The Abdus Salam
International Centre for Theoretical Physics

United Nations
Educational, Scientific and
Cultural Organization

IAEA
International Atomic Energy Agency

2155-19

International Workshop on Cutting-Edge Plasma Physics

5 - 16 July 2010

Yearning for Burning:
Plasma Physics and Fusion Energy Science

James W. Van Dam

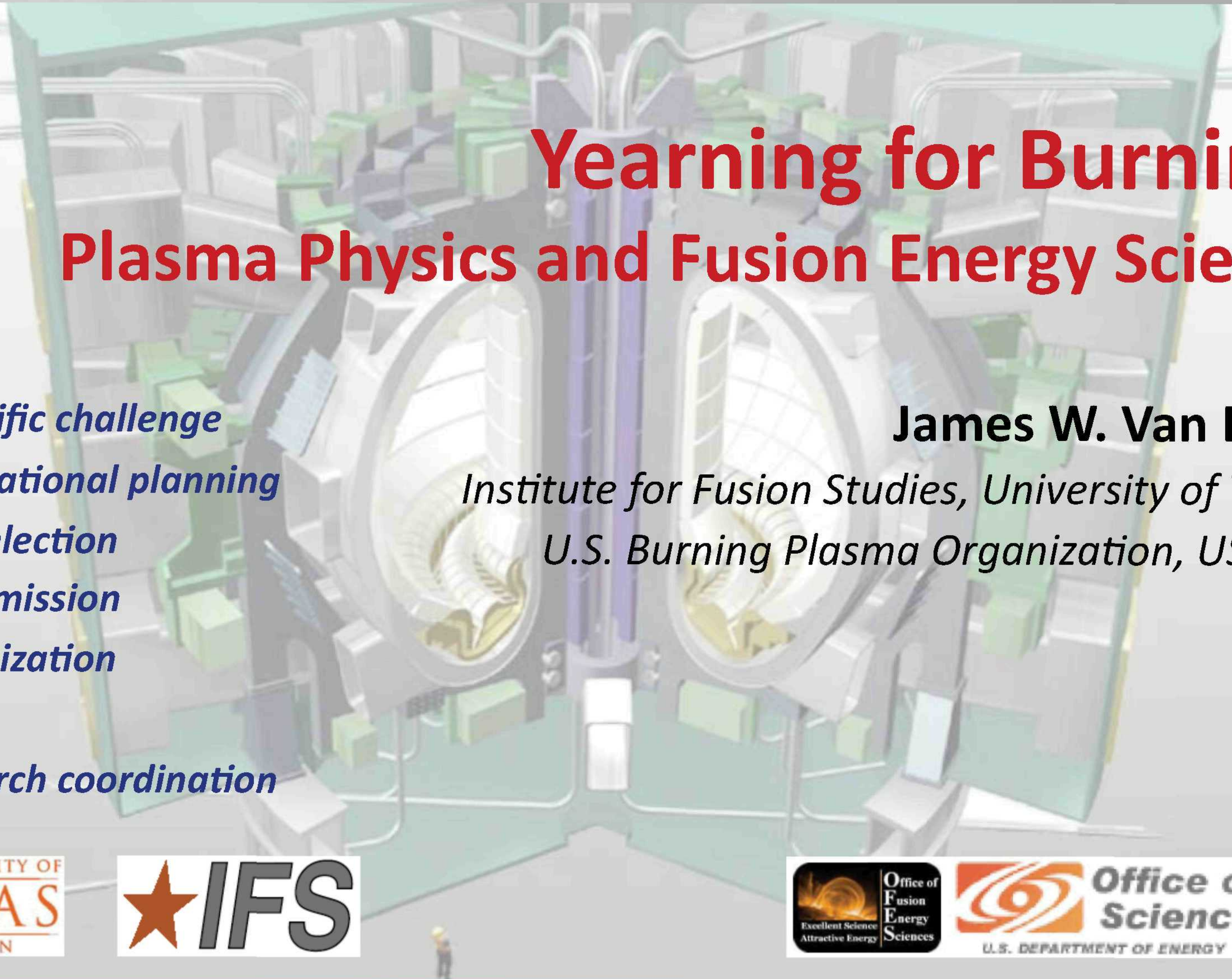
Institute for Fusion Studies
University of Texas
USA

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

Yearning for Burning:
Plasma Physics and Fusion Energy Science



- *Scientific challenge*
- *International planning*
- *Site selection*
- *Clear mission*
- *Organization*
- *Cost*
- *Research coordination*

James W. Van Dam

Institute for Fusion Studies, University of Texas

U.S. Burning Plasma Organization, USDOE

THE UNIVERSITY OF TEXAS AT AUSTIN

IFS

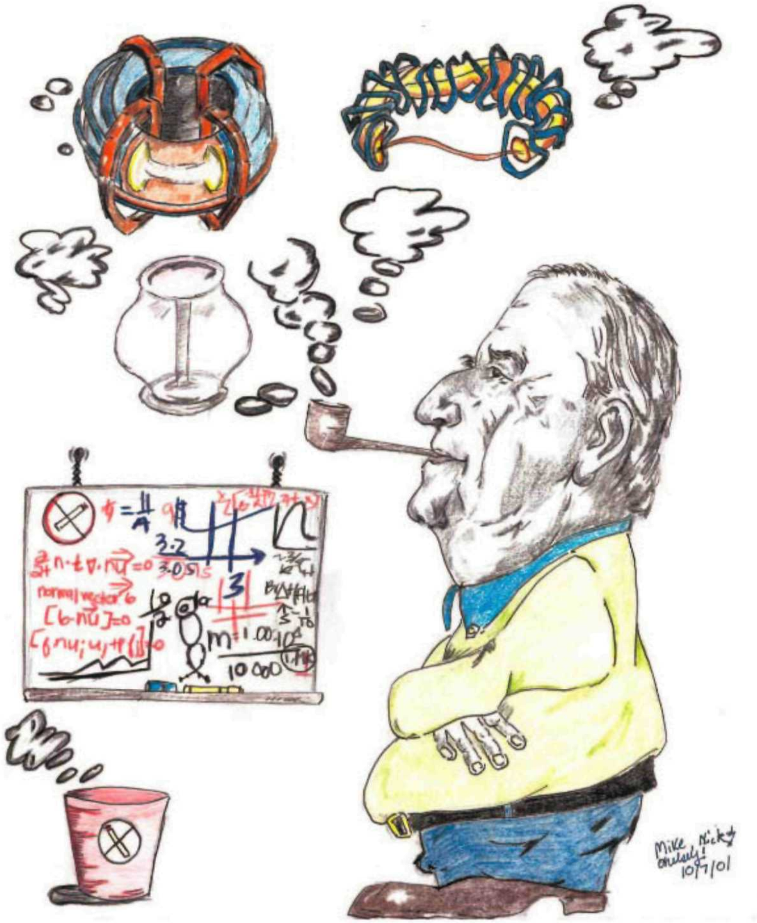
Office of Fusion Energy Sciences — Excellent Science Attractive Energy

Office of Science — U.S. DEPARTMENT OF ENERGY

“Pope” of fusion physics: M. Rosenbluth

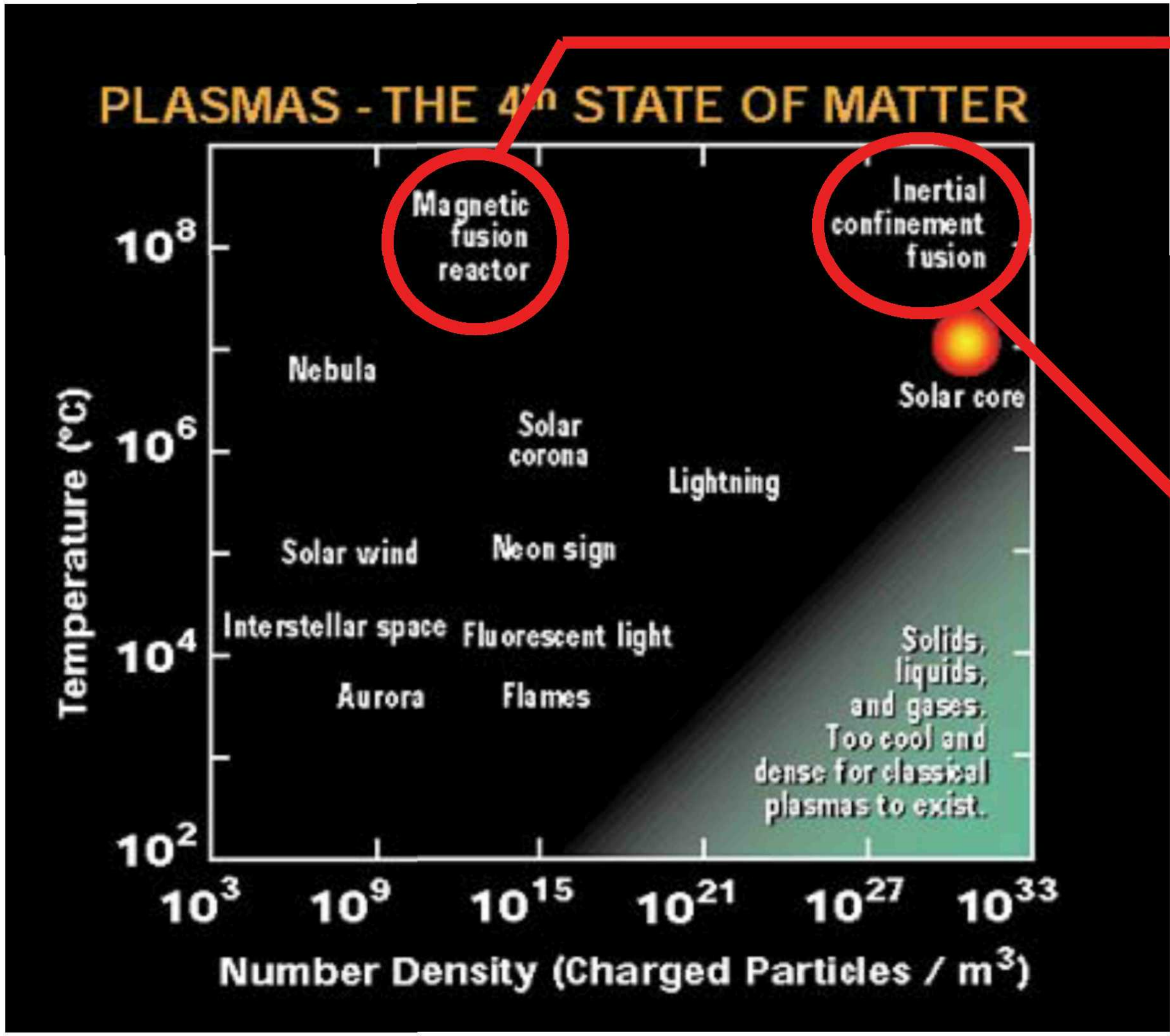
USBPO U.S. BURNING PLASMA ORGANIZATION

- **Early participant at ICTP Trieste**
  - Many original contributions to fusion and plasma physics
  - Before Texas: Professor at Institute for Advanced Study (Princeton)
  - Founder of IFS (U. Texas)
  - After Texas: Chief Scientist, ITER Organization (EDA phase)

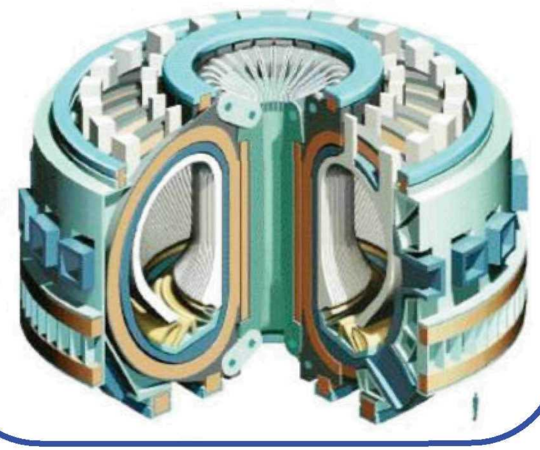


- ***From Yearning to Burning*** **(2000)**
  - “The ‘yearn to burn’ is well motivated. Most of us came into the fusion program with the dream of fusion energy. The dream persists.”

