USBPO

United States
Burning Plasma Organization

An Overview of ITER and US Efforts

- *Big project*
- *Big strategy*
- *Big mission*
- *Big involvement*
- *Big physics*

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U.S. ITER Project Office, USDOE

THE UNIVERSITY OF TEXAS AT AUSTIN

IFS

Office of Fusion Energy Sciences
Excellent Science Attractive Energy

Office of Science
U.S. DEPARTMENT OF ENERGY

ITER will demonstrate scientific and technical feasibility of fusion

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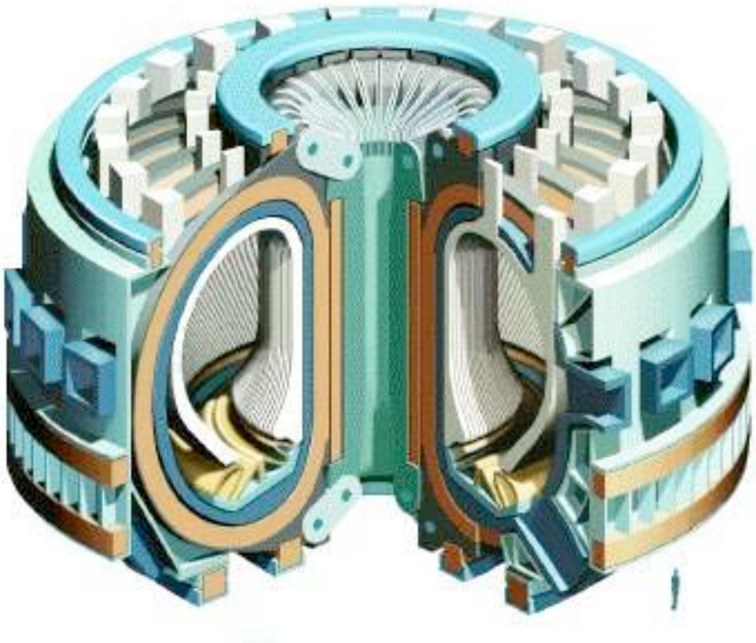

- **ITER ("the way") is essential next step in development of fusion energy**
  - Today: 10 MW, 1 sec, gain = 1
  - ITER: 500 MW, >400 sec, gain ≥ 10
- **ITER is the world's biggest fusion energy research project ("burning plasma")**
  - 15 MA plasma current, 5.3 T magnetic field, 6.2 m major radius, 2.0 m plasma minor radius, 840 m^3 plasma volume, superconducting
  - €10B to construct, then operate for 20 years ("first plasma" in 2019)
- **An international collaboration**
  - 7 partners, with 50% of world's population
  - EU the host Member, ITER sited in France
  - Excellent example of US involvement in big-science international physics collaboration (cf. Large Hadron Collider, ALMA telescope)

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

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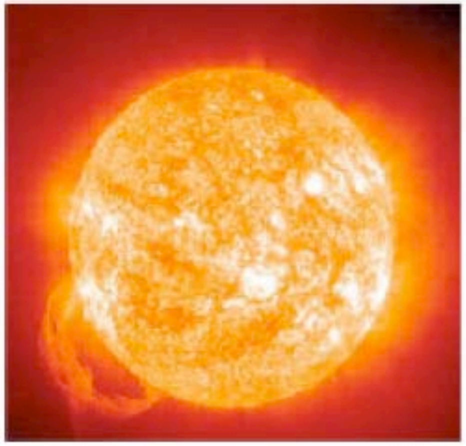
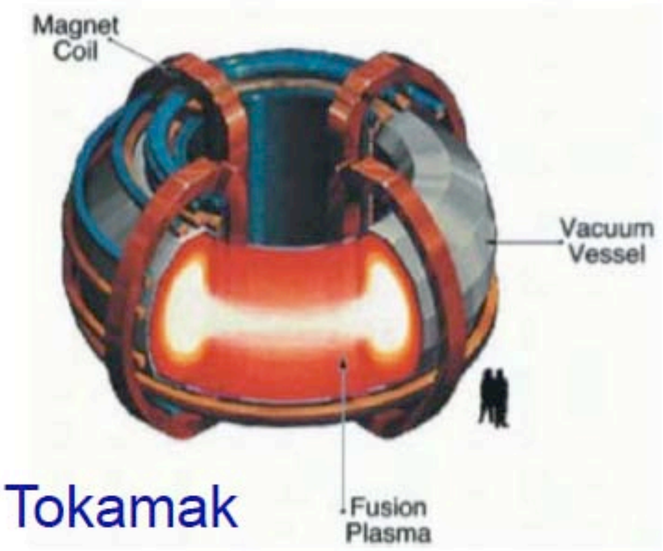




Tokamak

Lab fusion reaction of choice:

$$\mathrm{D}^2 + {}_1\mathrm{T}^3 \rightarrow \underbrace{\underset{(3.5\ \mathrm{MeV})}{{}_2\mathrm{He}^4} + \underset{(14.1\ \mathrm{MeV})}{{}_0\mathrm{n}^1}}$$

