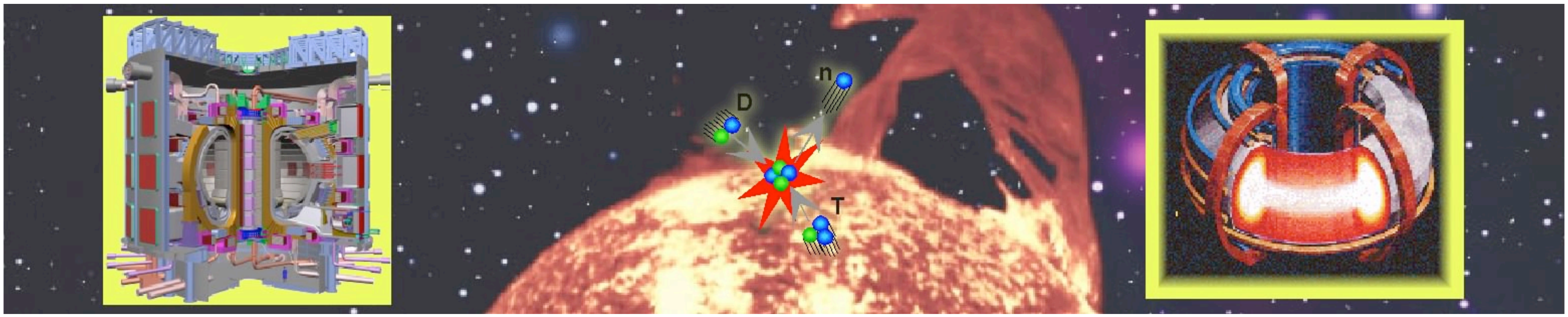
How to Make a Big International Project Happen: Lessons from ITER



- *Scientific challenge*
- *United strategy*
- *Site selection*
- *Clear mission*
- *Organization*
- *Cost*
- *Research coordination*

James W. Van Dam

Institute for Fusion Studies
University of Texas at Austin

US Burning Plasma Organization
US ITER Project Office

Supported by Office of Fusion Energy Sciences, Office of Science

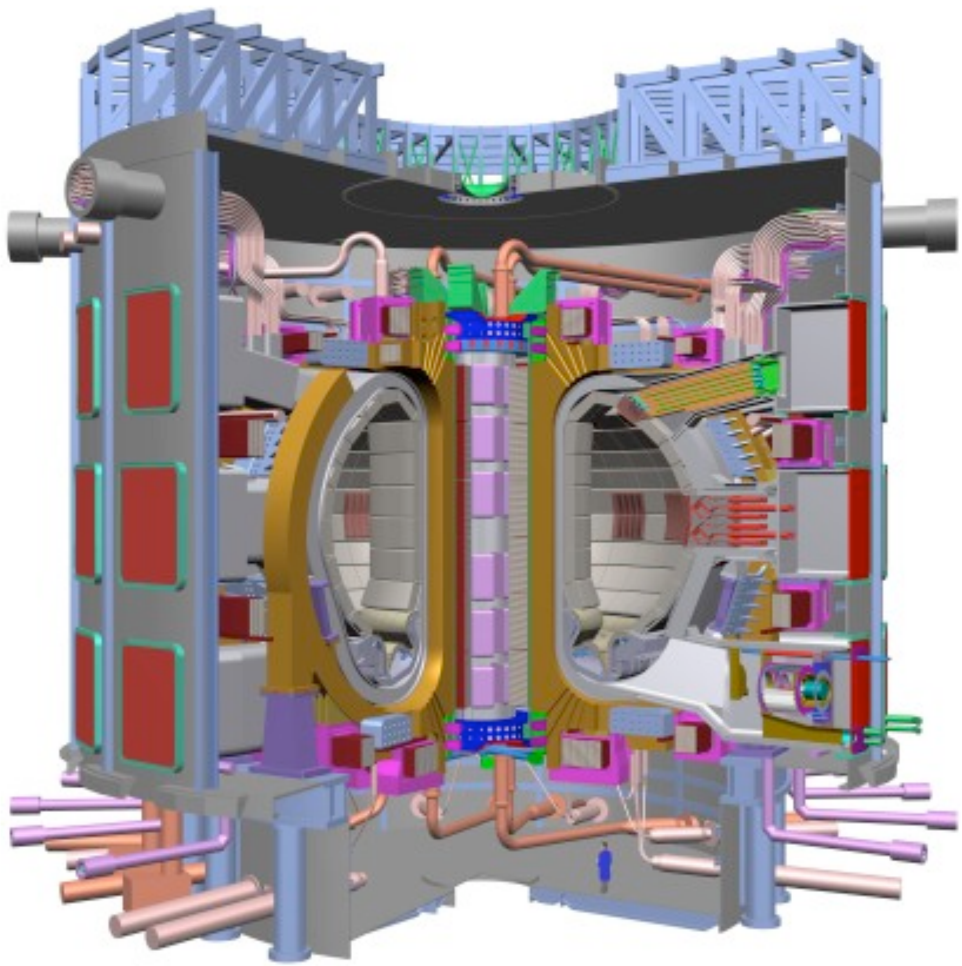
2007 APS April Meeting (April 14)

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

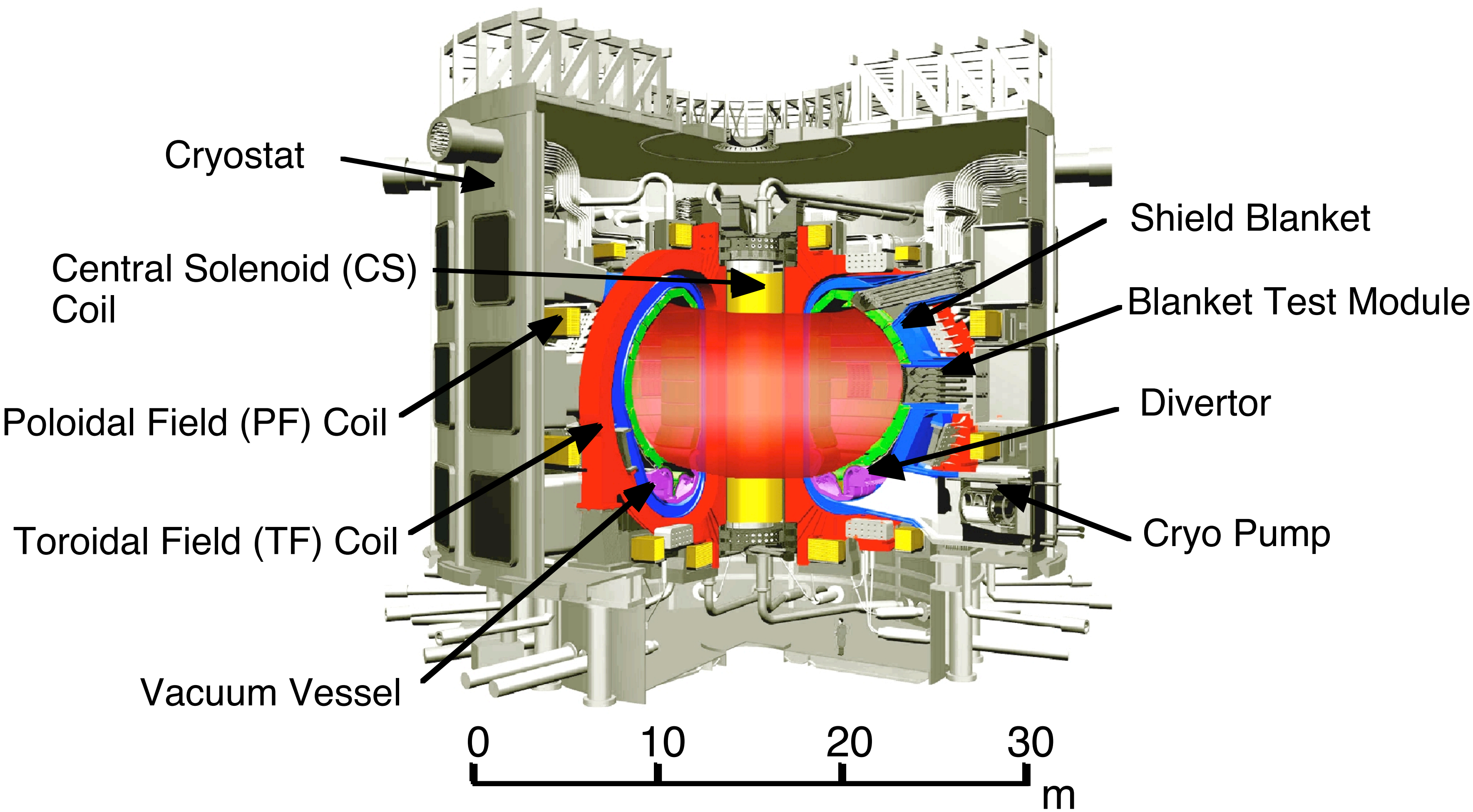
- The world's biggest fusion energy research project ("burning plasma")
  - 15 MA plasma current, 5.3 T magnetic field, 6.2 m major radius, 2.0 m plasma minor radius, 840 m^3 plasma volume, superconducting
  - 10B Euros to build and then operate for 20 years (first plasma in 2016)

- An international collaboration
  - 7 international partners, representing 50% of world's population



