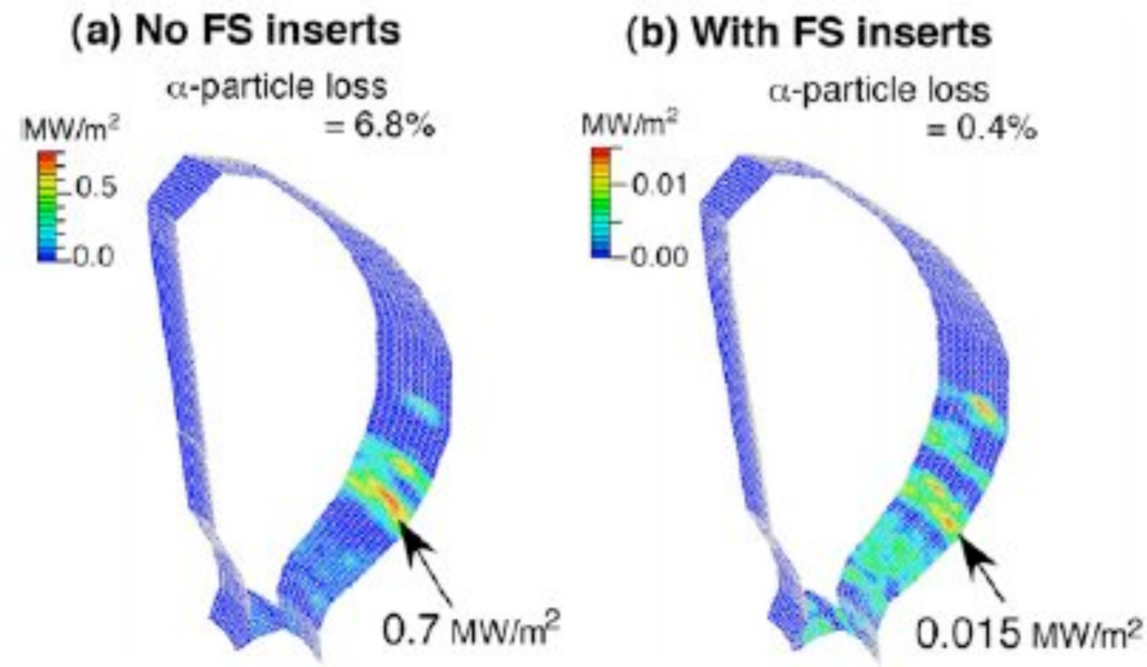
- **Small ripple in ITER for normal operation**
- **Larger ripple for reversed shear operation or with Test Blanket Modules**
  - Ripple loss minimized by introduction of ferritic inserts (ITER Baseline Design)



K. Tobita (PPCF 2003)

Fishbones and giant sawteeth

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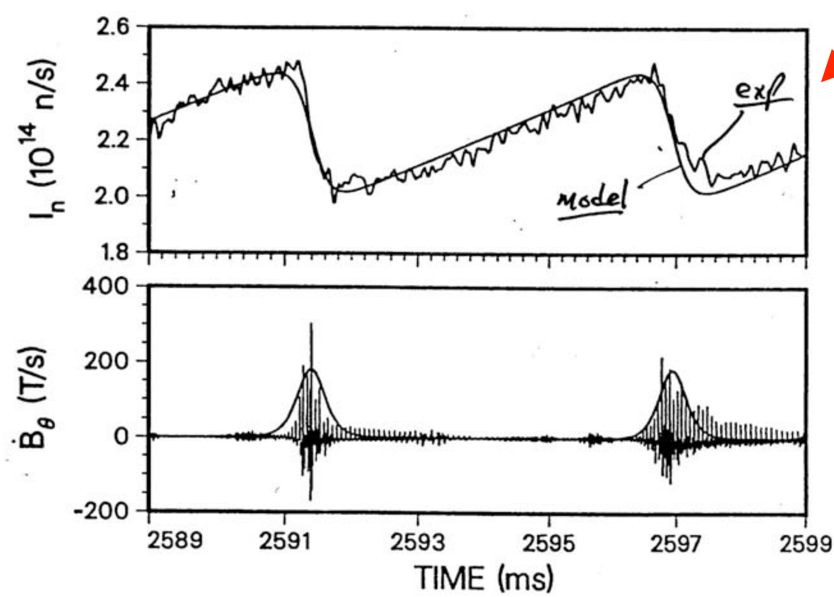
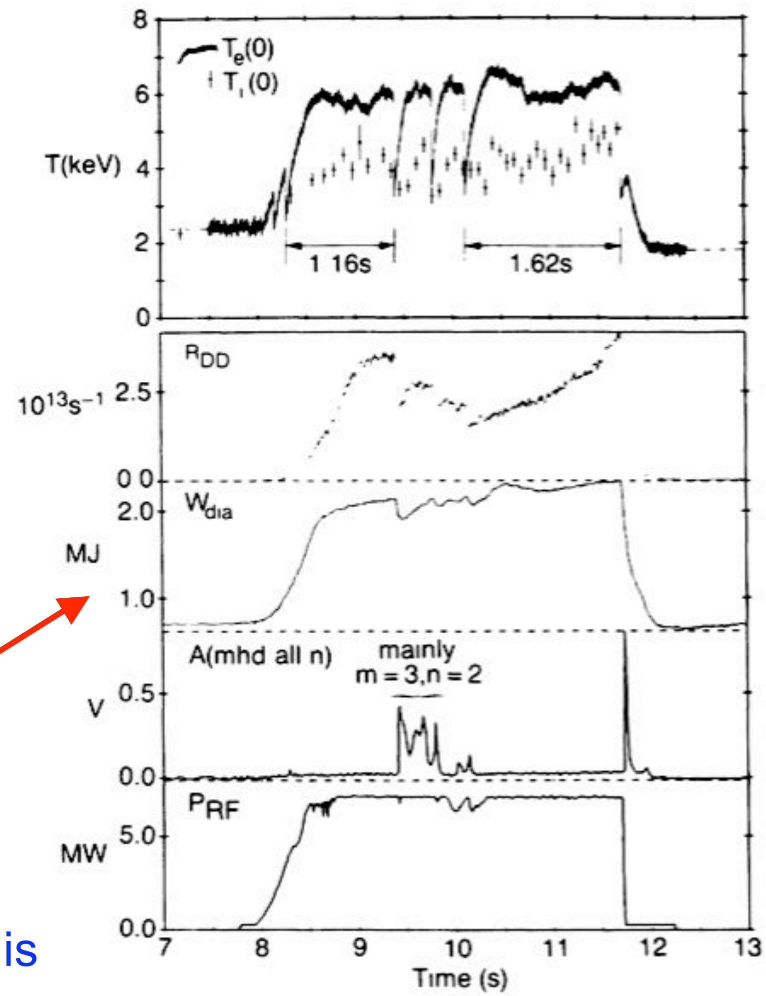
Resonant destabilization of n=m=1 internal kink ($\omega_d^{fast} = \omega$): "fishbone instability"





Off-resonant stabilization of fishbone ($\omega_d^{fast} >> \omega$): "monster sawtooth"

- Nonlinear kinetic/fluid behavior of sawteeth is a challenging problem

Alfvén eigenmode instabilities

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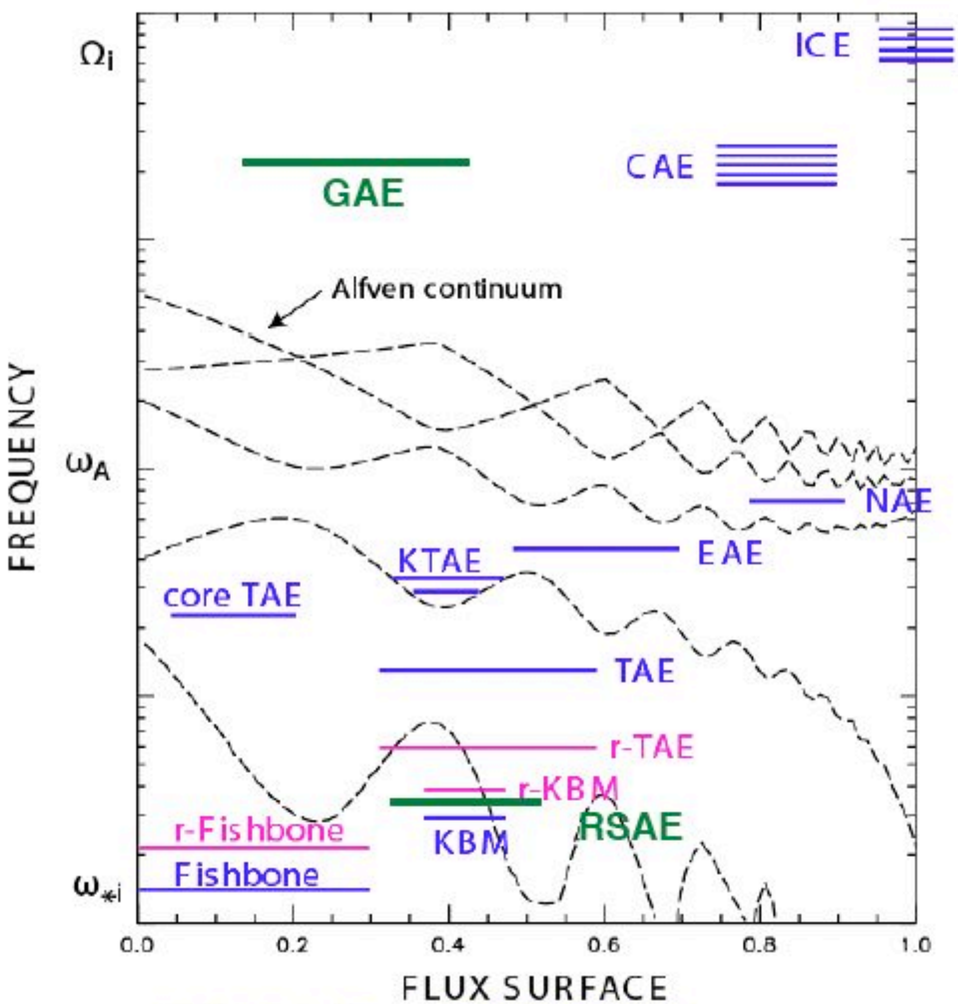

Heidbrink, Phys. Pl. 9 (2002) 2113

- **α particles from D-T fusion (3.5 MeV) are resonant with shear Alfvén waves:**

$$v_\alpha \geq v_A$$

- **Toroidal Alfvén Eigenmode (TAE)**
  - Analogy to band-gap theory in solid-state crystals ("fiberglass wave guide")
  - Zoology of other *AE instabilities
- **Could cause loss of α's**
  - Reduce self-heating; increase wall thermal loading
  - Nonlinear dynamics of multi-mode AE saturation and transport is important

Fast ion instabilities as plasma diagnostic

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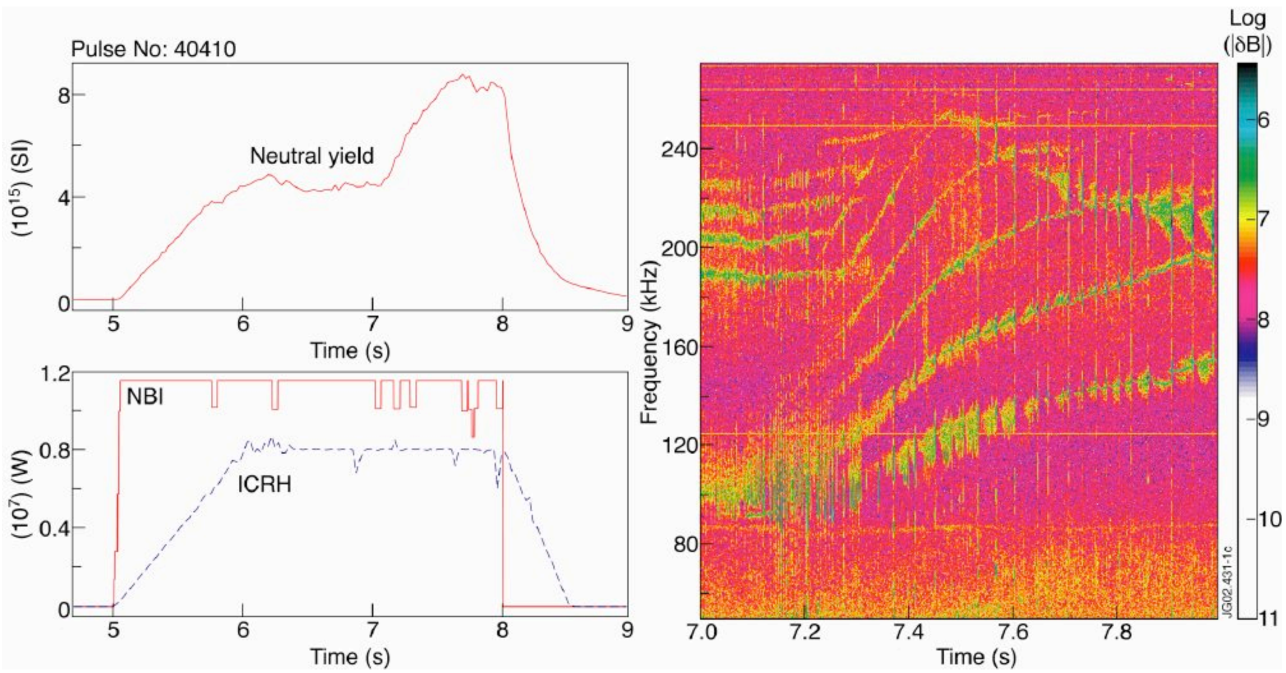
- **Internal transport barrier (ITB) triggering event**
  - "Grand Cascade" (many simultaneous n-modes) occurrence is coincident with ITB formation (when q_{min} passes through integer value)
  - Being used on JET as an internal diagnostic to monitor q_{min}
  - Can create ITB by application of main heating shortly before a Grand Cascade is known to occur



2. Self-heating

- Self-organized profiles
- Equilibrated ion & electron temperatures
- Low rotation
- Pedestal dependence
- Thermal stability

Autonomous plasma state

- **Self-organized profiles**
  - With dominant self-heating from fusion reactions, a burning plasma determines its own profiles (current, pressure, impurities)

- **Reduced profile control**
  - Hence, burning plasmas have 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