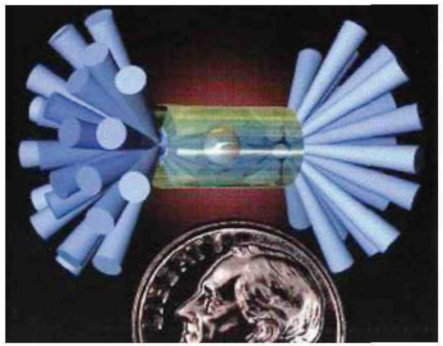
Plasmas are everywhere



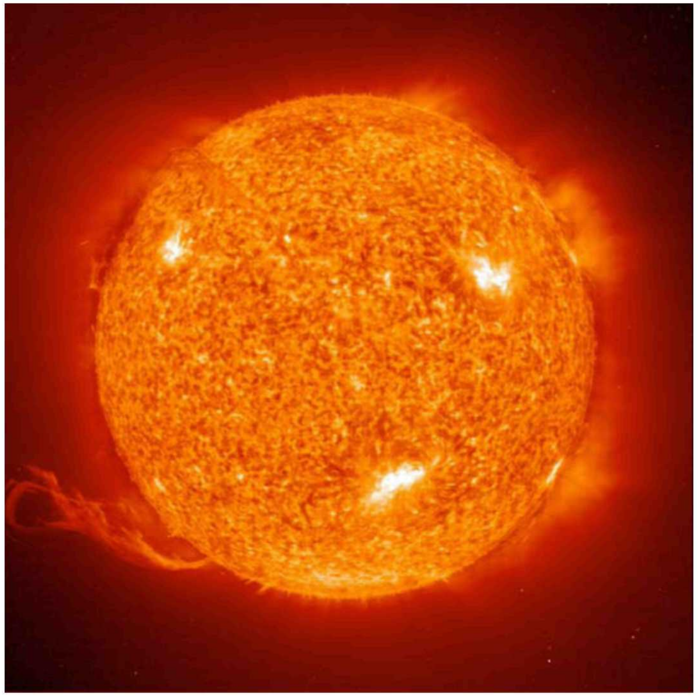
ITER



National Ignition Facility



Wide applicability of plasma physics



Makes use of: mechanics, E&M, stat mech, relativity, math physics, numerical analysis, quantum mech, solid state, AMO, …

- **Low-temperature plasmas**
- **Magnetosphere, solar, & astrophysical plasmas**
- **Geophysical fluid dynamics**
- **Laser interactions**
- **Meta-materials, photonics**
- **High-performance simulation techniques**
- **Nonlinear dynamics**
- **Applied mathematics**
- **Nuclear engineering**
- **Fusion energy sciences**

ITER will demonstrate scientific and technical feasibility of fusion

USBPO
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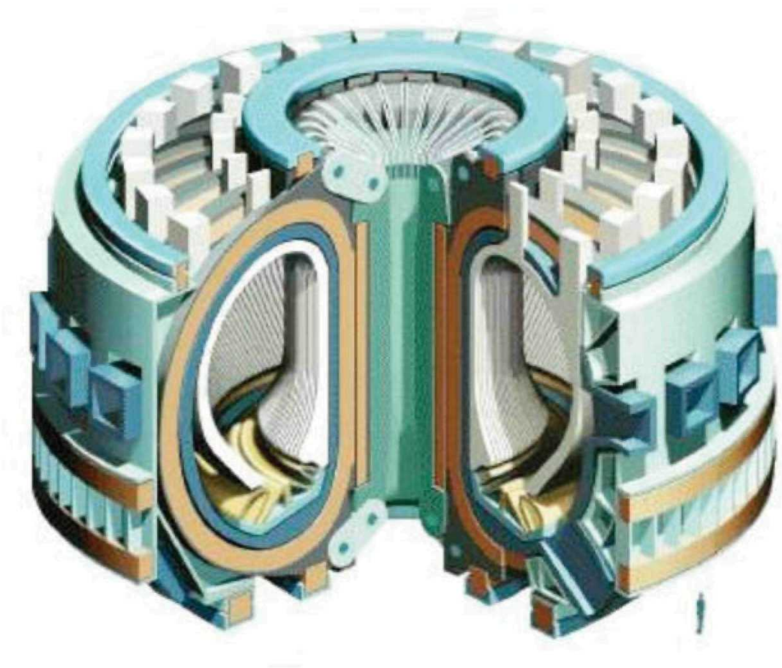
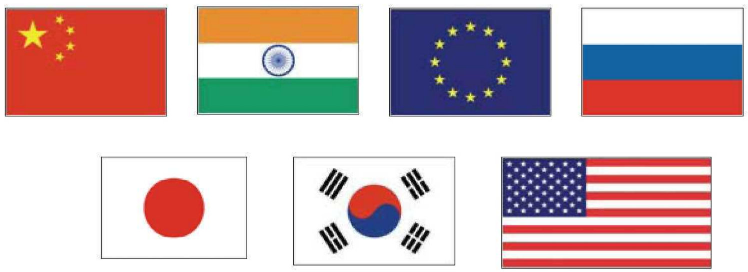
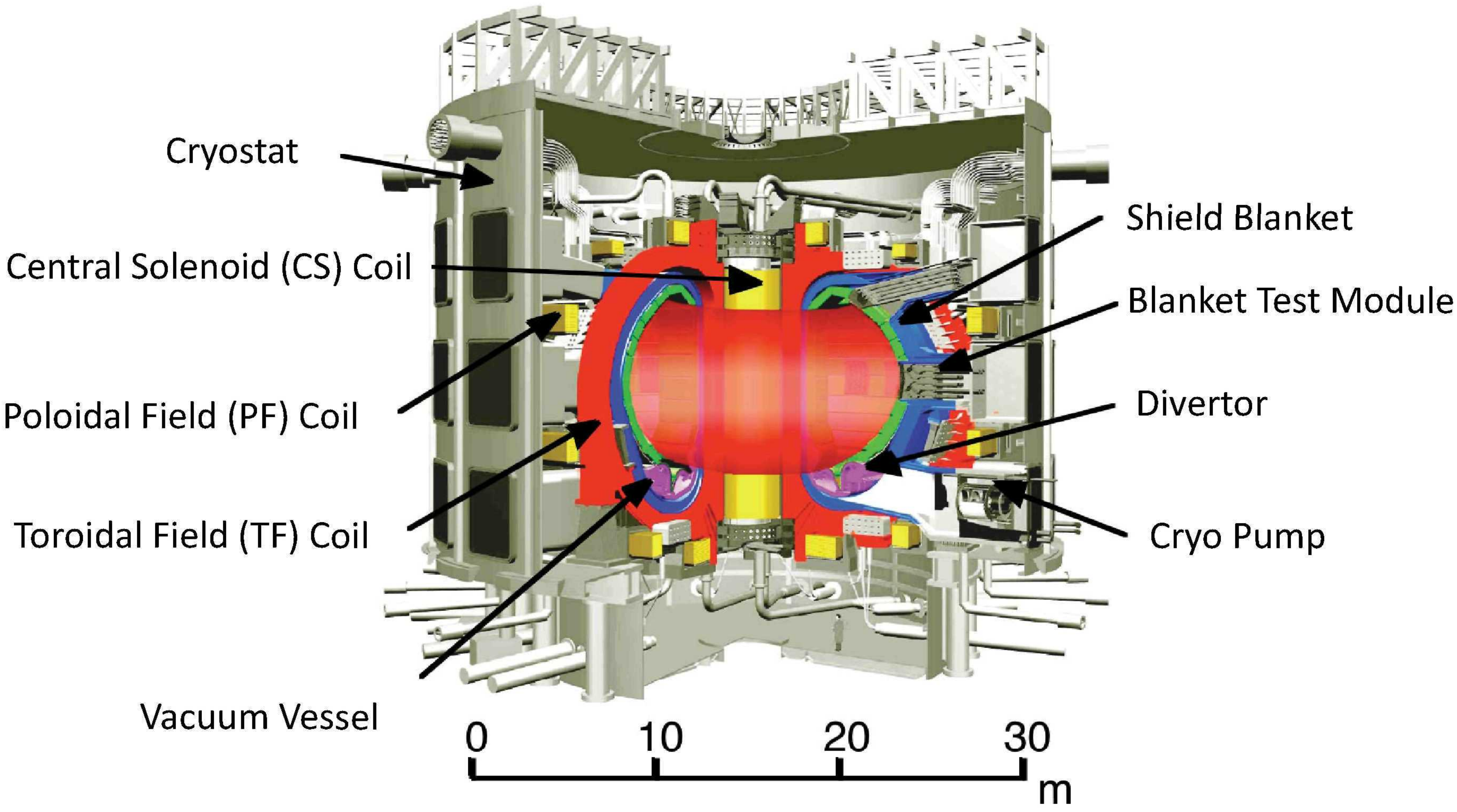




- **ITER ("the way") is essential next step in development of fusion**
  - Today: 10 MW, 1 sec, gain = 1
  - ITER: 500 MW, >400 sec, gain ≥ 10
- **The world's biggest fusion energy research project ("burning plasma")**
  - 15 MA plasma current, 5.3 T magnetic field, 6.2 m major radius, 2.0 m plasma minor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

Cutaway view of ITER



ITER is a "tokamak" = confines doughnut-shape **plasma** with helical magnetic fields

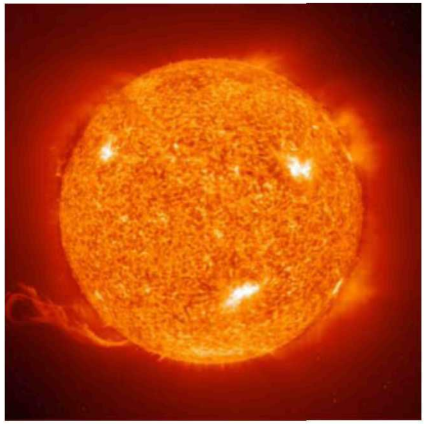
ITER:
A big international project motivated by a big international scientific challenge

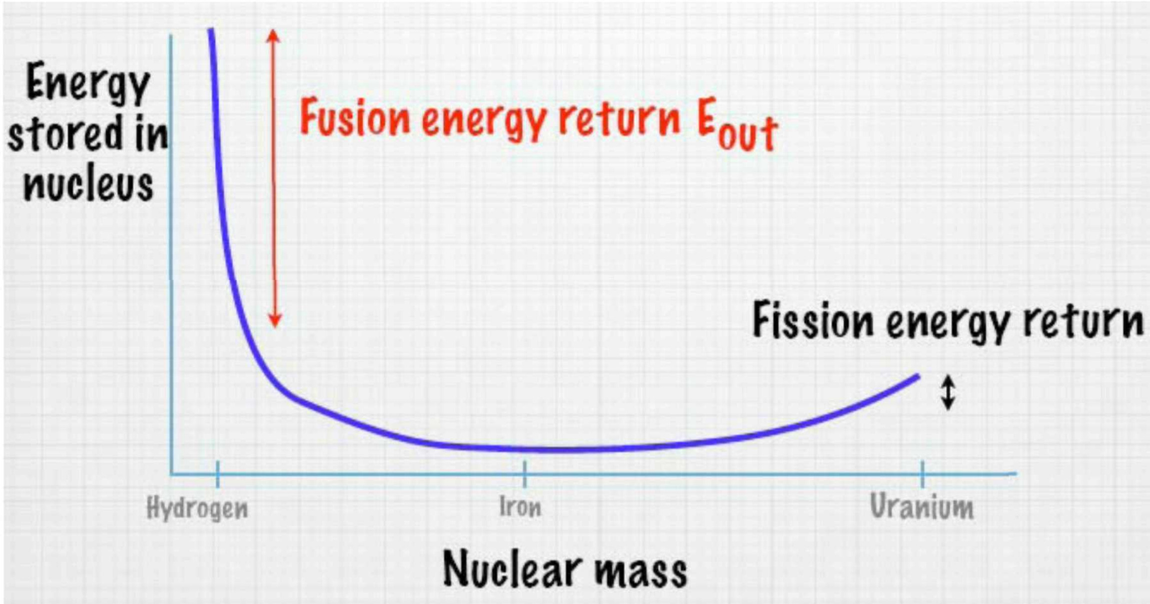
Producing a self-sustaining fusion-heated plasma is a grand challenge

1928	Fusion reactions explain energy radiated by stars [Atkinson & Houtermans]
1932	Fusion reactions discovered in laboratory [Oliphant]
1935	Fusion reactors understood as Coulomb barrier tunneling [Gamow]
1939	Theory of fusion power cycle for stars [Bethe–Nobel Prize 1967]
1950	US approval to develop hydrogen bomb "Super" [Teller]
1951-52	Invention of the tokamak [Tamm and Sakharov]
1950's	US Project Sherwood (classified) on controlled thermonuclear fusion
1958	2^{nd} UN Atoms for Peace Conference (Geneva): declassification of magnetic fusion research
1968	Russian tokamak results with high temperature presented at IAEA Fusion Energy Conference
Since then:	Worldwide explosion in tokamak research, culminating in experiments on TFTR (US), JET (EU), JT-60U (Japan), etc.