Energy/Fusion: $\varepsilon_f = 17.6$ MeV

Fusion energy gain:

$$Q \equiv \frac{P_{fusion}}{P_{heat}} = \frac{5\,P_\alpha}{P_{heat}}$$

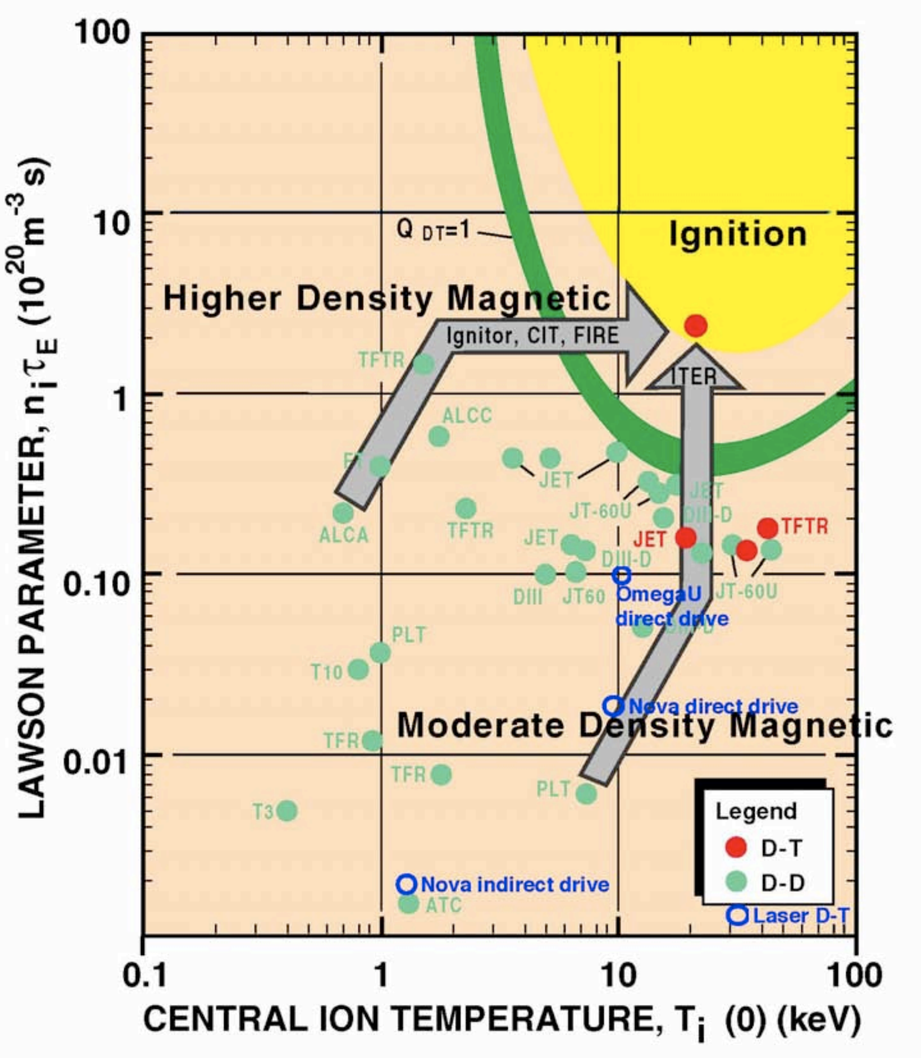
Alpha heating fraction:

$$f_\alpha \equiv \frac{P_\alpha}{P_\alpha + P_{heat}} = \frac{Q}{Q+5}$$

Breakeven	Q = 1	f_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%

Status of magnetic fusion

- **Lawson Diagram:**
  - Achieved T_i required for fusion, but need ~10 x n τ_E
  - Achieved n $\tau_E \approx$ ½ 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



