U.S. Department of Energy's

Office of Science

US International Collaboration in Fusion Research and Participation in the ITER Project

AAAS Symposium on
Progress in Magnetic Fusion Energy Research
Through 50 Years of International Collaboration and
Future Prospects
Boston, MA

Dr. Raymond Fonck
Associate Director
For Fusion Energy Sciences

February 14-18, 2008

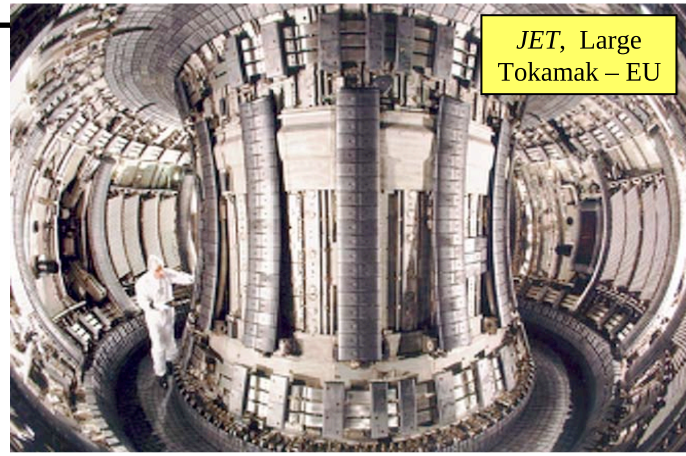
www.science.doe.gov/ofes

Fusion research is rooted in extensive and historic international activity

- **50th anniversary of international de-classification of fusion research**
  - 2nd Conference on Peaceful uses of Atom – Geneva; 1958
  - IAEA Fusion Energy Conference 2008 (FEC 2008) – Geneva, October 2008
- **US, EU, Japan, Russian Federation (Soviet Union) early partners**
- **The ITER Agreement brings new countries into fusion collaborations**
  - China, India, South Korea full ITER partners
  - Others possibly interested..
- **Motivation for Fusion research - potential for energy**
  - Environmentally attractive energy source with abundant fuel
- **integration of complex science and challenging technologies**
  - Basic sciences on plasmas, atomic to nuclear physics, materials…
  - Engineering sciences and technology

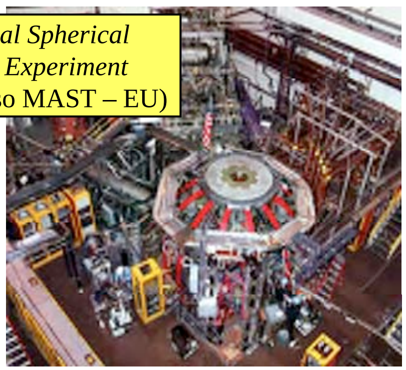
World Magnetic Fusion Research: Optimizing the Plasma Configuration

C-Mod, Tokamak MIT

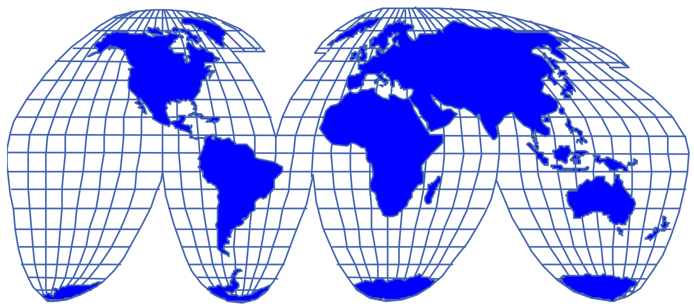


JET, Large Tokamak – EU

W7-X, Large Superconducting Stellarator – EU



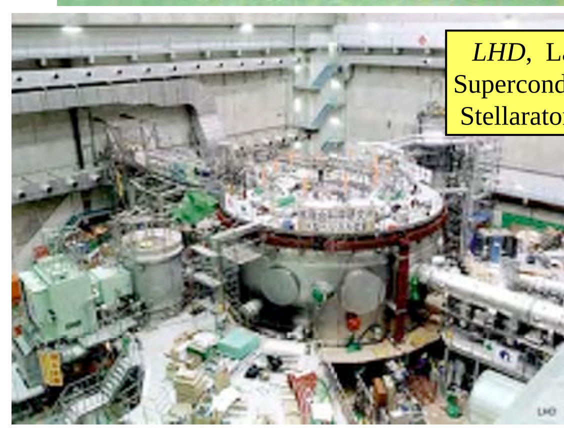
National Spherical Torus Experiment PPPL (also MAST – EU)



EAST, SST-1, *KSTAR* Superconducting Tokamaks, – China, India, Korea

DIII-D, Tokamak General Atomics

JT-60U, Large Tokamak– JA



LHD, Large Superconducting Stellarator – JA

International collaborations = an integral part of U.S. Fusion Science programs

- **Collaborations are reciprocal within foreign Parties and involve**
  - Small scale hardware exchanges (diagnostics, heating or fueling systems…)
  - Personnel exchanges to conduct experiments and data analysis
  - Workshops, meetings, and conferences

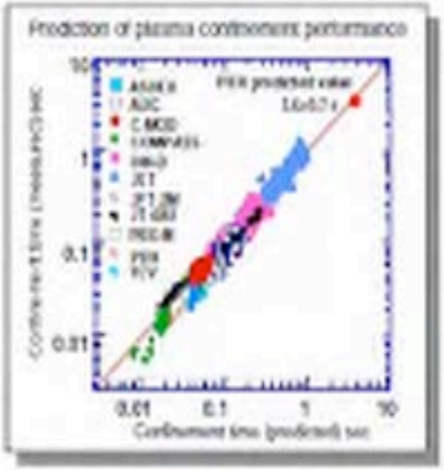
- **Bilateral and IEA Implementing Agreements provide legal framework**
  - **Bilateral agreements** with EU, JA, CN, KO, IN, and RF
  - **IEA Implementing Agreements** under Fusion Power Coordinating Committee (FPCC)
    - Tokamaks, Alternate Concepts, and Technology and Safety related
  - **DOE-Germany agreement on Dense Plasmas**

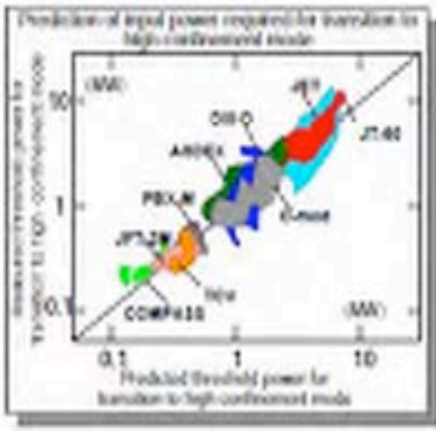
- **IAEA sponsors Technical Committee Meetings and Conferences**
  - IAEA provided a platform for ITER negotiations, and holds documents for the ITER Agreement
  - ITPA operation under International Fusion Research Committee (IFRC)

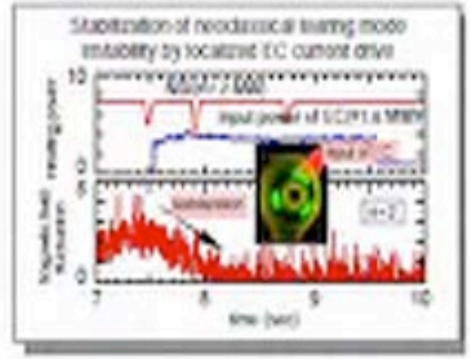
- **ITER Agreement is unique, establishing a new international legal entity**
  - Current focus is on construction of the facility

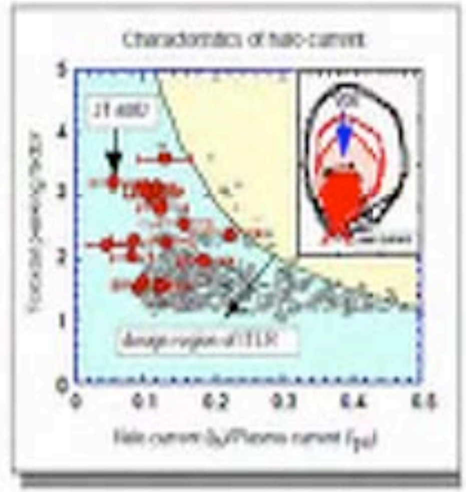
Attachment 6 Achievements of ITER Physics R&D

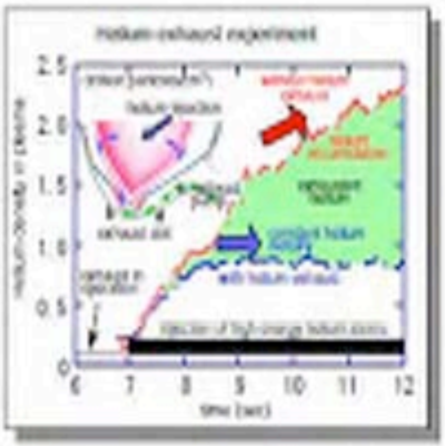
Integrate experimental results of tokamaks from all over the world to establish physics basis for plasma performance of ITER