What is a “burning plasma”?

Sun





- **“Burning” plasma** = ions undergo thermonuclear fusion reactions, which supply self-heating to the plasma

- The energy output E_{out} is huge (global implications):

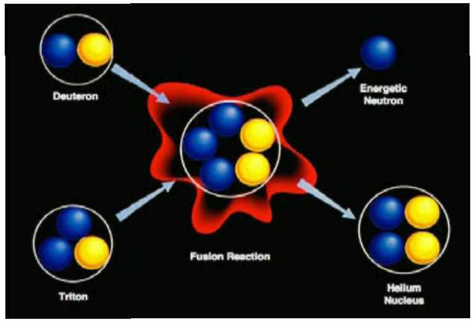
  E_{out} = 450 x E_{in}

- The required energy input E_{in} is also large:

  20 keV = 200 million °K

D-T fusion

- **The "easiest" fusion reaction uses hydrogen isotopes: deuterium (D) and tritium (T)**
  - D is plentiful in sea water
  - T can be generated from lithium
  - He is harmless (even useful)

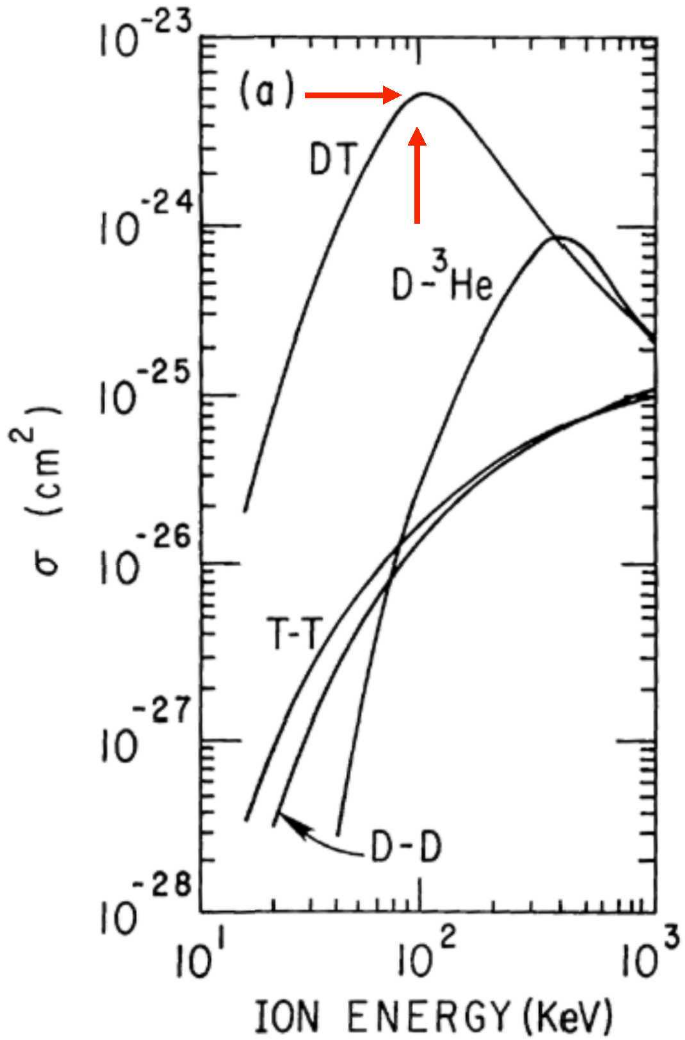


$${}_1D^2 + {}_1T^3 \rightarrow {}_2He^4 + {}_0n^1$$

(3.5 MeV) (14.1 MeV)

Energy/Fusion: $\varepsilon_f = 17.6$ MeV

Nuclear cross sections



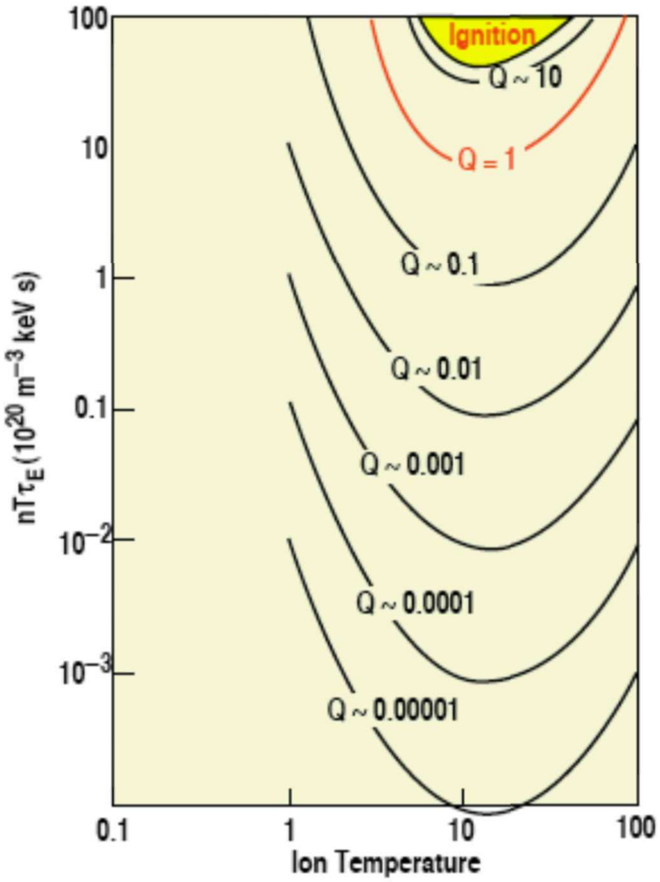
Fusion gain Q

$$\frac{dW}{dt} \rightarrow 0 \Longrightarrow P_\alpha + P_{heat} = \frac{W}{\tau_E}$$

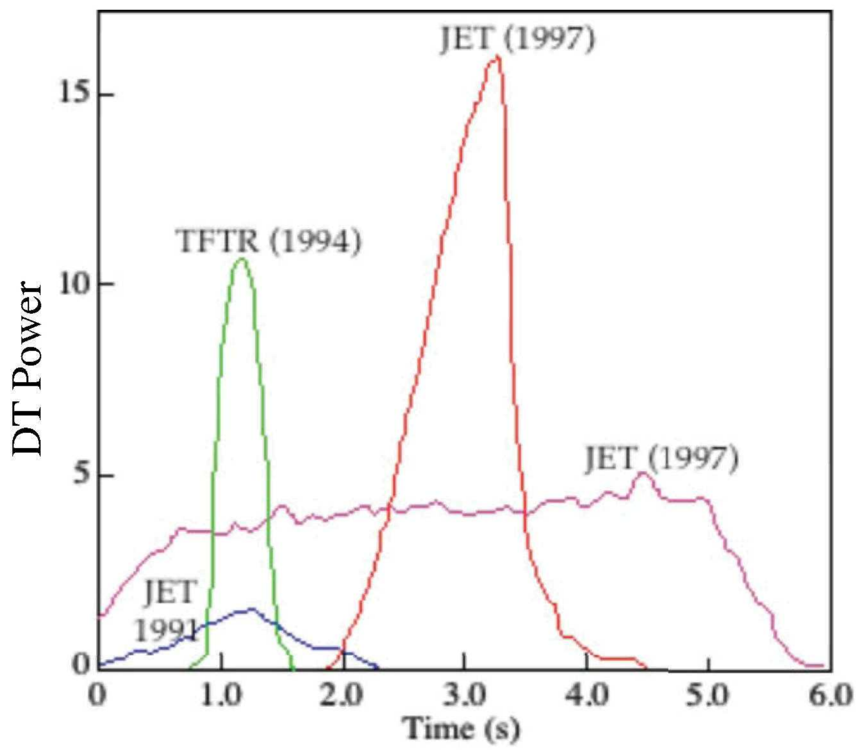
Define fusion energy gain, $Q \equiv \frac{P_{fusion}}{P_{heat}} = \frac{5\,P_\alpha}{P_{heat}}$

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

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



Initial D-T experiments

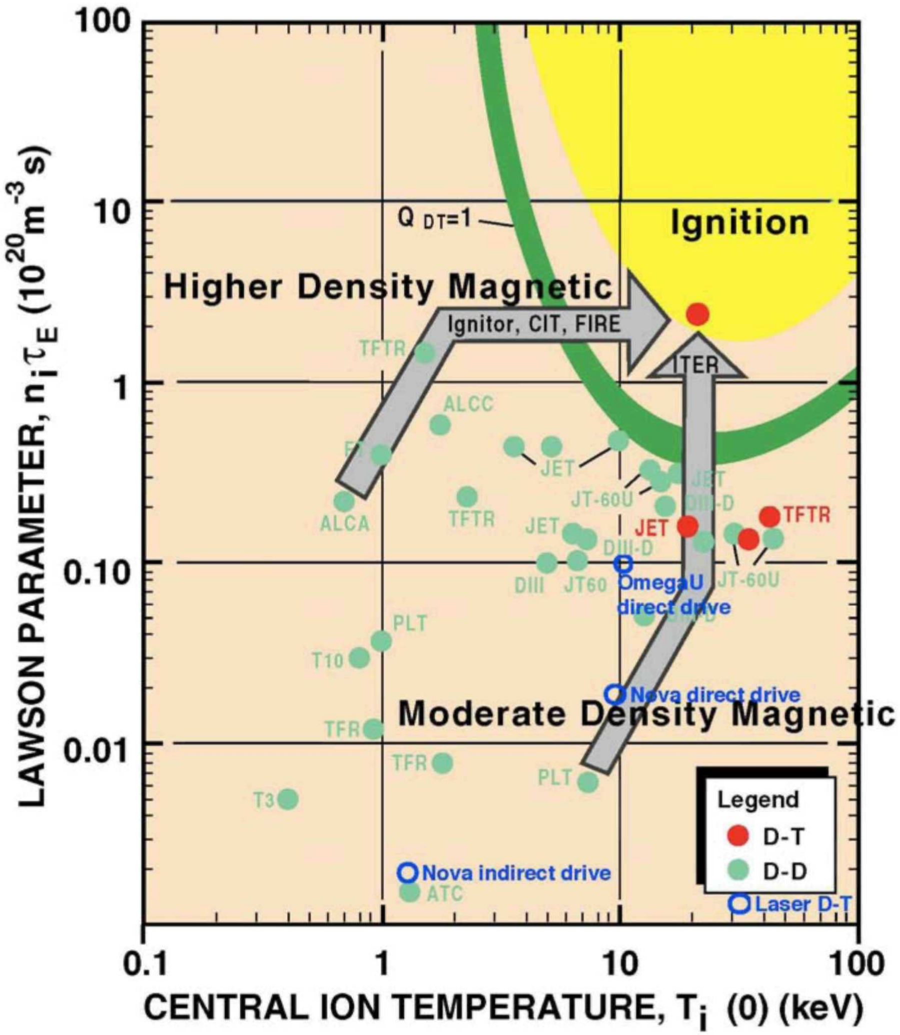


- **Joint European Torus (JET)**
  - "Preliminary Tritium Experiment" (1991): $P_{DT} > 1$ MW
  - Subsequently: Q=0.9 (transient breakeven), Q=0.2 (long pulse)
  - 16 MW fusion power