Macrostability

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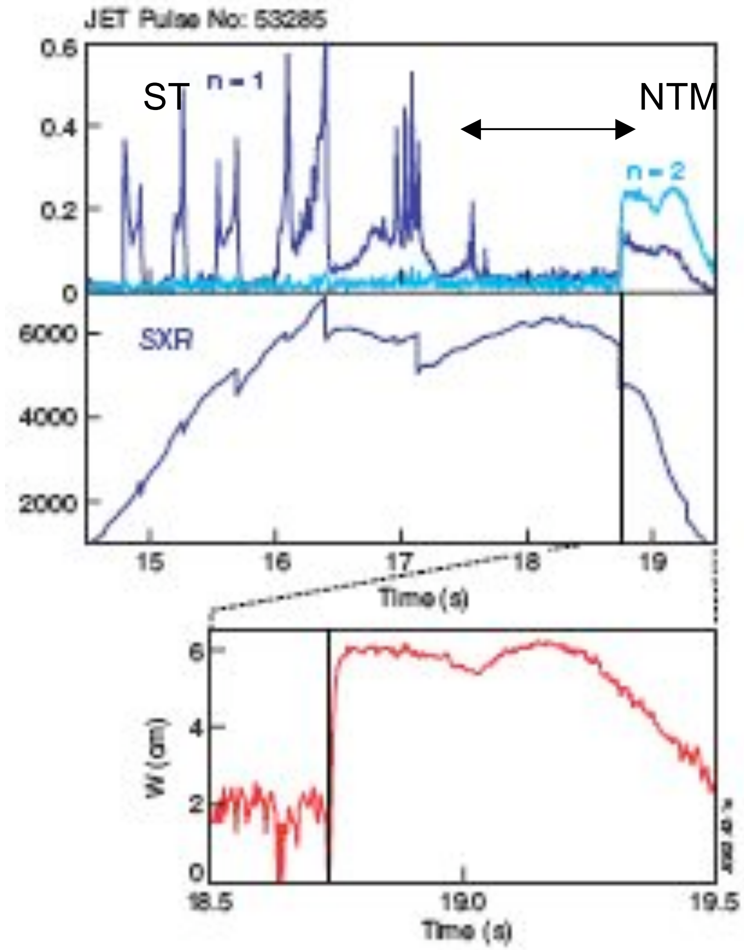
- **New challenges for MHD in burning plasmas**
  - High Q implies operation near maximum allowable thermal and magnetic energies —> high beta
  - Self-heating implies control of p, J profiles will be difficult
  - Diagnostics for internal profiles and plasma instabilities will be difficult

- **“Monster” sawtooth**
  - Fusion α particles could stabilize sawtooth (ST)—until it crashes more strongly and then possibly provides island “seeds” for neoclassical tearing mode (NTM) instability



NTM (m=3/n=2) triggered by sawtooth crash (n=1) delayed by ICRF fast ions [Sauter, 2002 PRL]

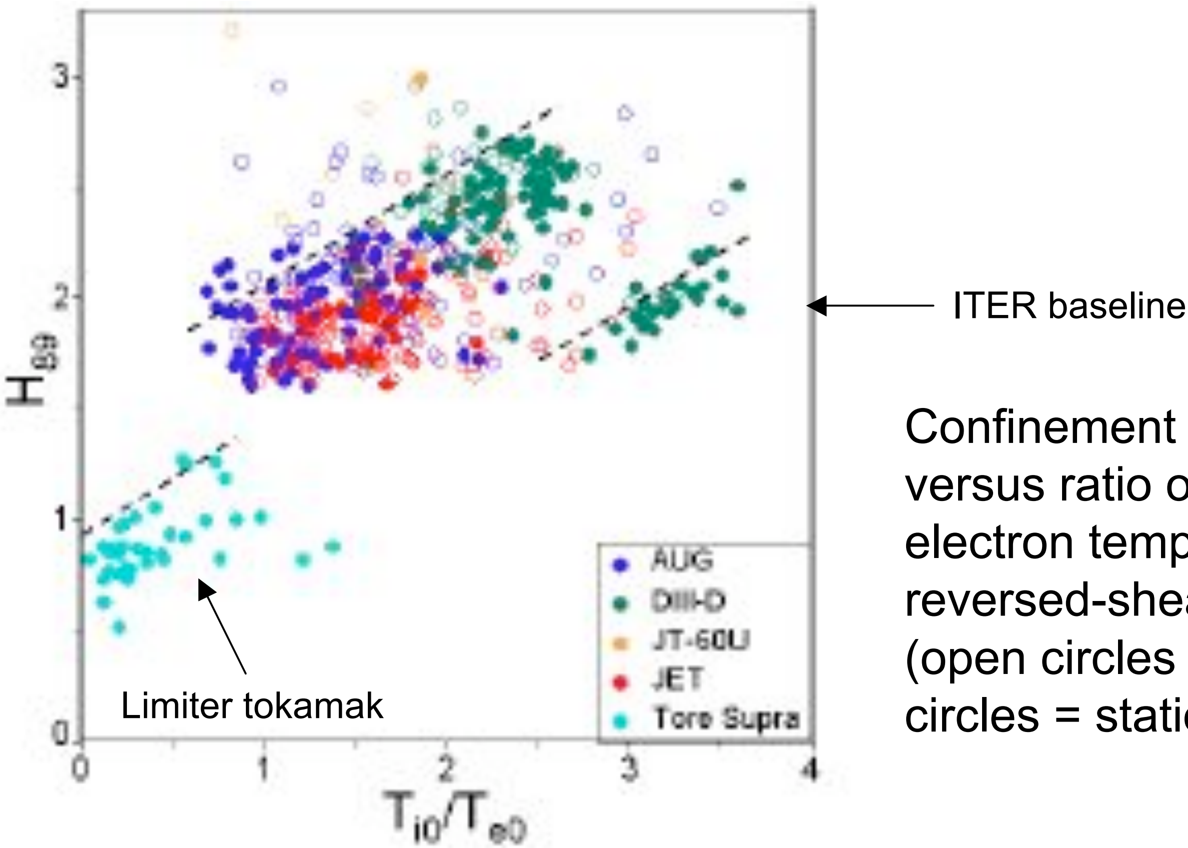
Equilibrated temperatures ($T_i \sim T_e$)

- **Dominant electron heating**
  - In burning plasmas, fusion alphas will dominantly heat electrons, leading to centrally peaked electron heating and weaker ion heating
  - Negative-ion NB (MeV range) and ICRH/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 BP 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 $T_i \sim T_e$



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

- **Toroidal rotation and ExB velocity shear are important in current 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 in reactor-grade plasmas**
  - Short penetration depth
  - Requires high injection energy E, hence imparted momentum $\propto P_{inj} / E^{1/2}$ is modest

- **Low rotation in burning plasmas**
  - Isotropic fusion alphas lead to little toroidal momentum input

RWM control coils

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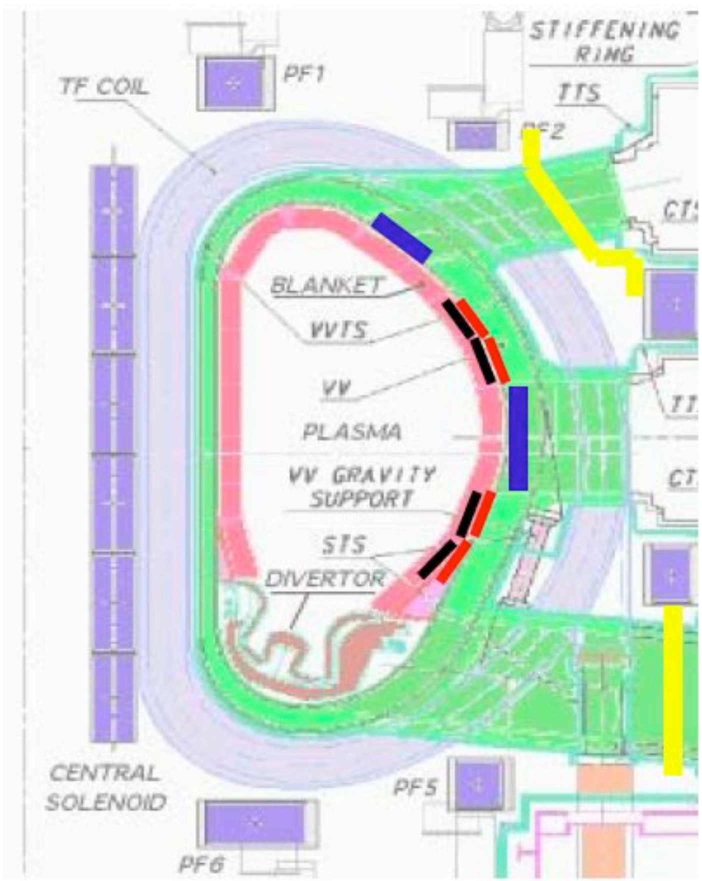
- **RWM control:** **enables operation at high β_N , for required fluence**
  - Rotation in ITER may be too low for stabilization; hence may need active control by means of internal coils



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

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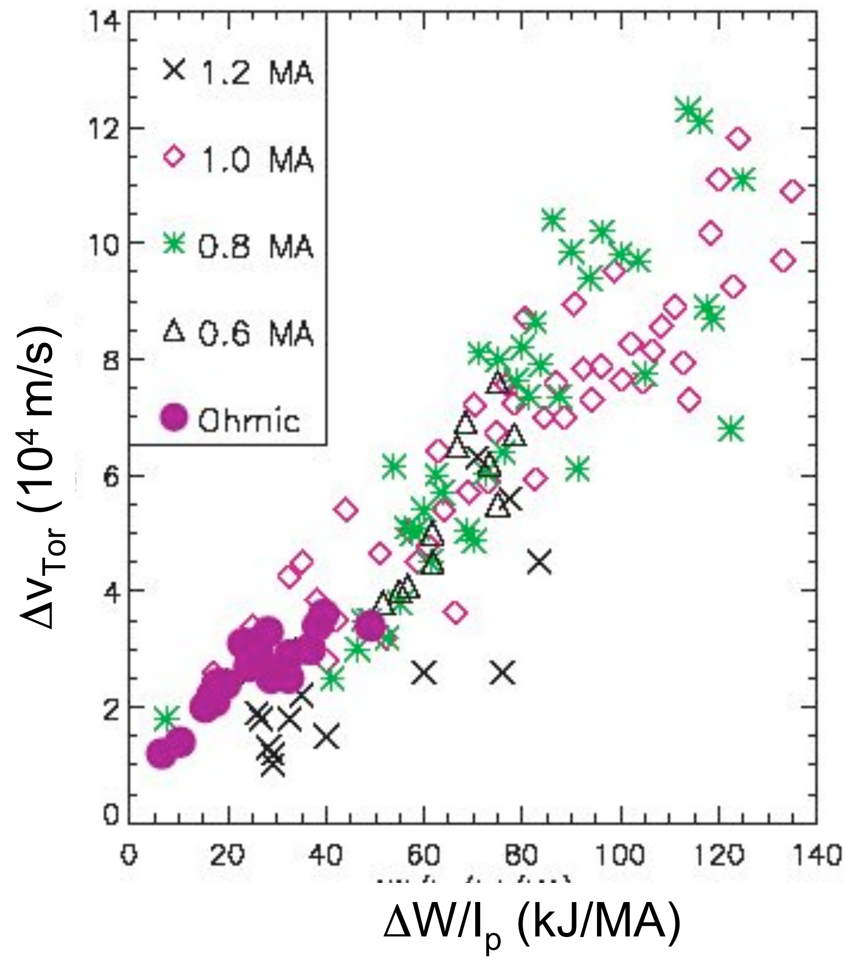
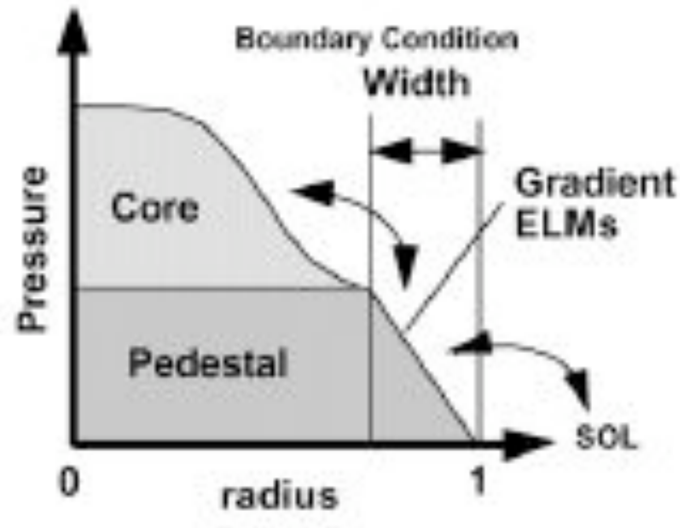
- **Considerable interest in “intrinsic” toroidal rotation**
  - Observed to be spontaneously generated, without externally applied torque (i.e, no NBI), in tokamaks with Ohmic and cyclotron frequency (IC/EC) heating, especially in H mode
- Experiments find intrinsic rotation velocity is proportional to **plasma stored energy** (or pressure) and scales inversely with **current**
- **Intrinsic rotation is ~2% of Alfvén speed**
  - Possibly strong enough to stabilize MHD modes in ITER

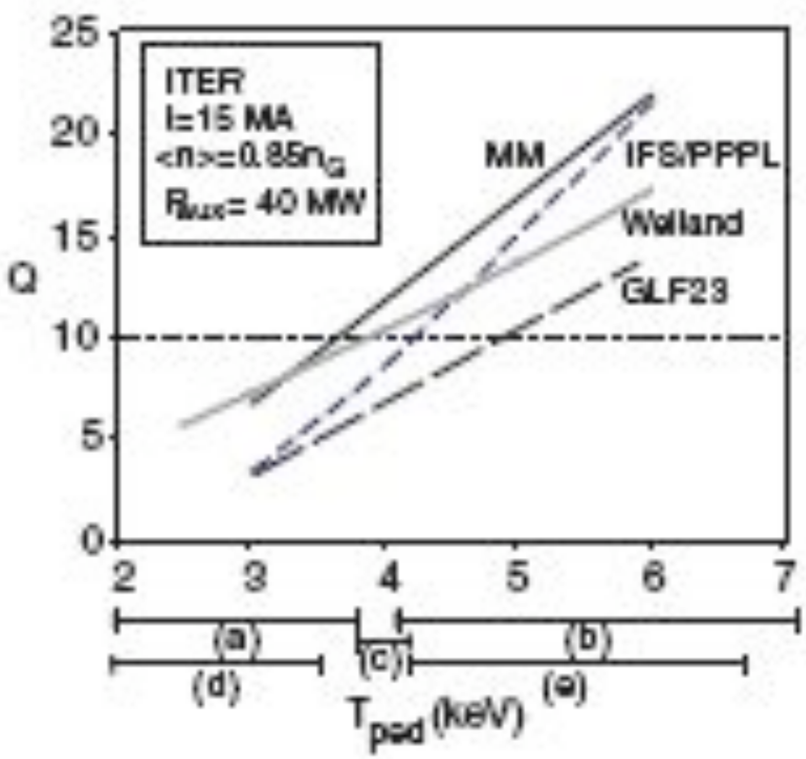


Rice et al. (NF 2001)