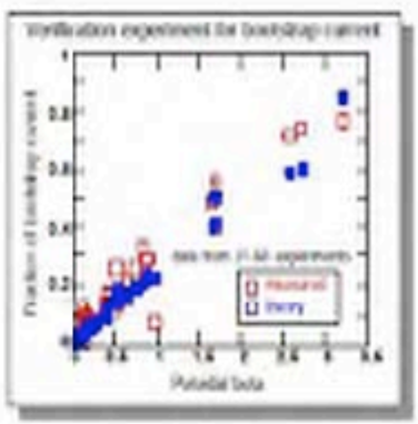


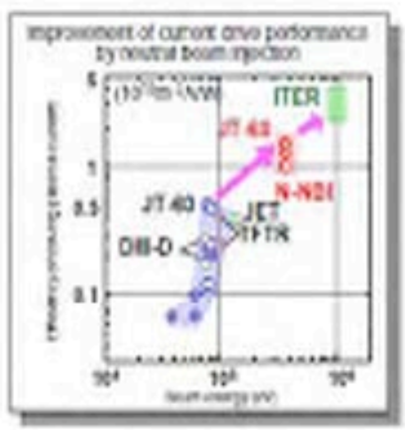


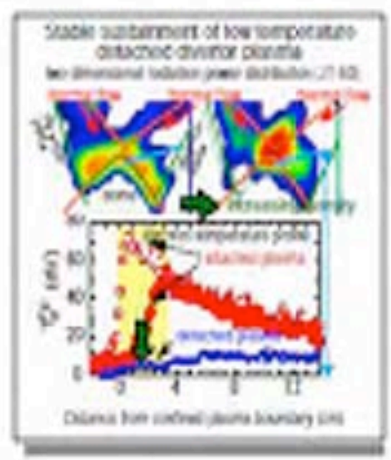












ITER – a bold and unprecedented international scientific endeavor

- **Mission: To demonstrate the scientific and technical feasibility of fusion power**
  - Culmination of 50 years of international research effort on plasma physics and fusion
  - Explores new and complex science of burning plasmas
  - Integrates challenging enabling technologies

- **A 35 year collaboration among seven ITER Members, representing more than half of the world population**
  - Joint design, construction, operation, and decommissioning
  - Common integrated research program

- **U.S. Participation - a Presidential Initiative of January 30, 2003**
  - Supported by technical accomplishments, and by community and NRC reviews
  - Highest priority in the Office of Fusion Energy Sciences programs

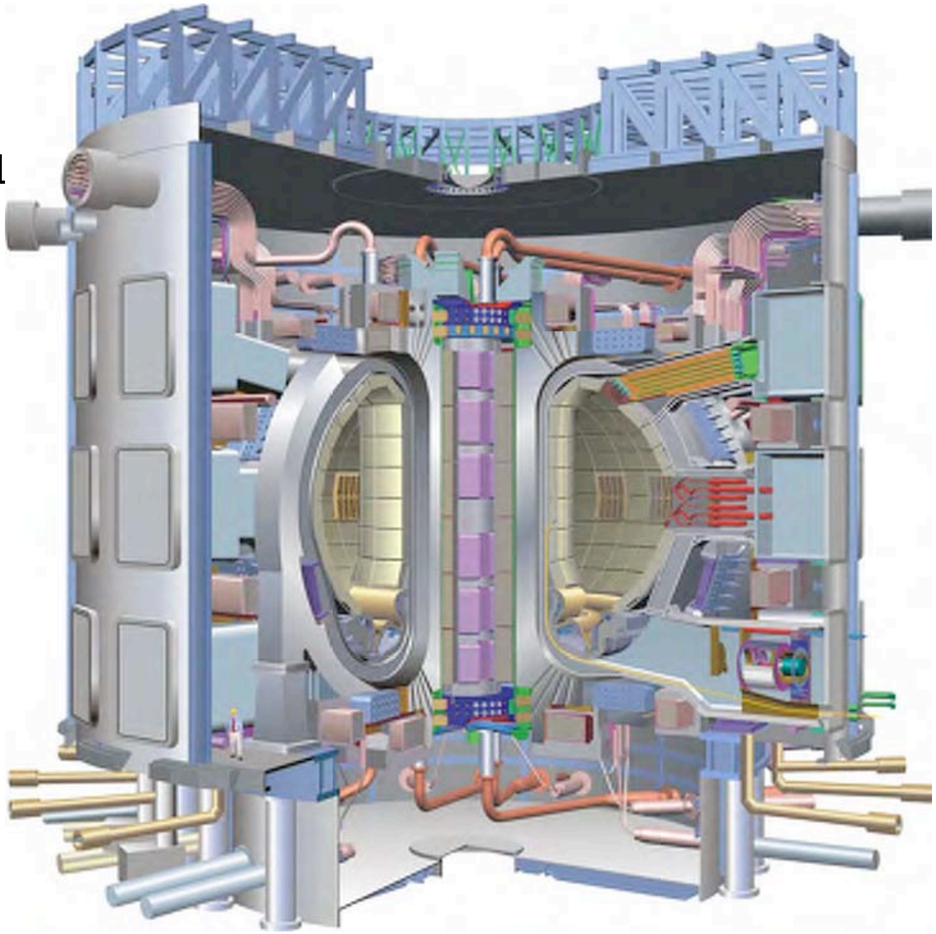
- **Current ITER focus on design and construction**
  - Extensive ongoing scientific support of design, and preparations for operations

ITER will demonstrate scientific and technological feasibility of fusion

- **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 issues**



ITER Agreement Ratification Process Complete

- November 21, 2006 – the ITER Agreement was signed by the seven Members.
- October 24, 2007 – the ITER Agreement entered into force and the ITER Organization became a legal entity.
- November 27-28, 2007 - with completion of the above milestones, the first official ITER Council Meeting was held.

IAEA
Atoms for Peace: The First Half Century
1957-2007

الوكالة الدولية للطاقة الذرية
国际原子能机构
International Atomic Energy Agency
Agence internationale de l'énergie atomique
Международное агентство по атомной энергии
Organismo Internacional de Energía Atómica

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The Secretariat of the International Atomic Energy Agency presents its compliments to the Permanent Mission of the United States of America and has the honour to acknowledge the deposit, on 8 June 2007, of the instrument of acceptance, by the United States of America, of the Agreement on the Establishment of the ITER International Fusion Energy Organization for the Joint Implementation of the ITER Project.

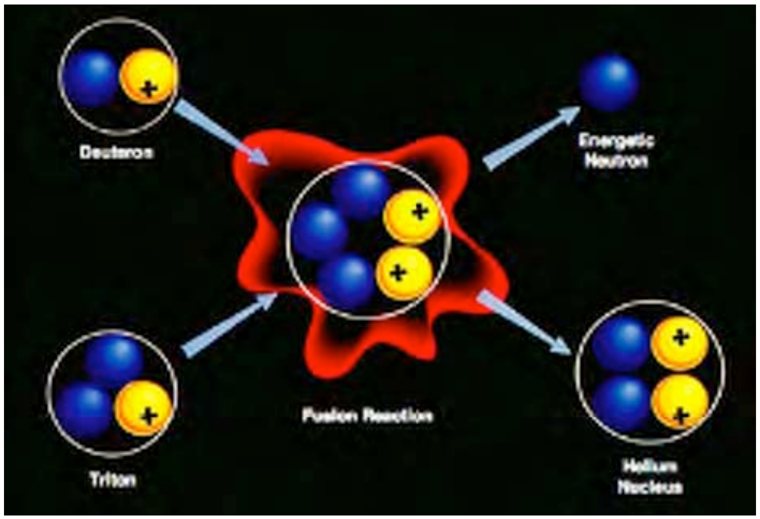
The deposit of the instrument of acceptance by the United States of America will be duly notified in accordance with the terms of the above Agreement.

The Agreement on the Establishment of the ITER International Fusion Energy Organization for the Joint Implementation of the ITER Project, pursuant to Article 22, "shall enter into force thirty days after the deposit of instruments of ratification, acceptance or approval of this Agreement by the People's Republic of China, EURATOM, the Republic of India, Japan, the Republic of Korea, the Russian Federation and the United States of America." Accordingly, the Agreement will become effective for the United States of America on the date of its entry into force.

The Secretariat of the International Atomic Energy Agency avails itself of this opportunity to renew to the Permanent Mission of the United States of America the assurances of its highest consideration.