Cutaway view of ITER

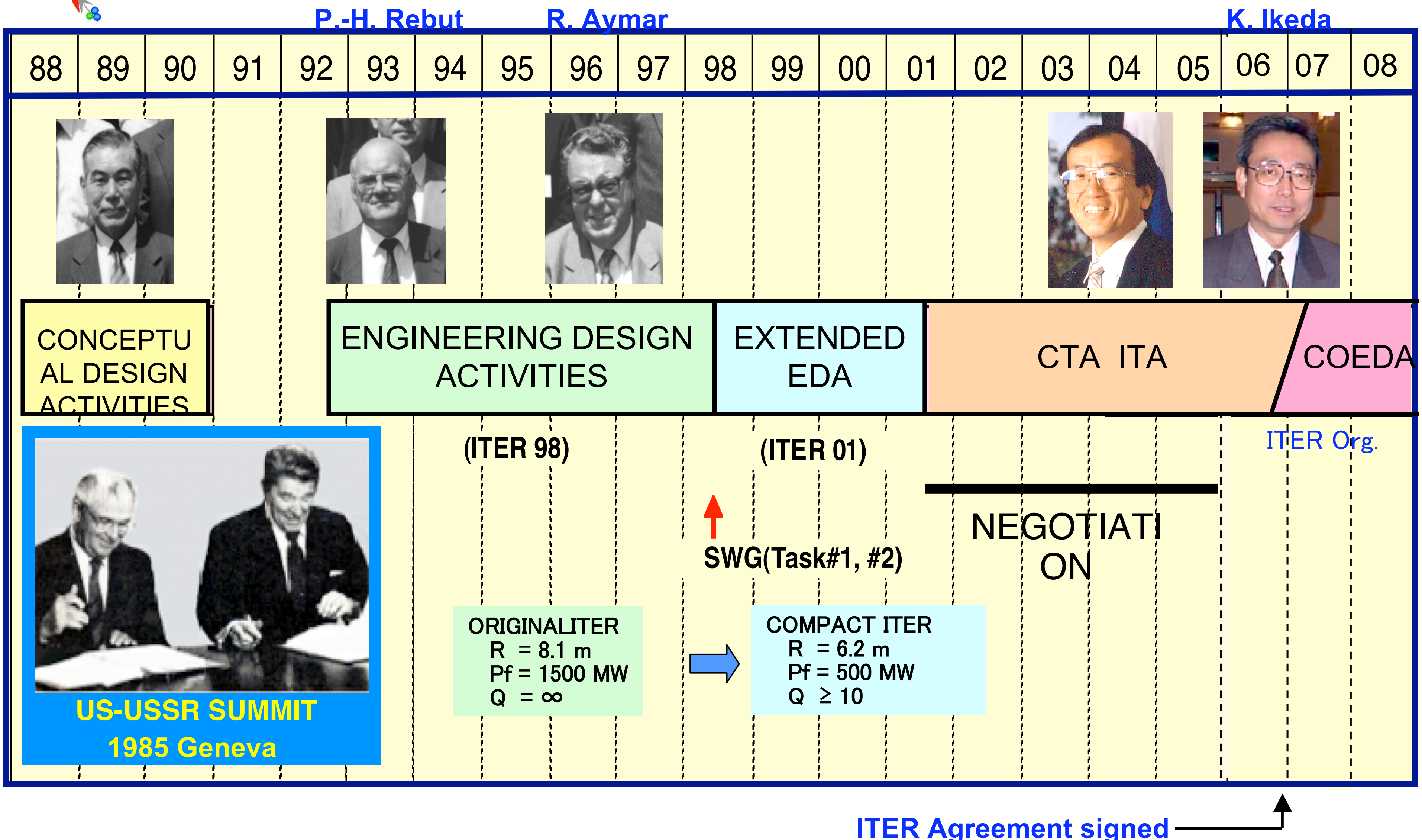
USBPO



ITER is a **tokamak**: confines **plasma** with helical magnetic fields in donut shape

History of the ITER project

USBPO



ITER—an international project

- **Implementing agreement signed November 21, 2006, between EU, Japan, Russia, USA, Korea, China, India**
  - Signing ceremony hosted by President Chirac at Elysée Palace
  - Dr. Raymond Orbach (Under-Secretary for Energy) signed for US

LESSON:

A big international project is motivated by a big international scientific challenge

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

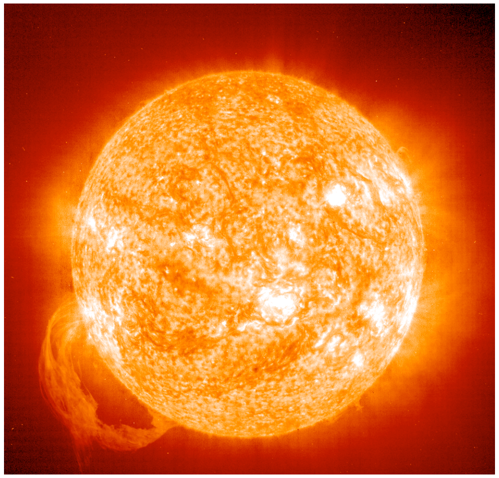
USBPO

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	US approval to develop hydrogen bomb "Super" [Teller]
1951-52	Invention of the tokamak [Tamm & Sakharov]
1950's	US Project Sherwood (classified) on controlled thermonuclear fusion
1958	2nd UN Atoms for Peace Conference (Geneva): magnetic fusion research was declassified
1968	Russian tokamak results with high temperature presented at IAEA Fusion Energy Conference
Since then:	Worldwide explosion in tokamak research, culminating in TFTR (US), JET (EU), and JT-60U (Japan) experiments

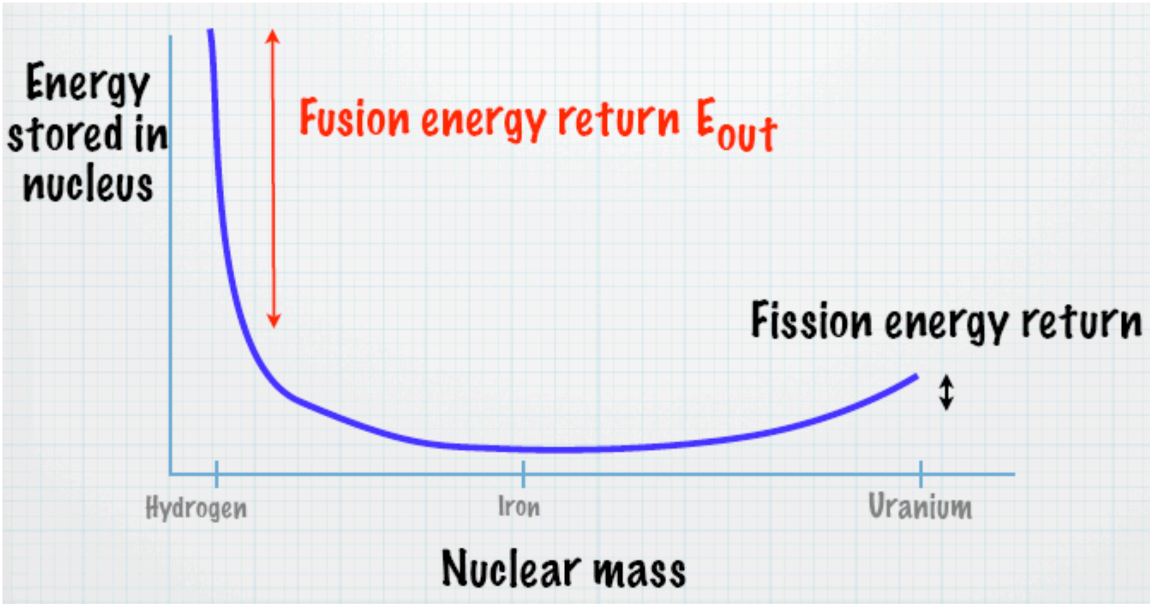
What is a "burning" plasma?

USBPO

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}

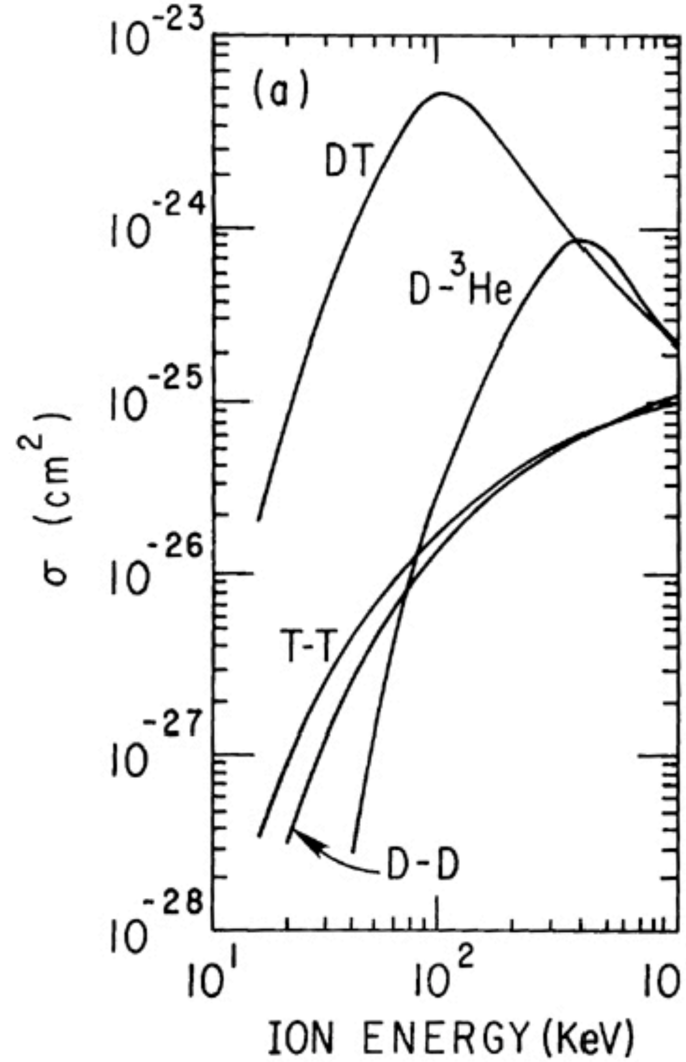
- The required energy input E_{in} is also large:

  20 keV = 200 million °K

D-T fusion

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

$$ {}_1D^2 + {}_1T^3 \rightarrow \underbrace{\underset{(3.5\ \text{MeV})}{{}_2He^4} + \underset{(14.1\ \text{MeV})}{{}_0n^1}}_{\text{Energy/Fusion: } \varepsilon_f = 17.6\ \text{MeV}} $$