- **Tokamak Fusion Test Reactor (TFTR)**
  - Dec 1993 to Apr 1997: 1000 discharges with 50/50 D-T fuel
  - $P_{DT} = 10.7$ MW, Q=0.2 (long pulse)
  - Results:
    - Favorable isotope scaling
    - Self-heating by alpha particles
    - Alpha-driven instability
    - Tritium and helium "ash" transport
    - Tritium retention in walls and dust
    - Safe tritium handling (1M curies)

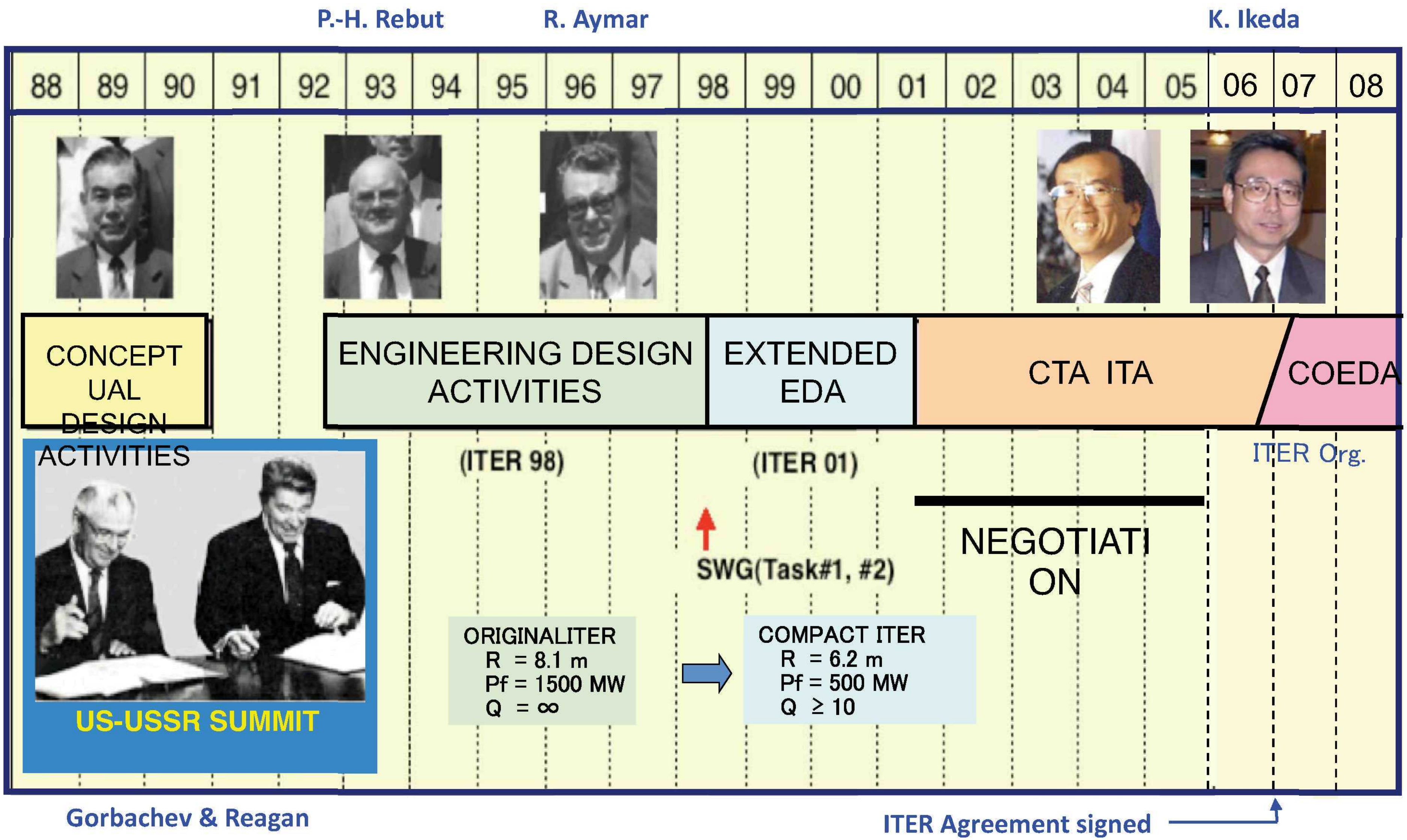
Status of magnetic fusion

- **Lawson Diagram:**
  - Achieved T_i required for fusion, but need ~10 x n 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



International planning for ITER

History of the ITER project



International developments

- **International Tokamak Reactor (INTOR) Workshop: 1978-1981**
  - Four partners: Euratom, Japan, US, and USSR
  - Sponsored by IAEA
  - Produced conceptual design for 600 MW(th) device and 860-page accompanying report
- **ITER Conceptual Design Activity (CDA): 1987-1990**
- **ITER Engineering Design Activity (EDA): 1992-98**
  - Four partners: EU, JA, RF, and US
  - Work sites in San Diego, Naka (JA), and Garching (EU)
  - US withdrew from ITER Project in 1998
  - San Diego site shut in 1999; personnel transferred to Naka Site
- **ITER Fusion Ignition Advanced Tokamak (FIAT)**
  - CTA and ITA phases 1999-2003
  - US re-entered ITER in 2003
- **ITER Implementing Agreement signed 21 Nov 2006**
  - Seven partners: CN, EU (host), IN, JA, KO, RF, US
- **ITER Organization became legal entity in Oct 2007**

ITER: an international project

- **ITER Implementing Agreement signed 21 Nov 2006 by EU, Japan, Russia, USA, Korea, China, and India**
  - Signing ceremony hosted by French President Chirac (Elysée Palace)
  - Dr. Raymond Orbach (Undersecretary for Energy) signed for the US

Deciding on the site for ITER

Site bids: 4 → 2 → 1

Japan - Rokkasho

Spain - Vandellòs

Canada - Clarington

France - Cadarache

2LV8R

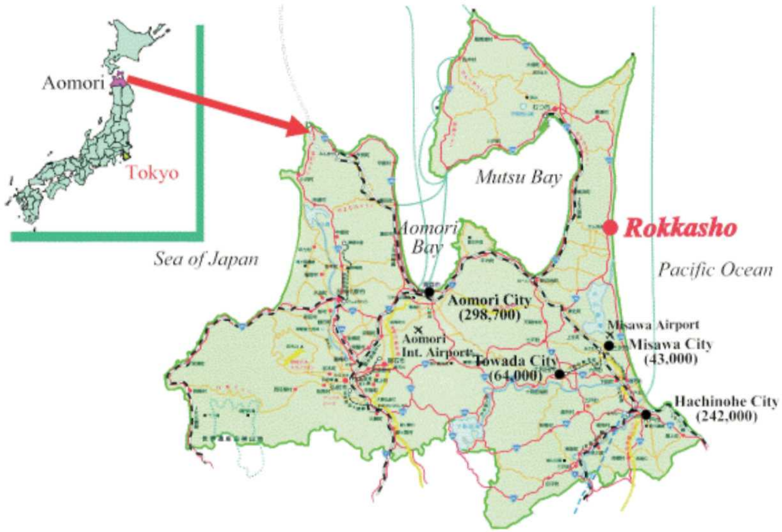
87

Time line on decision of ITER host

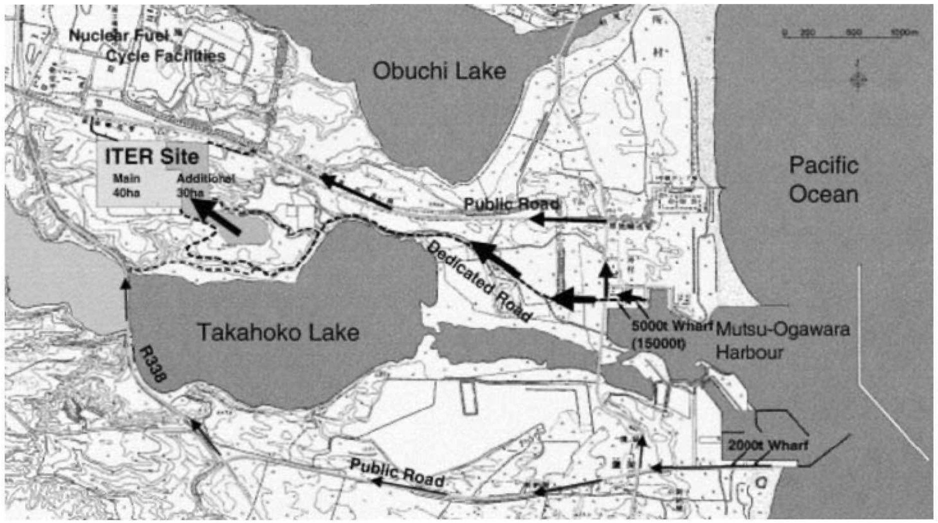
2001 May	Bid submitted by Canada (Toronto).
2001	Bids submitted by France, Spain, and Japan.
2003 Nov	EU support concentrated on France; Canada withdrew. Deadlocked vote by ITER partners between Japan and EU.
2004 June	Japan increased its bid by $1B; EU matched it.
2004 Dec	EU hinted it would build ITER by itself if no 6-party agreement.
2004-2005	EU and Japan negotiated privately. Japan agreed to withdraw its bid, in return for a concessions package: 20% of the research positions while providing only 10% of the expenses; EU to subsidize half the cost for certain new fusion facilities in Japan ("Broader Approach"); EU support for for Japanese candidate as ITER director-general)
2005 June	Unanimous vote by ITER partners to accept EU bid
2006 May	Initialing of ITER Agreement. Transmittal to Congress for 120-day review required by Energy Policy Act of 2005
2006 Nov	Signing of ITER Agreement in Paris

Proposed site in Japan

- **Rokkasho-mura**
  - Aomori Prefecture (northern Japan)
  - Mutsu-Ogawara Development Area, close to existing nuclear fuel cycle facilities
  - Under JA-EU Broader Approach, will house IFERC