11 June 2007

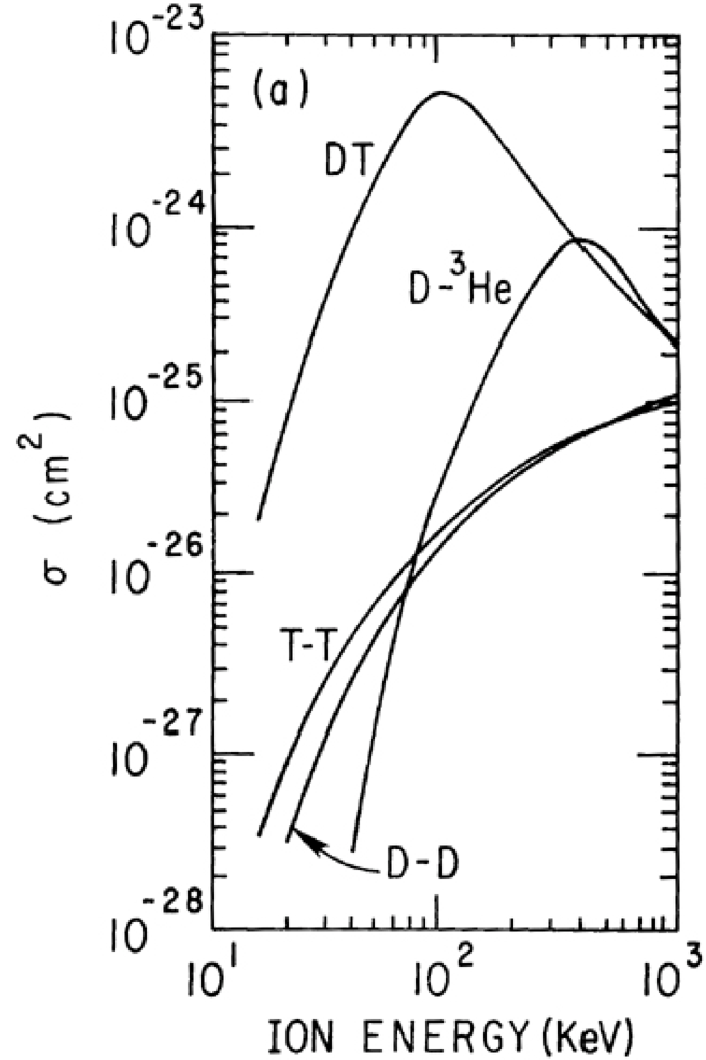
D-T fusion



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

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

Energy/Fusion: ε_f = 17.6 MeV



Nuclear cross sections

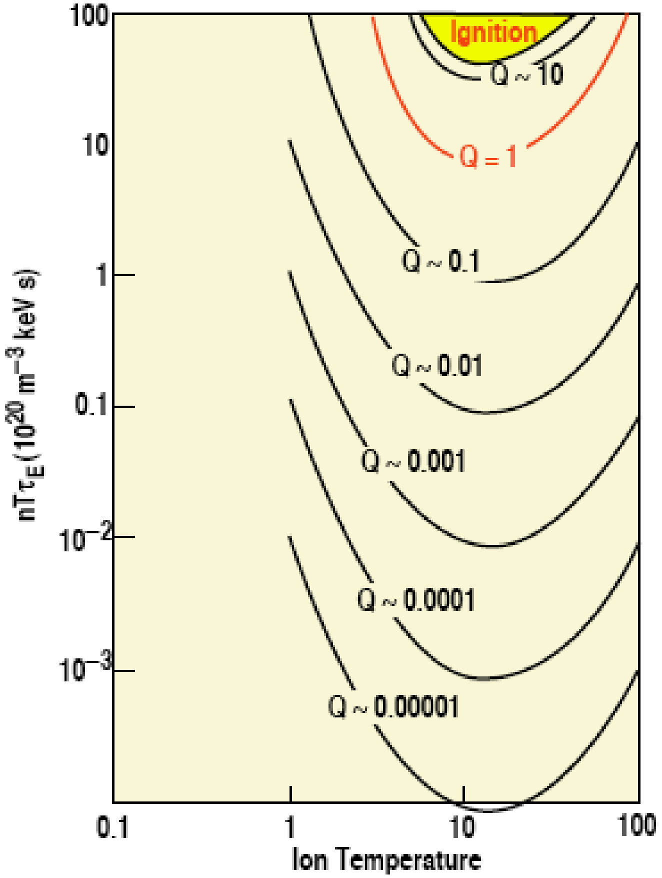
Definition of “burning”

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

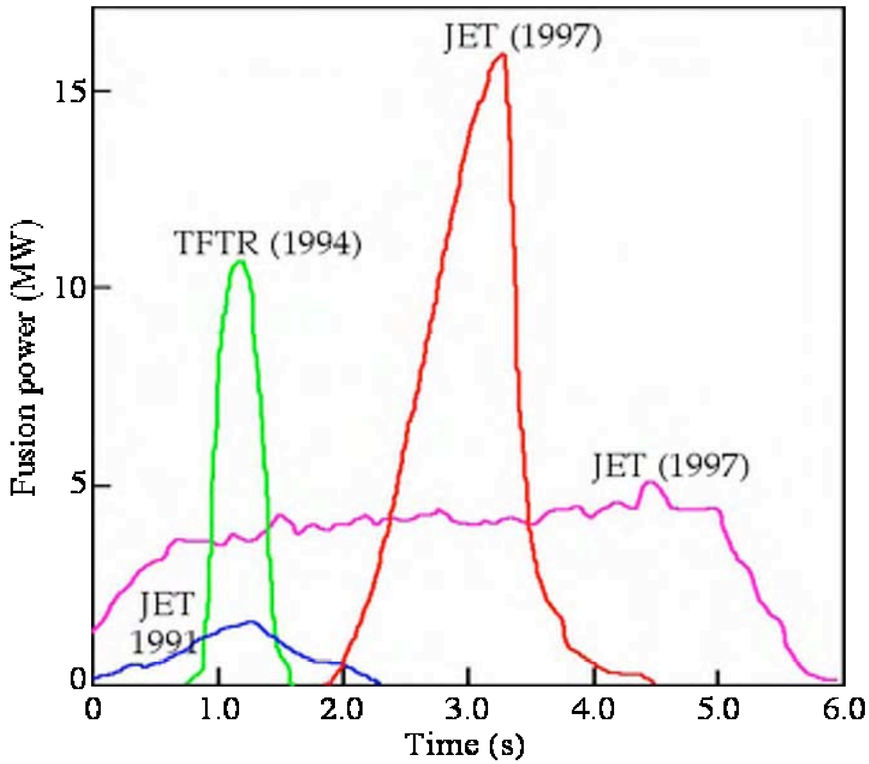
Define fusion energy gain, $Q \equiv \frac{P_{fusion}}{P_{heat}} = \frac{5\,P_\alpha}{P_{heat}}$

Define α-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)	$f_\alpha = 100\%$



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)

New burning plasma challenges

Uniquely BP issues

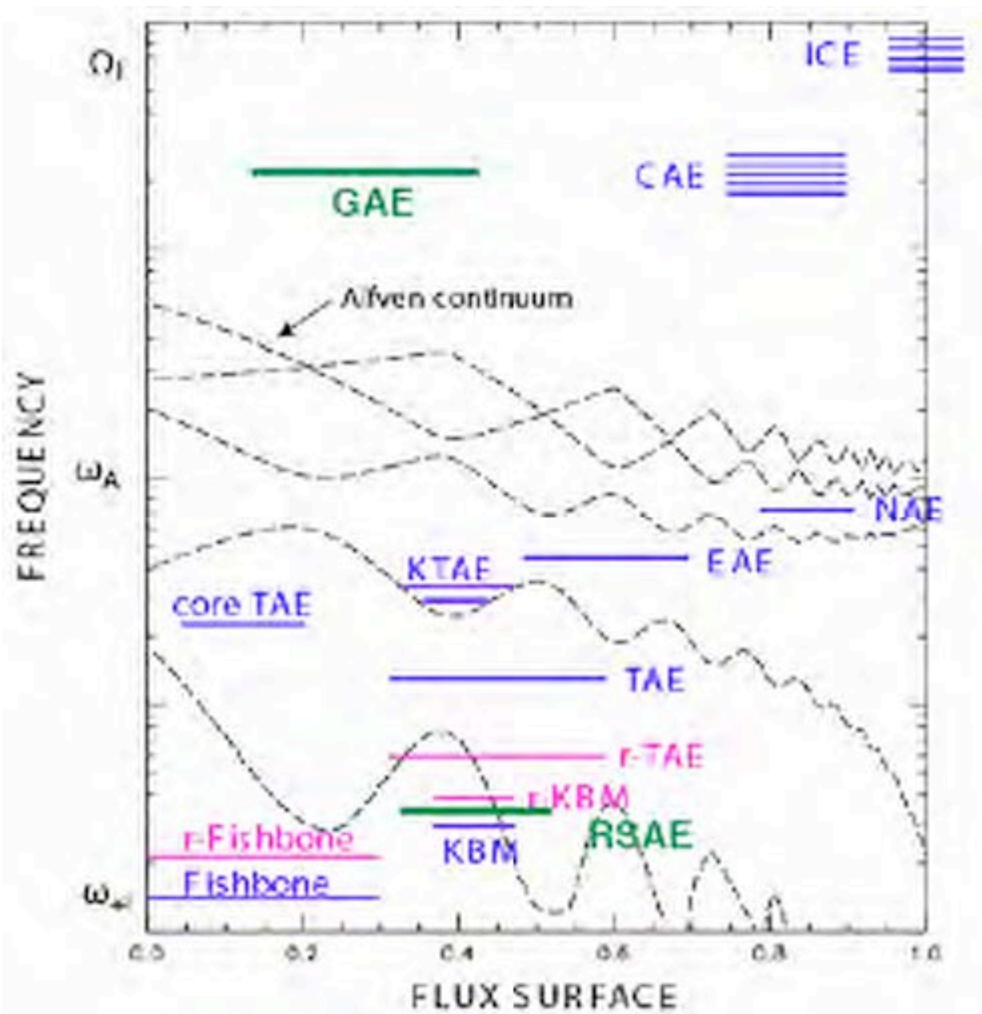
- Alpha particles
  - Large population of supra-thermal ions
- Self-heating
  - “Autonomous” system (self-organized profiles)
  - Thermal stability

Reactor-scale BP issues

- Scaling with size and B field
- High performance
  - Operational limits, heat flux on PFCs
- Nuclear environment
  - Radiation, tritium retention, dust, tritium breeding

Integration of nonlinearly coupled elements

Zoology of Possible alpha-instabilities



Heidbrink, Phys. Pl. 9 (2002) 2113

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

  $v_\alpha \geq v_A$

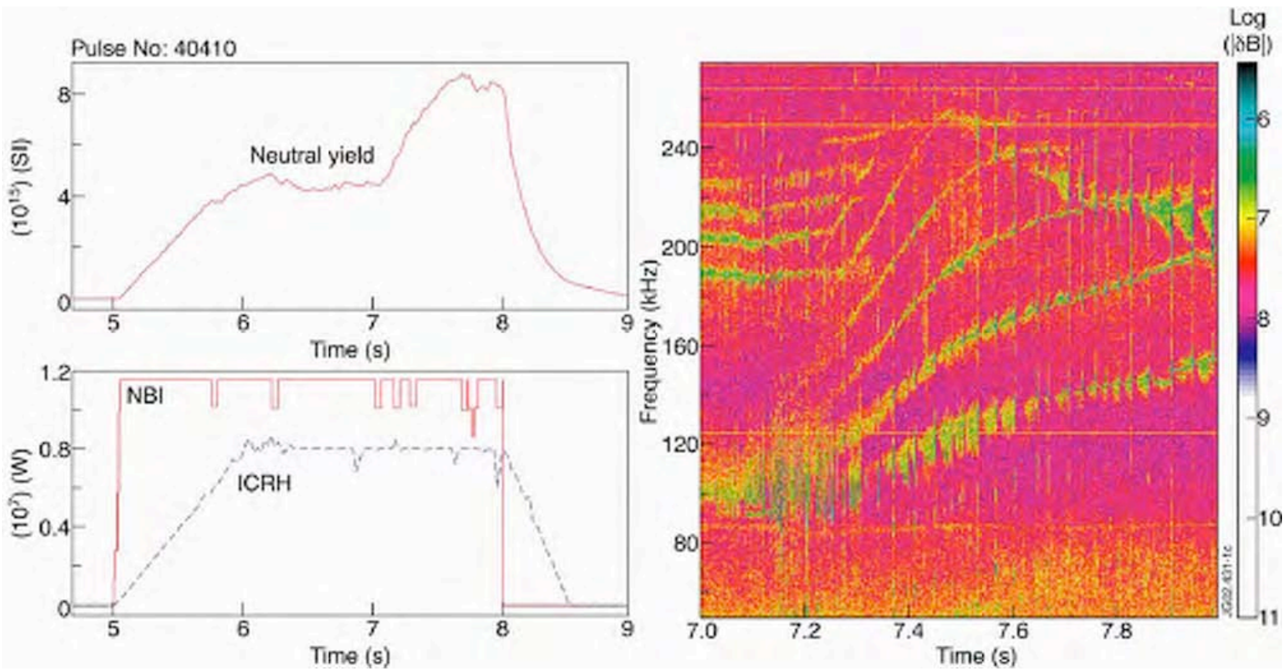
- **One of these instabilities is the Toroidal Alfvén Eigenmode (TAE)**
  - Analogy to band-gap theory in solid-state crystals (Mathieu equation, Bloch functions): "fiberglass wave guide"