Pedestal dependence

- **Profile sensitivity**
  - For “stiff” plasma profiles, core profiles and global confinement are determined by edge pedestal values





  - Thus, in a burning plasma with stiff profiles, fusion performance Q is strongly dependent on the edge pedestal temperature T_{ped}, high values of which are difficult to achieve and are a challenge for divertor operation

Mukhovatov (PPCF 2003)

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

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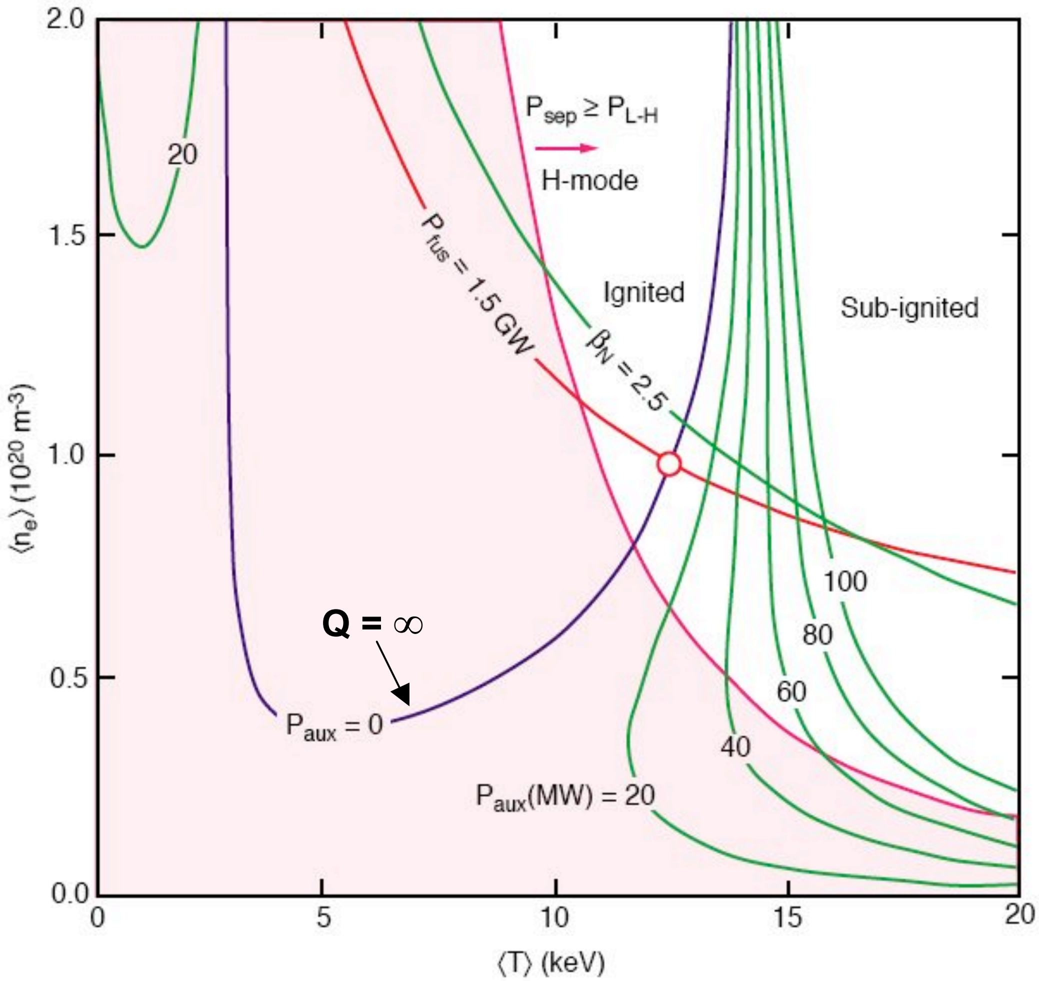


- **Representative plasma operation contour (popcon)**
  - Sustained, thermally stable fusion is possible for ignition (P_{aux} = 0) and finite-Q (P_{aux} > 0) contours in the H-mode domain ($P_{sep} \geq P_{L\text{-}H}$) and below the beta limit
  - Plasma burn in ITER will be stable since it operates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

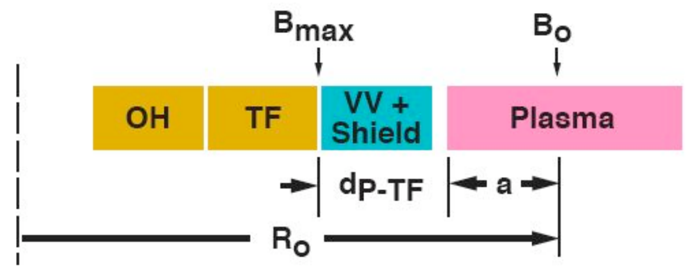
ITER Phys Basis Doc (1999)

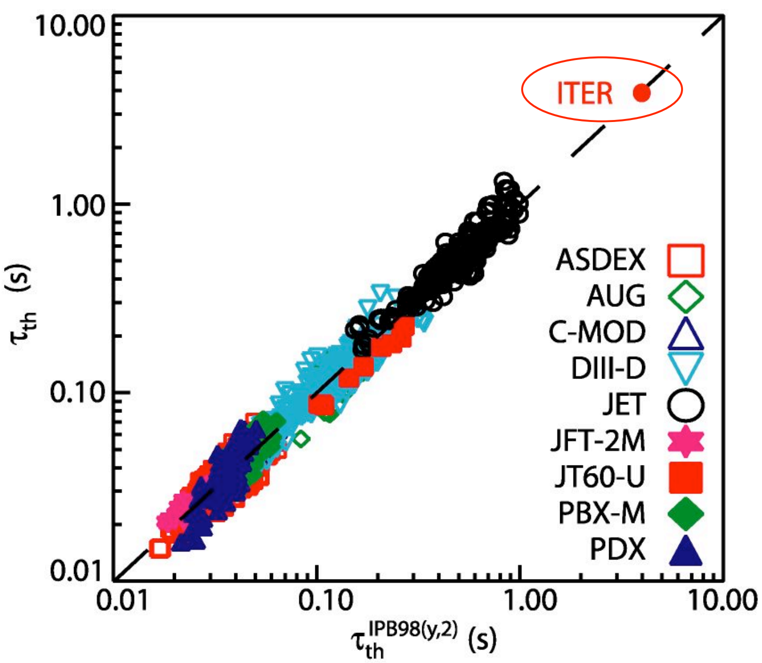
3. Size and magnetic field scaling

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

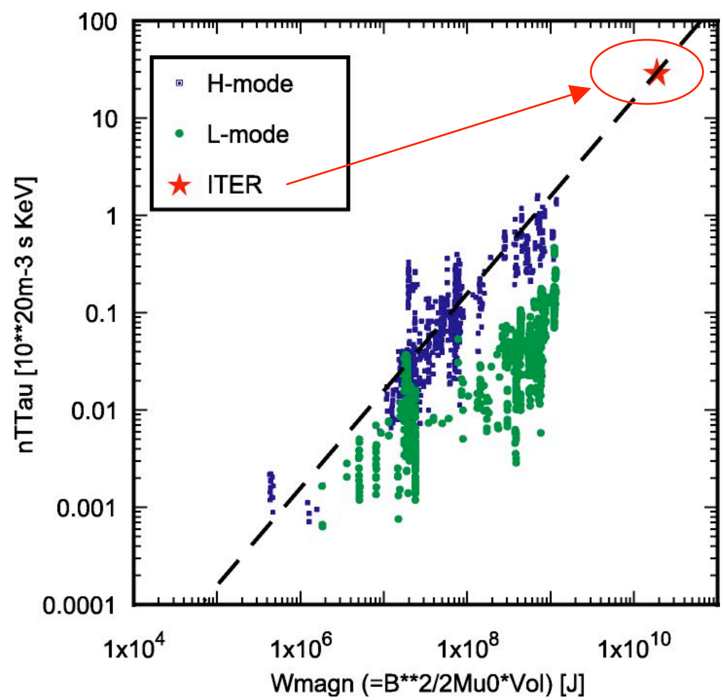
Determining the size of a burning plasma

- **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

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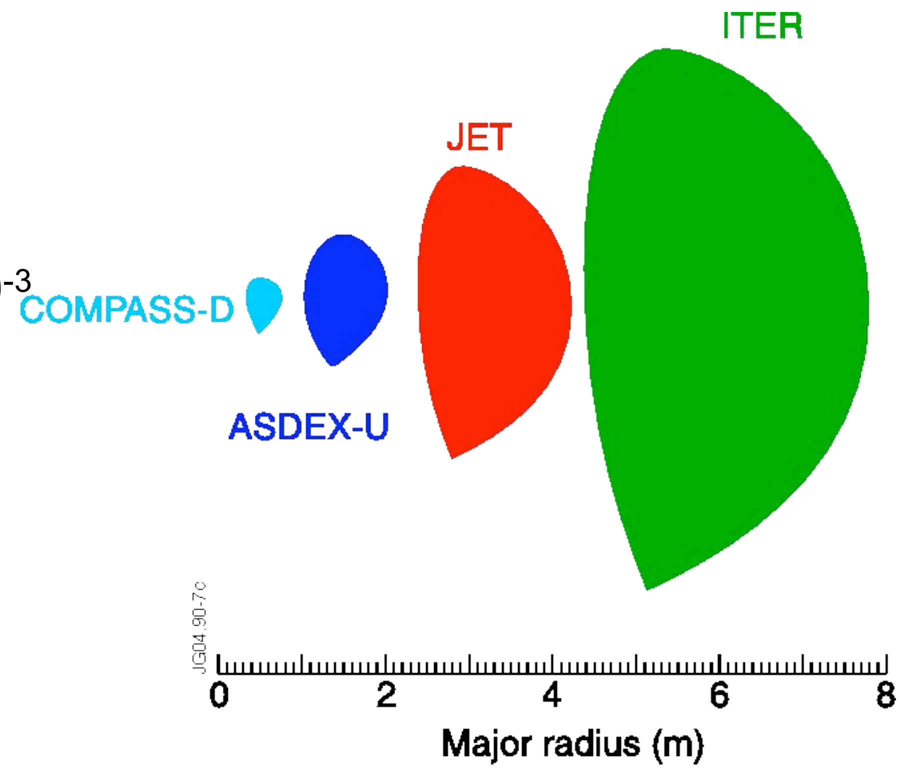
- **Significant difference**
  - Current tokamaks have $\rho_i^* = \rho_i/a \sim 0.5\text{-}1.5 \times 10^{-2}$, whereas burning plasmas (ITER) have $\rho_i^* \sim 1\text{-}2 \times 10^{-3}$
- **Issues for very small ρ_***
  - ITB formation
  - Hybrid regimes
  - Confinement scaling
  - NTM threshold beta
  - Alfvén eigenmode spectrum



Cross sections of present EU D-shape tokamaks compared to the cross section of ITER

Consequences of size scaling

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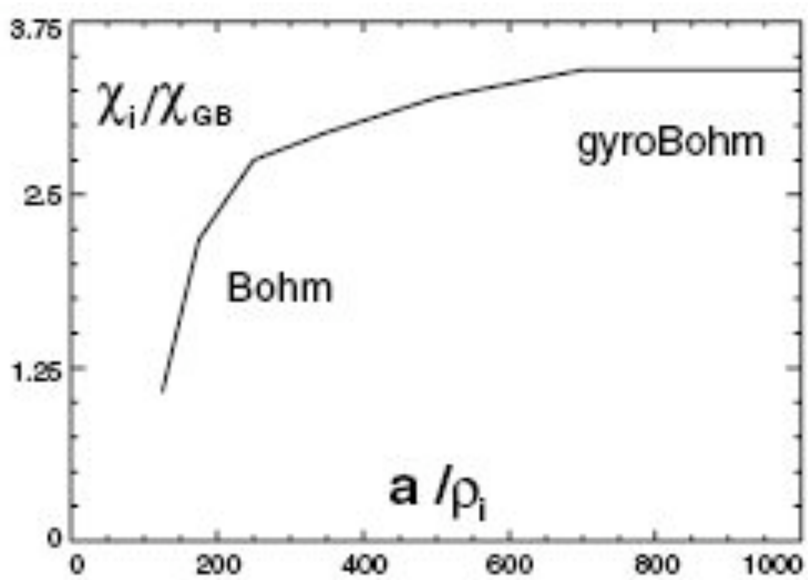
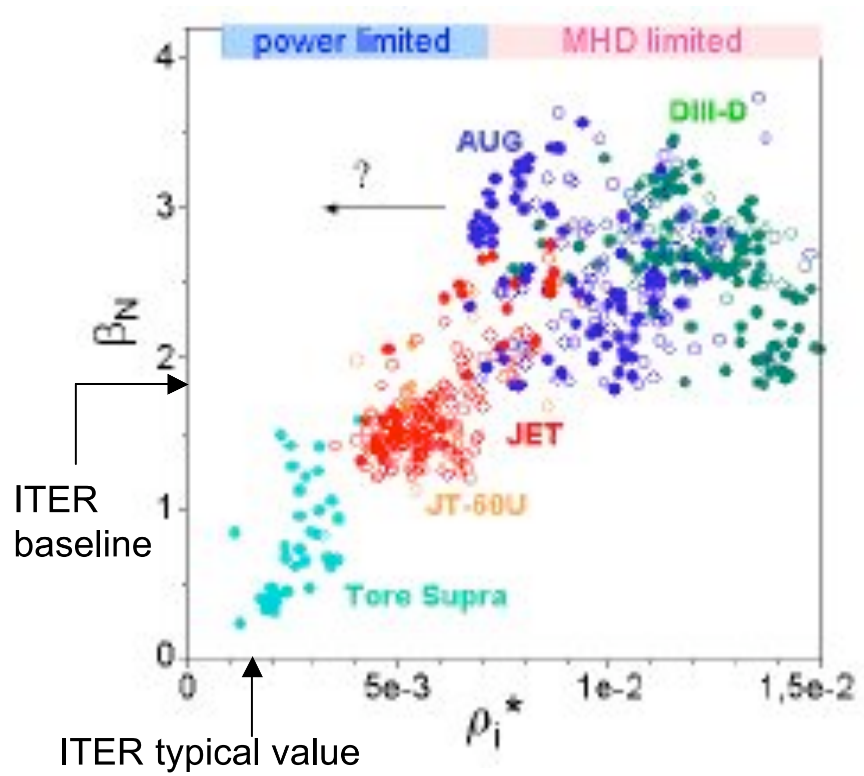
Transport scaling