Nuclear cross sections

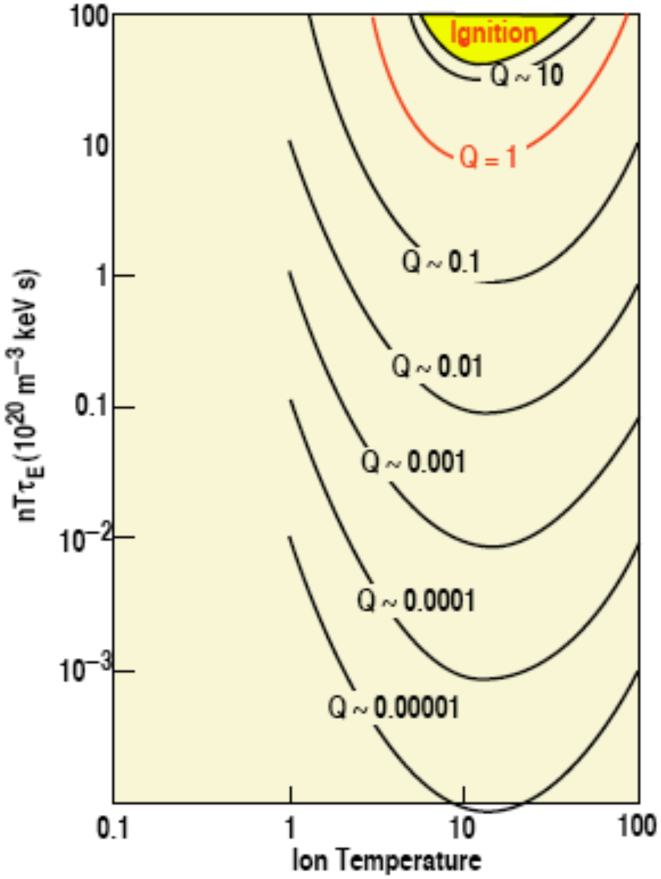
Fusion gain Q

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

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 = ∞	f_α = 100%

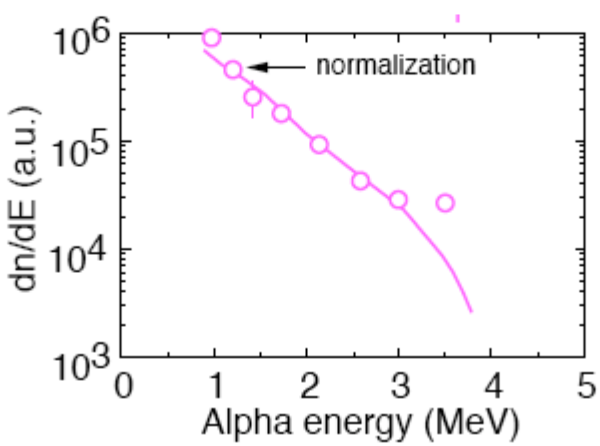


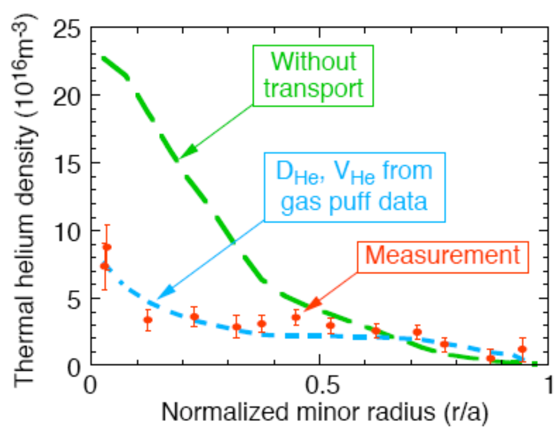
Initial D-T experiments

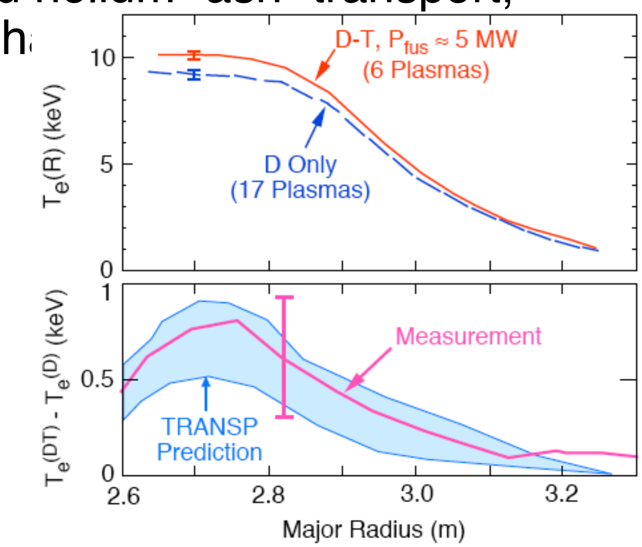
USBPO

- **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), favorable isotope scaling, self heating by α-particles, α-driven instabilities, tritium and helium "ash" transport, tritium retention in walls and dust, safe tritium h



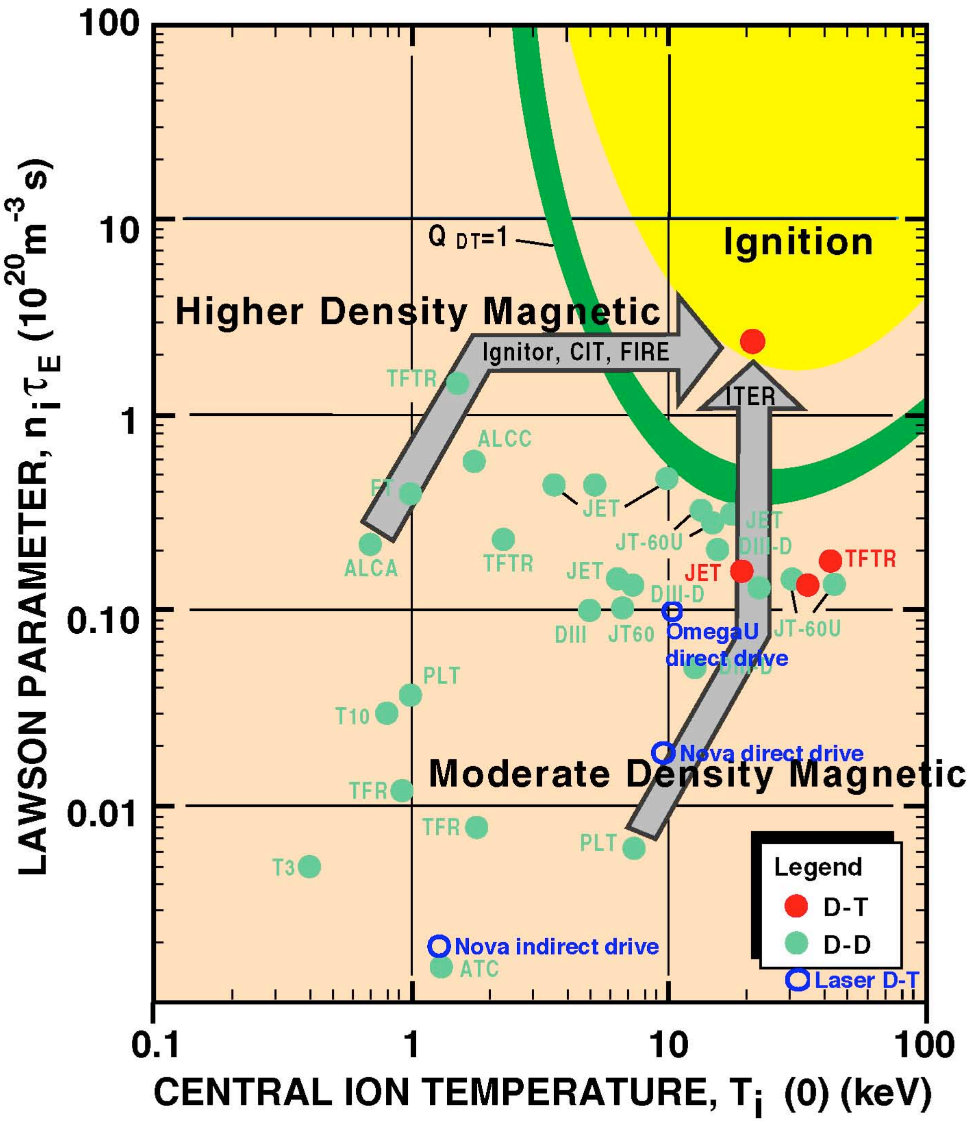




Status of magnetic fusion

USBPO

- **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



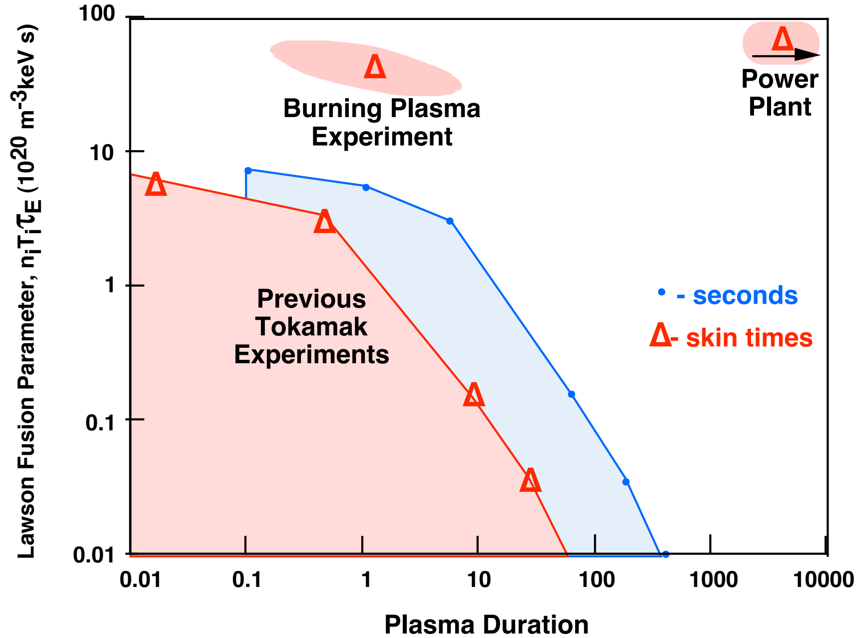
New features in a burning plasma (1)

USBPO

- **Dominant self-heating (exothermic)**
  - 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 a burning plasma experiment

- **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

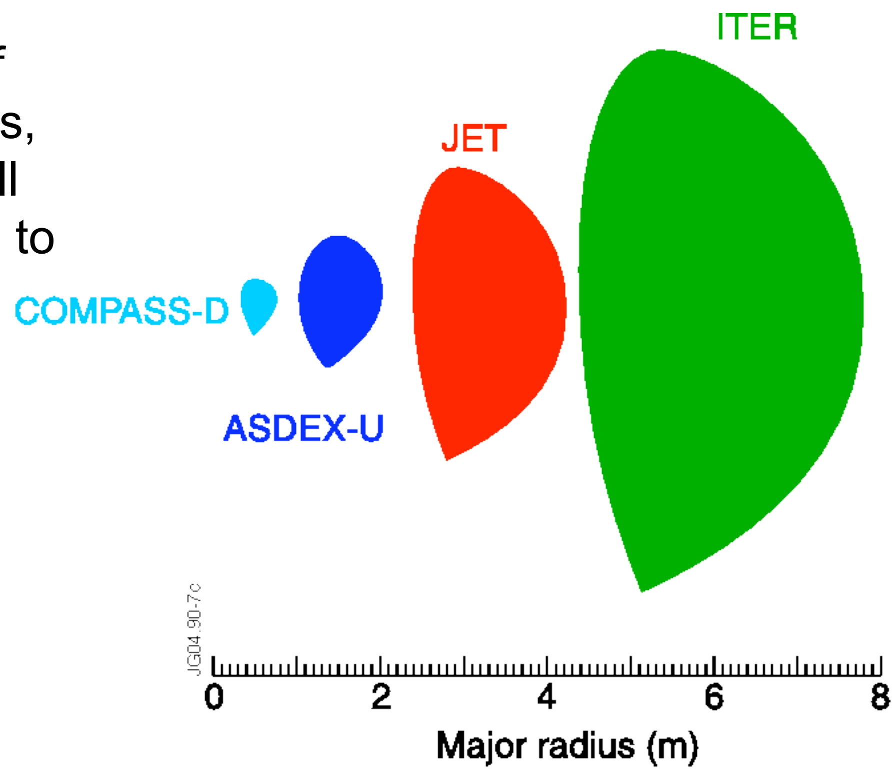
- **Long pulse length**
  - BP experiment should have pulse length long compared to the current redistribution time ($\tau_{pulse} >> \tau_{CR}$) to investigate resistively equilibrated current and pressure profiles in the presence of strong alpha heating



New features in a burning plasma (2)