- **Zoology of *AE instabilities:**
  - Ellipticity Alfvén Eigenmode (EAE)
  - Triangularity Alfvén Eigenmode (NAE)
  - Reversed-Shear Alfvén Eigenmode (RSAE), "Cascade"
  - Global Alfvén Eigenmode (GAE)
  - Compressional Alfvén Eigenmode (CAE)
  - etc.

- **Could cause anomalous loss of α's**
  - Reduce self-heating; increase wall thermal loading

“Grand” cascades

- 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 a diagnostic to monitor q_{min}
  - Can create ITB by application of main heating shortly before a Grand Cascade is known to occur



Autonomous plasma state

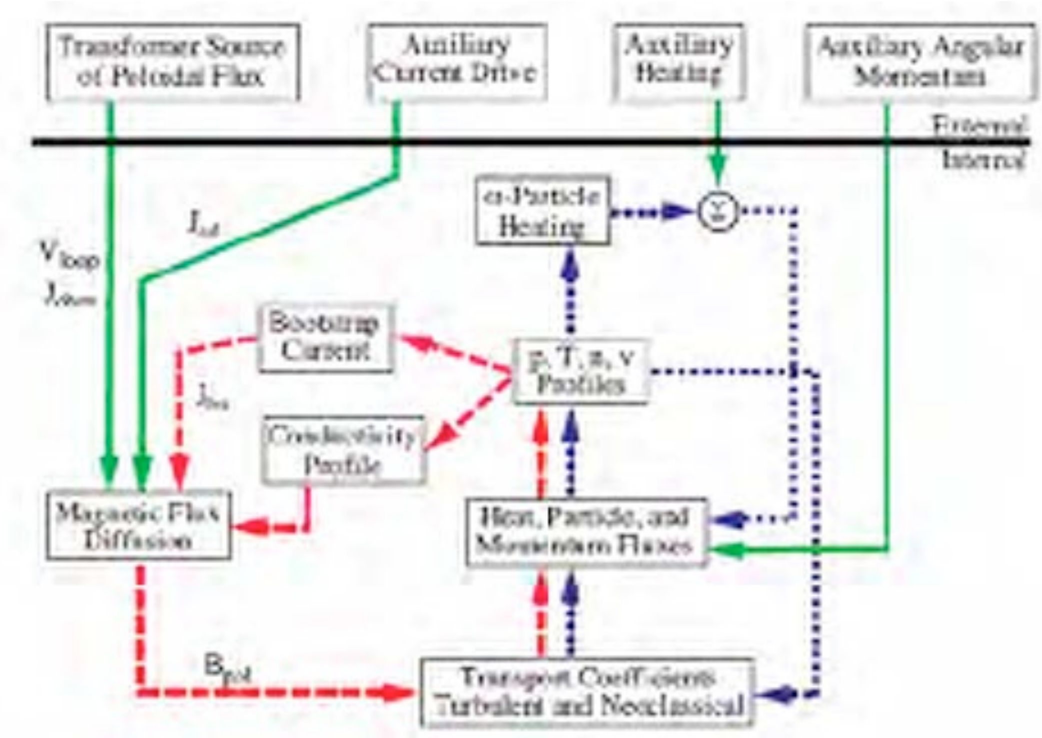
- **Self-organized profiles**
  - With dominant self-heating from fusion reactions, a burning plasma determines its own profiles (current, pressure, impurities)

- **Less profile control**
  - Hence, flexibility in present-day experiments to control current, pressure, and rotation profiles by means of external RF power and neutral beams is dramatically reduced in burning plasmas

Nonlinear coupled system

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

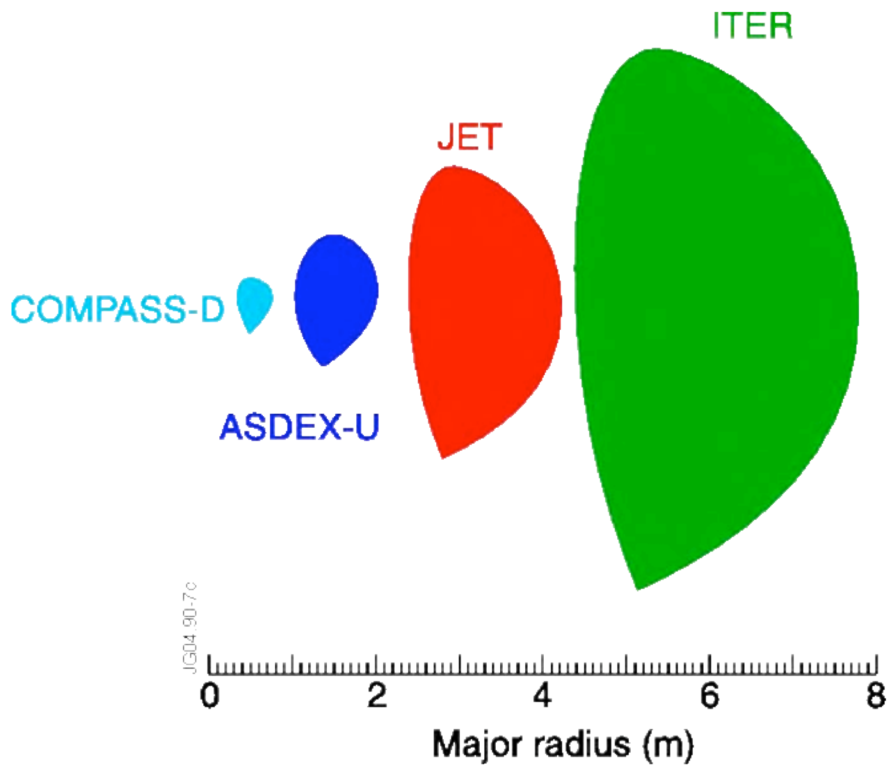
- **Integrated scenarios**
  - Strong nonlinear coupling of current profile, pressure gradient, BS current, and fusion power, as they evolve in time
  - Successful operation of burning plasma requires not just optimization of individual parameters
  - Must demonstrate that all essential requirements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



Size scaling

- **Scaling**
  - Since burning plasmas for energy production will have significantly larger volume than present experiments, size scaling also becomes important for confinement

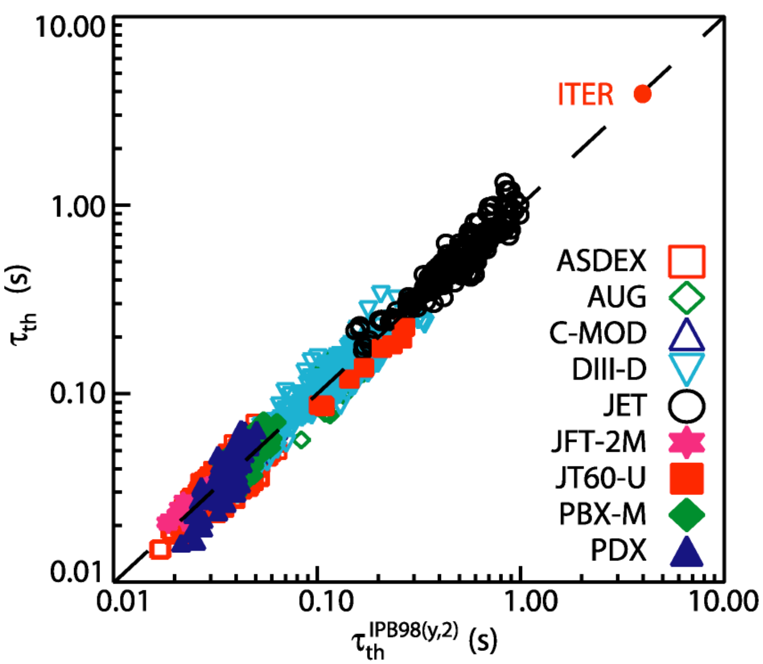
- **Issues for $\rho^* = \rho_L/a << 1$**
  - ITB formation
  - Hybrid regimes
  - Confinement scaling
  - NTM threshold beta
  - Alfvén eigenmode spectrum