US in-kind hardware contributions

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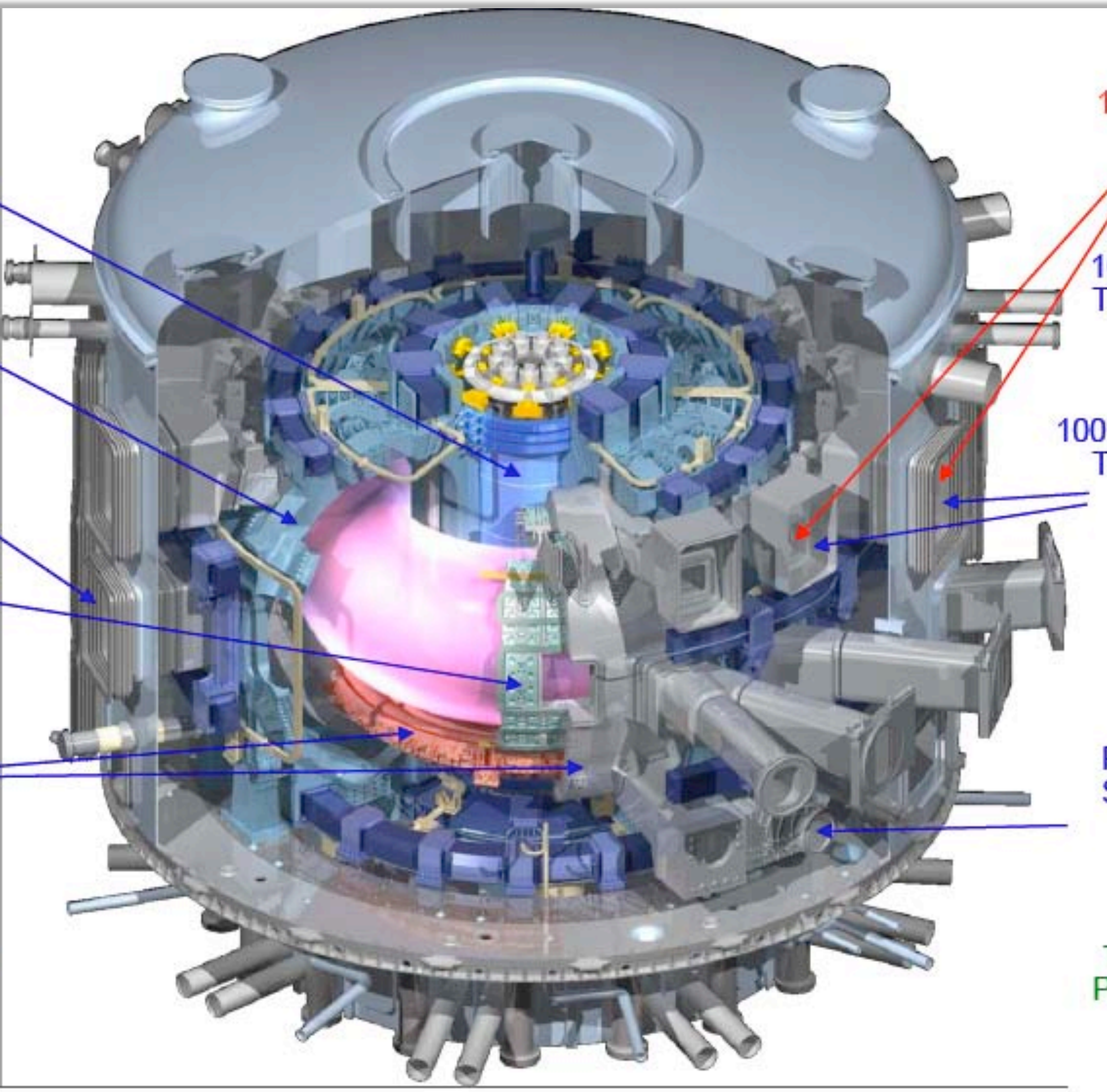


ORNL
7 Central Solenoid Coils

ORNL
8% of Toroidal Field Conductor

ORNL
Pellet Injector

ORNL
20% First Wall/Shield

ORNL
75% Cooling for Divertor, Vacuum Vessel, …

PPPL
Steady State Power Components

PPPL
15% of Port-based Diagnostics

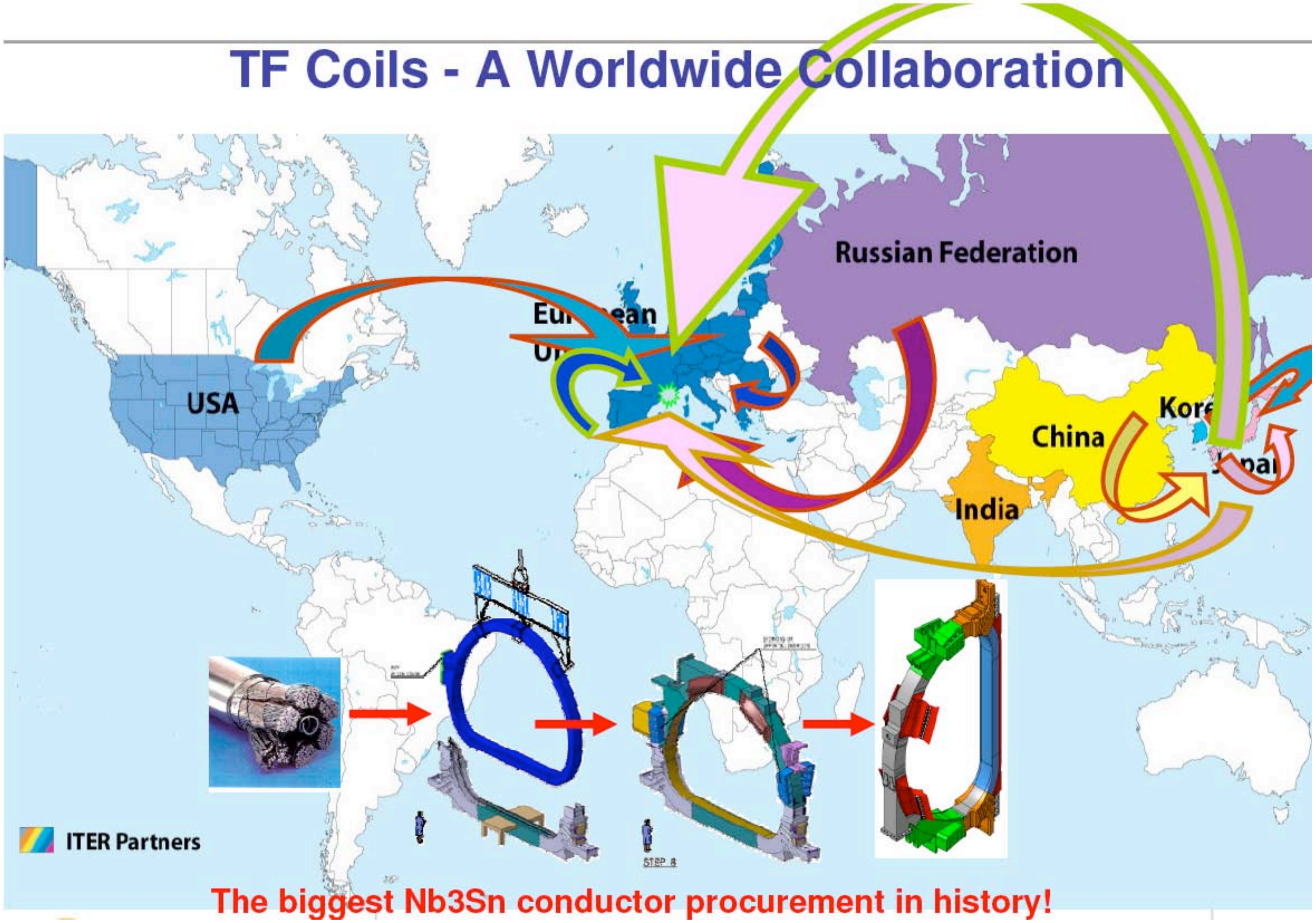
ORNL
100% Ion Cyclotron Transmission Lines