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

Z. Lin (PRL 2002)

Stability for NTM



ITER could exceed NTM beta threshold at low ρ_i^*

G. Sips et al. (IAEA 2004)

Size scaling of fast particle instability

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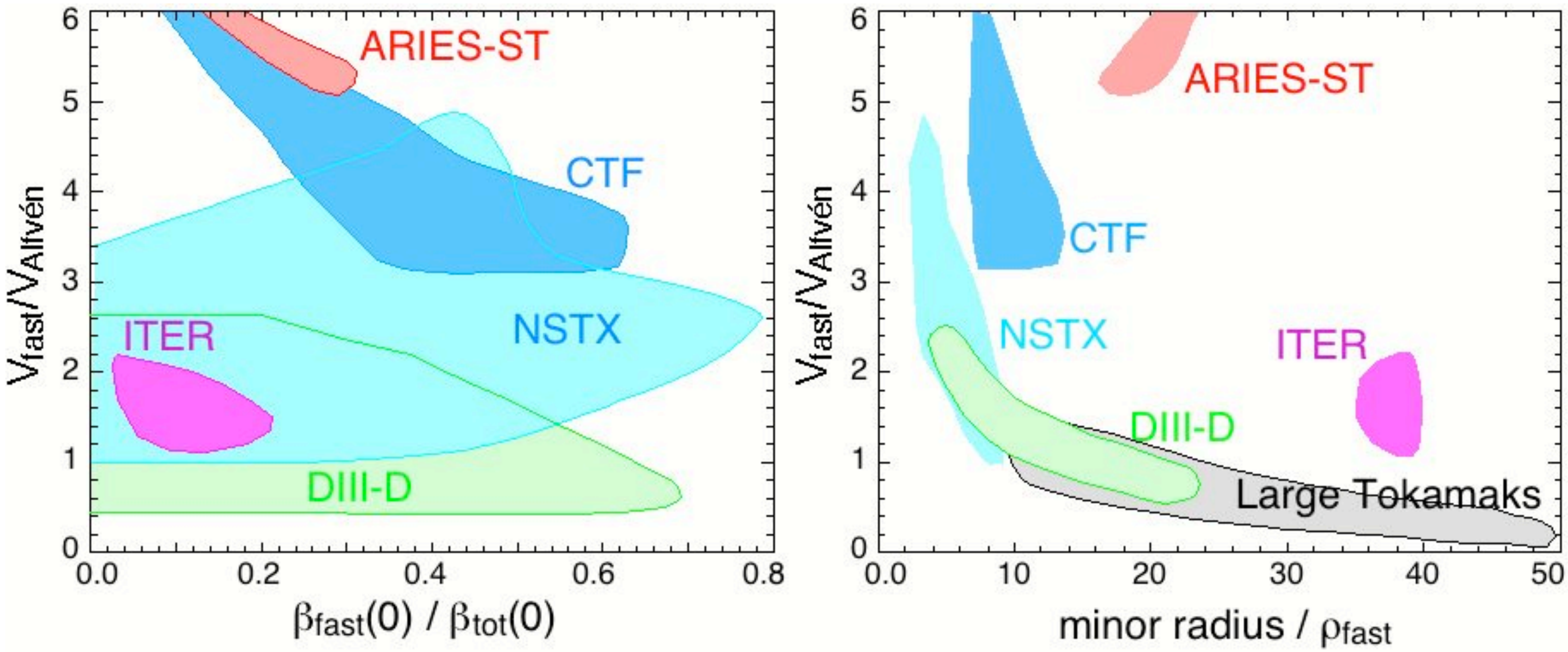
- **Alfvén Mach number** (v_α/v_A) and **pressure** (β_α) for ITER α-particles have similar values as in existing experiments

- However, ITER's **large size** [i.e., small-wavelength ($a/\rho_{*fast} >> 1$) regime] implies "sea" of many high-n potentially unstable modes (n^2 problem)
  – Could cause outward redistribution/loss of α's (domino-effect "avalanche")



E. Fredrickson

Neutral 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

Instability due to N-NBI ions

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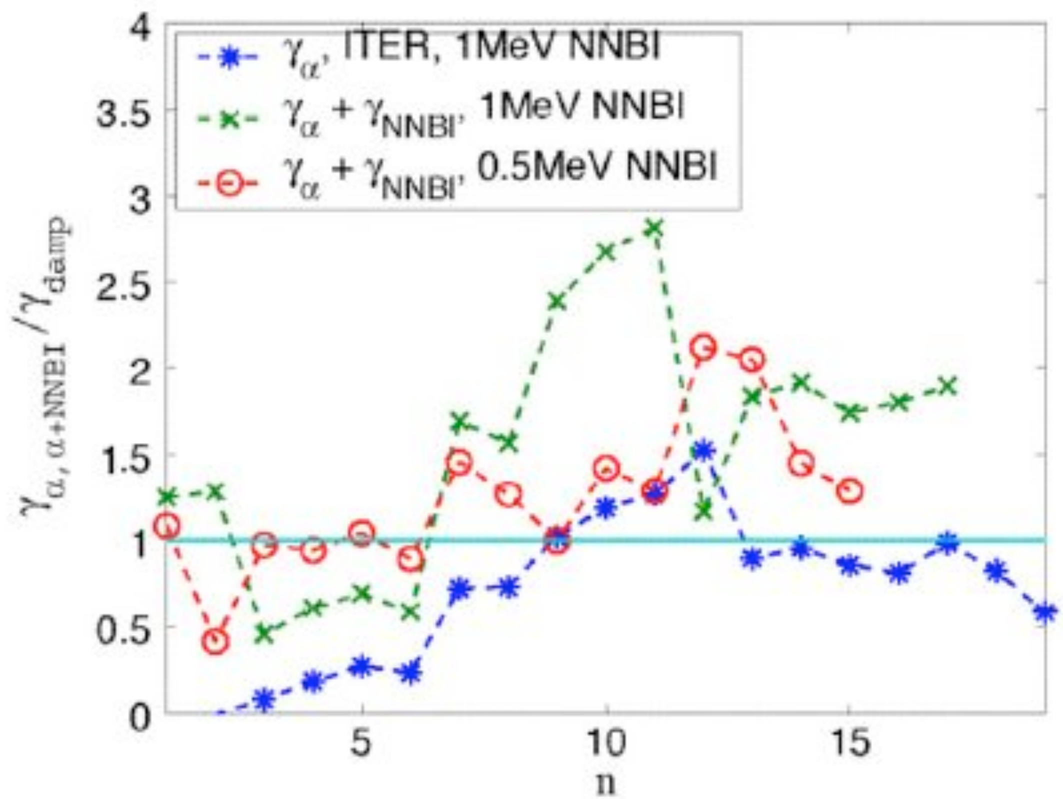
- TAE instability drive from neutral beam ions can be comparable to that from alpha particles in ITER



N. Gorelenkov

RF heating in burning plasmas

- **Electron cyclotron heating (ECH)**
  - Because EC 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)
  - 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 H 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

4. High performance

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

High heat loads

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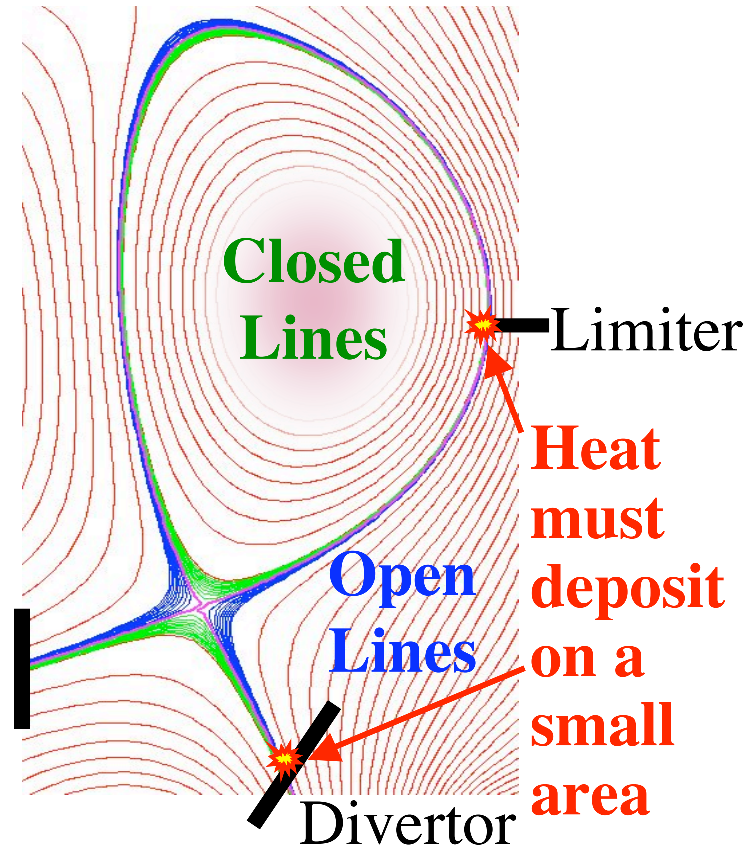
- **Burning plasma will have large steady power fluxes and longer pulses**
  - Hence larger erosion of these components, during steady-state plasma conditions and especially during off-normal events (disruptions, ELMs)
  - High fraction of power must be radiated before divertor plate contact
- **ITER**:
  - 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)

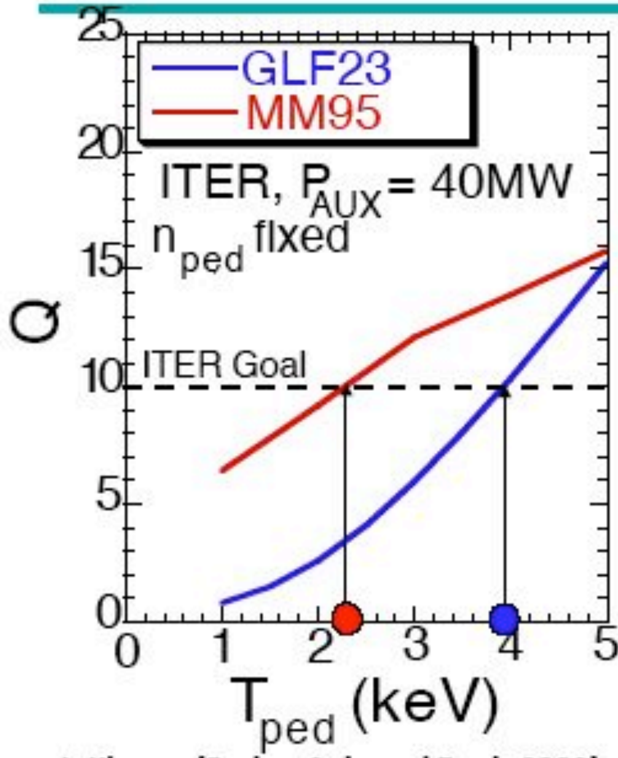
- **Disruption mitigation methods**
  - Massive gas injection (to dissipate the plasma energy through radiation over the entire chamber before it reaches the divertor)
  - Pellet injection (multi-pellet, hyper-velocity pellets)
  - High-density liquid jet injection

Edge localized modes (ELMs)

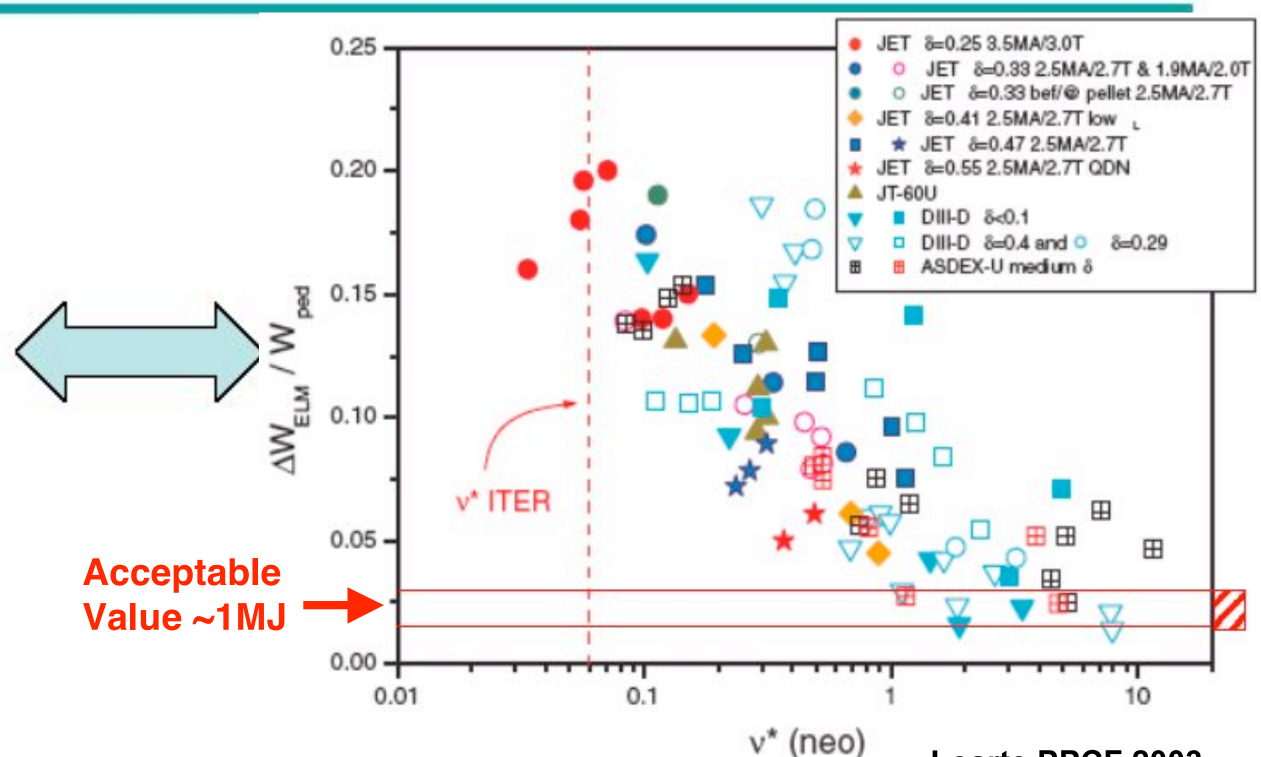
- **H-mode tokamaks are susceptible to ELMs**
  - Can cause significant heat loading on divertor, erosion of PFCs, and loss of internal transport barrier (ITB)
  - Will already be a concern for ITER with HH and DD operation

- **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)