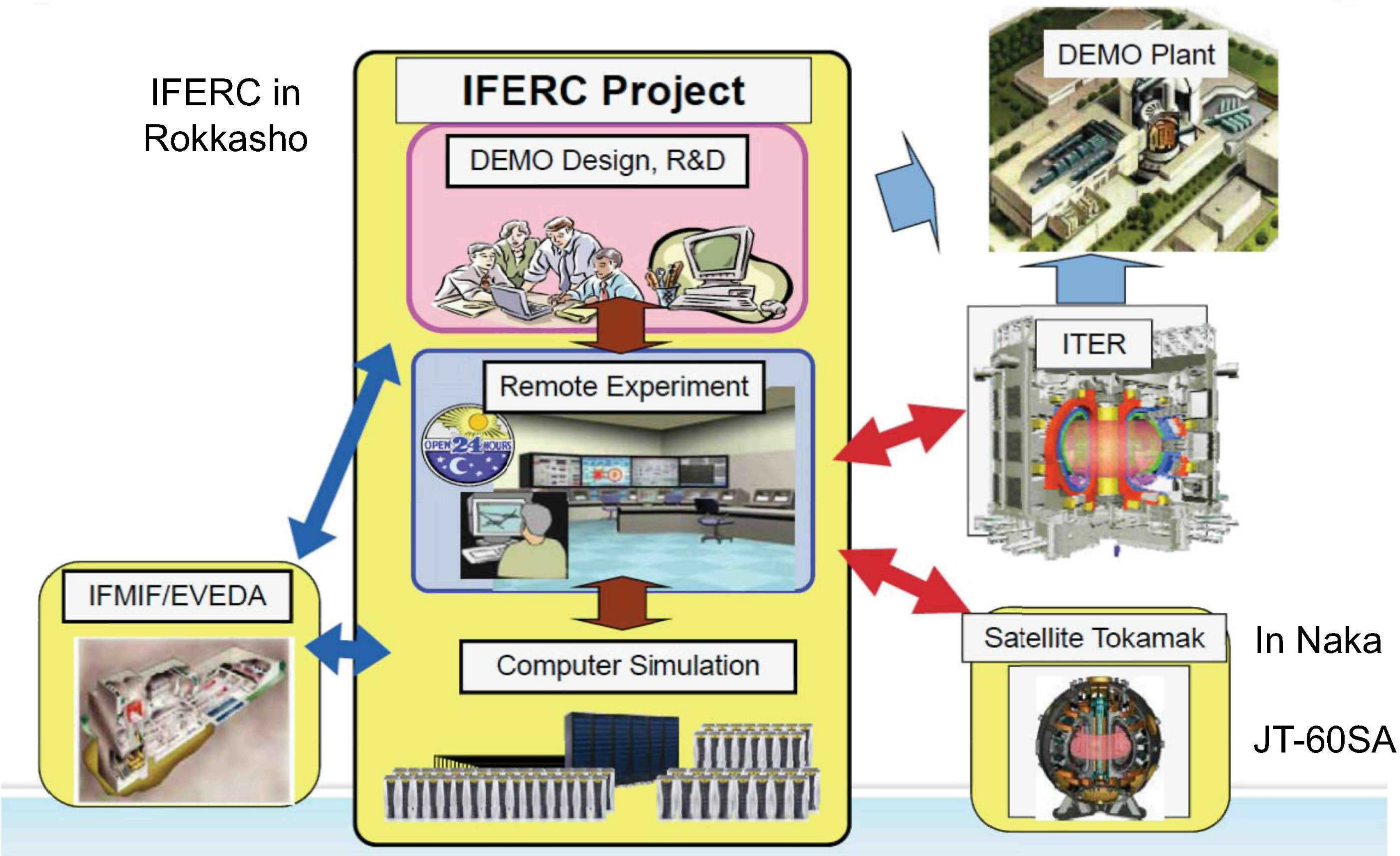


(a) Aomori Prefecture

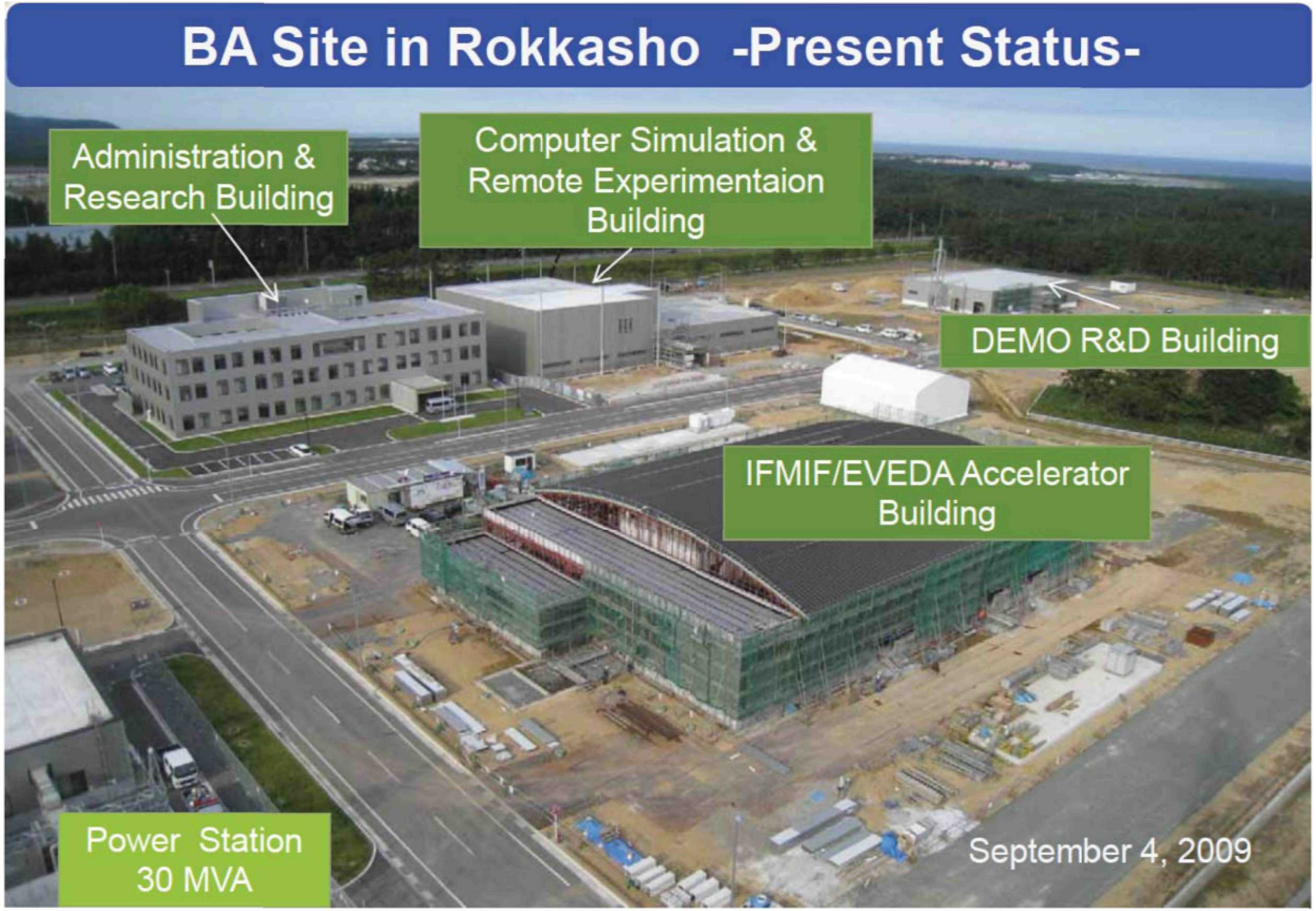


(b) Rokkasho Area

EU-Japan Broader Approach

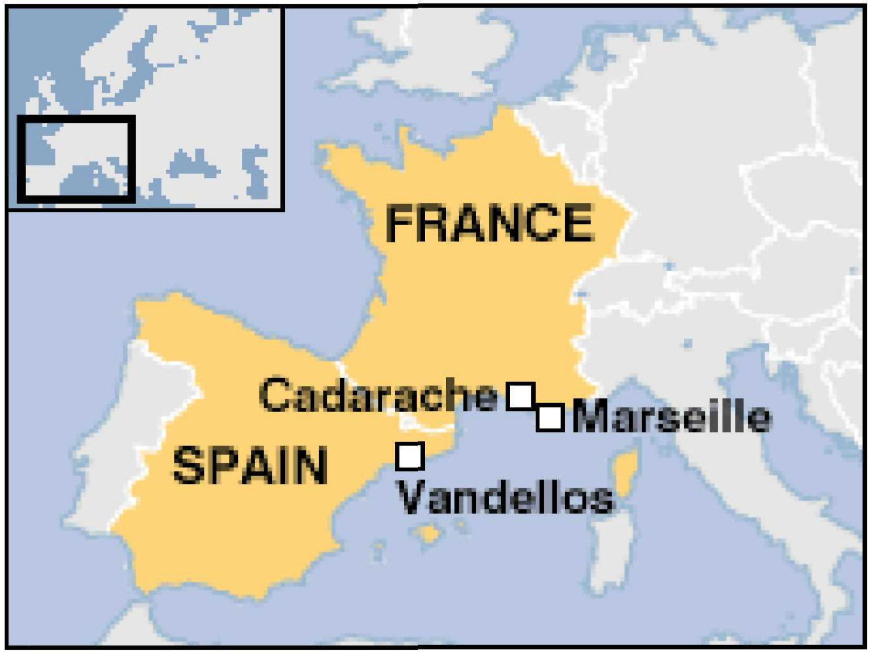


Broader Approach site

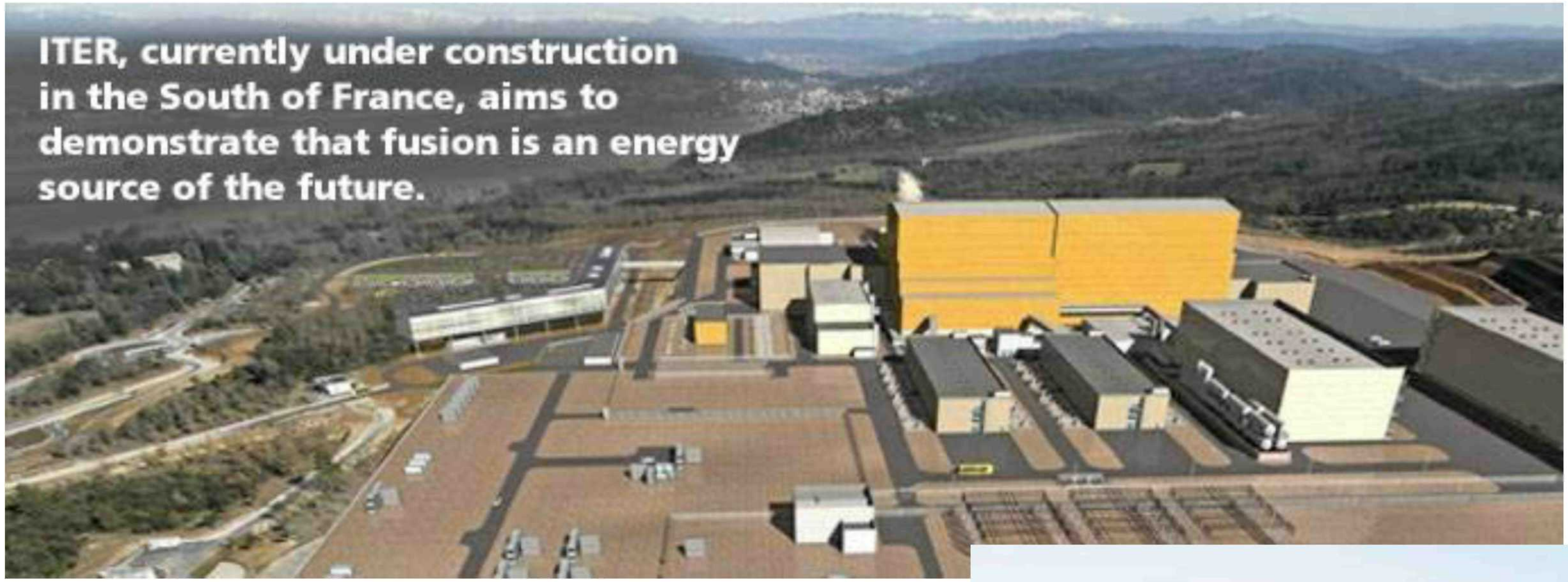


ITER's final location

- **To be built in Cadarache, France (EU)**
  - Near Marseille (in Provence-Alpes-Cote d'Azur region)
  - First plasma operation in 2019, D-T operation by 2027



Site: present and future



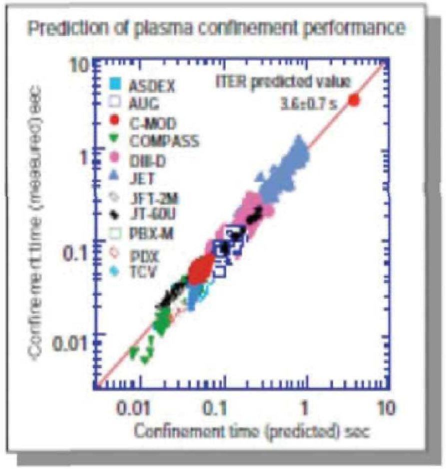
Future layout

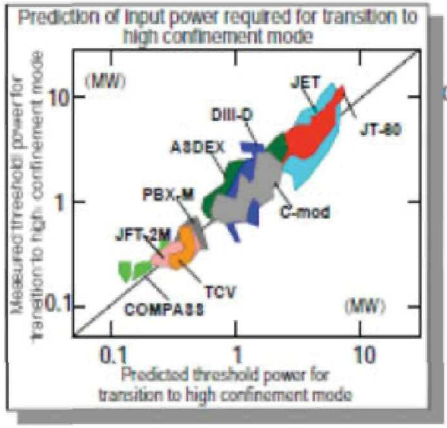
Present (Mar 2010)