ORNL
100% Electron Cyclotron Transmission Lines

ORNL
Roughing Pumps, Standard Vacuum Components

SRNL
Tokamak Exhaust Processing System

Construction and assembly of superconducting toroidal field coils


TF Coils - A Worldwide Collaboration

The biggest Nb3Sn conductor procurement in history!

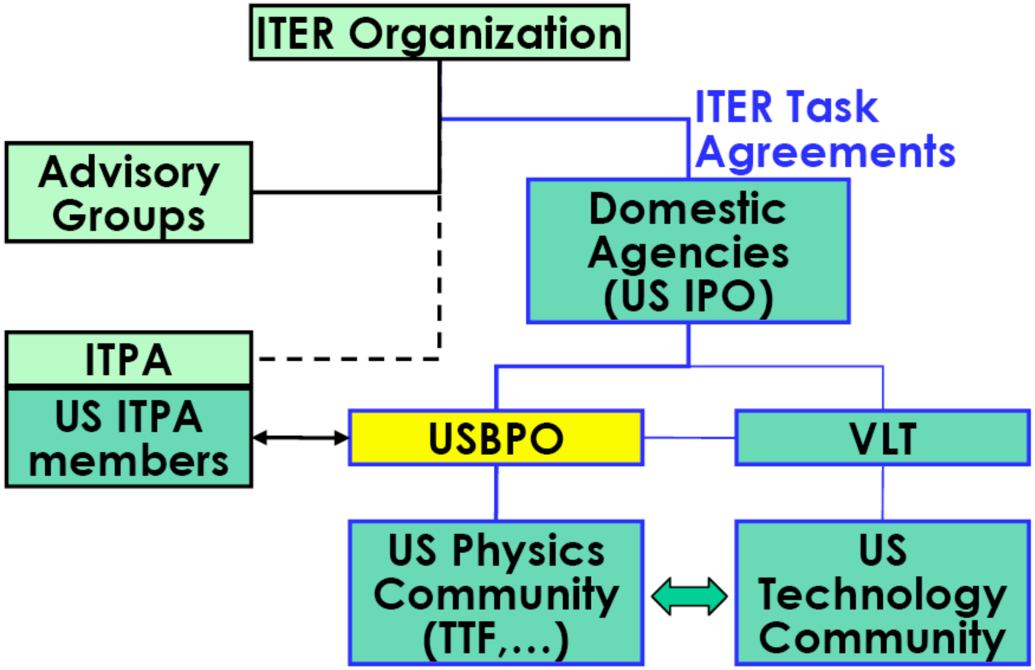
Courtesy of G. Johnson (ITER): *Progress of the ITER Project*
http://w3fusion.ph.utexas.edu/ifs/iiss2010/iisstalks/Johnson_Gary_talk.pdf

USBPO: Physics support for ITER

- **U.S. Burning Plasma Organization is community-based**
  - Mission: *Advance the scientific understanding of burning plasmas and ensure the greatest benefit from burning plasma experiments by coordinating relevant U.S. fusion research with broad community participation*
- **Broad community participation:**
  - Regular members (316 from 55 institutions)
  - Associate members (15 from 9 non-US institutions)
- **USBPO web site (www.burningplasma.org)**
  - All presentations, white papers, progress reports are publicly available
  - *eNews* monthly newsletter: 480 subscribers (from 95 institutions)
    - "Director's Corner" column, feature articles, ITPA meeting reports, calendar of fusion events, research highlights, community reports

USBPO role in ITER support

- **US ITER Project Office (ORNL)**
  - Main link to ITER
  - Provides hardware & technical contributions
- **USBPO**
  - Coordinates US burning plasma physics research
  - USBPO director is also the US ITER Project Office chief scientist
  - Companion to Virtual Laboratory for Technology



Burning plasma goals of ITER

- **Physics:**
  - Produce a plasma dominated by alpha particle heating
  - Produce significant fusion power amplification ($Q \geq 10$) in long-pulse operation
  - Achieve steady-state operation of a tokamak ($Q\ =5$)
  - Retain the possibility of exploring “controlled ignition” ($Q \geq 30$)

- **Technology:**
  - Demonstrate integrated operation of technologies for a fusion power plant
  - Test components required for a fusion power plant
  - Test concepts for a tritium breeding module