Loarte PPCF 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

A. Leonard (BP Workshop 2005)

Large ELMs cannot be tolerated

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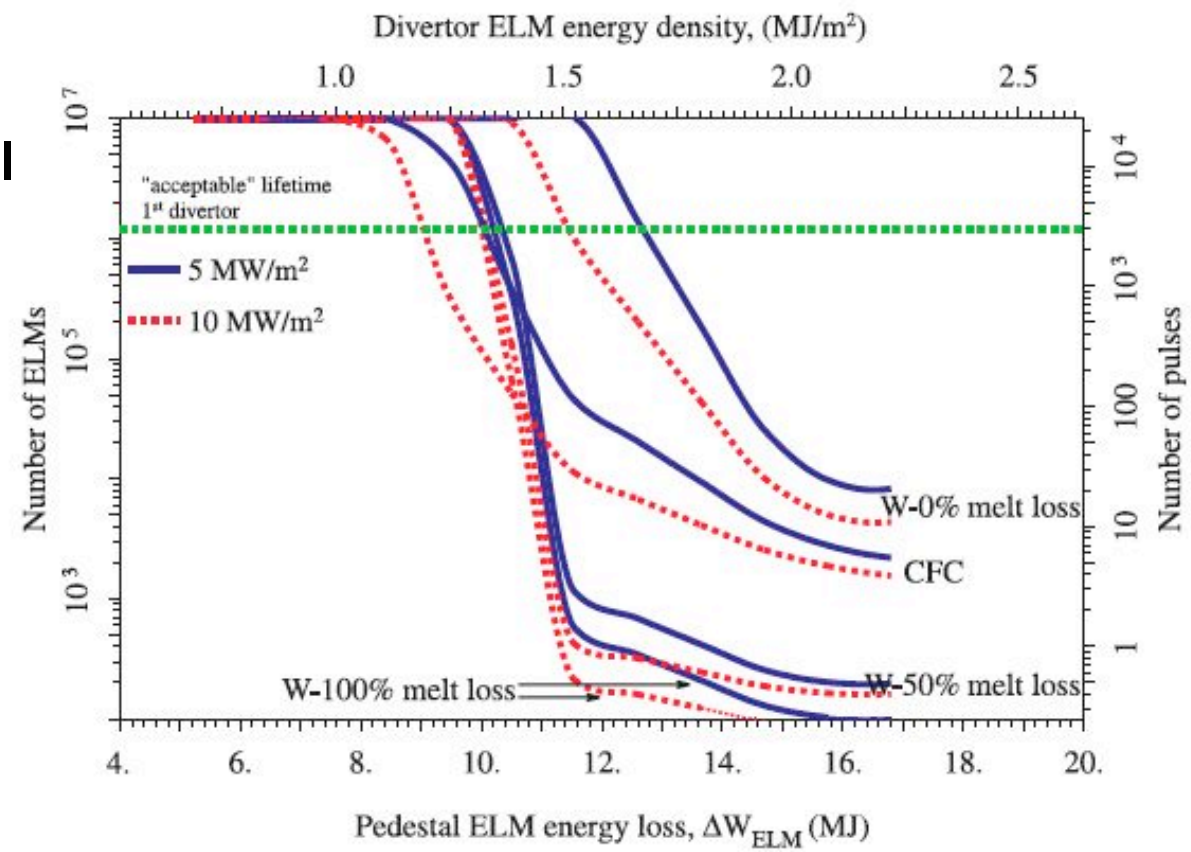
- **Large Type I ELMs will likely damage ITER divertor structure**



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

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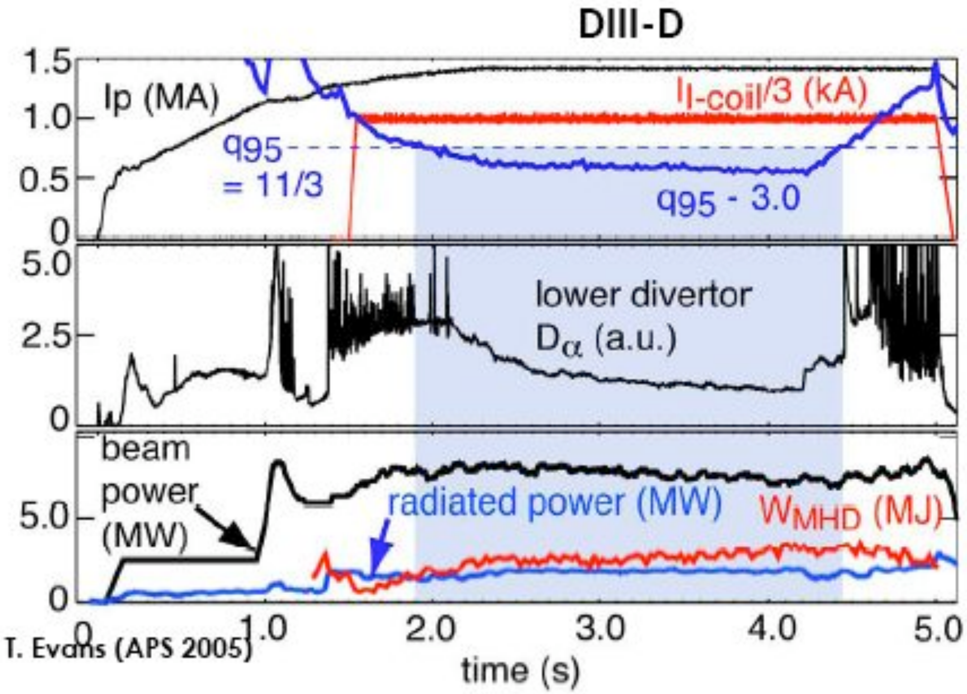

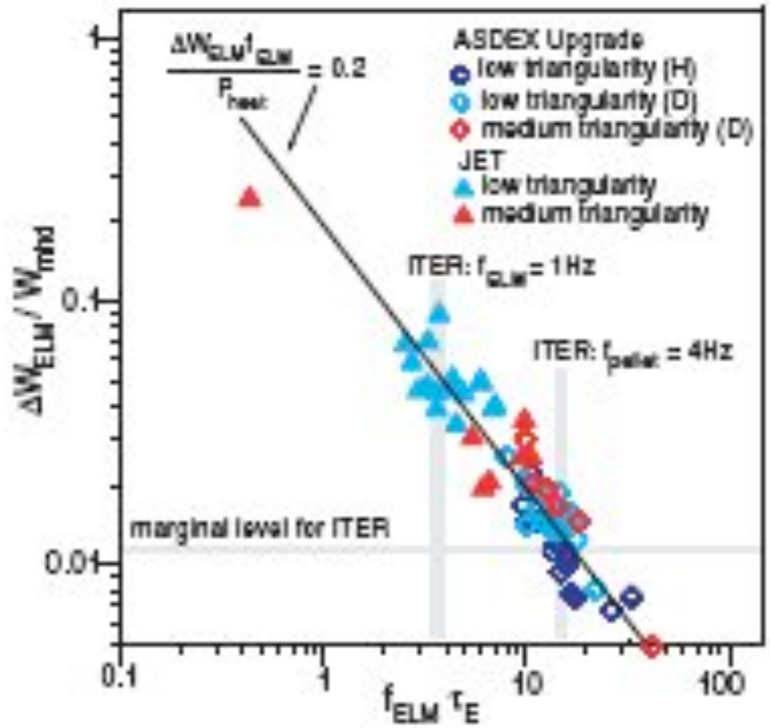

- **Edge ergodization (Resonant Magnetic Perturbation coils)**
  - Being explored for ITER
  - Issues: distance from plasma; compatibility with other hardware

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

Mukhovatov (PPCF 2003)

Impurity accumulation

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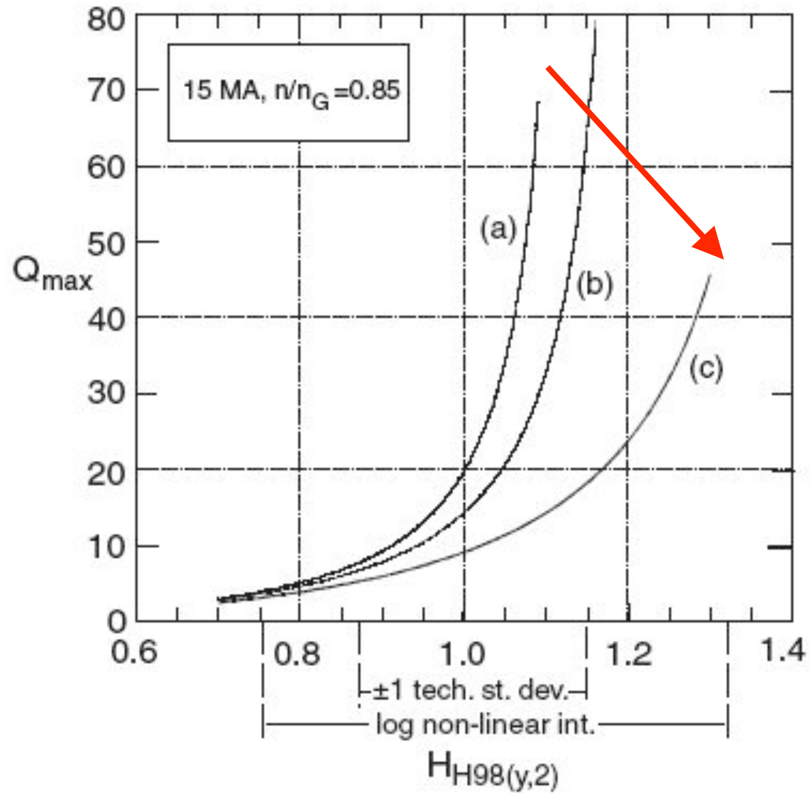
- **Consequences of impurities**
  - Radiative cooling in the core
  - Dilution of the fusion fuel (by helium "ash")
- **Sub-ignition DT experiments (TFTR and JET)**
  - Studied tritium particle transport coefficients
  - Also studied helium ash transport coefficients



- 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)

Plasma-facing components

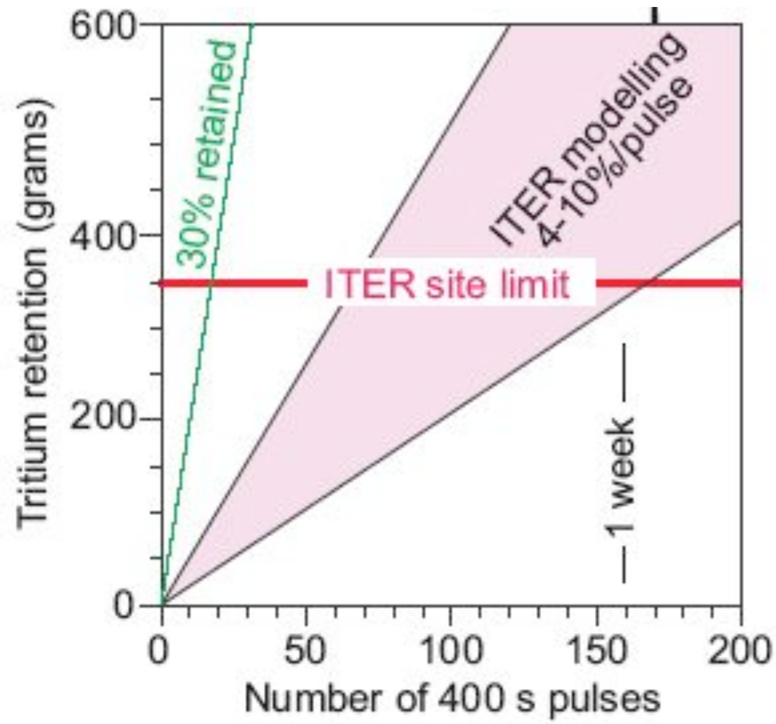
- **Plasma performance-related limitations on PFC materials:**
  - Plasma contamination
  - PFC surface lifetime and viability
    - Energy density and energy throughput (discharge length) are very high in burning plasma
    - Ablation or melting caused by uncontrolled transient surface heat loading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



- **ITER will require higher T removal rates than have been demonstrated**
  - Oxygen bake, RF conditioning, disruptive-radiative heating, grit-blast, replace tiles

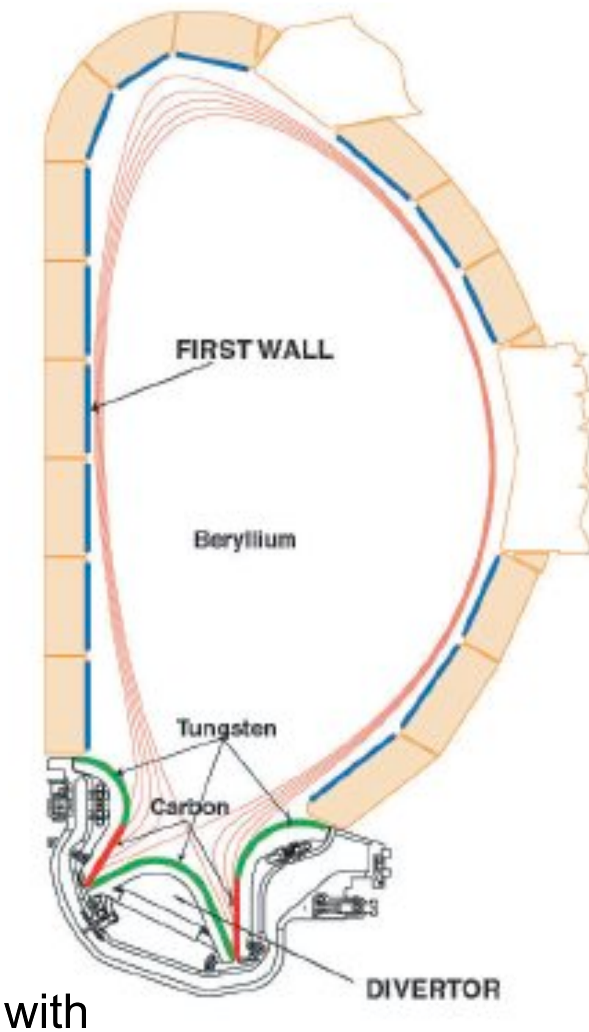
Parameter	TFTR experience	JET experience	ITER requirement
Time devoted to T removal	1.5 months	3 months	5-14 hours
Fraction of T removed	50%	50%	~100%
Tritium removal rate	~ .0014 g/hr	~ .0028 g/hr	~25-70 g/hr