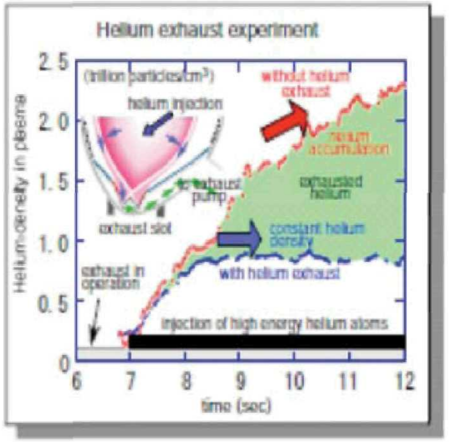
A clear mission for the ITER project

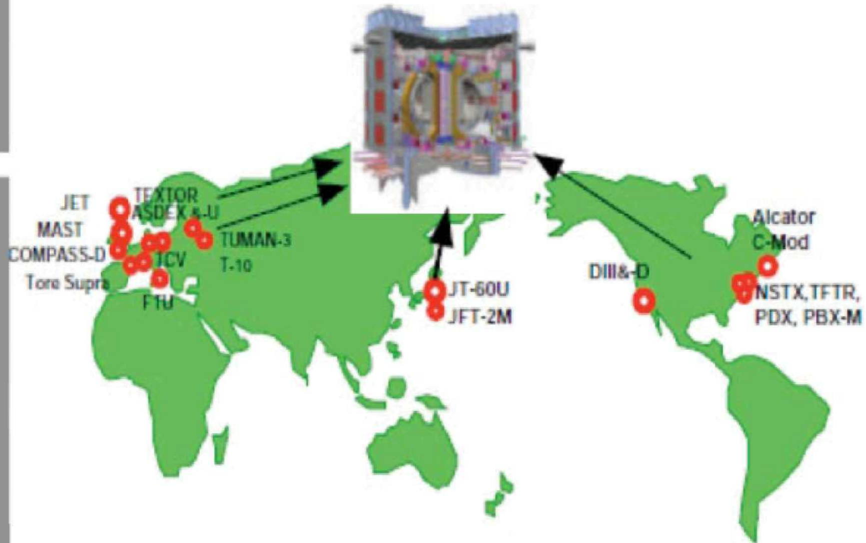
Attachment 6 Achievements of ITER Physics R&D

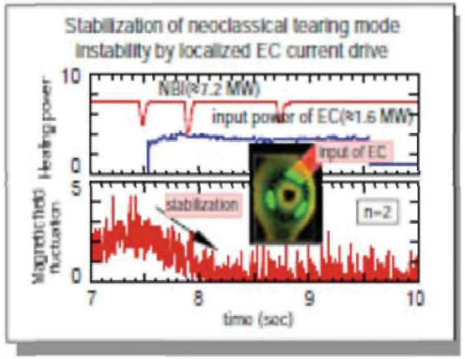
Integrate experimental results of tokamaks from all over the world to establish physics basis for plasma performance of ITER

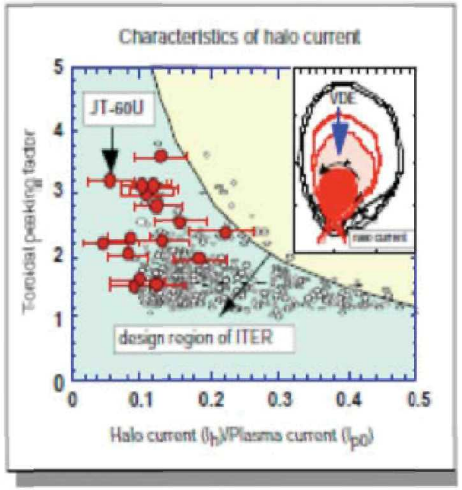


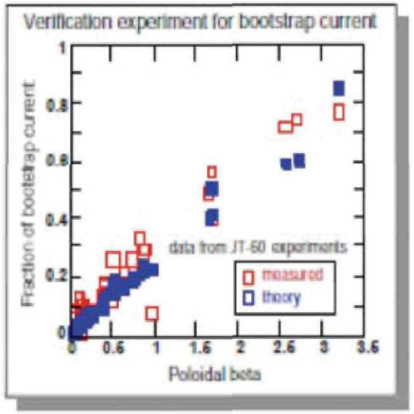


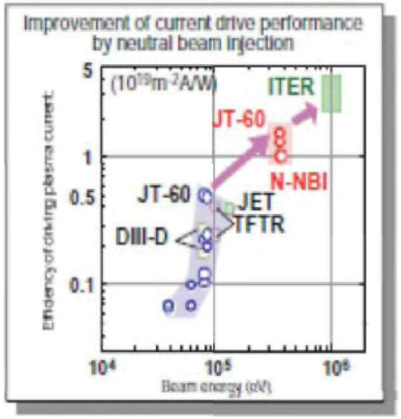


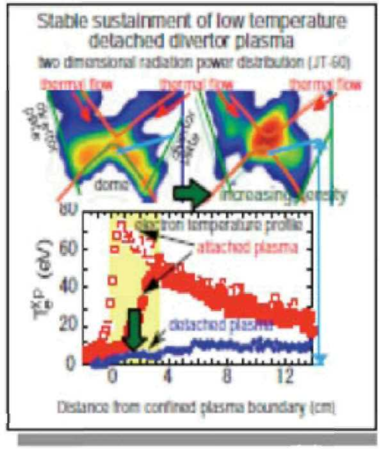












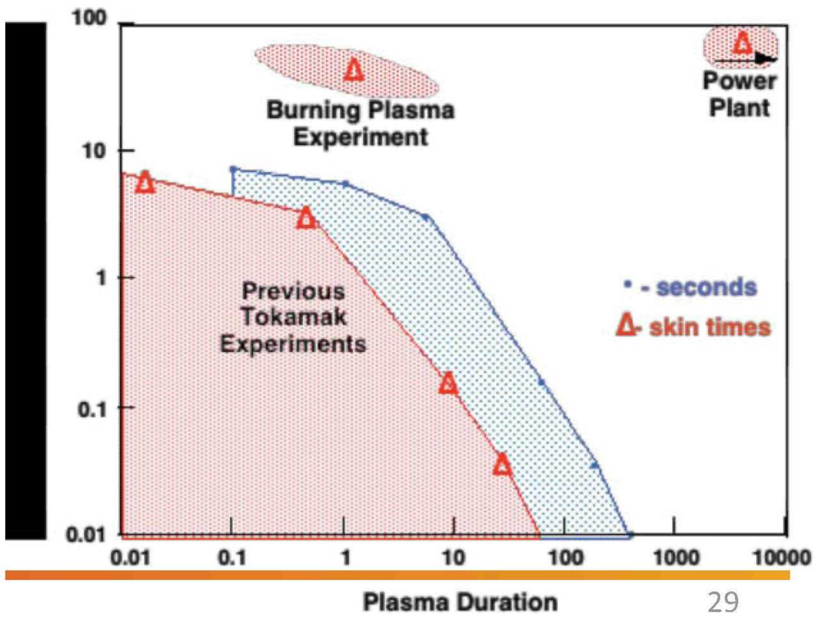
ITER design goals

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

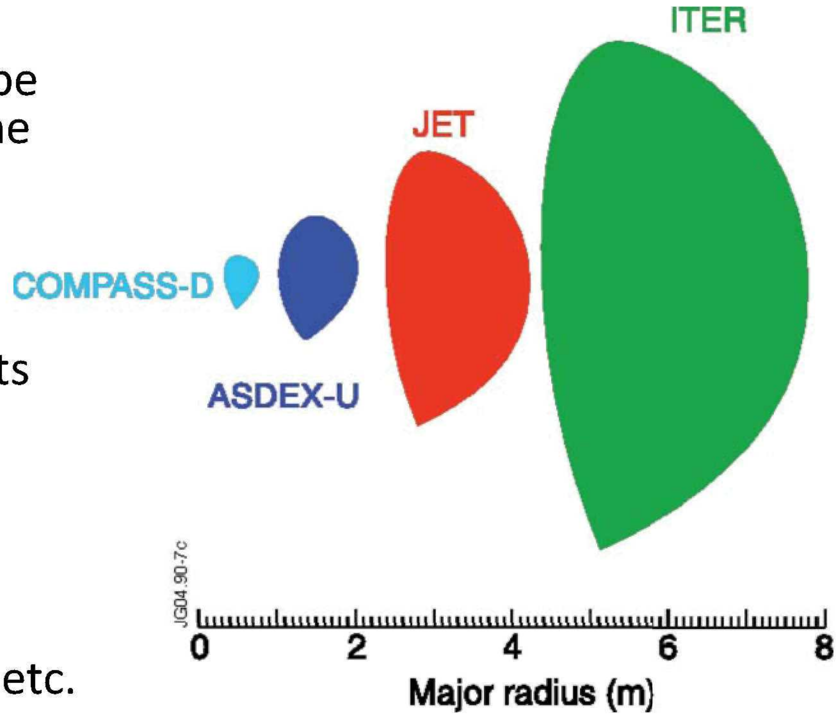
New features in a burning plasma

- **Dominant self-heating (exothermic)**
  - "Autonomous" system: reduced capability to control current, pressure, and rotation profiles by means of external RF power and neutral beams
- **High performance requirements**
  - Sustained, simultaneous achievement of high temperature and density, good macroscopic stability, good confinement of plasma energy
  - Robust plasma-wall facing components and diagnostics that can withstand high heat and neutron wall loadings
- **Long pulse length**
  - BP experiment should have pulse length long compared to the current redistribution time ($\tau_{pulse} >> \tau_{CR}$) to investigate resistively equilibrated current and pressure profiles in the presence of strong alpha heating



More new features in burning plasma

- **Strong coupling**
  - Transport, stability, boundary physics, energetic particles, heating, etc., will be strongly coupled nonlinearly due to the fusion self-heating
- **Size scaling**
  - Much larger volume than present expts
- **Large population of super-thermal alpha particles**
  - Different behavior from thermal ions
  - Affect stability, confinement, heating, etc.
- **Nuclear environment**
  - Gamma/neutron radiation, tritium retention, dust, tritium breeding