USBPO

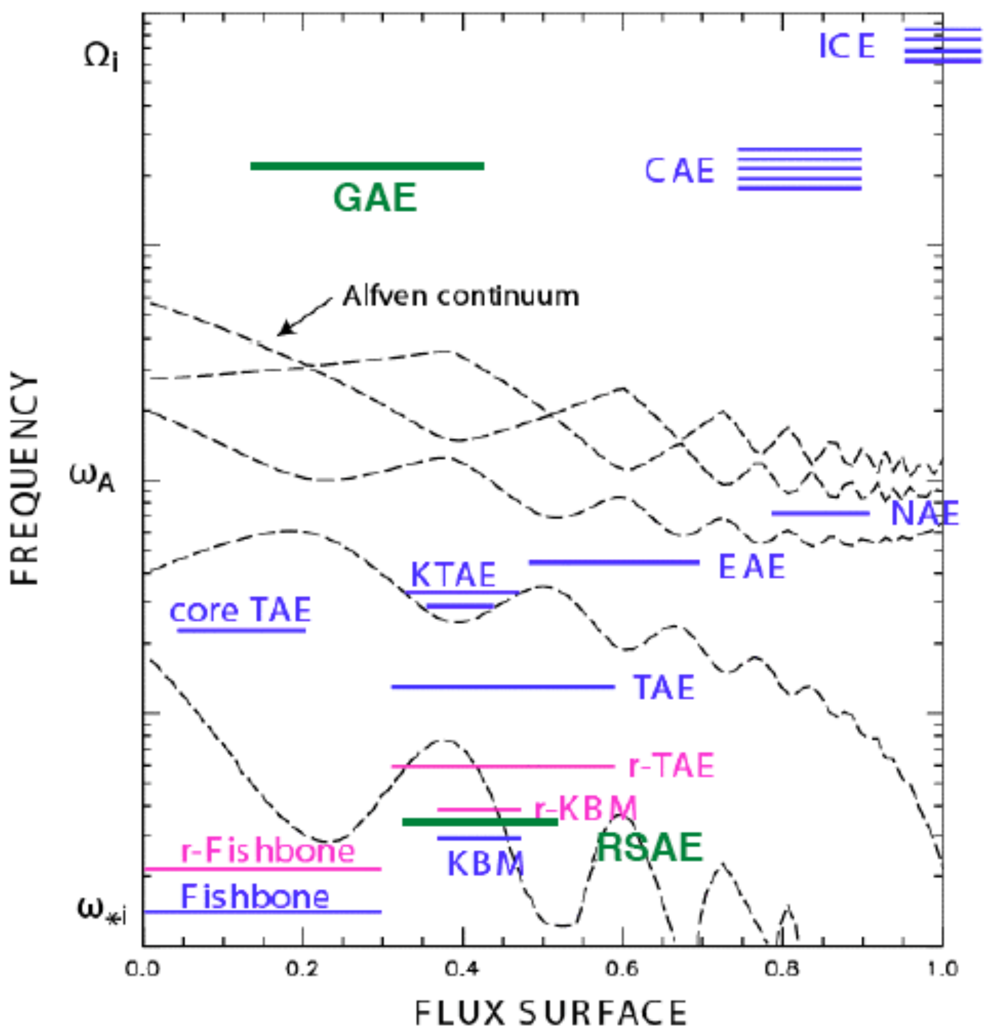
- **Strong coupling**
  - The critical elements in the areas of transport, stability, boundary physics, energetic particles, heating, etc., will be strongly coupled nonlinearly due to the fusion self-heating
- **Size scaling**
  - Due to much larger volume than present experiments, size scaling becomes important for confinement
- **Large population of high-energy alpha particles**
  - Different behavior from thermal ions
  - Affect stability and confinement



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

α particles can excite Alfvén waves

USBPO



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.

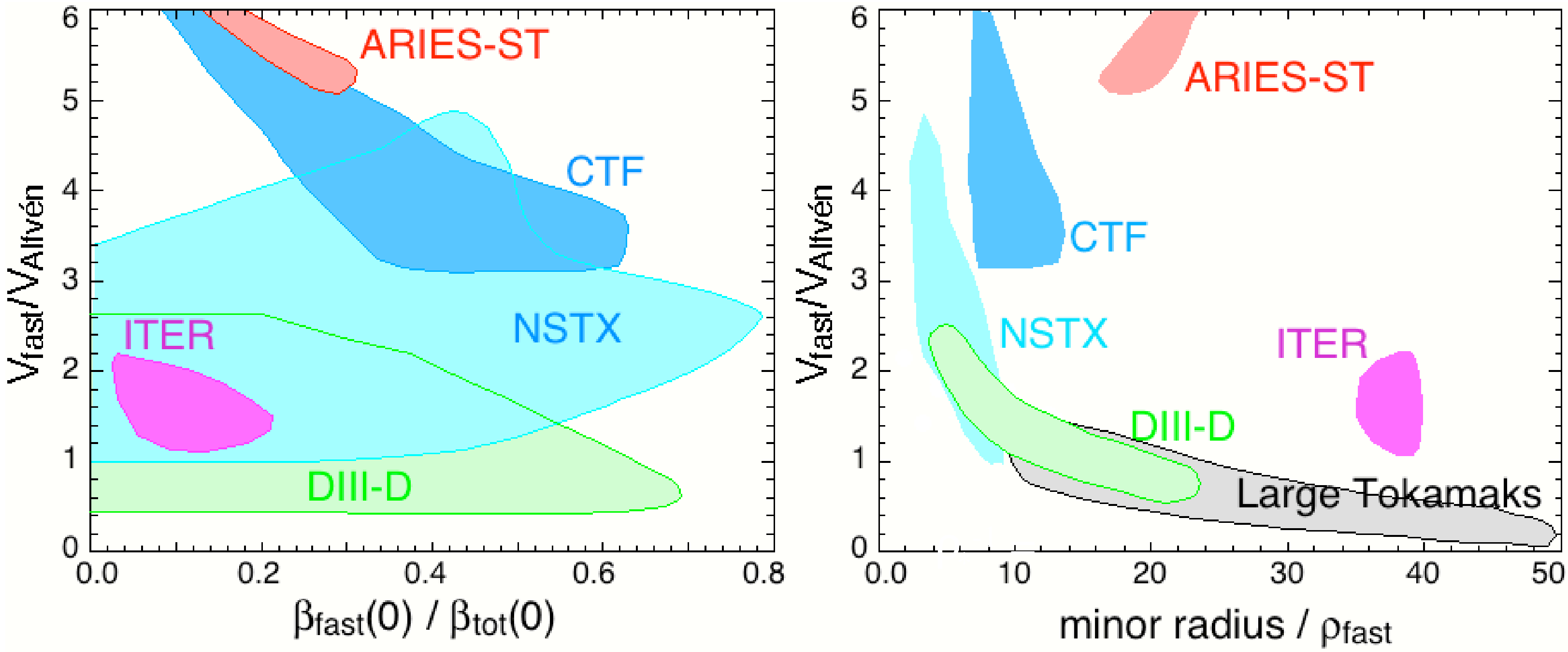
- **Could cause anomalous loss of α's**
  - Reduce self-heating; wall thermal loading

ITER stability to Alfvén eigenmodes

USBPO

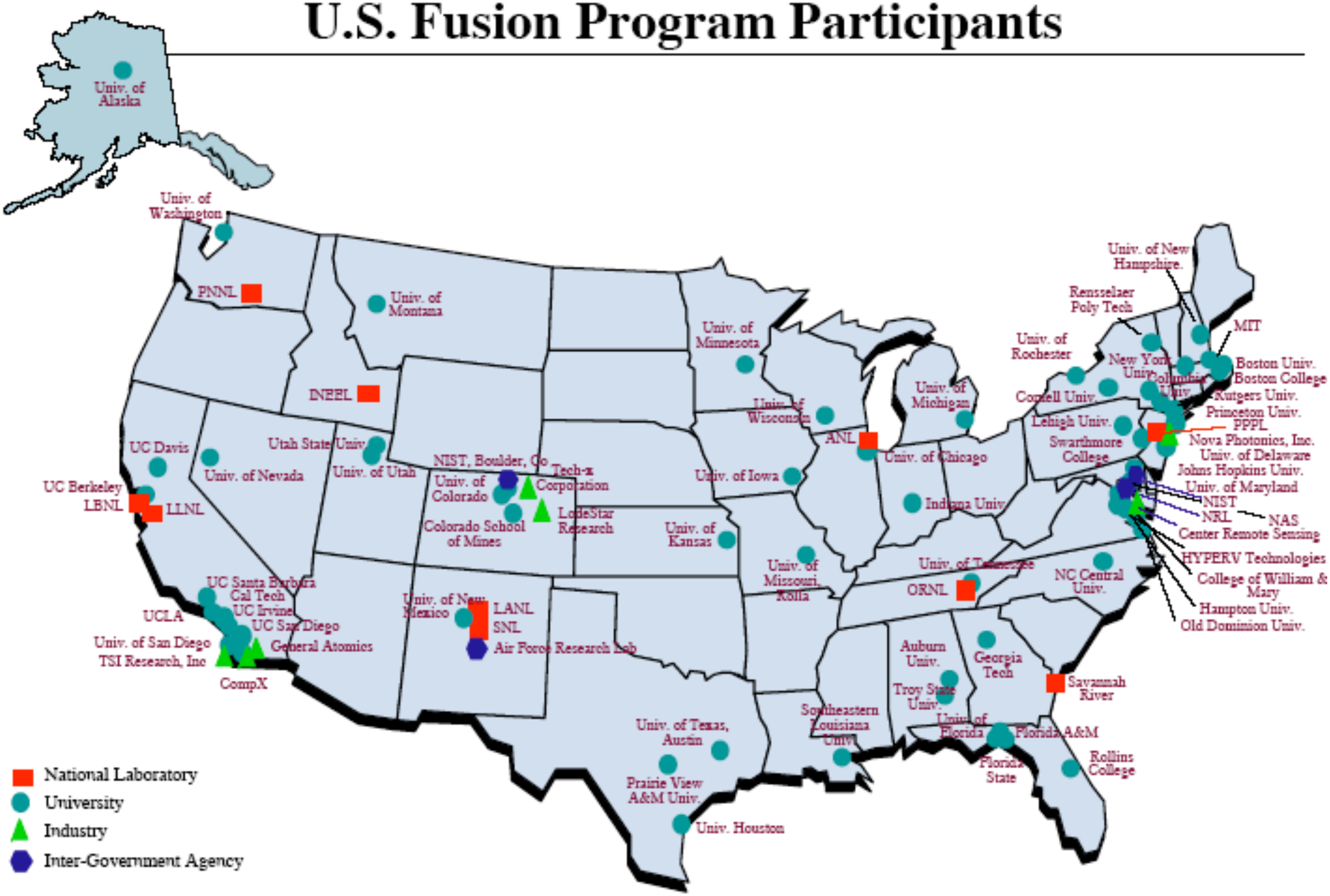
- **Alfvén Mach number** (v_α/v_A) and **pressure** (β_α) for ITER α-particles have similar values as in existing experiments

- However, ITER's **large size** [I.e., small-wavelength (a/ρ_{*fast} >> 1) regime] implies presence of many potentially unstable modes
  - Could cause outward redistribution/loss of α's (domino-effect "avalanche")



LESSON:
Strategize as a united community

U.S. Fusion Program Participants



07/19/06

Community planning exercises

1998 April	Forum for Major Next-Step Experiments (Madison, WI)
1999 June	Fusion Summer Study (Snowmass, CO)
2000 Dec	Burning Plasma Science Workshop I (Austin, TX)
2001 May	Burning Plasma Science Workshop II (San Diego, CA)
2002 July	Fusion Summer Study “Major Next Steps in Fusion” (Snowmass, CO)

Advisory committee assessments

2001 Sept	*Review of Burning Plasma Physics* (FESAC panel report)
2002 Sept	*A Burning Plasma Program Strategy to Advance Fusion Energy* (FESAC panel report)
2003 March	*A Plan for the Development of Fusion Energy* (FESAC panel report)
2004 March	*Fusion in the Era of Burning Plasma Studies: Workforce Planning for 2004 to 2014* (FESAC panel report)
2004 April	*Burning Plasma: Bringing a Star to Earth* (National Research Council, Burning Plasma Assessment Committee)
2005 April	*Scientific Challenges, Opportunities, and Priorities for the US Fusion Energy Sciences Program* (FESAC panel report)
2006 June	*Planning for US Fusion Community Participation in the ITER Program* (USBPO, Energy Policy Act Task Group)

Alignment of the stars

2002 June At a meeting with fusion program leaders, Dr. Raymond Orbach (Director, DOE Office of Science) noted that "the Fusion stars are aligned if we are ready for the energy route" because he likes fusion, John Marburger (OSTP) likes fusion, President Bush and Prime Minister Tony Blair like fusion, and Congress likes fusion.