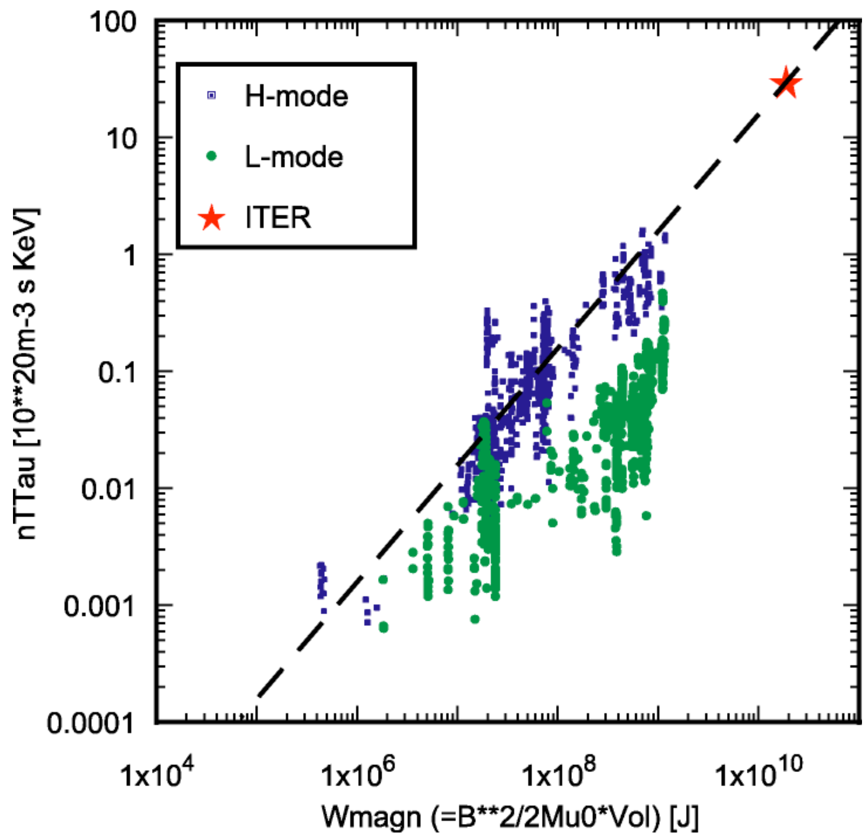
Cross sections of present EU D-shape tokamaks compared to the cross section of ITER

Determining the size of a BP

- **Large size determined by:**
  - Need for sufficient confinement
  - Radiation shielding of SC magnets



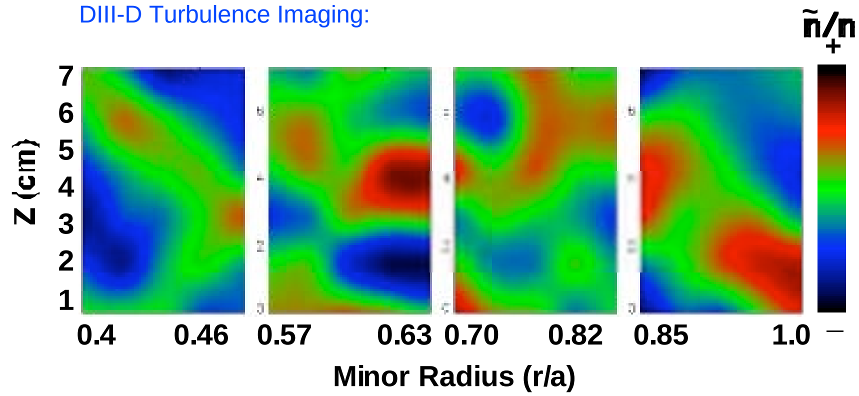
Scaling prediction for energy confinement time τ_{th}

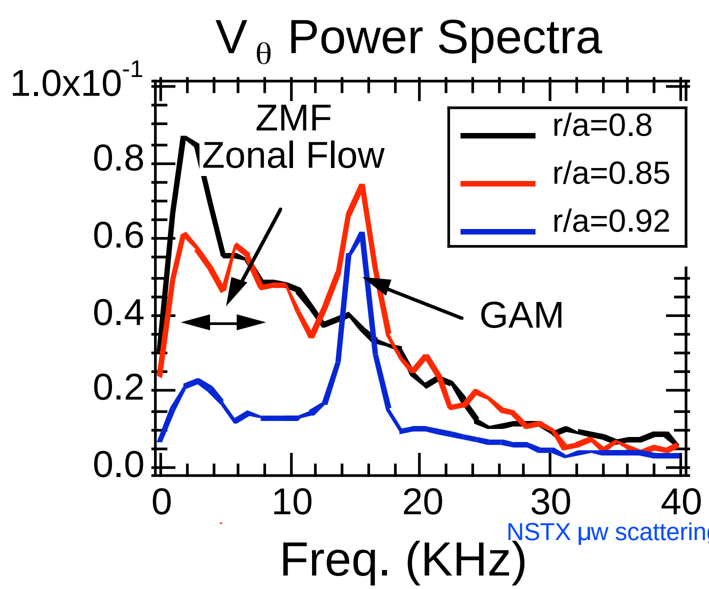


Confinement scaling for fusion triple product

Multi-scale Nonlinear Turbulence Coupling and And Shear Flows Regulate Confinement Properties

DIII-D Turbulence Imaging:

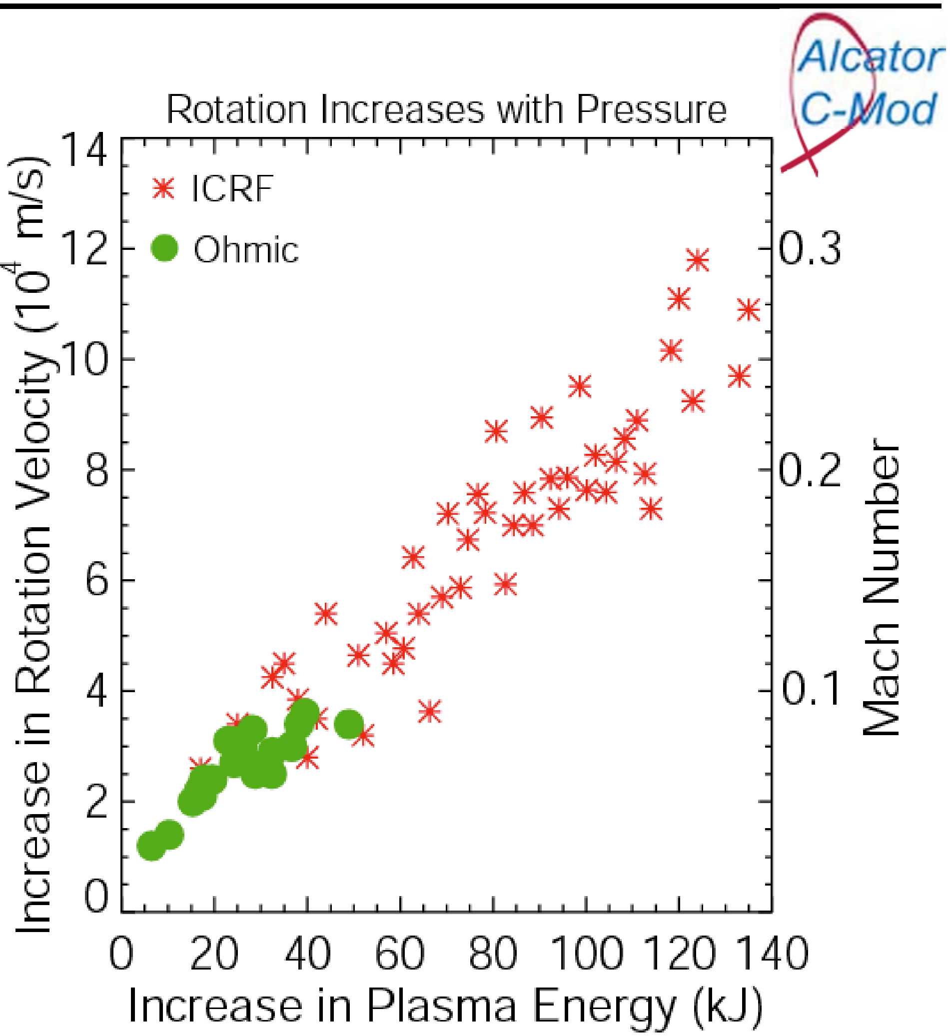




NSTX µw scattering

"Spontaneous" Plasma Rotation with No External Momentum Input?

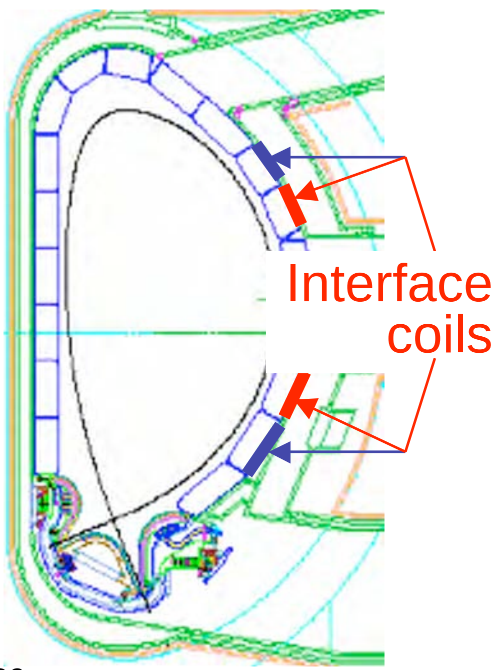
- •Spontaneous/intrinsic toroidal rotation and enhanced confinement regimes
  - •Rotation increases with stored energy or pressure.
- •For ITER, possibly high enough for resistive wall mode suppression.
- •At present, there is no quantitative theoretical explanation.
  - •Needs pre-ITER resolution
  - •Connections to momentum transport and self-generated rotation in turbulent astrophysical and geophysical systems