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

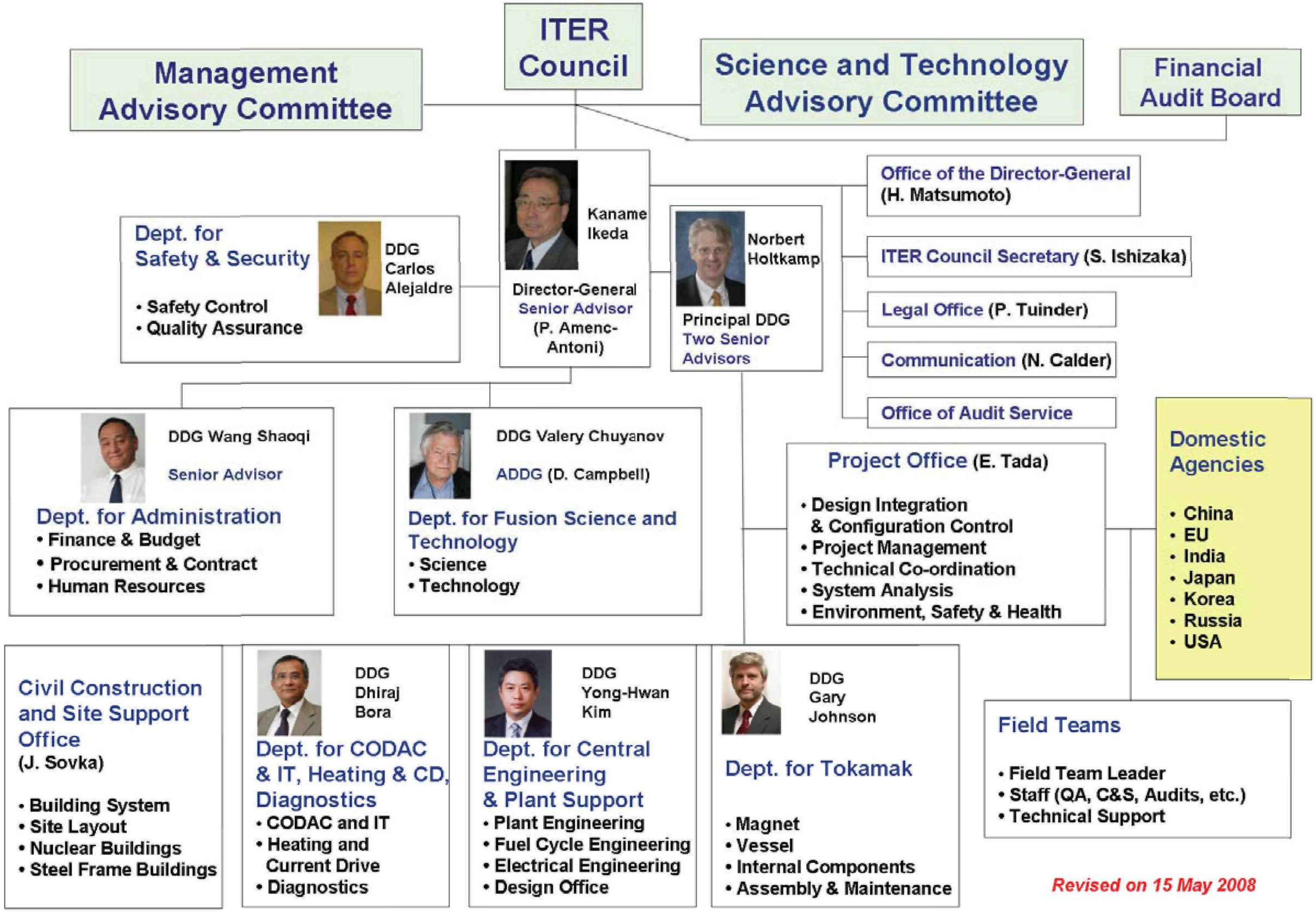
ITER physics R&D needs

- **Issues listed by ITER as urgent**
  - Mitigation of disruptions and runaway electrons
  - Access to high confinement (H-mode)
  - ELM control
  - Plasma-facing component material
  - Plasma scenarios
  - Integrated modeling
  - Tritium breeding

- **ITER science challenges to be discussed in lecture #2**

Organization can be as much of a challenge as science and technology

ITER org chart

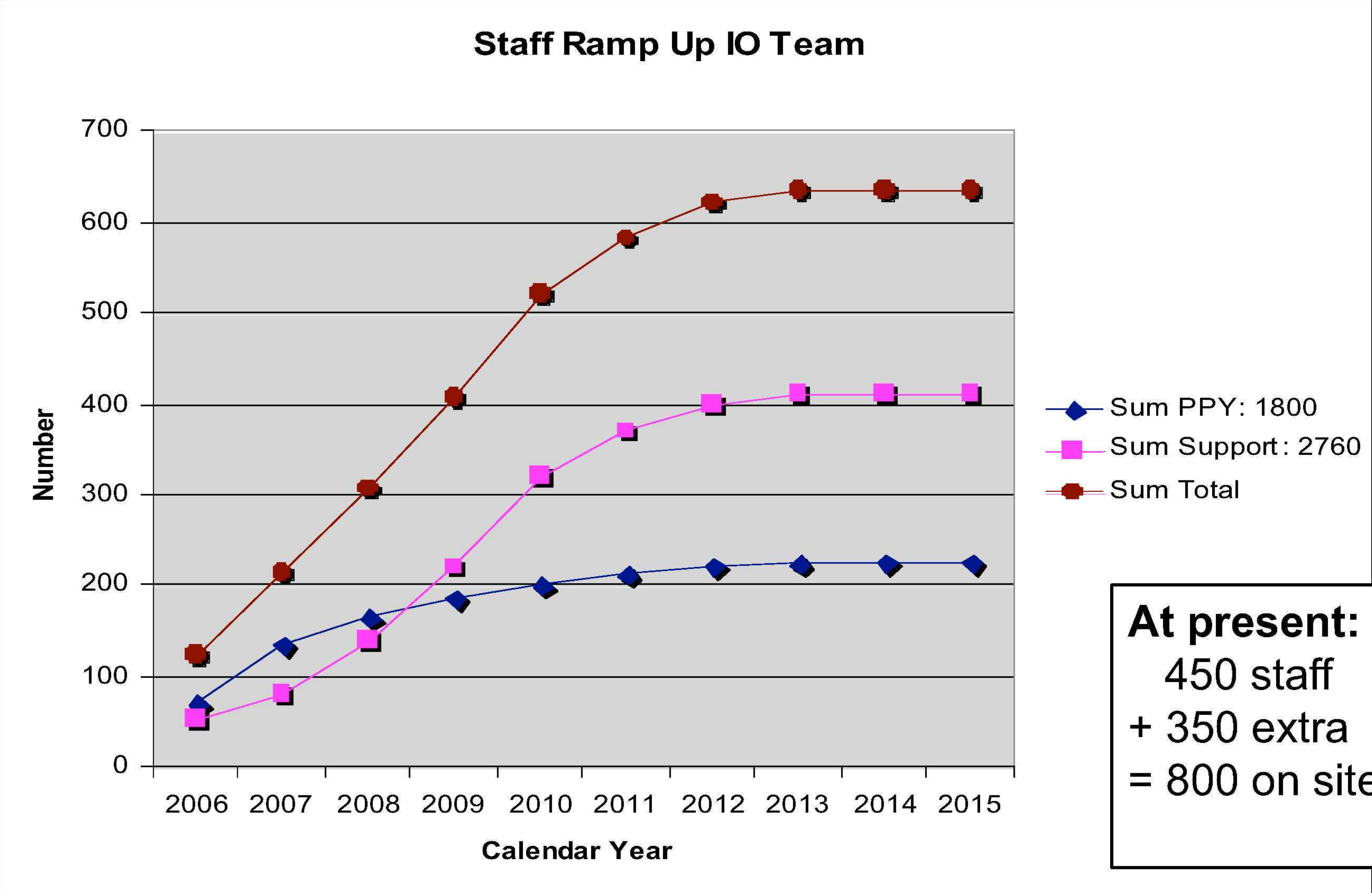


ITER top leadership

- **Director-General Kaname Ikeda**
  - Deputy Minister for Science and Technology, Japan
  - Executive Director, National Space Development Agency, Japan
  - Ambassador to Croatia

- **Principal Deputy Director-General & Project Construction Leader Dr. Norbert Holtkamp**
  - Research Group Head, S-Band Linear Collider, DESY, Germany
  - Division Director, Spallation Neutron Source, ORNL, USA

ITER staffing projection



At present:
450 staff
+ 350 extra
= 800 on site

Other organizational challenges

- **Communication**
  - International video-conferencing techniques
  - Integrated document management
- **Intellectual property rights to data**
  - Who owns ITER's photons?
- **Management styles, cultural differences, flag waving,…**
- **Multi-national safety regulations**
- **Import/export regulations**
- **Outreach for public visibility**
  - Web site, newsletter, movies, brochures, PR and educational materials,…
  - YouTube movies on ITER

US ITER Project Office booth at 2008 AAAS Meeting

Determining the cost and how to pay for ITER

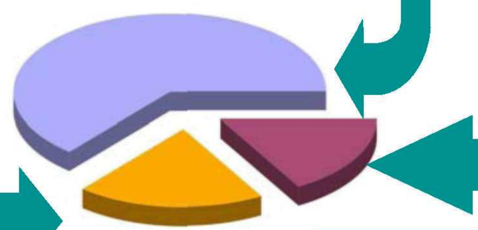
ITER construction cost-sharing

C

"Contributions in Kind"
Major systems provided directly by Members

A

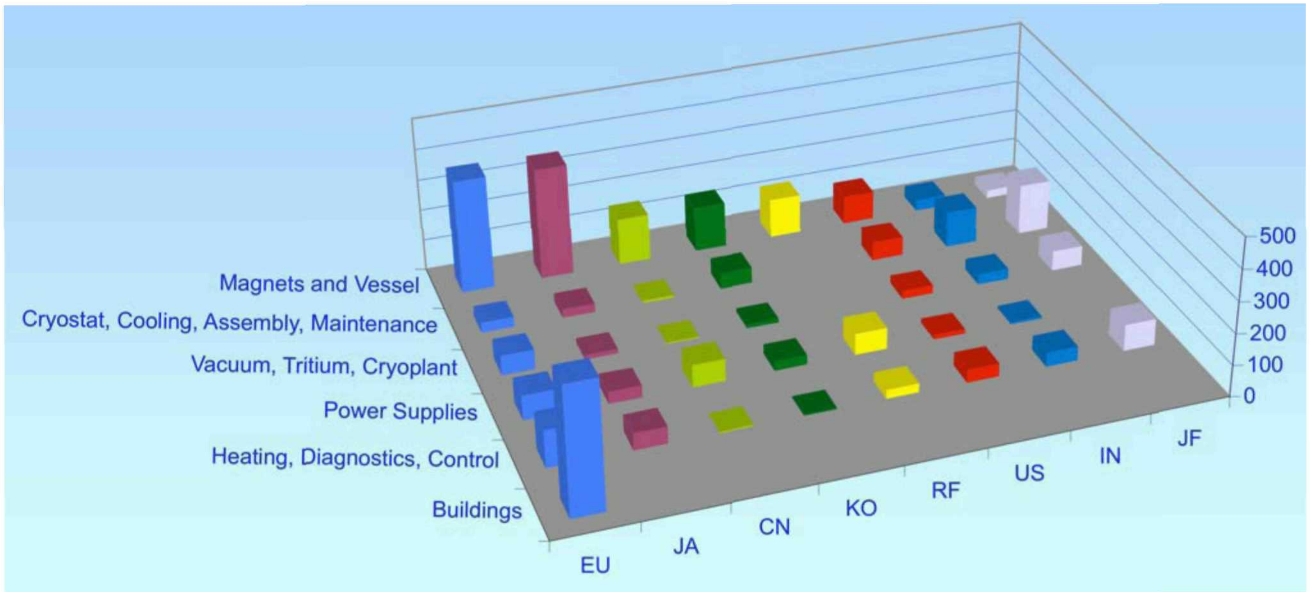
Systems suited only to Host Party industry
- **Buildings**
- **Machine assembly**
- **System installation**
- **Piping, wiring, etc.**
- **Assembly/installation labour**