2003 Jan President Bush announced that the US would rejoin ITER.

2003 Nov *Facilities for the Future of Science: A Twenty-Year Outlook* (DOE Office of Science) – listed ITER as the #1 priority.

Recent years Soaring domestic energy prices, geopolitical concerns about fossil fuel availability, climate change.

2005 Dec *Rising Above The Gathering Storm: Energizing and Employing America for a Brighter Economic Future* (report of the Augustine commission, National Academies of Science).

Leads to American Competitiveness Initiative and a presidential proposal for large increases in science and technology R&D budgets.

2007 Feb Bipartisan support for science in FY07 Continuing Resolution budget.

LESSON:
Deciding on the site requires patience

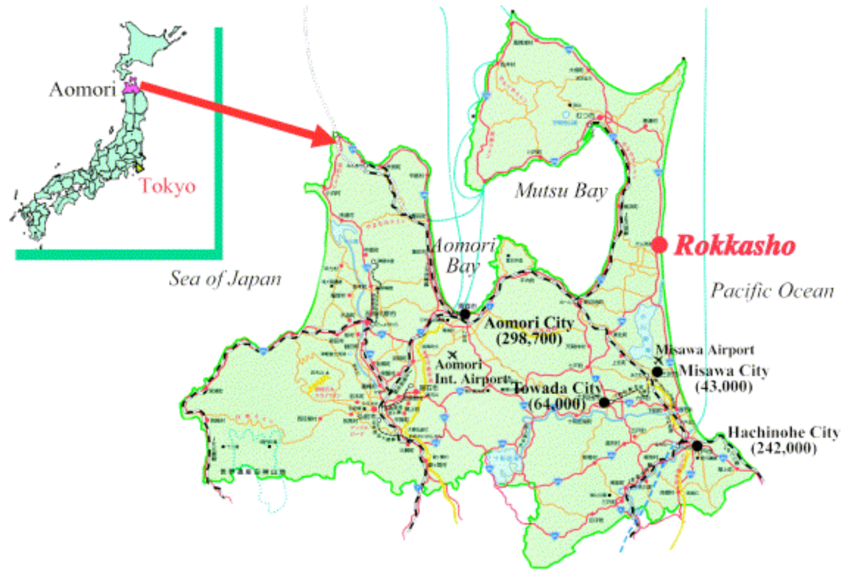
Time line to host ITER

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

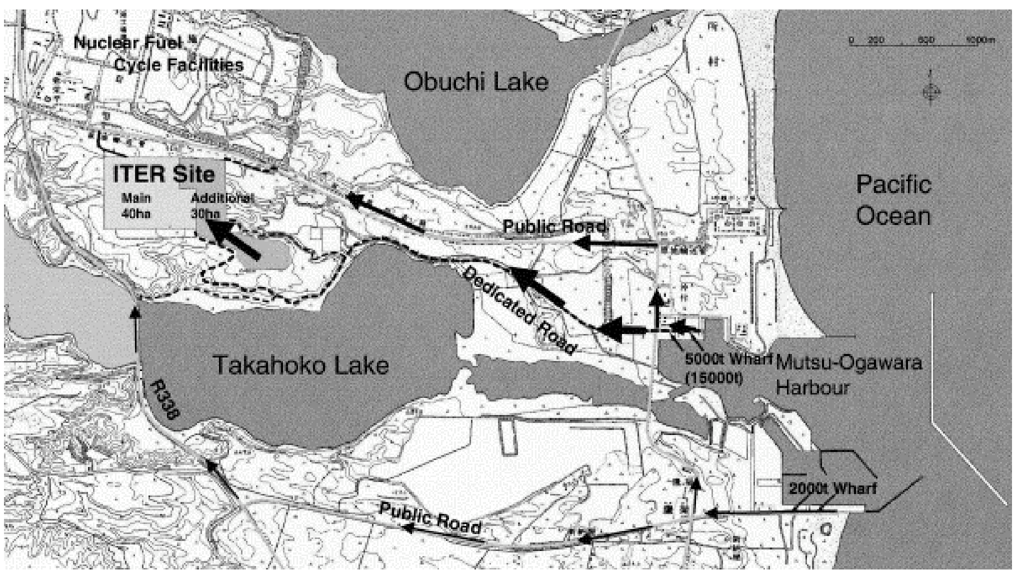
Japanese proposed site

USBPO

- Rokkasho-mura, in Aomori Prefecture (northern part of the main island of Japan)
- Located in Mutsu-Ogawara Development Area, close to nuclear fuel cycle facilities.