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



G. Federici (PPCF 2003)

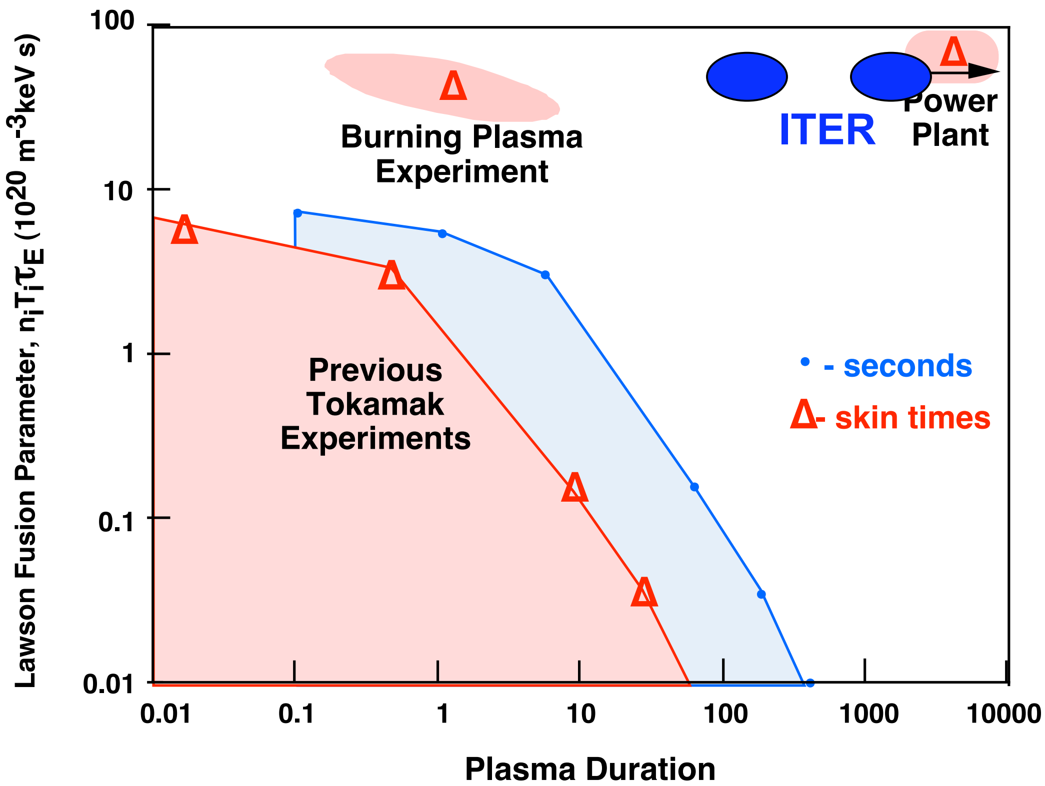
Layout of PFCs in ITER with different armor materials

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

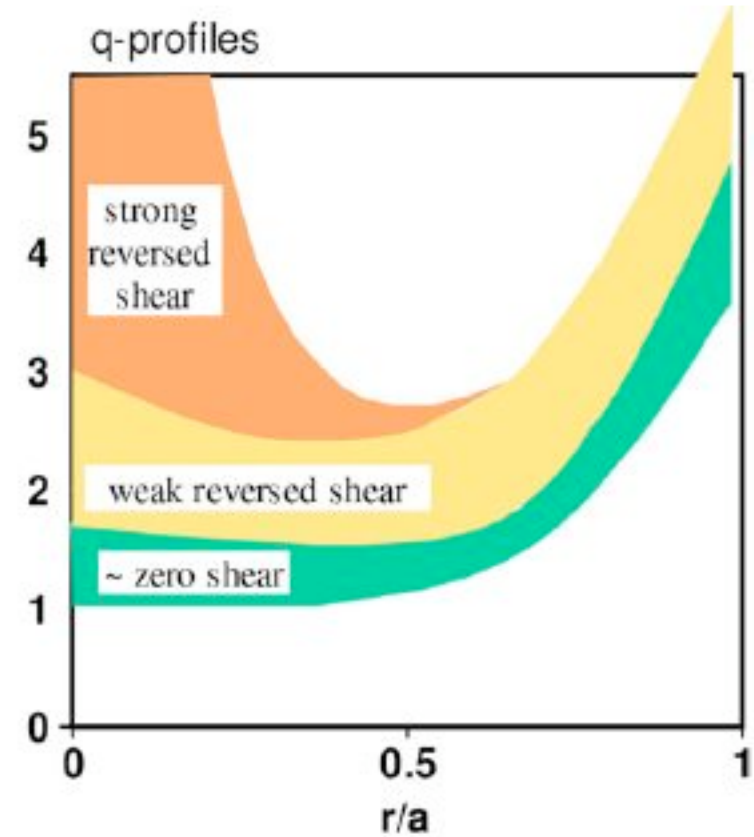
- **ITER aims for:**
  - 400 s with Q=10
  - 3000 s steady state (Q~5)



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

5. Thermonuclear environment

- Neutron radiation
- Tritium breeding
- Burning plasma diagnostics

Neutron radiation damage

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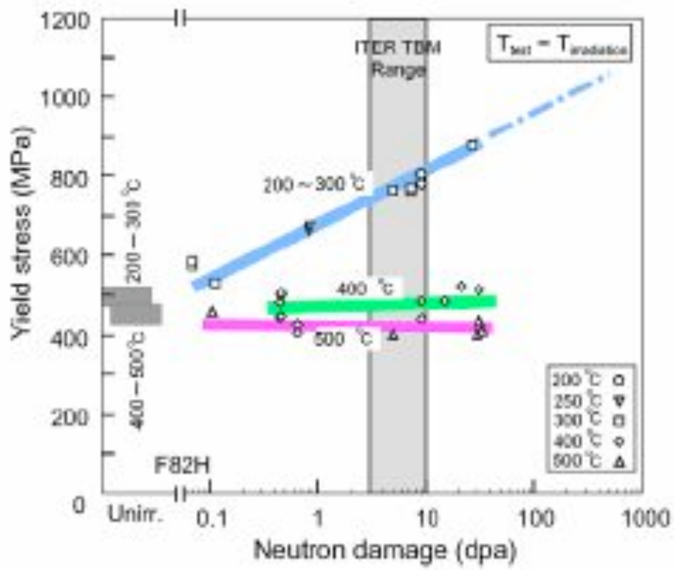
- **Radiation damage will affect all fusion materials**
  - Structural materials
  - Breeding and neutron multiplying media
  - Diagnostic and electronic materials
  - Insulators



- **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

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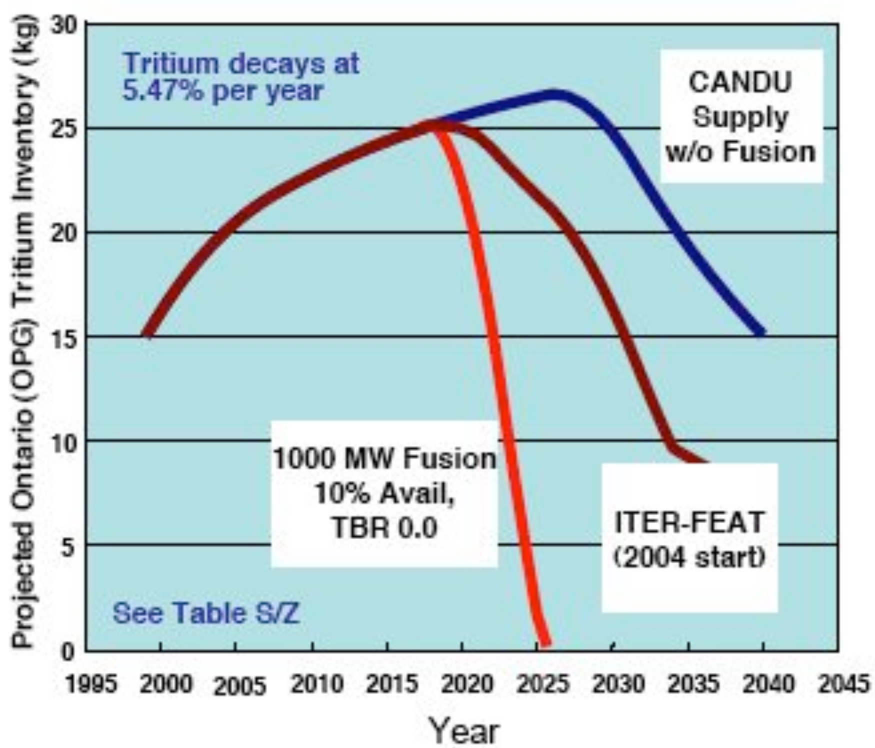
- **Large consumption of tritium during fusion**
  - 55.8 kg per 1000 MW of fusion power per year
- **Production and cost**
  - CANDU reactors: 27 kg over 40 years, $30M/kg currently
  - Other fission reactors: 2-3 kg/yr @$84-130M/kg

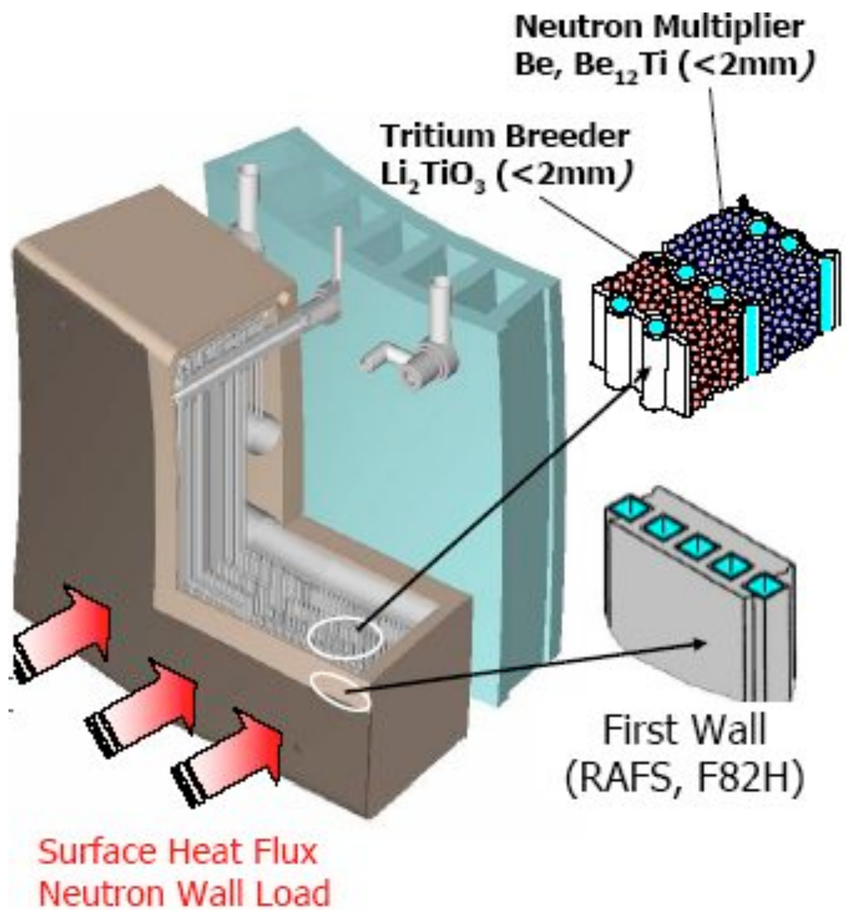


- **Tritium breeding for self-sufficiency**
  - World supply of tritium is sufficient for 20 years of ITER operation (will need ~17.5 kg, leaving ~5 kg)
  - Tritium breeding technology will be required for DEMO and reactors

M. Abdou (TBM Workshop 2007)

Test Blanket Modules

- **TBMs**
  - 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 ferritic content lead to large magnetic field ripple?
- **Other methods**
  - Fission reactors, accelerator-based point neutron sources, non-neutron test stands



Burning plasma diagnostics

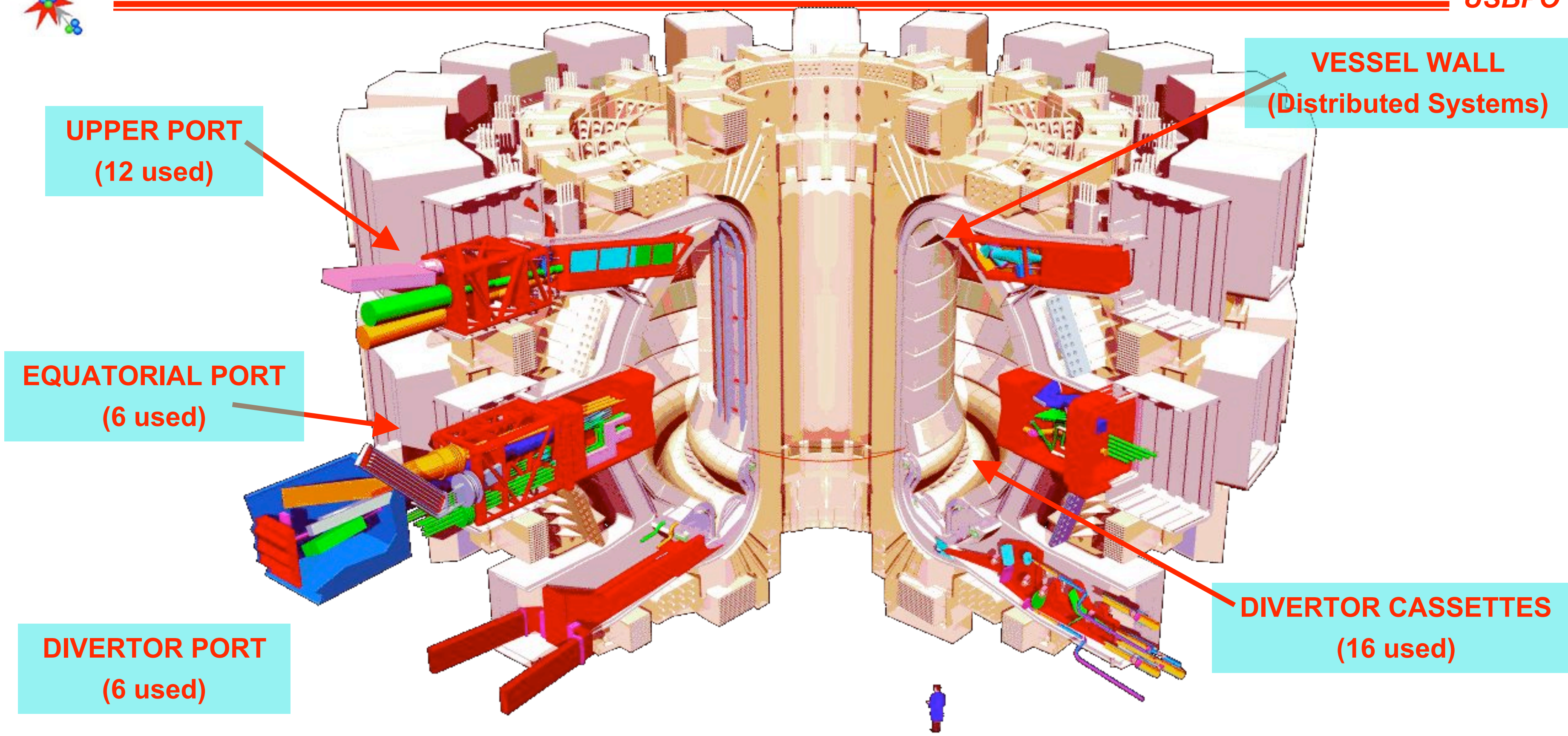
- **Essential for operation**
  - Plasma and first wall measurements will be critical in burning plasma for (1) machine protection, (2) plasma control, and (3) physics evaluations