B

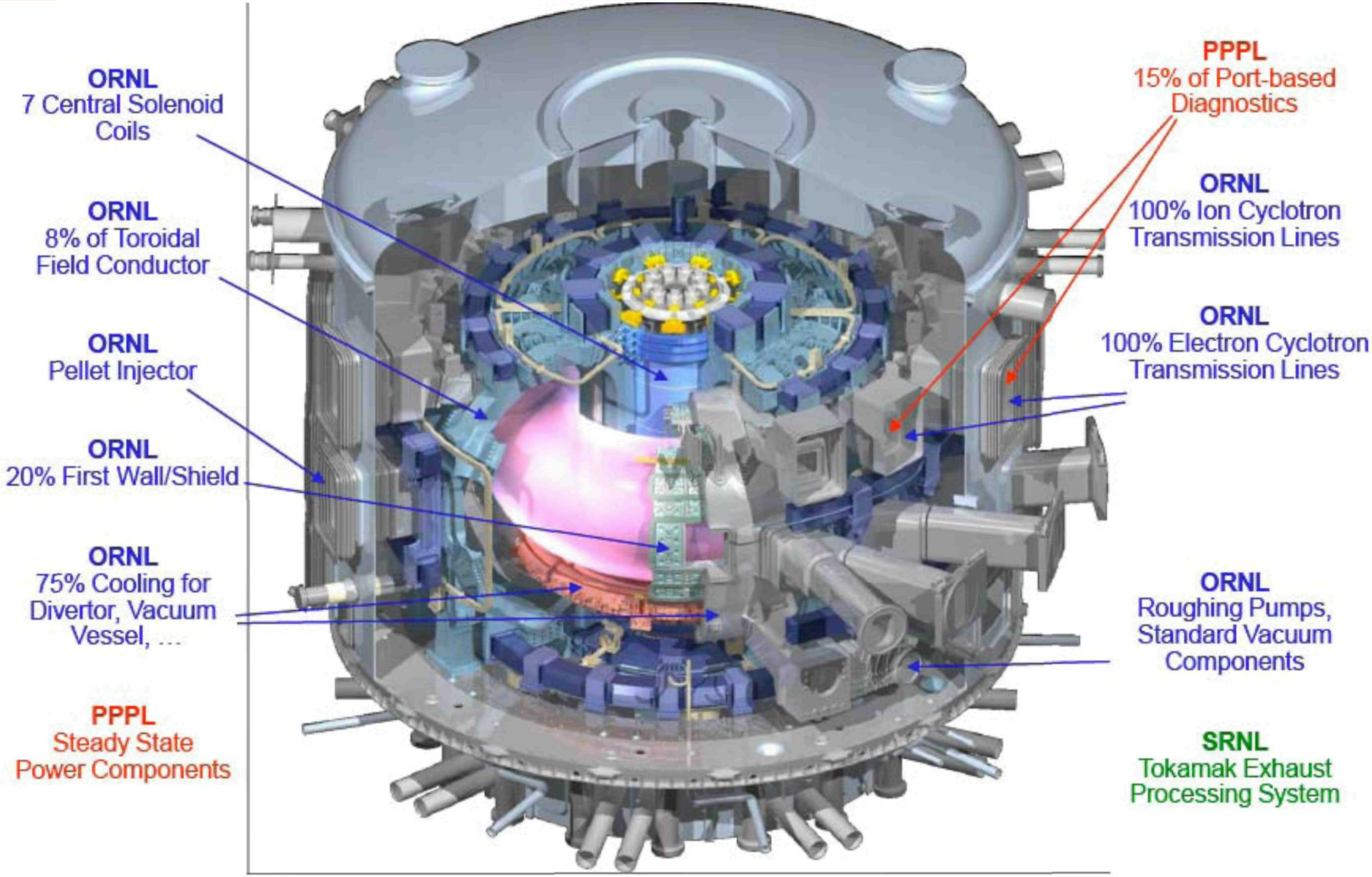
Residue of systems, jointly funded, purchased by ITER Project Team

Overall cost sharing:
EU 5/11, Others 6 Members 1/11 each, Overall contingency up to 10% of total.



Overall costs shared according to agreed evaluation of A+B+C

US in-kind hardware contributions



U.S. Burning Plasma Organization:

To coordinate, facilitate, and promote burning plasma science in the US research program

Preparing for "burning plasma era"

- **U.S. Burning Plasma Organization (USBPO) was created in 2005 as a community-based entity**
  - 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)
  - Council (12 members)
  - Research Committee (20) = leaders/deputy leaders of 10 Topical Groups
  - Directorate (5)
  - International Tokamak Physics Activity (ITPA): 49 Topical Group members + 3 Coordinating Committee members from the US

Broad Expertise of USBPO Topical Groups

USBPO
U.S. BURNING PLASMA ORGANIZATION

Jim Van Dam (Director)
Chuck Greenfield (Deputy Director)
Nermin Uckan (Assistant Director for ITER Liaison)

Council:
Amanda Hubbard (Chair)
Mike Zarnstorff (Vice Chair)
+10 members at large +
ITER Chief Techologist

Executive Committee members in red

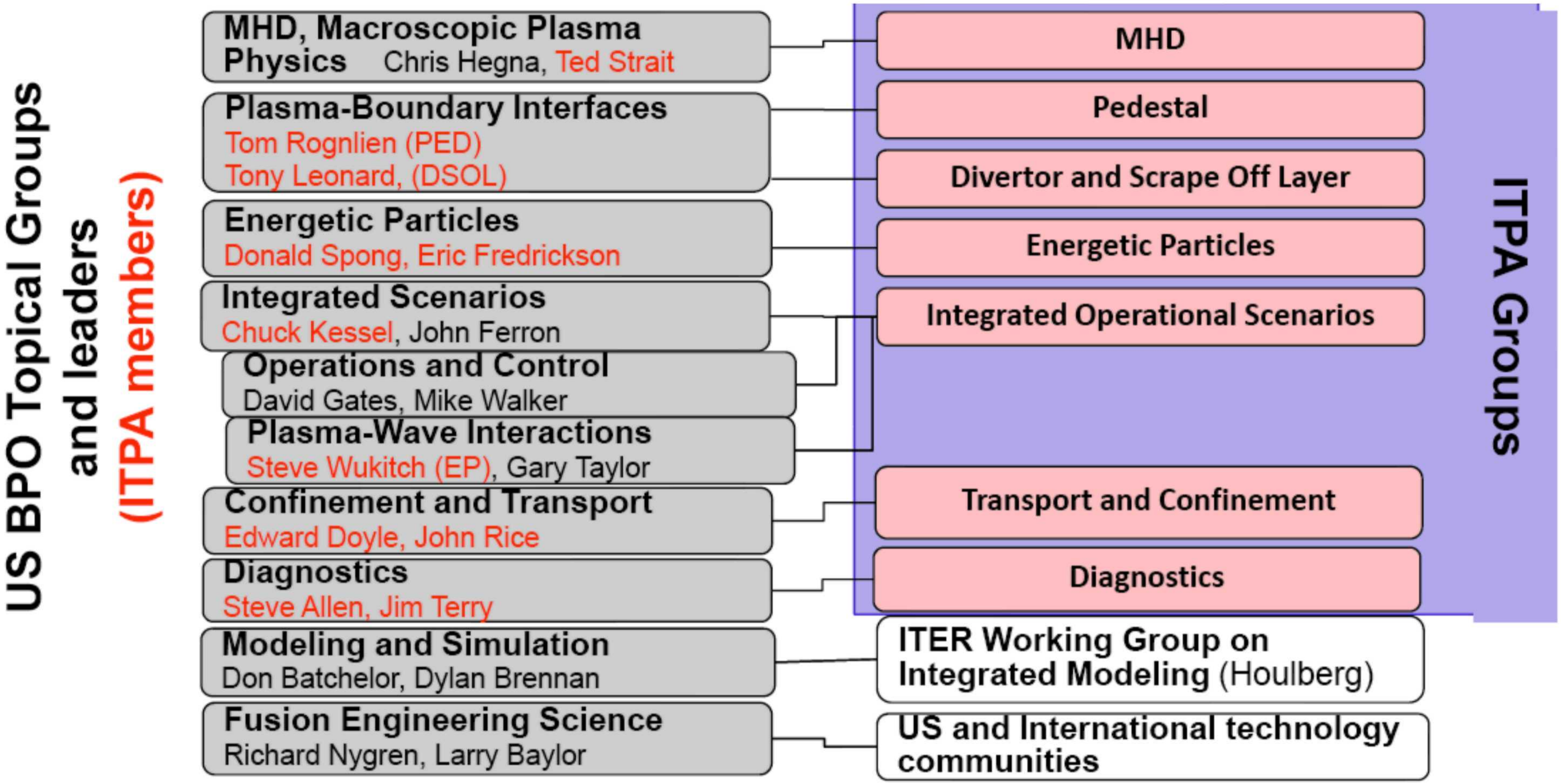
Research Committee made up of Leaders and Deputies of 10 Topical Groups

MHD, Macroscopic Plasma Physics	Integrated Scenarios
Plasma-Boundary Interfaces	Operations and Control
Fusion Engineering Science	Modeling and Simulation
Diagnostics	Confinement and Transport
Plasma-Wave Interactions	Energetic Particles

MEMBERS
(currently 331)

Membership in USBPO is open to any fusion researcher who joins one or more topical groups.

USBPO integrated with ITPA in US



March 2010: Plasma-Boundary Interfaces topical group was renamed "Pedestal and Divertor/SOL."

USBPO communication role

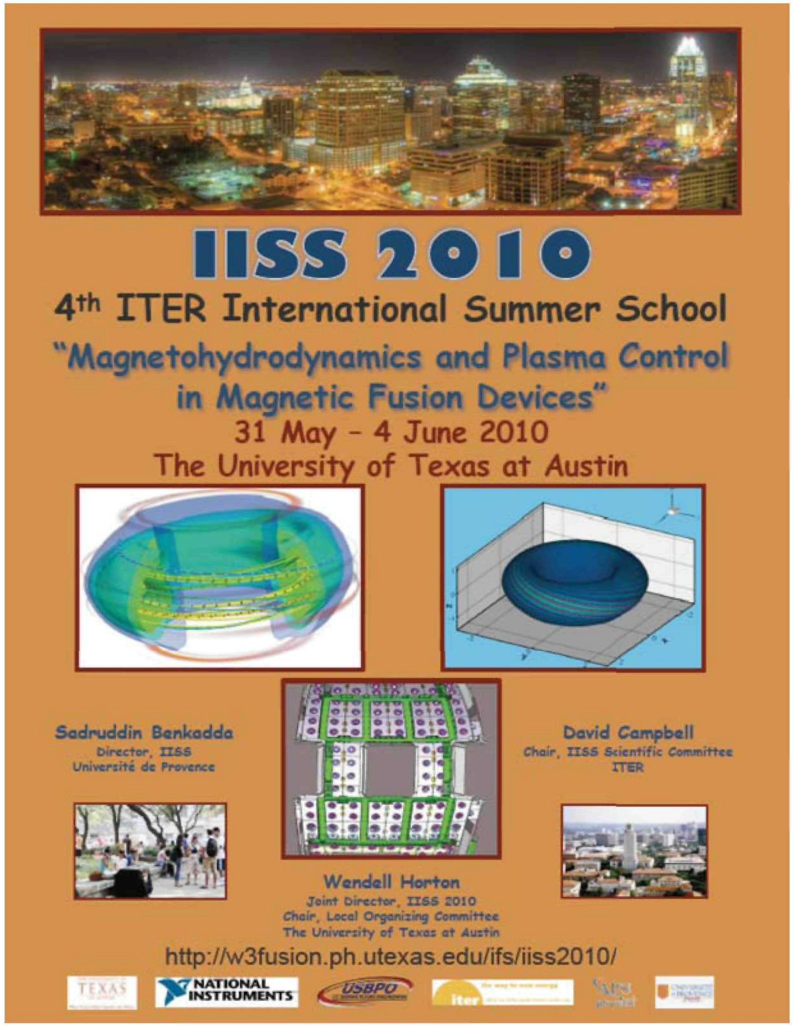
- **USBPO web site (www.burningplasma.org)**
  - All presentations, white papers, progress reports are publicly available
  - Limited-access pages for US STAC, Council, Topical Groups, …

- **USBPO *eNews***
  - 480 subscribers (from 95 institutions); Jan 2010 *eNews* was 40th issue
  - "Director's Corner" column, feature articles, ITPA meeting reports, calendar of fusion events, research highlights

- **IT capabilities**
  - Bi-weekly videoconference Research Comm and Executive Comm meetings; quarterly video conference Council meetings
  - Technical briefings for US STAC members
  - Remote seminars: e.g., "LH Capabilities for ITER" (Feb 2009)

4th ITER International Summer School

- **ITER Summer School held in US this year**
  - May 31-June 4, University of Texas
  - Sponsors: USBPO, National Instruments Corp, French Embassy
- **Theme:** *MHD and Plasma Control in Magnetic Fusion Devices*
  - Lectures (20), poster sessions (2), hands-on computer lab sessions (4)
- **Participation**
  - 133 participants from 17 countries and 48 institutions



References

- ***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)**
- ***Progress in the ITER Physics Basis*****, Nuclear Fusion (2007)**