- **These are exciting opportunities for scientific discovery and innovation in the new burning plasma regime**

New science for burning plasmas

Uniquely BP issues

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

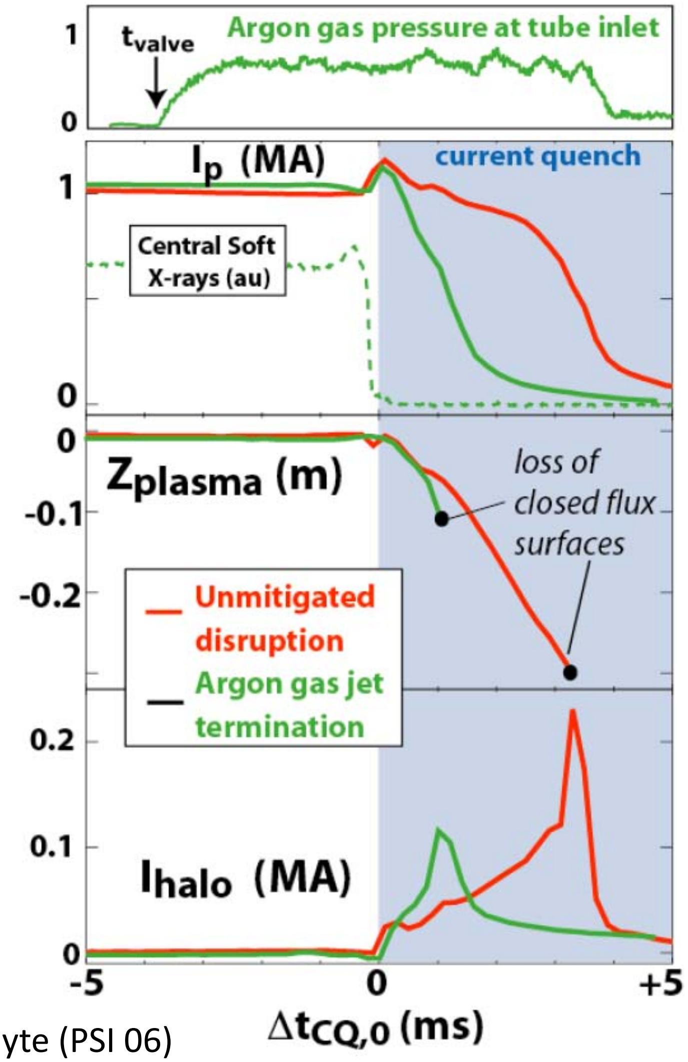
Reactor-scale BP issues

- *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

Mitigation of disruptions

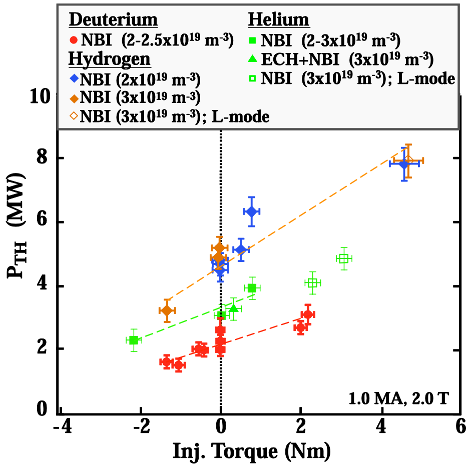
- **ITER plans to use massive impurity-gas injection (MGI)**
  - DIII-D and C-Mod have shown good mitigation of heat loads, vessel currents, & resulting forces with MGI
- **Other possible methods**
  - Injection of "killer" pellets (shell pellets, shattered pellets)
  - Injection of liquid jets
- **Some open science issues**
  - Early prediction and detection
  - Better theoretical understanding



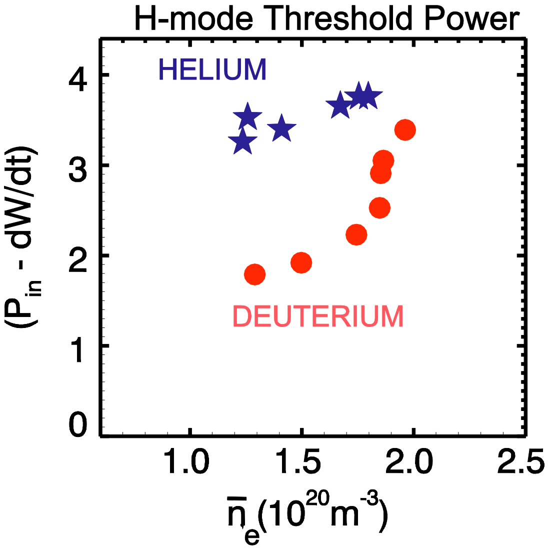
D Whyte (PSI 06)