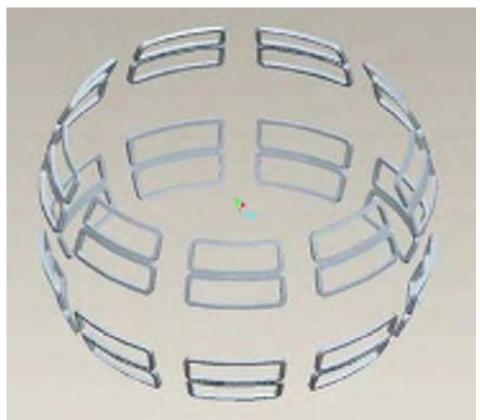


Blanket-vessel wall “interface” coils

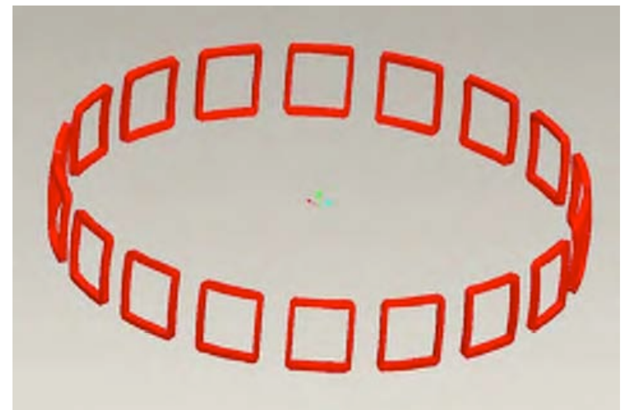
USBPO

- **Coils to be attached to the inner surface of inner shell, “under” blanket modules 12, 13, 16, and 17**
  - Coils would run ~30 degrees toroidally and be about one blanket module in poloidal extent
  - Max continuous coil current ~55 kA-turns



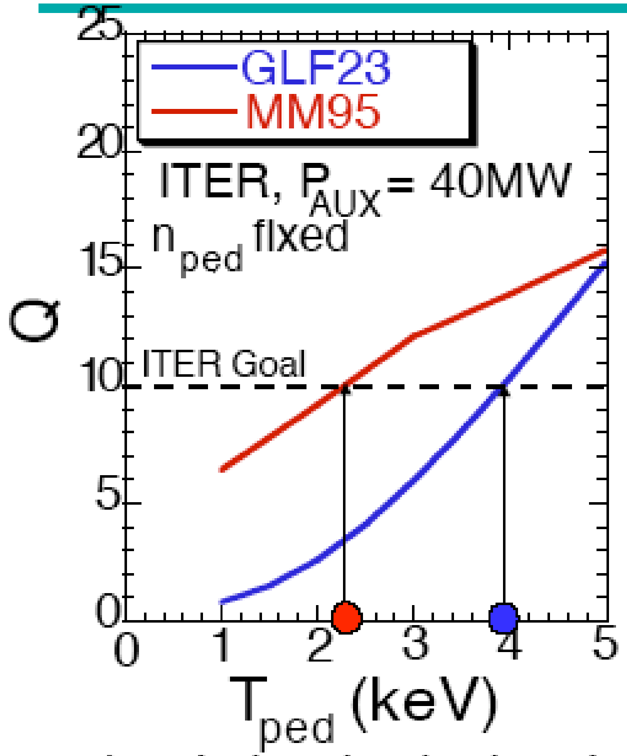


from R. Hawryluk

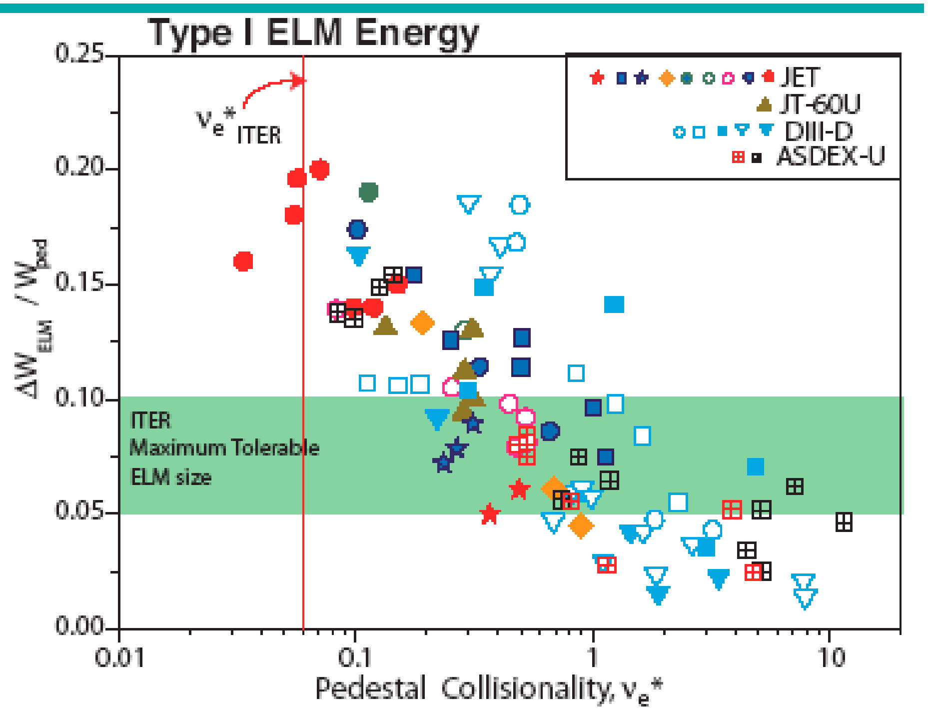


- **“Picture frame” ELM coils are an alternative to 36-coil blanket/wall array**
  - 18 locations
  - Required cross section reduced due to radial position and larger coil size ~ 150 kA-turns

The Pedestal Requirement: High Pressure with Small ELMs



J. Kinsey (Fusion Sci. and Tech 2003)



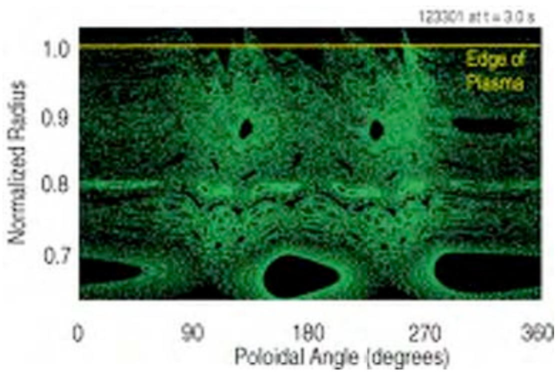
A. Loarte (PSI 2002)

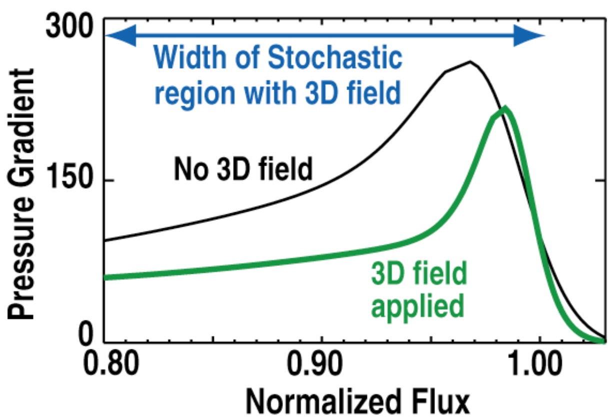
- Burning plasma performance dependence on pedestal pressure varies with stiffness of the core transport model
- Low collisionality pedestals in current devices usually result in large ELMs that are incompatible with a burning plasma first wall

Controlling Instability @ Plasma Edge

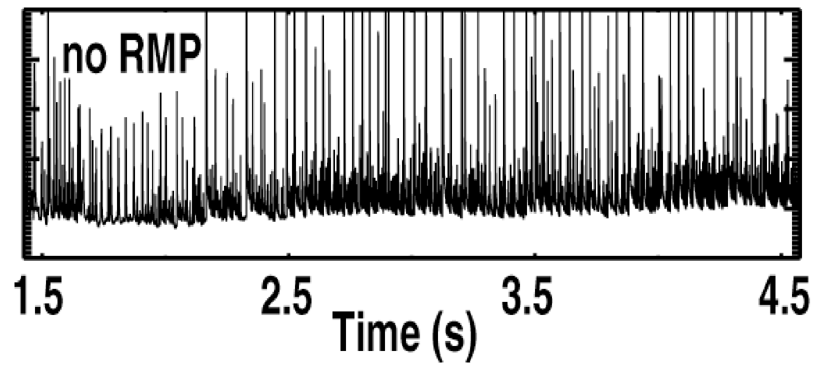
Critical Edge Instability Controlled by Purposefully Degrading Magnetic Surfaces

Applying 3D fields produces Stochastic region leading to stabilization of edge instabilities