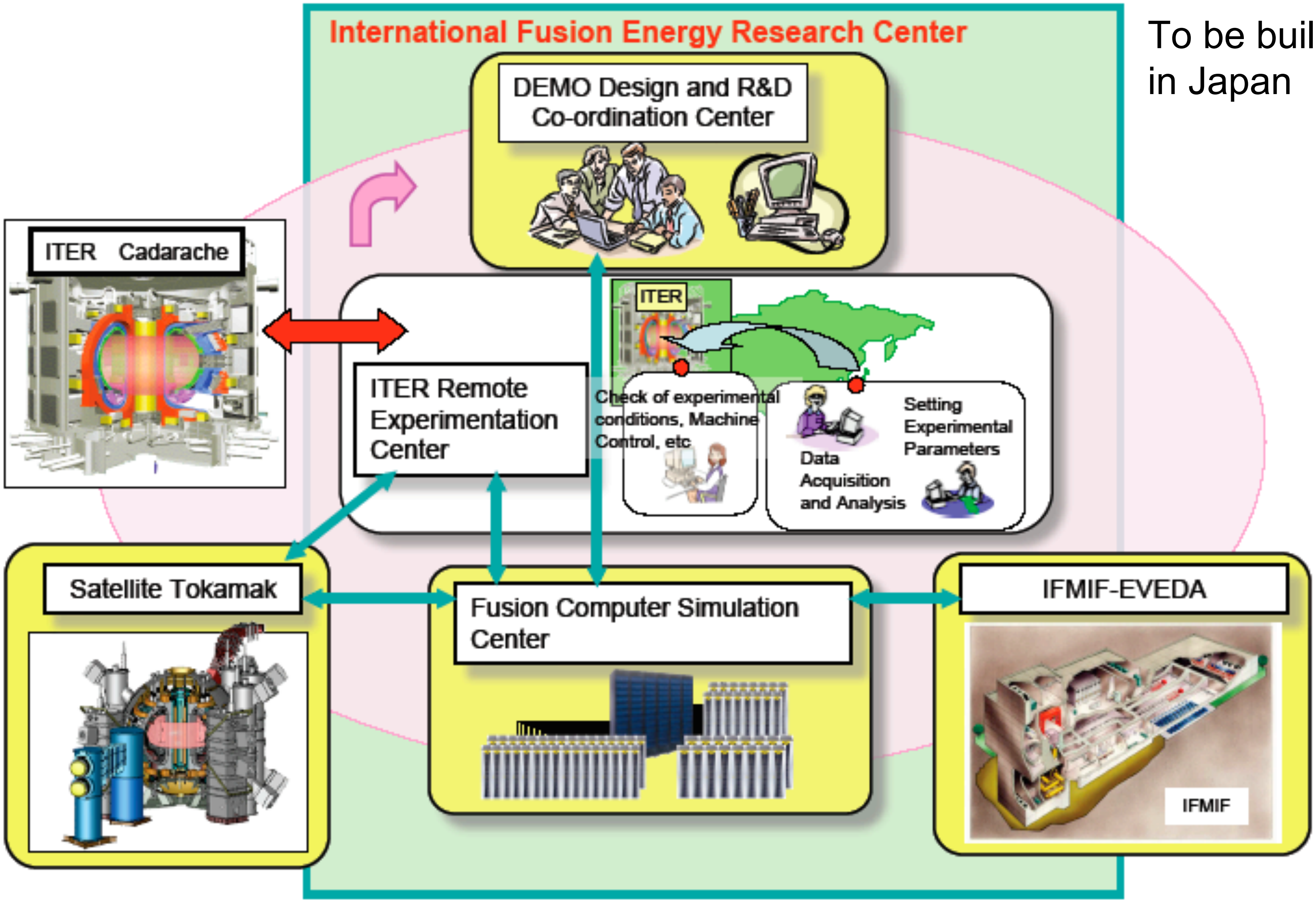


(a) Aomori Prefecture



(b) Rokkasho Area

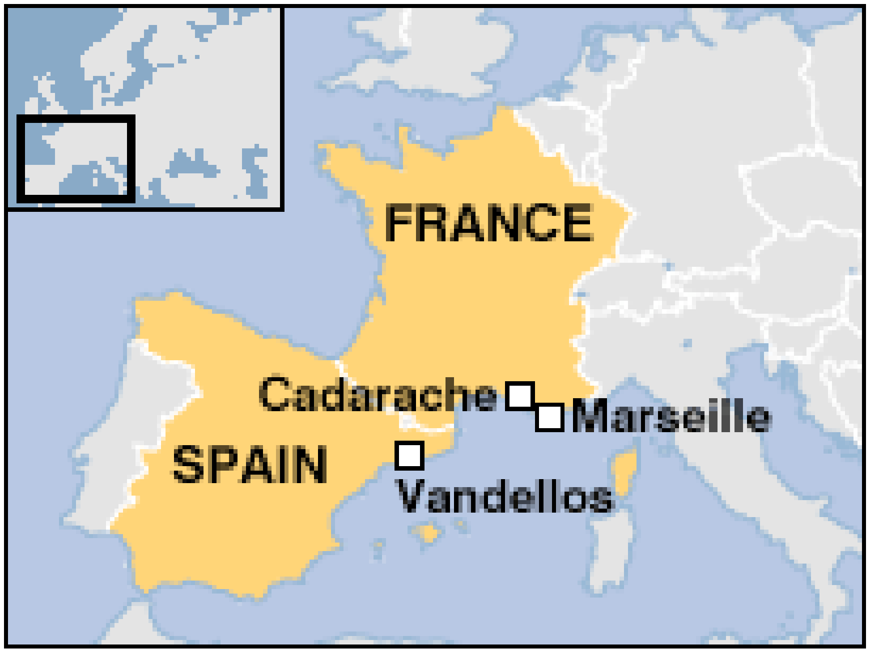
EU-Japan Broader Approach



To be built in Japan

ITER—final location

USBPO



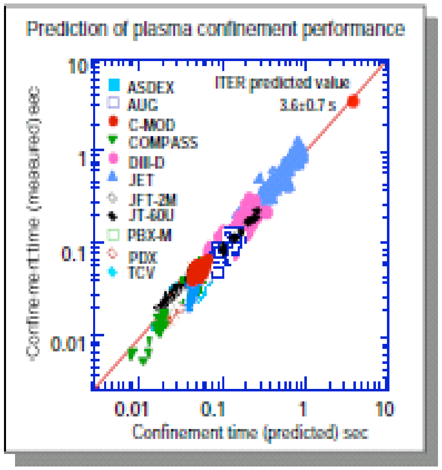
- To be built in Cadarache, France
  - Near Marseille (in Provence-Alpes-Cote d'Azur region)
  - First plasma operation in 2016, D-T operation in 2021

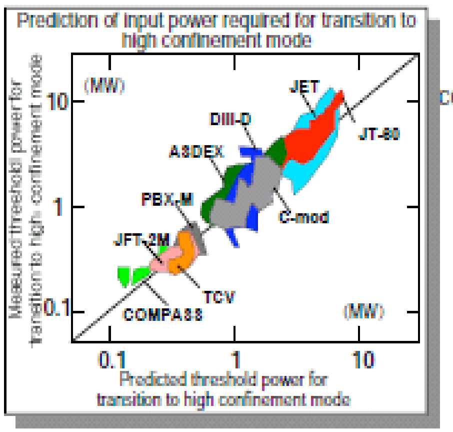
LESSON:

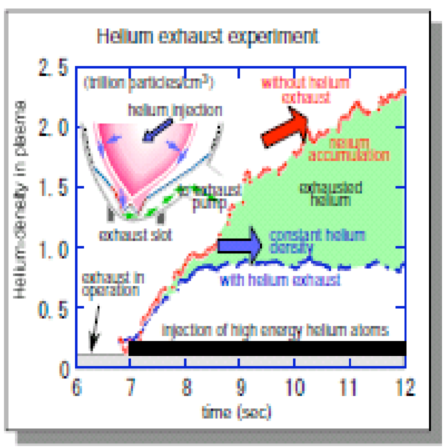
Have a clear mission for the project

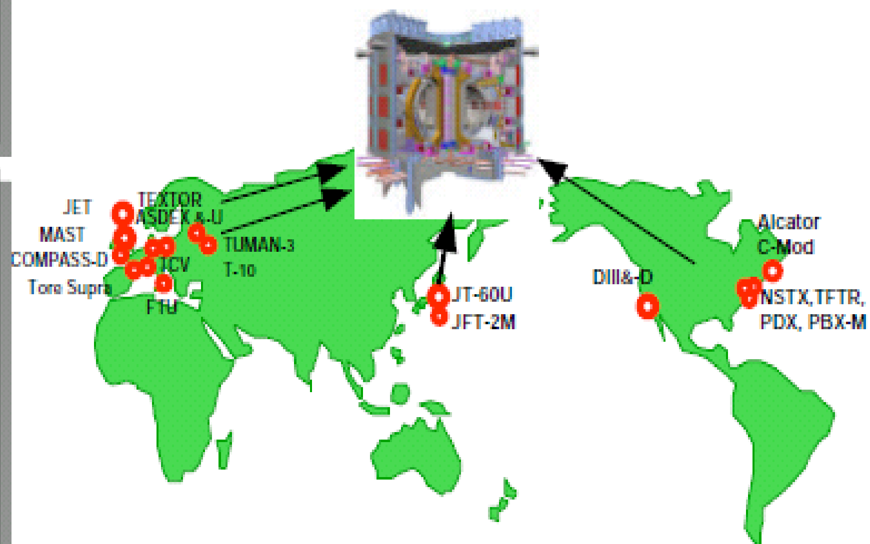
Attachment 6 Achievements of ITER Physics R&D

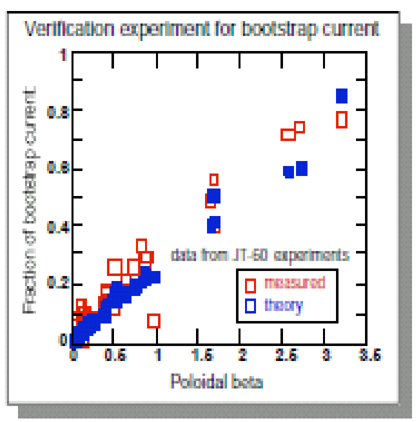
Integrate experimental results of tokamaks from all over the world to establish physics basis for plasma performance of ITER

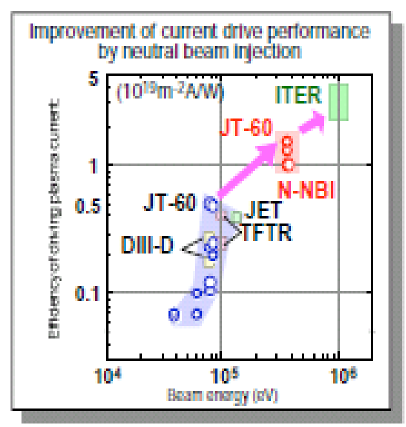


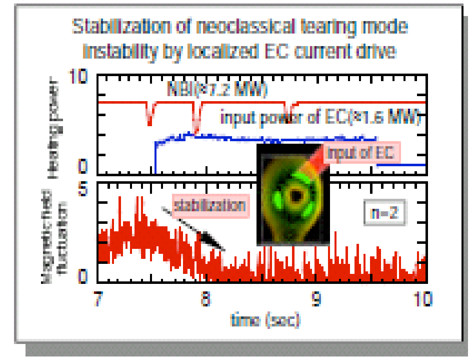


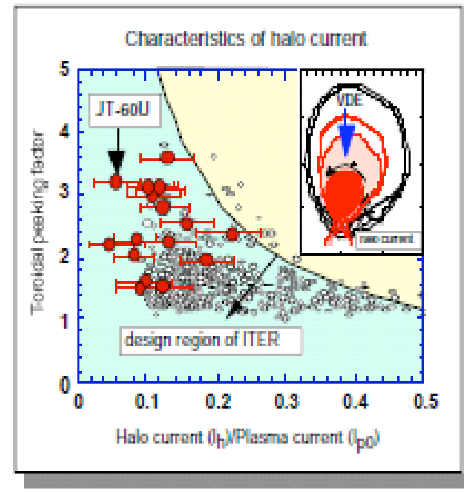


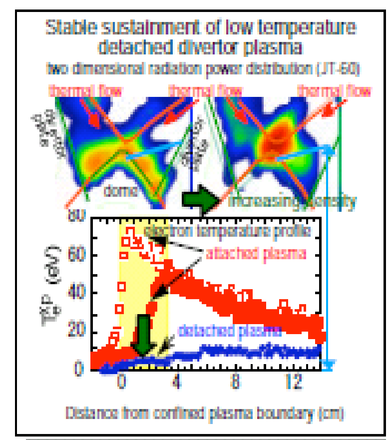












ITER design goals

USBPO

Physics:

- ITER is designed to produce a plasma dominated by α-particle heating
- produce a significant fusion power amplification factor ($Q \geq 10$) in long-pulse operation
- aim to achieve steady-state operation of a tokamak ($Q = 5$)
- retain the possibility of exploring 'controlled ignition' ($Q \geq 30$)

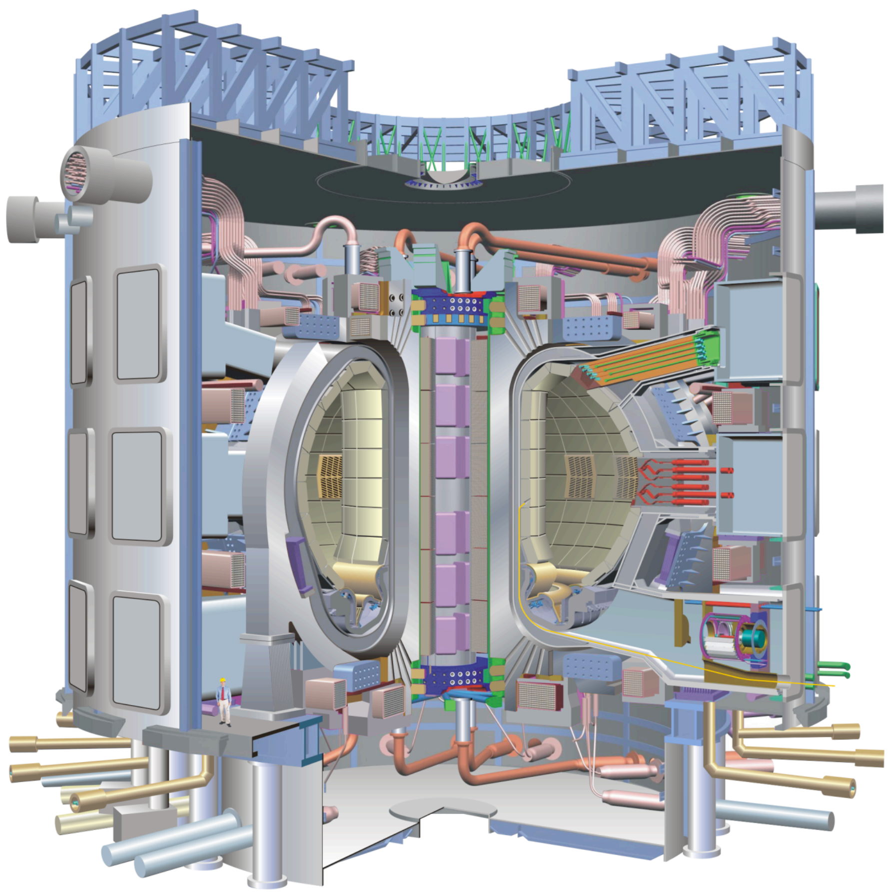
Technology:

- 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

ITER strategy

USBPO

- **Conservative design**
  - Maintain flexibility to use advances
- **Step-wise research program:**
  - HH, DD, DT, I_p, heating power, etc.
- **Flexibility**
  - Wide operation space, replaceable divertor and first wall, heating and current drive
- **Diagnostics**
- **Experimental control tools:**
  - ECCD (for NTM control)
  - Saddle coils and H&CD (for RWM control)
  - Current drive (for TAE control), gas injection and neural network (for disruption control)
  - Pellet injection (for ELM control)