- **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)

Burning plasma diagnostics on ITER

USBPO



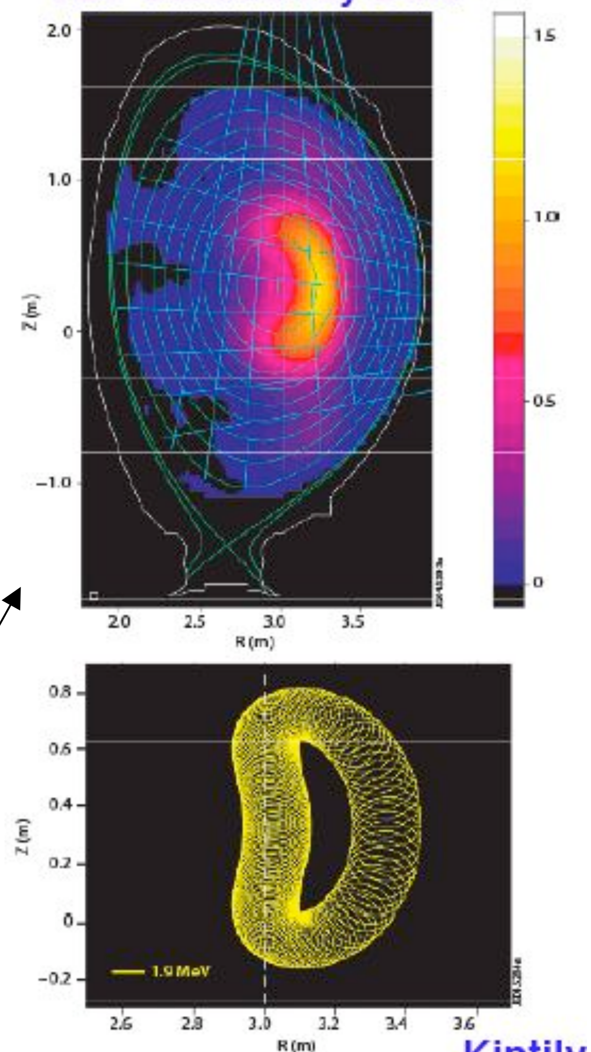
- **About 40 large scale diagnostic systems are foreseen for ITER:**
  - Diagnostics required for protection, control and physics studies
  - Measurements from DC to γ-rays, neutrons, α-particles, plasma species
  - Diagnostic Neutral Beam for active spectroscopy (CXRS, MSE ….)

Alpha diagnostics: confined

USBPO

- **Confined alpha particle diagnostics**
  - Measurement of confined alphas is still a challenge
  - Need good spatial resolution for studies of transport, ITBs, and alpha particle-driven instabilities
  - Alpha velocity-space distribution measurements are important for Alfvén instability studies
  - Candidate techniques:
    - collective Thomson scattering
    - Charge exchange recombination spectroscopy
    - alpha knock-on
    - charge-exchange neutralization
    - gamma-ray spectroscopy

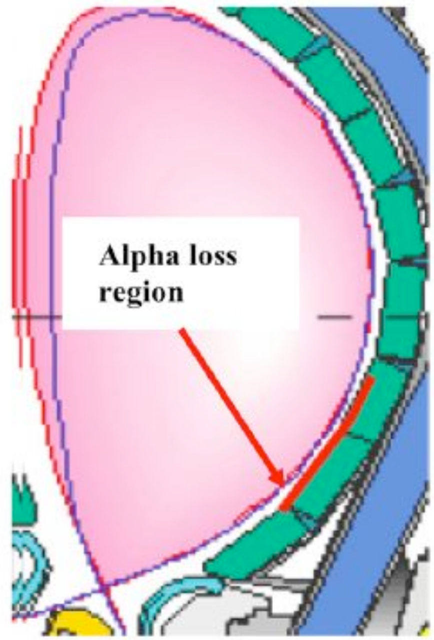
JET Gamma-ray Data



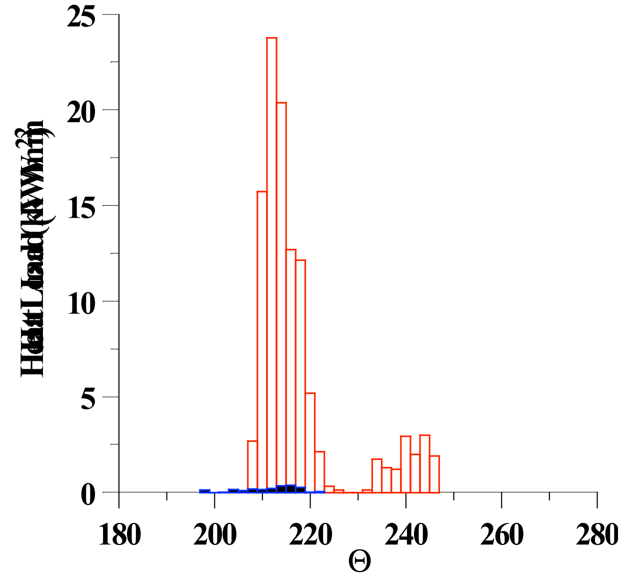
Kiptily

Alpha diagnostics: lost

- **Lost alpha particle diagnostics**
  - Measurement of lost alphas is also still a challenge
  - Need to measure bombardment location, pitch angle and energy distribution, temporal behavior during MHD
  - Candidate techniques:
    - Faraday cups
    - scintillator probes
    - IR camera imaging
    - gamma-ray spectroscopy



First wall region marked by the thick red line undergoes α particle bombardment due to TF ripple loss



Poloidal distribution of heat load due to banana particle loss (red) and locally trapped α loss (blue)

M. Sasao et al. (PPCF 2004)

6. Integrated system

- Nonlinearly coupled elements
- CODAC

Integrated performance

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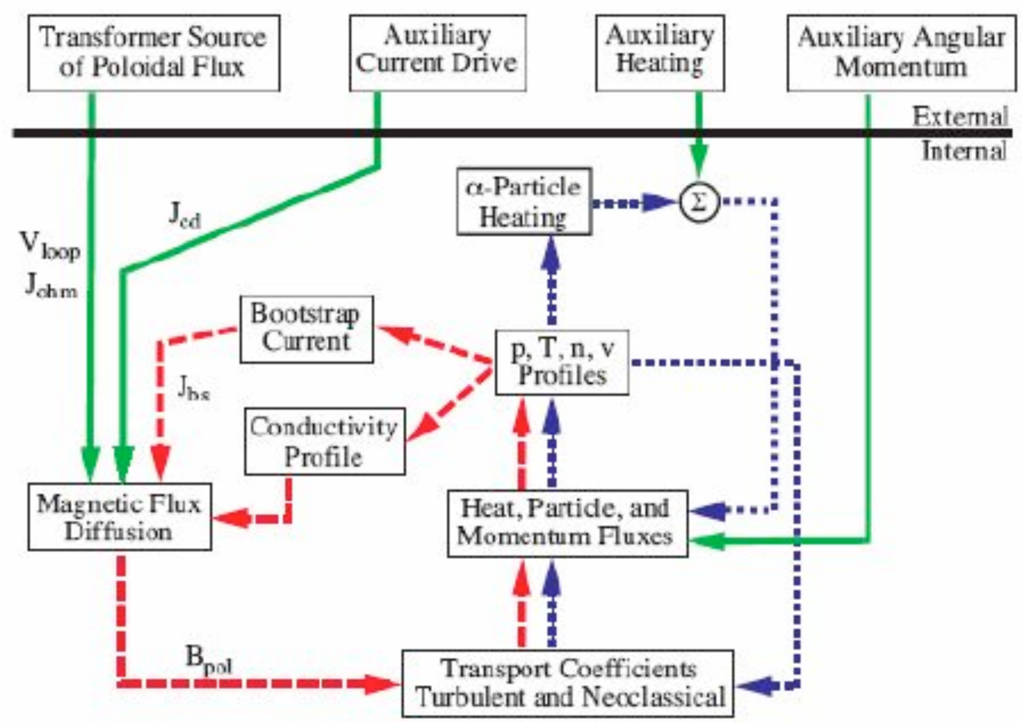
- **Nonlinear coupling of burning plasma behavior**
  - The critical elements in the areas of transport, stability, boundary physics, energetic particles, heating, etc., will be strongly coupled nonlinearly in a burning plasma due to the fusion self-heating
  - New phenomena arise from full nonlinear 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 nonlinear coupled system

USBPO

- **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)

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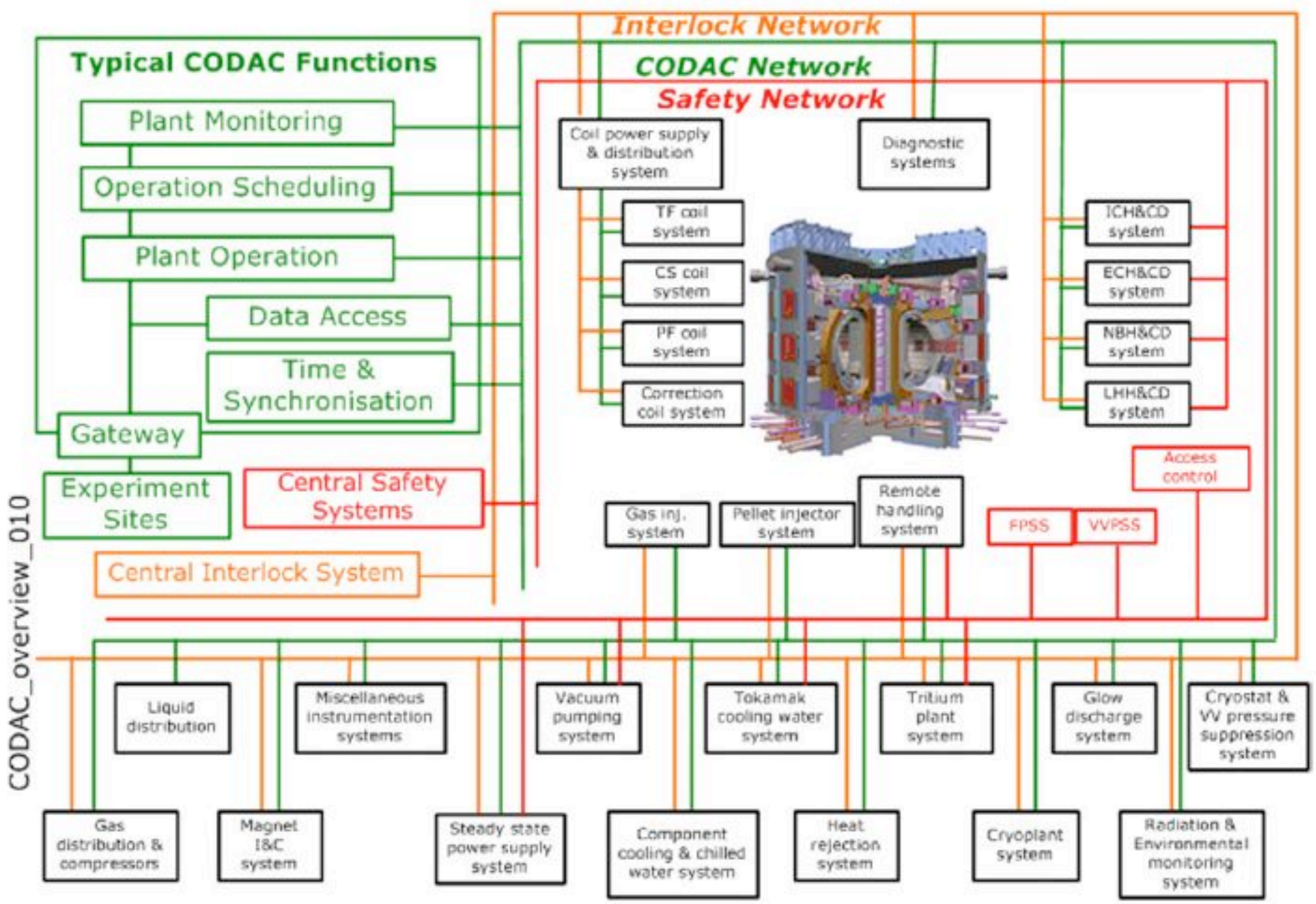
- **ITER plant control system**

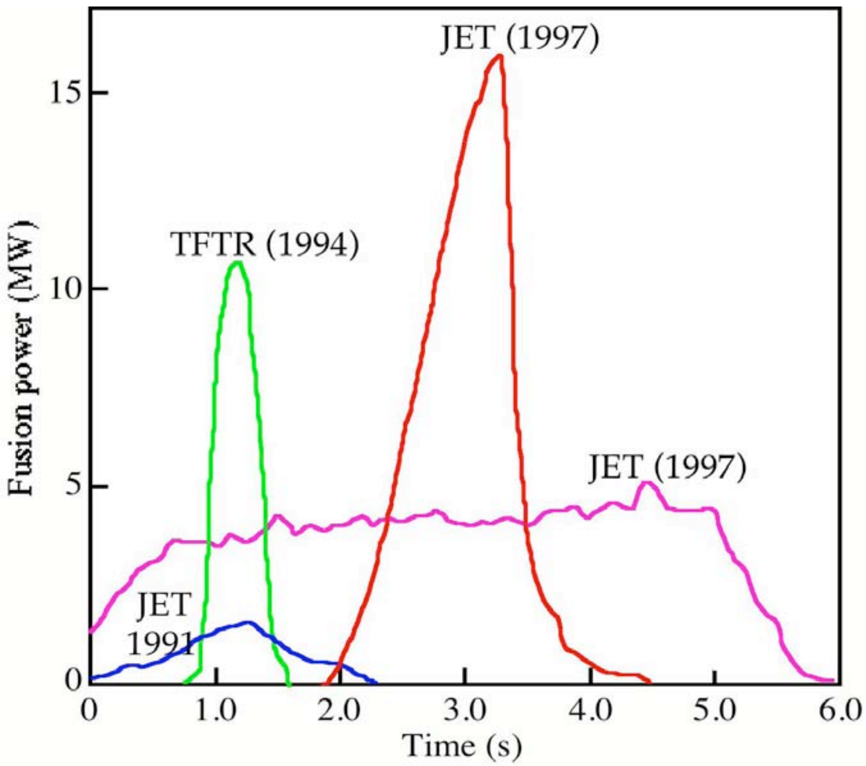


GRAND CHALLENGE OF BURNING PLASMAS

Producing a self-sustaining fusion-heated plasma is a grand challenge

1928	Fusion reactions explain energy radiated by stars [Atkinson & Houtermans]
1932	Fusion reactions discovered in laboratory [Oliphant]
1935	Fusion reactions understood as Coulomb barrier tunneling [Gamow]
1939	Theory of fusion power cycle for stars [Bethe–Nobel Prize 1967]
1950	Use of fusion for military objective
1950's	Invention of tokamak, helical system, mirror, etc.
1958	2nd UN Atoms for Peace Conference (Geneva): magnetic fusion research was de-classified
1968	Russian results on high-temperature plasmas presented at IAEA Fusion Energy Conference
Since then:	Worldwide explosion in toroidal plasma research, leading to the attainment of fusion-grade plasma parameters