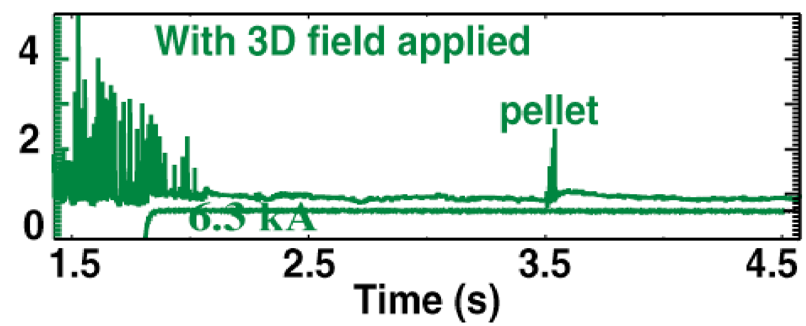




Unstable with high edge pressure gradients: sharp spikes in heat loss



Stable with relaxed edge pressure gradients

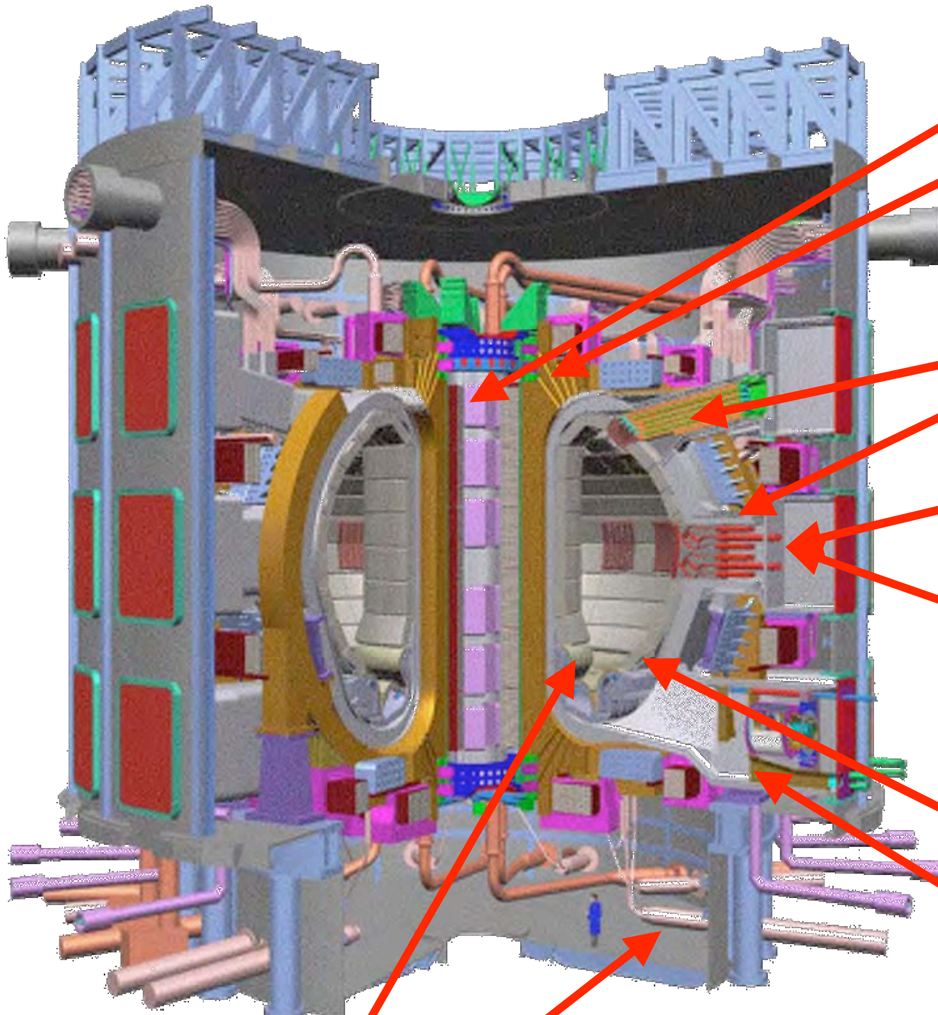


US fusion science community is actively preparing for a "burning plasma world"

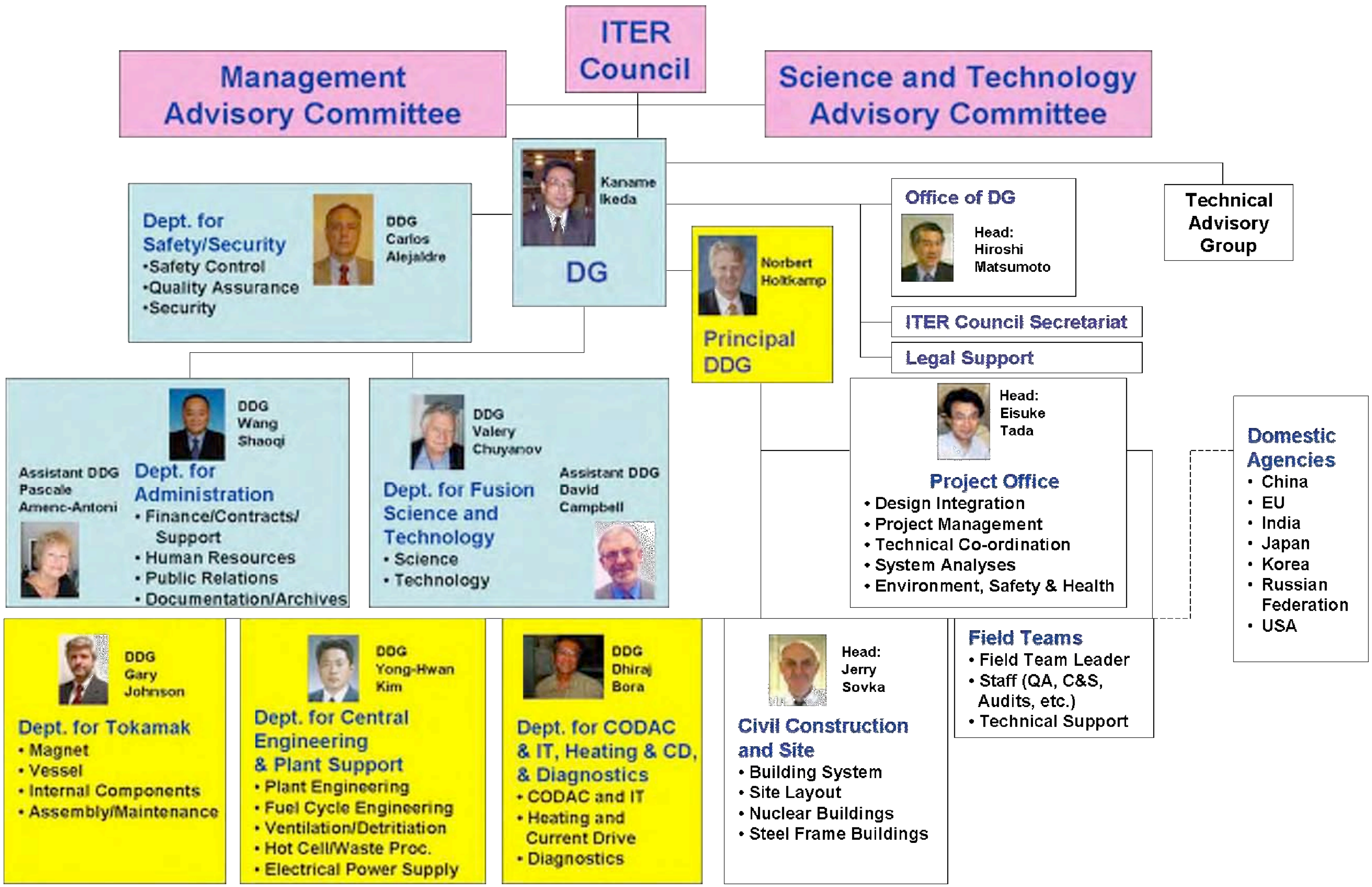
USBPO

- **US Burning Plasma Organization created to organize community to prepare for, carry out, and benefit from burning plasma research**
  - Broad participation: 289 registered members from 49 institutions representing a cross-section of the community (magnetic confinement)
- **Strategic planning**
  - EPAct Report (2006): USBPO response to Energy Policy Act of 2005
    - Follow-on panel (led by E. Marmar): Long-Term Program Plan for USBPO
      - Will need to take into account the ITER research plan, which is being developed
  - Other planning exercises
    - Plasma 2010 (led by S. Cowley and J. Peoples): NAS Decadal Survey of Plasma Science and Engineering (2007)
    - FESAC panel (led by M. Greenwald): Towards a Long-Range Strategic Plan for MFE (2007)
- **US community is a major participant in the ITER Design Review**
  - Provided 21% of the world-wide effort
  - Other U.S. research (not specific to the Design Review) continues to build the scientific basis needed for successful burning plasma experiment