Research agenda for ITER

USBPO

Research Agenda for ITER

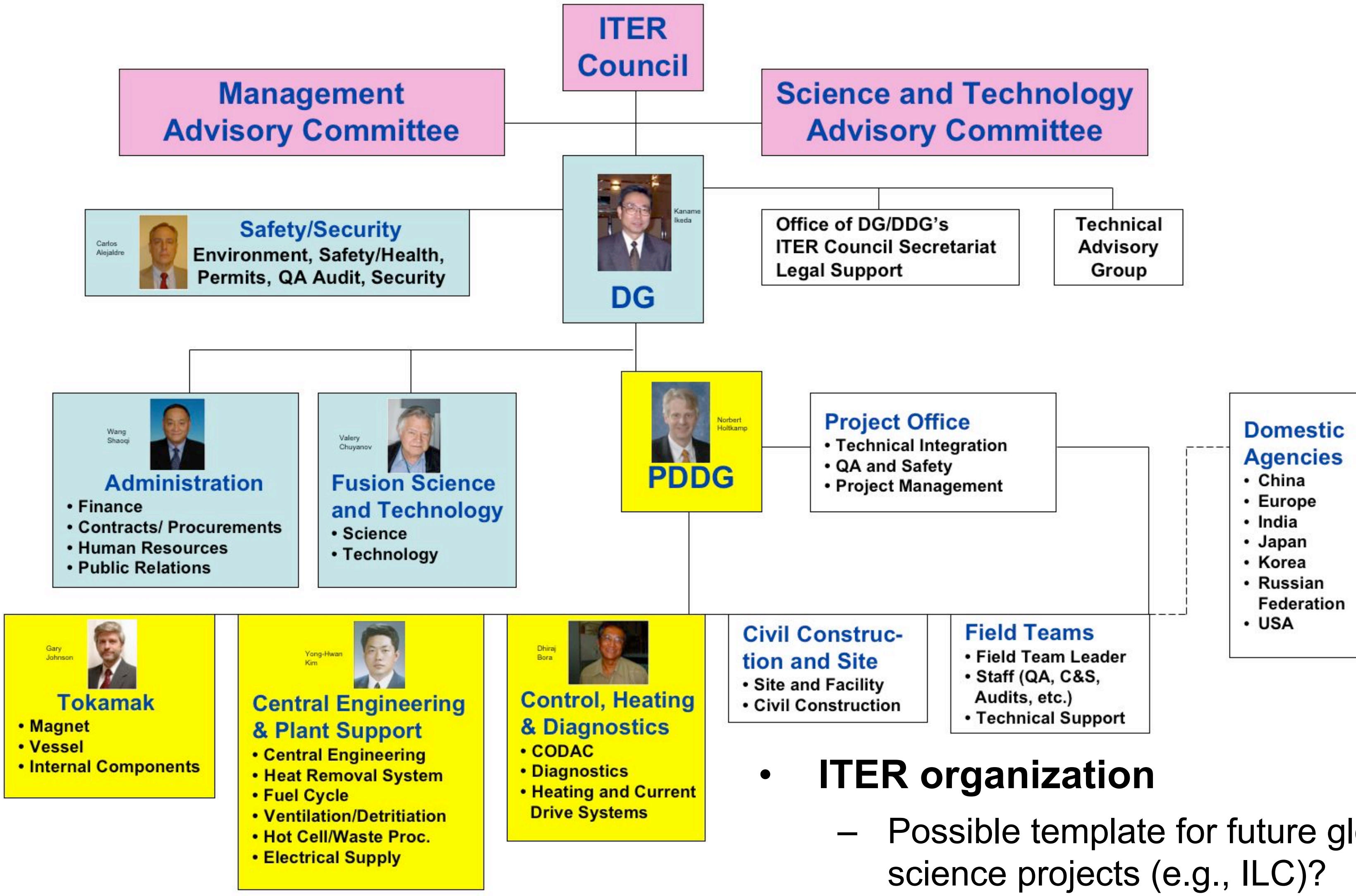
Fusion Science Campaigns	2005–2010	2010–2015	2015–2020	2020–2035
Phases of ITER Development	DESIGN SUPPORT	PRE-OPERATIONS	COMMISSIONING First Plasma H, D	HIGH GAIN DT DT MODEST GAIN DT LONG PULSE, NONINDUCTIVE FUSION TECHNOLOGY TESTS
The Integrated Burning Plasma System	High energy gain long pulse inductive scenarios for ITER Develop integrated plasma control	High energy gain steady-state scenarios for ITER Develop integrated plasma model		Achieve high gain long pulses in ITER Achieve modest gain steady-state capability Optimize gain in noninductive plasmas High duty cycle operation in burning plasma Study alpha heating effects Establish integrated model on ITER Control complex, burning plasmas in ITER
Macroscopic Plasma Physics	Design suppression coils for pressure limiting instabilities	Develop disruption avoidance and mitigation methods Specify rf systems to stabilize confinement limiting instabilities	Mitigate disruptions in ITER Suppress confinement limiting instabilities in ITER	Stabilize pressure limiting instabilities in ITER
Waves and Energetic Particles	Resolve rf and microwave issues Investigate energetic particle instabilities	Specify Upgrade of H&CD systems for ITER Develop alpha particle diagnostics		Achieve 100% noninductive current drive in ITER Understand instabilities driven by alpha particles
Multi-Scale Transport Physics	Understand electron heat transport Develop turbulence diagnostics for ITER Decide how to spin the ITER plasma Understand transport barriers			Understand transport in the burning plasma regime Control how the ITER plasma spins Use transport barrier physics to achieve high gain in ITER
Plasma-Boundary Interface	Understand edge pedestal physics Identify approaches to minimize the impact of edge instabilities Understand role of density in divertor physics		Achieve a sufficient edge pedestal for high gain Implement edge instability suppression in ITER Understand how to project edge physics	
Fusion Engineering Science	Study first wall material options Participate in a test blanket module program Develop advanced fueling for ITER Support superconducting magnet construction Develop rf sources and wave launchers Develop diagnostic techniques		Handle unprecedented power exhaust Provide central fueling in ITER Assess the performance of power-plant scale magnets Use rf systems to control the plasma	Operate with sufficiently low tritium inventory Deploy, operate, study test blanket modules in ITER Operate very long pulses for blanket test Deploy turbulence and alpha diagnostics

LESSON:

Organization can be as much of a challenge as science

ITER—international organization

USBPO



- **ITER organization**
  - Possible template for future global science projects (e.g., ILC)?

ITER top leadership

Director-General:

Dr. Kaname Ikeda

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

Principal Deputy Director-General & Project Construction Leader

Dr. Norbert Holtkamp

- Research Group Head, S-Band Linear Collider, DESY
- Division Director, Spallation Neutron Source, ORNL

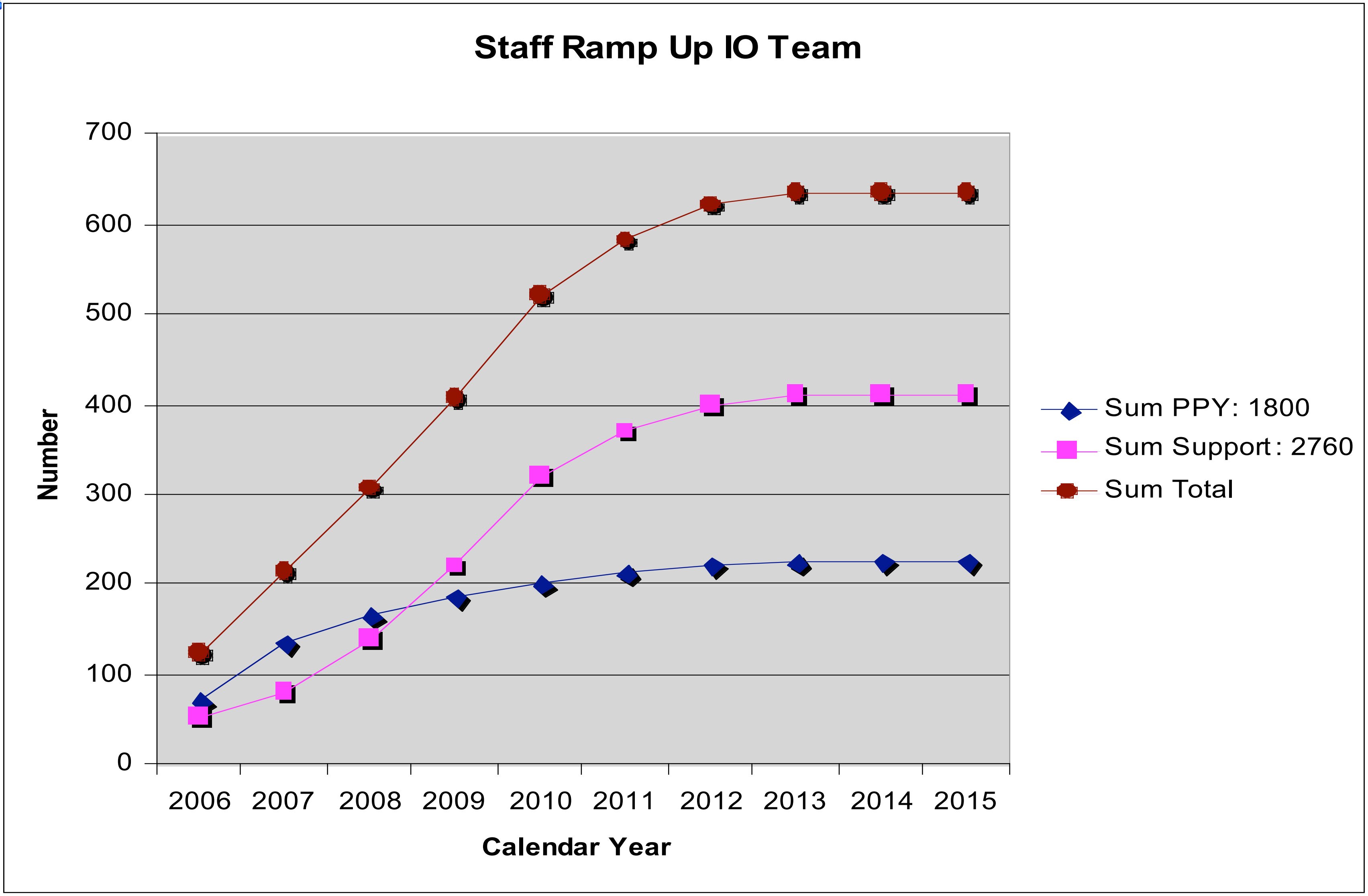
US support to the ITER international organization (IO)

US secondees
(as of 3/07)

	IO Staff Support (Employees and Secondees)	Cash Contribution*
FY 2007:	~ 20 man years	$6M
FY 2008:	~35 man years	$20M
FY 2009:	~40 man years	$30M