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



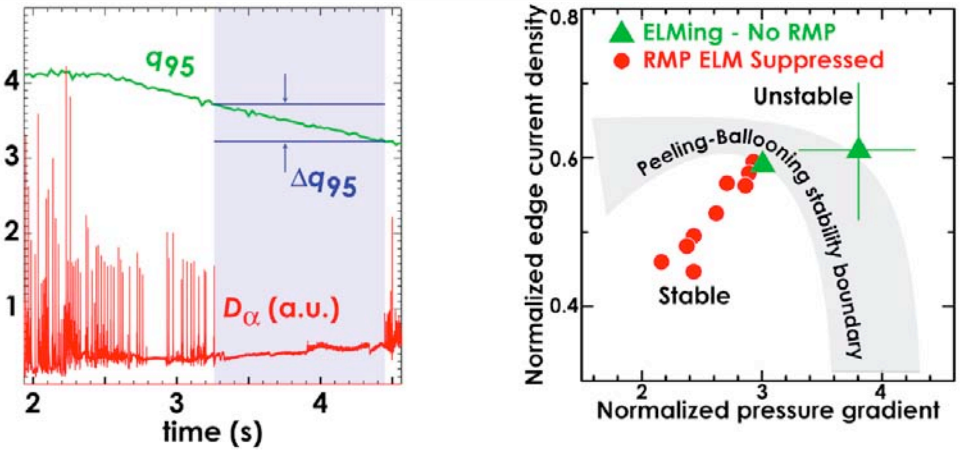
P. Gohil et al., 12th international workshop on "H-mode physics



- **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

Understand and control ELMs

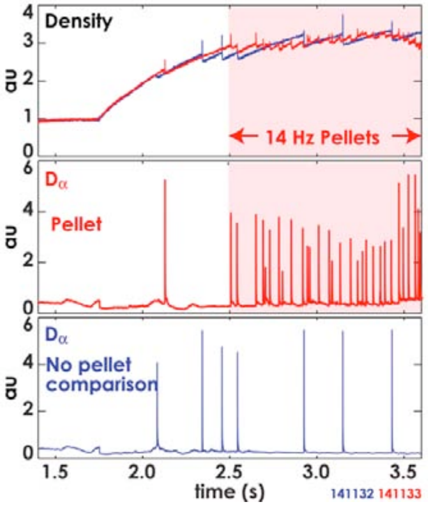
- **Issue**
  - Edge Localized Modes (ELMs) are periodic rapid relaxations of edge temperature & density.
  - Such heat pulses in ITER could damage wall and divertor.



RMP suppression of ELMs on DIII-D

Greenfield (IAEA 2010)

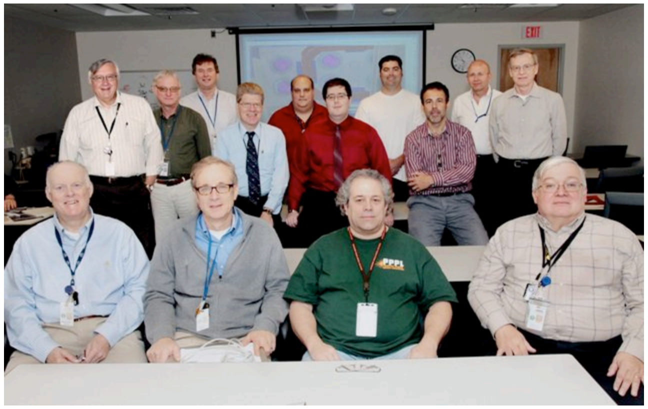
- **Methods to mitigate/avoid ELMs planned for ITER**
  - Edge ergodization by resonant magnetic perturbation coils
    - Why RMPs increase transport?
  - Pellet pace-making
    - 14 –> 25 Hz pellets; ELM energy fraction reduced ~4X

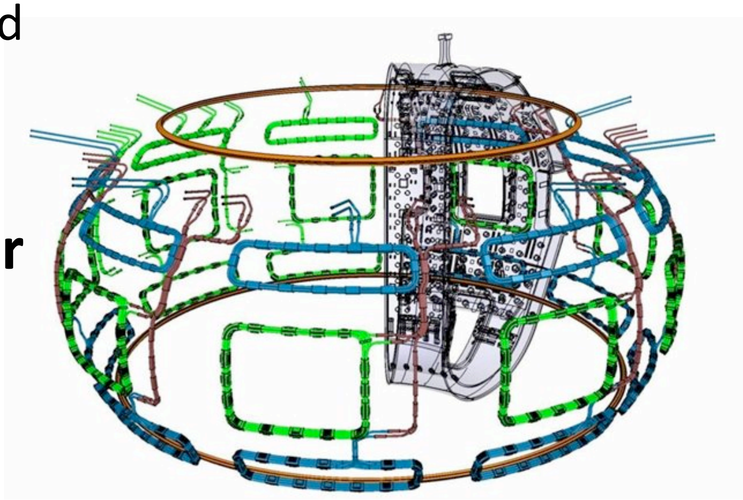


Baylor (IAEA 2010)

In-vessel coils for ITER

- **IVC design team has been led by PPPL**
  - IVC system comprised of two subsystems:
    - Vertical stability coils (2 PF coils above and below the midplane): orange
    - ELM control coils (27 RMP coils on wall of vacuum vessel): green & blue
  - Successful Preliminary Design Review held week of Oct 18

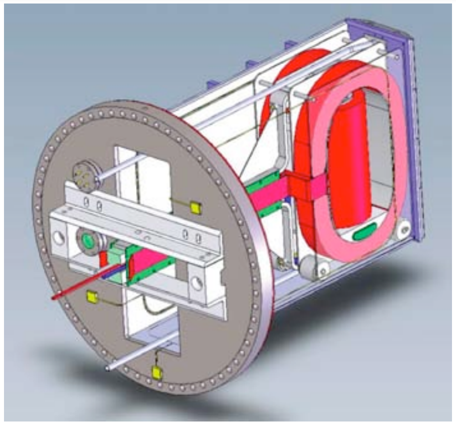




- **Each IVC wound from 50 m conductor**
  - Conductor consists of 59-mm OD SS jacket, magnesium oxide insulating layer, and inner Cu conductor (water cooled)