Initial D-T experiments

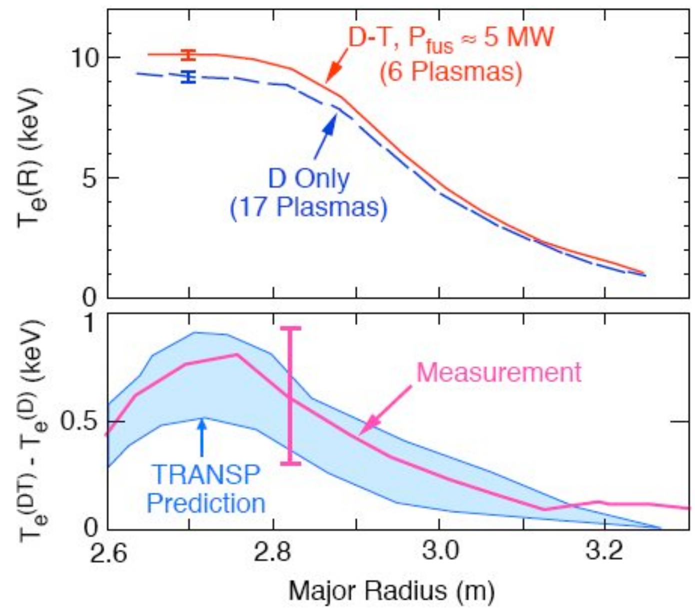


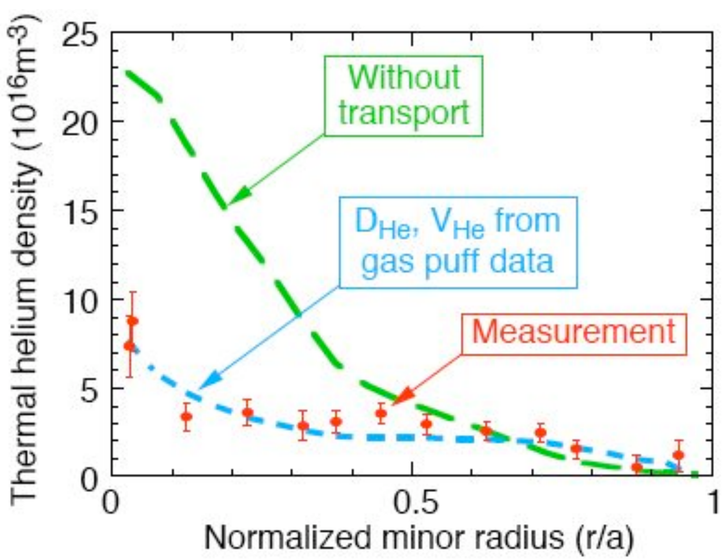
- **Joint European Torus (JET)**
  - "Preliminary Tritium Experiment" (1991): $P_{DT} > 1$ MW
  - Subsequently: Q = 0.9 (transient break-even), Q = 0.2 (long pulse)
  - 16 MW fusion power
- **Tokamak Fusion Test Reactor (TFTR)**
  - Dec 1993–Apr 1997: 1,000 discharges with 50/50 D-T fuel
  - $P_{DT} = 10.7$ MW, Q = 0.2 (long pulse)

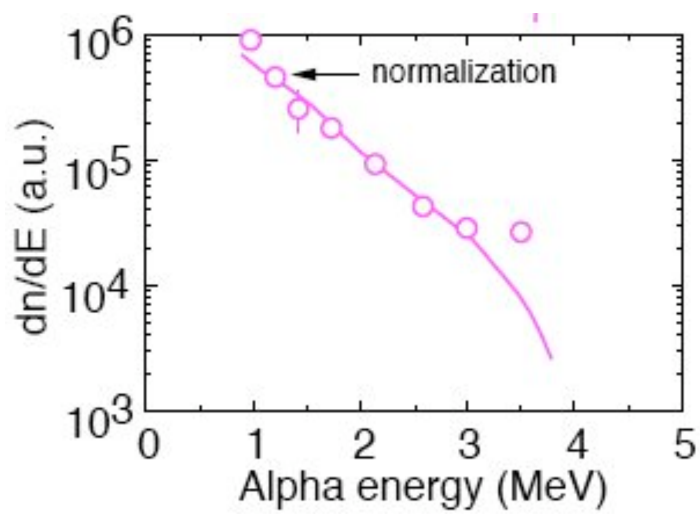
Initial tritium results

USBPO

- **D-T experiments on TFTR measured:**
  – Favorable isotope scaling
  – α-particle heating
  – α-driven instability
  – Tritium and helium "ash" transport
  – Tritium retention in walls and dust
  – Safe tritium handling (1M curies)



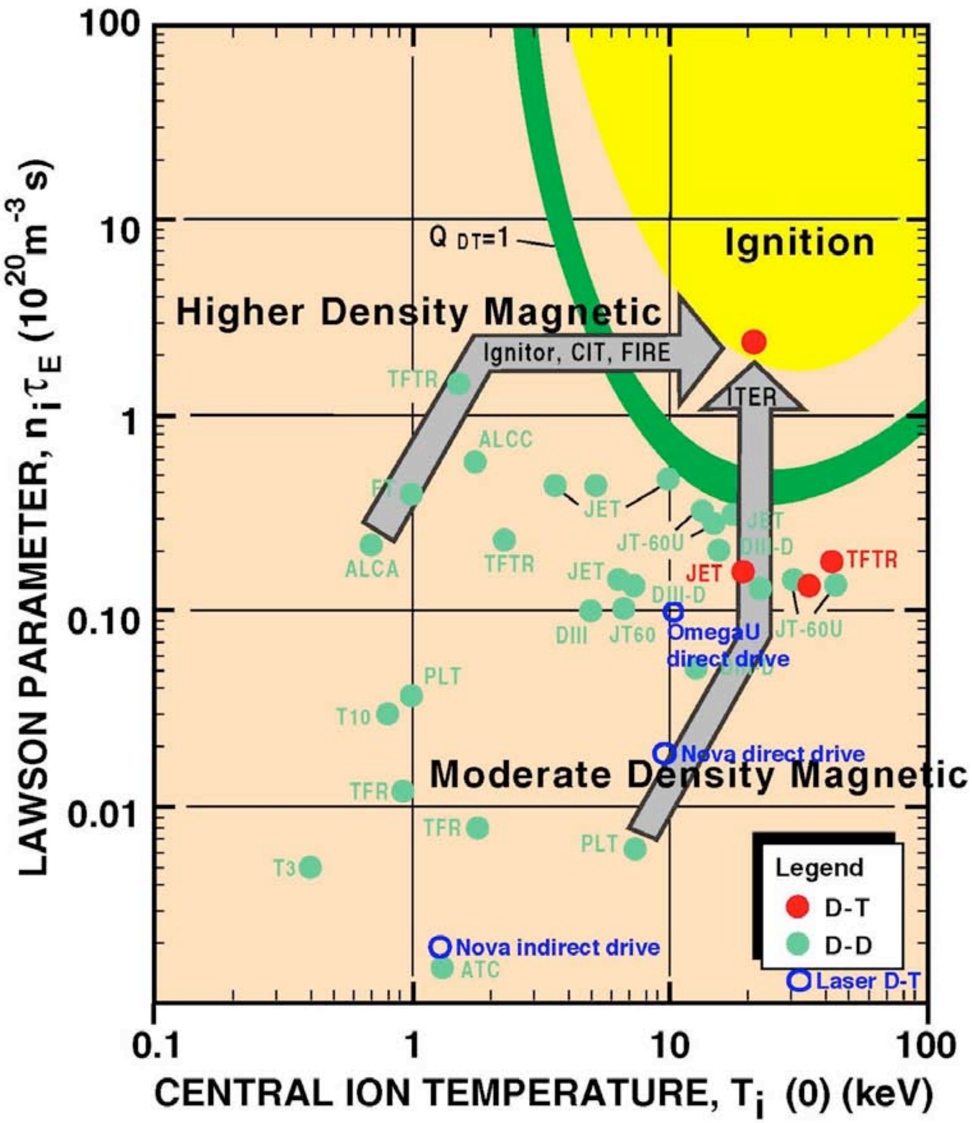




Status of magnetic fusion

- **Lawson Diagram:**
  - Achieved T_i required for fusion, but need ~10 X $n\tau_E$
  - Achieved $n\tau_E \approx$ 1/2 required for fusion, but need ~10 X T_i

- **No experiment has yet entered the burning plasma regime**
  - Such an experiment is the next logical step forward on the path to fusion energy
  - The world fusion program is technically and scientifically ready to proceed now with a burning plasma experiment



ITER—next step for magnetic fusion

- **Large (R = 6.2 m) superconducting tokamak**
  - Produce and study ignited ($Q \geq 10$) deuterium-tritium plasmas

- **International project located in Cadarache, France**
  - 7 partners (EU, JA, RF, US, KO, CN, IN) = 50% of world's population
  - First plasma operation in 2016, D-T operation in 2021

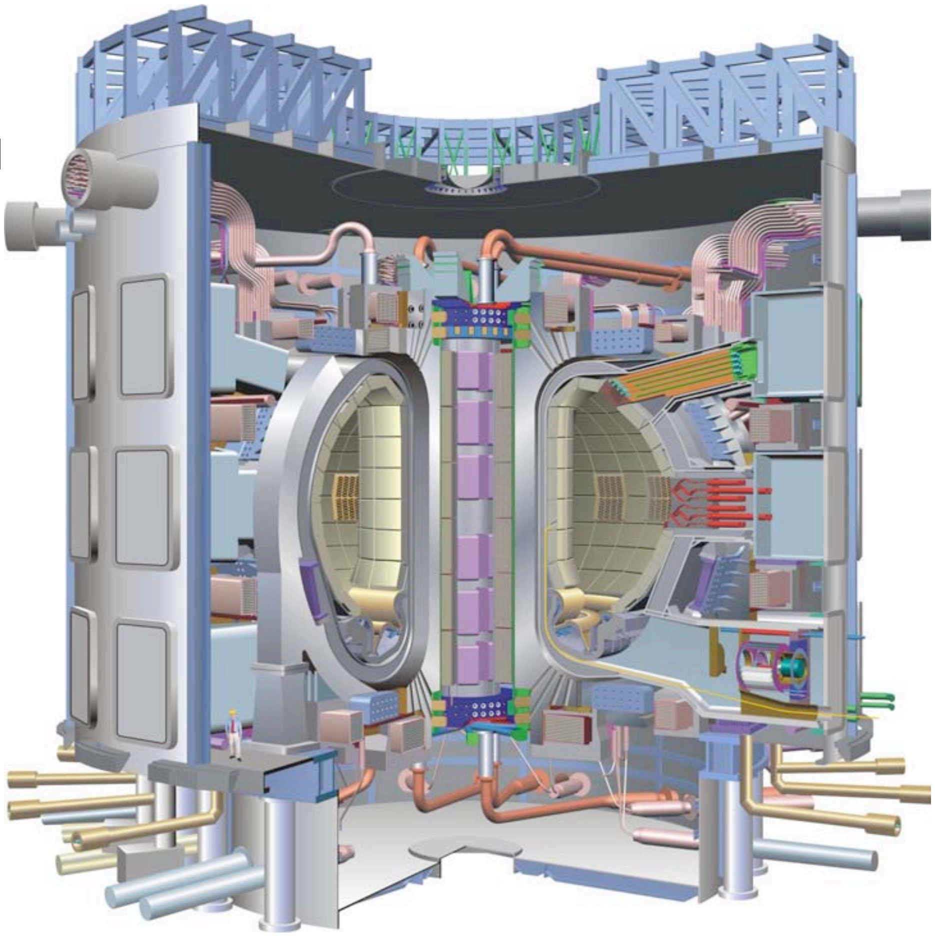
ITER will demonstrate scientific and technological feasibility of fusion

USBPO

- **ITER (“the way” in Latin) is essential next step in development of fusion**
  - **Today**: 10 MW(th) for 1 sec with gain ~ 1
  - **ITER**: 500 MW (th) for >400 sec with gain ≥10

- **Advances in science & technology are needed for a demonstration power plant**
  - 2500 MW(th) with gain >25, in a device with similar size and field
  - Higher power density
  - Efficient continuous operation
  - Tritium self-sufficiency

- **Research is needed to address these and many other issues**



Many exciting burning plasma research challenges exist now

USBPO

- *National Academies NRC Burning Plasma Report*

  BP Research Opportunities in Next Decade:

  - Understand dynamics of edge Pedestal region
  - Physics and control of Edge-Localized Modes
  - Stabilization of neoclassical tearing modes
  - Develop ss & advanced tokamak regimes
  - The density limit and high density operation
  - Turbulence and transport
  - Disruption avoidance and mitigation
  - Diagnostics of burning plasmas
  - Plasma facing components and tritium interactions
  - Divertor Science & Technology development
  - Tritium breeding blankets

References: burning plasmas

USBPO

- R. Hawryluk, **Results from Deuterium-Tritium Tokamak Confinement Experiments**, Rev. Mod. Phys. v. 70, p. 537 (1998)
- ***Final Report–Workshop on Burning Plasma Science: Exploring the Fusion Science Frontier*** (2000)
- ***Review of Burning Plasma Physics*** (Fusion Energy Sciences Advisory Committee, 2001)
- ***Burning Plasma: Bringing a Star to Earth*** (National Academy of Science, 2004)
- Presentations at **Burning Plasma Workshop 2005** (www.burningplasma.org/reference.html)
- **ITER Physics Basis** (Nuclear Fusion 1999); ***Progress in the ITER Physics Basis*** (Nuclear Fusion, 2007)