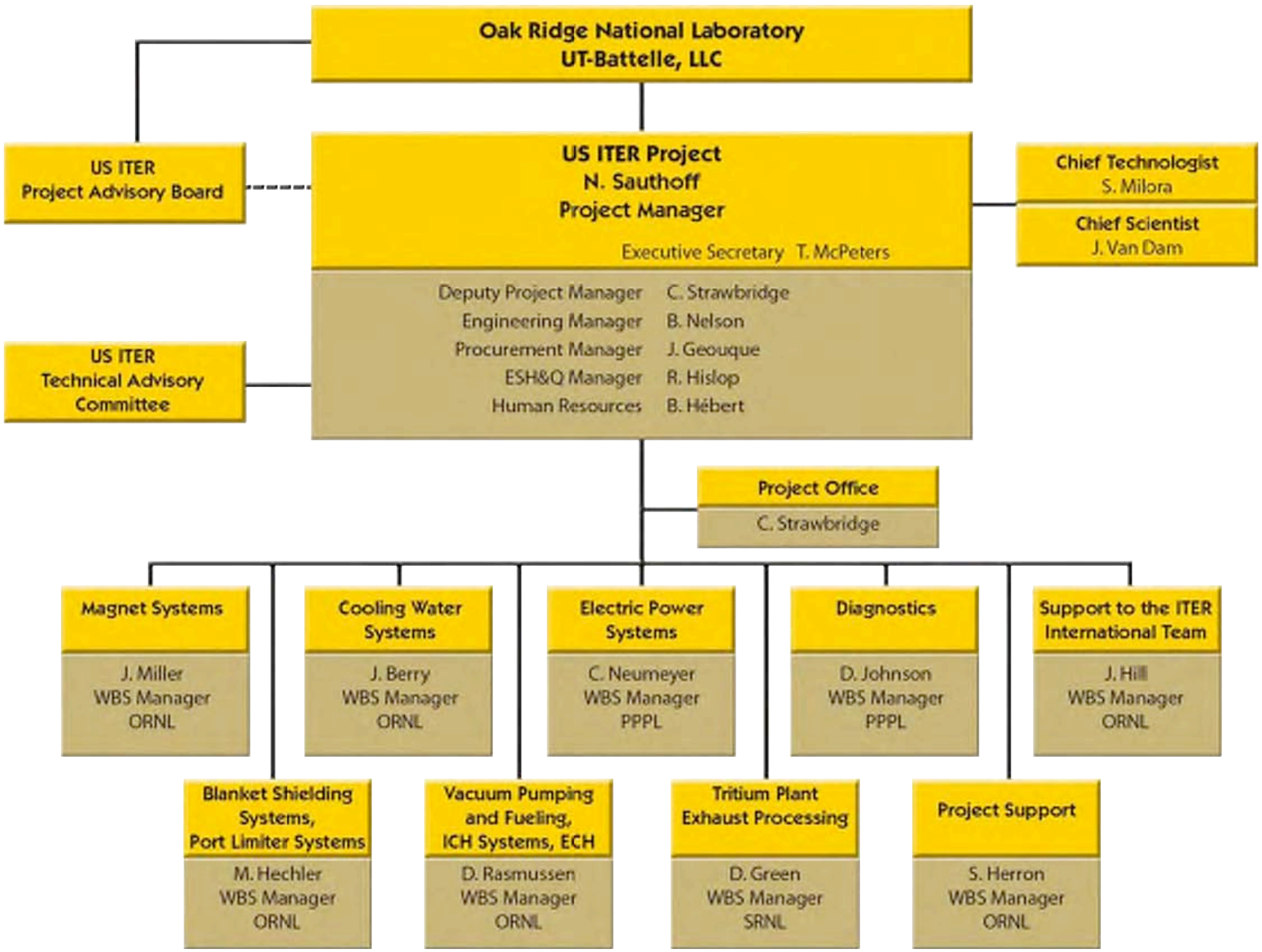
US ITER In-kind Hardware Contributions



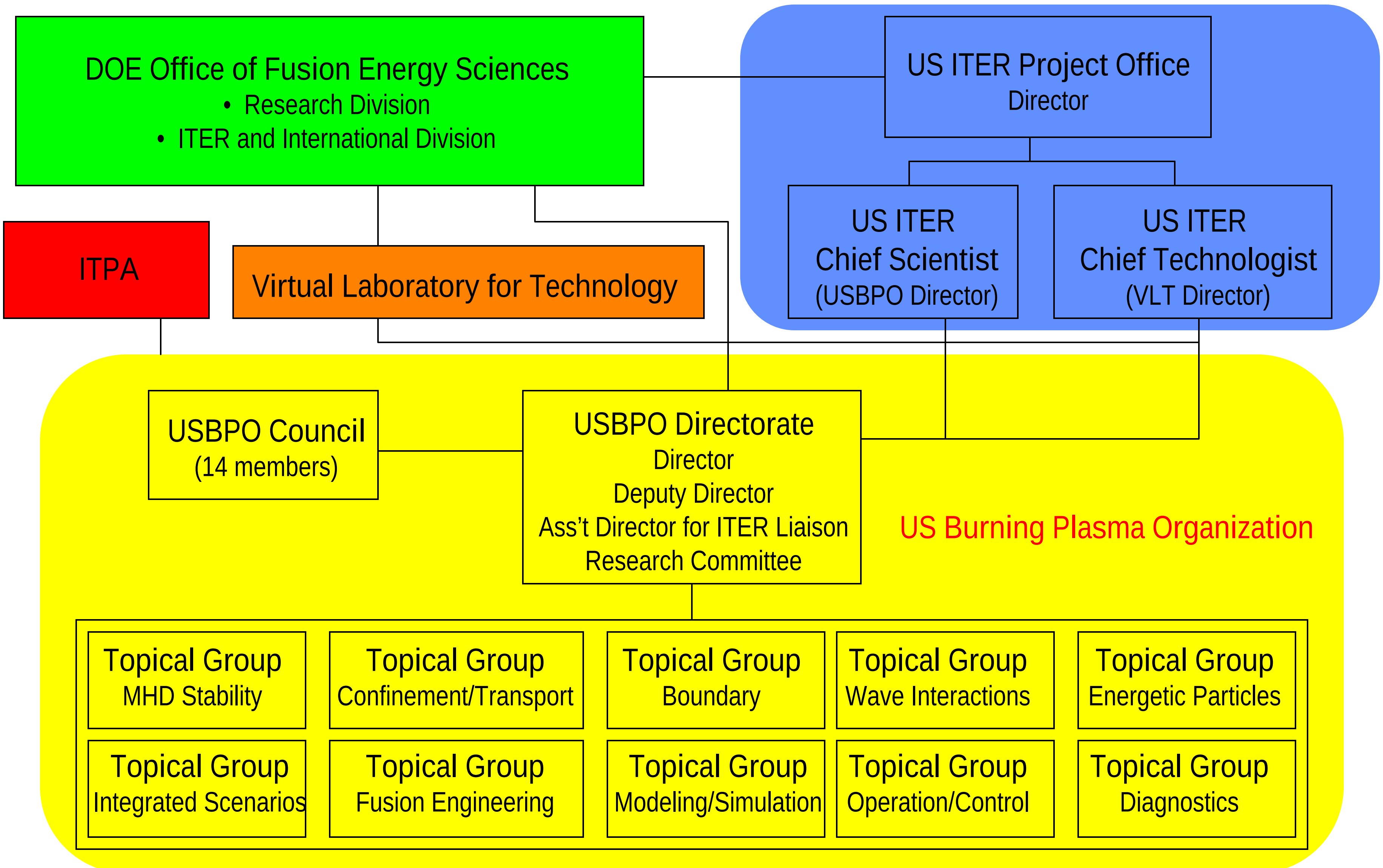
Management Structure of the ITER Organization



USIPO Management Team



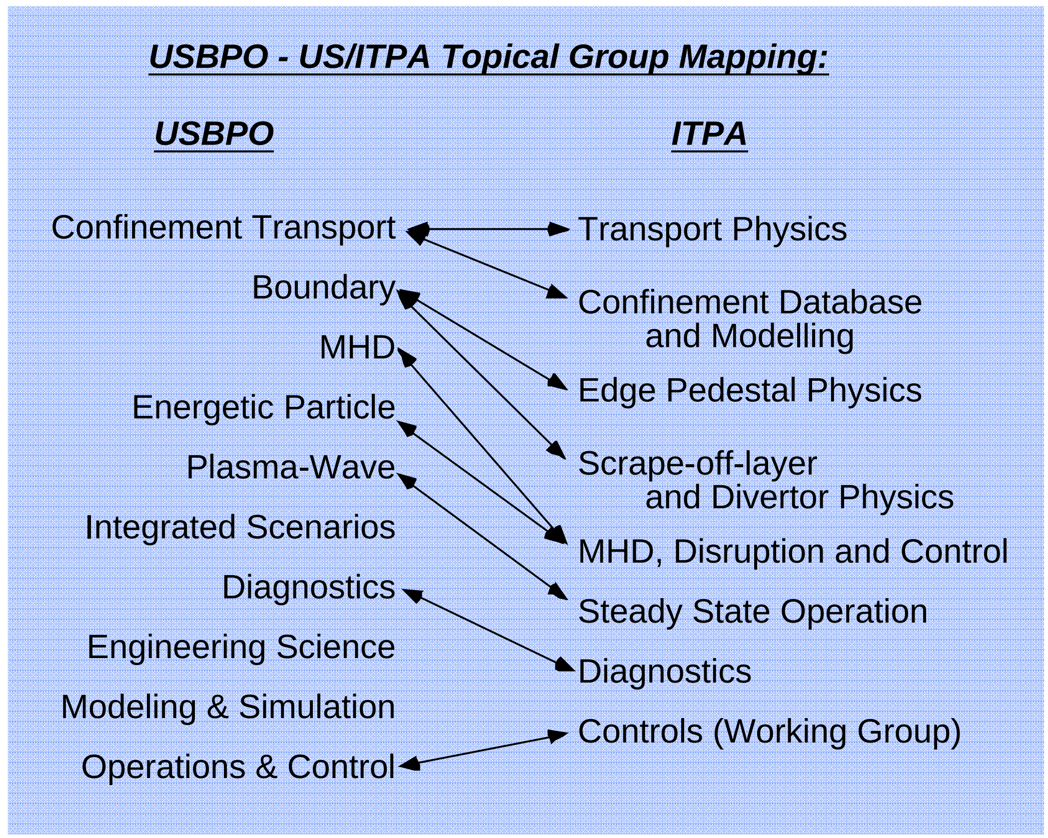
Coordinating the US burning plasma effort



National USBPO Activity Integrated with International Tokamak Physics Activity

- **Plan: USBPO to facilitate ITPA activities in U.S.**
  - Topical Groups interface U.S. community to ITPA activities
  - Provide participants to ITPA activities
  - ITPA participants bring issues and info
  - back to community via USBPO
  - Engages broader US community
  - Communicate ITPA activities in U.S.

- **Expands access to ITER:**
  - USIPO as Domestic Agency
  - Communication with ITER Team
  - ITPA and Bilateral Agreements



ITER operational procedures to be defined

USBPO

- **During the Operational Phase:**
  - US scientists would work on site
  - Expect there would be run teams (integrated internationally) and run campaigns
- **US scientists are familiar with proposal-based process for selecting experimental proposals (which should incorporate theory and modeling)**
  - Ideas Forums held annually for each major U.S. facility
- **JET, which is operated as an international project within Europe, might provide a model for how ITER could be run and operated**
  - Would still require a strong central physics team on site, since a tokamak is not a modular "user facility" in the same way that an accelerator is
  - Would be best to organize experiments not along national lines
- **Other models:**
  - Large Hadron Collider, ATLAS detector, Compact Muon Solenoid detector, Atacama Large Millimeter Array (ALMA), International Space Station, …

Summary

- **The U.S. Fusion Energy Sciences program has been extensively engaged with the international community for decades**
  - Bilateral Agreements, and IEA Implementing Agreements
  - IAEA organizes technical meetings and major bi-annual conference
- **ITER is a major new and unique agreement for international collaboration.**
  - A strong organizing element for international fusion science collaborations
- **Confront new and unique science in the burning plasma regime**
  - Large-scale confinement physics
  - Interactions with fusion-produced alpha particles
  - Non-linear coupling of self-heating with plasma properties
- **U.S. fusion community organizing to make collaborations on ITER an integral part of the broad-based fusion science programs**
  - USIPO, USBPO, VLT, ITPA integration