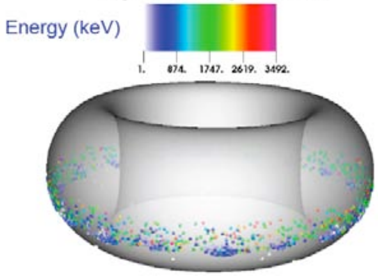
TBM simulation experiments for ITER

- **Issue**
  - ITER plans to test 6 tritium-breeding Test Blanket Modules (@ ~ 1 ton ferromagnetic steel)
  - Will create localized, non-axisymmetric error fields larger than toroidal field ripple (0.4%)
  - Potential effects on H-mode confinement, rotation, ELMs, alpha particle loss, etc.
- **TBM simulation experiments on DIII-D**
  - Fabricated and installed coil to mock up error field of 2 TBMs in one port
  - Expts conducted Nov 2009 by international team, with 12 scientists from ITER & 5 Members
  - Results help set limits on allowable magnetic field ripple [Schaffer (IAEA & APS 2010)]
- **Theory simulations of ITER alpha loss due to TBMs**

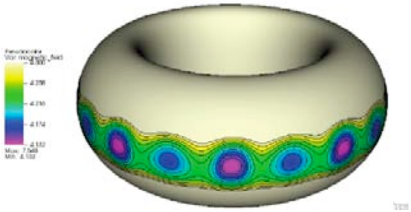


DIII-D coil

ITER with 3 TBMs and TF ripple alpha loss patterns



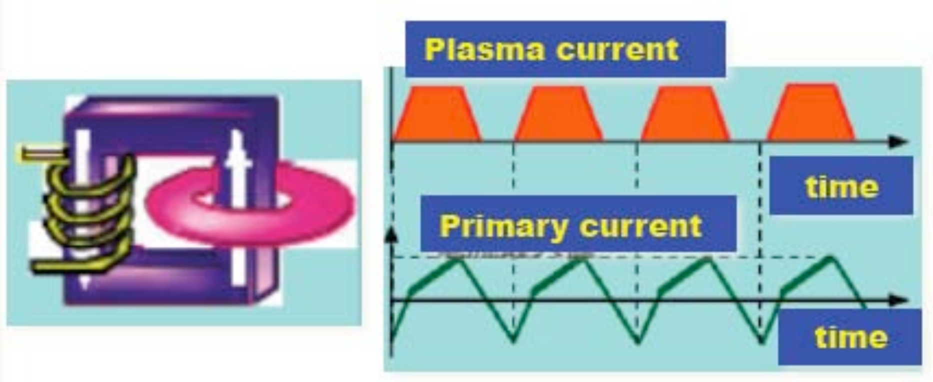
Ripple contours – outer surface



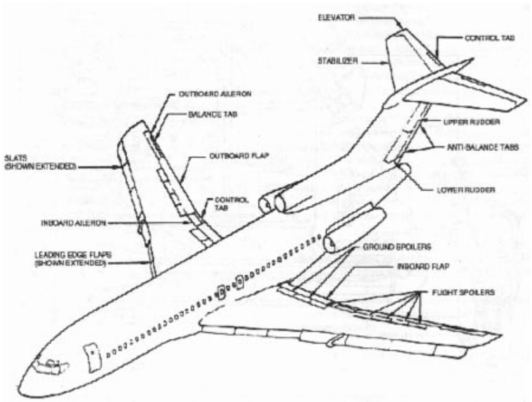
Spong (APS 2010)

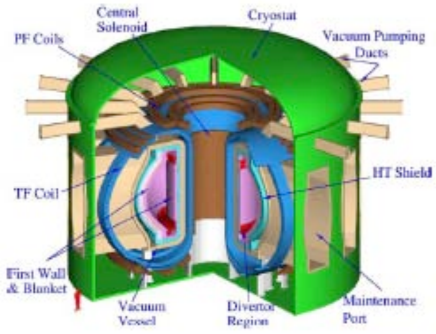
Plasma control system required for high-performance ITER operation

- **Tokamak is not intrinsically steady-state**
  - Current is inductively driven
  - For long pulse operation, use bootstrap current and active current drive (waves, beams)
  - Requires plasma control to achieve high reliability, availability, and performance



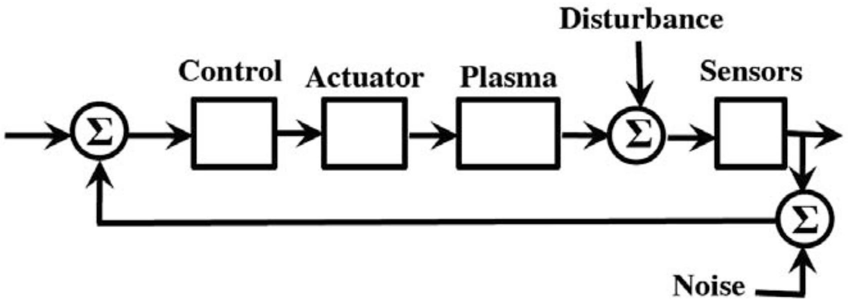
- **ITER will be similar to modern aircraft**
  - Same degree of control complexity, requirements on performance





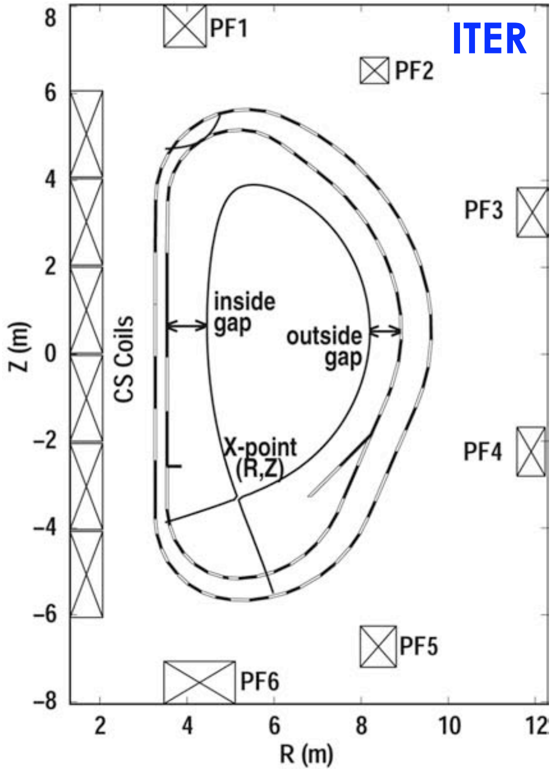
~ 10^3 sensors, 10^2 controlled parameters, 10^2 actuators

Key features of plasma control systems



- **Plasma control systems must have:**
  - Operator interface
  - Sensor/data acquisition (input)
  - Actuator commands (output)
  - Scheduling manager (what happens when)
  - Feed-forward command generators
  - Feed-back algorithms
  - Algorithms to interpret inputs

- **Example: shape and position control**




Power Supply Commands

Shape Control System

Shape & Position Parameters (e.g. gaps, X point R,Z)

ITER will have 5 control subsystems

SUBSYSTEMS	ACTUATORS	MEASUREMENTS
Plasma axisymmetric magnetic control	Central Solenoid (CS), Poloidal Field (PF), and internal Vertical Stability (VS) coils & power supplies	Neutral pressure, impurity radiation, stray fields, plasma current & position, poloidal field & flux, coil currents, toroidal field, and vessel eddy currents
Plasma kinetic control	Heating and current drive (ion/electron cyclotron waves & neutral beam injection), gas and pellet injection (Ar, Ne, H, D, & T), real-time pumping, strike point control	Particle flux and heat load on first wall and divertor, impurity content, radiated power, D_α emission, neutral pressure, core and divertor helium content, electron/ion/impurity densities, core DT mix, temperature & current density profiles
Non-axisymmetric control	Heating and current drive systems, ELM coils and pellet pacing, gas and pellet fuelling, shape control, external correction coils	MHD eigenmode profiles, error field characterization, plasma rotation
Event handling	Axisymmetric magnetic control & disruption mitigation	Plant system status, high first wall and divertor heat load, oscillating and locked modes, and runaway electrons
Wall conditioning and tritium removal	Ion and electron cyclotron waves, high-frequency glow discharge cleaning	Residual gas species and partial pressures

ITER International Summer School

- **4th ITER International Summer School held in US in 2010**
  - May 31-June 4, University of Texas
  - Sponsors: **National Instruments**, USBPO, French Embassy in US, ...
- **Theme:** ***MHD and Plasma Control in Magnetic Fusion Devices***
- **Participation**
  - 133 participants from 17 countries and 48 institutions

IISS 2010

4th ITER International Summer School

"Magnetohydrodynamics and Plasma Control in Magnetic Fusion Devices"

31 May – 4 June 2010

The University of Texas at Austin

Sadruddin Benkadda
Director, IISS
Université de Provence

David Campbell
Chair, IISS Scientific Committee
ITER

Wendell Horton
Joint Director, IISS 2010
Chair, Local Organizing Committee
The University of Texas at Austin

http://w3fusion.ph.utexas.edu/ifs/iiss2010/

ITER International Summer School

Left: Dr. James Truchard (CEO, NI Corp)
Right: Prof. Juan Sanchez (VP Research, Univ of Texas Austin)

20 lecturers from 7 countries & ITER

4 computer lab sessions

“Fusion is the future, and the future is in your hands.”

Lectures posted at
w3fusion.ph.utexas.edu/ifs/iiss2010/

Summary

- **Burning plasma studies on ITER open up new regime of plasma physics of an exothermic medium**
  - A "Grand Challenge" problem, with outlook for societal benefit
- **US program contributing strongly to ITER R&D needs**
  - Involves experiments, diagnostics, theory, and simulations
  - Coordinated efforts of program facilities, university/lab/industry scientists, and organizations (USIPO, ITPA, USBPO, VLT, etc.)
- **Many exciting research issues in burning plasma science for ITER operation and next-generation experiments (DEMO)**
  - Near-term urgent R&D needs
  - Medium-term R&D issues leading up to First Plasma and DT Operation
  - Longer-term R&D for ITER long-pulse campaign and beyond