ITER staffing projection

USBPO



Other challenges

- **Communication**
  - Embrace modern 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**
  - Public relations and educational material, movies, photos, brochures, web site, posters, …

LESSON:

Carefully determine the cost and how to pay for it

Cost of ITER

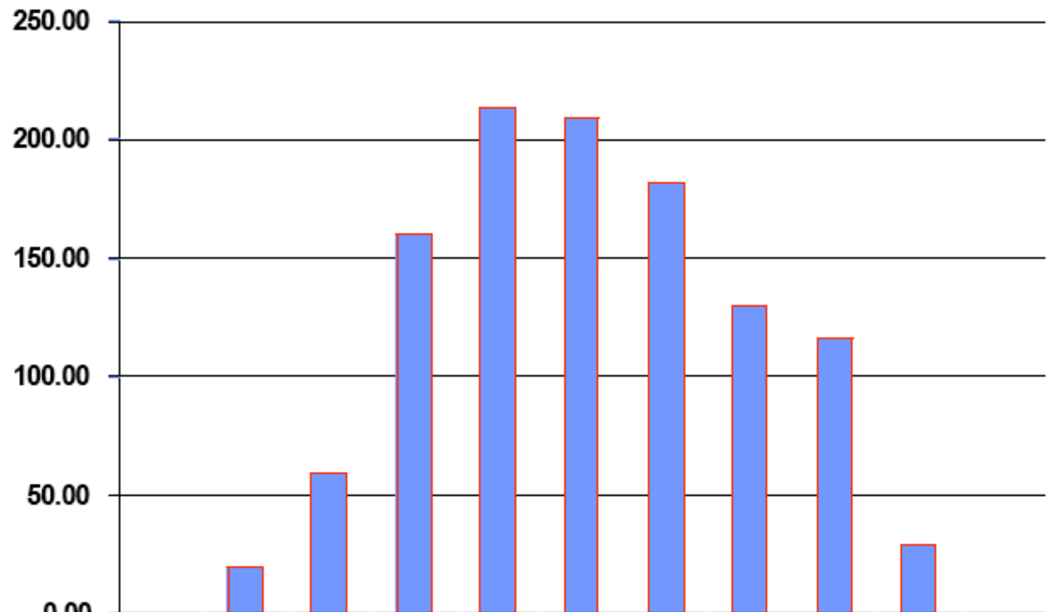
USBPO

- **ITER EDA design was completed in 1996**
  - US withdrew from ITER in 1998 due to projected cost
- **ITER FEAT team (led by Dr. R. Aymar, now CERN director) redesigned ITER and reduced cost to 4.57B euros (at 2000 prices)**
  - US re-entered ITER project in 2003
  - In-kind contributions calculated in units of IUA ("international unit of accounting"): 1 IUA = $1,000 (in 1989 currency value)
- **Lehman costing of the US in-kind contributions to ITER construction led to congressional $1.122B cap on the US share**
  - US costing includes contingency and labor costs; sometimes not included in costing done by other ITER partners
  - Project management culture is needed: planning & scheduling, progress tracking, financial reporting, cost control strategy, risk mitigation, …

Paying for ITER

USBPO

- **5/11ths from European Union as the host ITER partner**
- **1/11th in-kind contribution from each of the other six international partners (China, India, Japan, Korea, Russia, US)**
  - India joined as the 7th ITER partner in late 2005; hence there is now a 10% contingency
- **US share**
  - Capped at $1.122B
  - Managed by US ITER Project Office (ORNL)
  - Funding profile roll-off starts in 2011



	FY05	FY06	FY07	FY08	FY09	FY10	FY11	FY12	FY13	FY14
Budget request	0.00	19.32	60.00	160.00	214.50	209.32	181.96	130.00	116.90	30.00

ITER construction cost-sharing

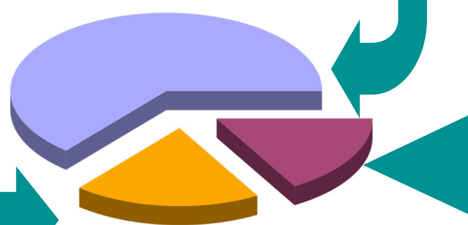
USBPO

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**

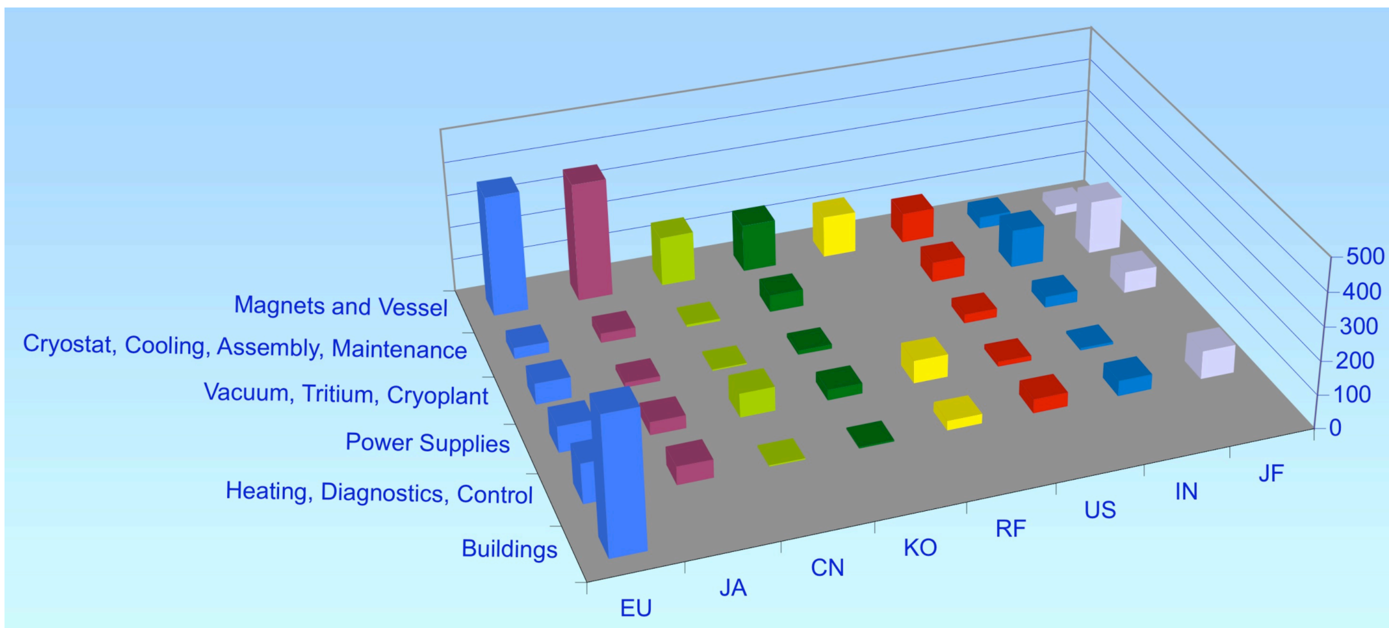


Overall cost sharing:
EU 5/11, Others 6 Members 1/11 each, Overall contingency up to 10% of total.

B

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

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



LESSON:

Coordinate, facilitate, and promote burning plasma research in the US domestic program

Overseeing the US burning plasma effort

USBPO

DOE Office of Fusion Energy Sciences
R. Fonck, SC Assoc Director
Research Division
ITER and International Division

US ITER Project Office
N. Sauthoff, Director

US ITER Chief Scientist
(USBPO Director)

US ITER Chief Technologist
(VLT Director)

USBPO Council
(12 members)

USBPO Directorate
Director
Deputy Director
Ass't Director for ITER Liaison
Research Committee

US Burning Plasma Organization

Topical Group MHD Stability	**Topical Group** Confinement/Transport	**Topical Group** Boundary	**Topical Group** Wave Interactions	**Topical Group** Energetic Particles
Topical Group Integrated Scenarios	**Topical Group** Fusion Engineering	**Topical Group** Modeling/Simulation	**Topical Group** Operation/Control	**Topical Group** Diagnostics

ITER-related research activities

- **US Burning Plasma Organization (USBPO)**
  - Integrated on national level with the International Tokamak Physics Activity (ITPA) expert topical groups
  - Coordinates with US Virtual Laboratory for Technology
- **FY07 ITER Physics Tasks**
  - 76 submitted, 14 selected by USBPO to work on (work is underway)
- **ITER design review**
  - Last baseline design was established in 2001; this is now being updated
  - US scientists submitted 13 Issue Cards
  - ITER set up 8 Working Groups with members from the 7 partner teams
  - US experts for the “urgent issues” have been identified, and program managers have analyzed impacts of redirecting personnel effort; this activity is off-project (i.e., subsidized from domestic program budget)
  - “Baseline Design 2007” to be submitted to ITER Council Nov. 29, 2007

Example: Integrated analysis of RWM, ELM, and error field coils for ITER

USBPO

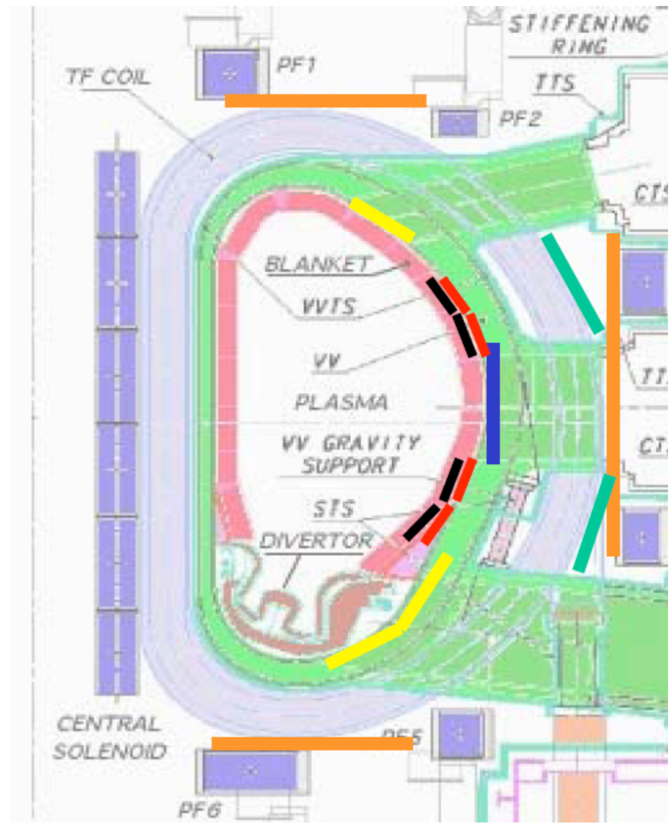
Macroscopic Stability USBPO Topical Group

- **Questions:**
  - Is there a single magnetic-field coil set that can provide good control of Edge Localized Modes, error fields, and Resistive Wall Modes in ITER?
  - If it exists, what are the I, V, power/cooling requirements for such a coil set?

Upper/lower port plug coils

(#2 and #6 are different from original design

1. Error field correction coils
2. Coils on inner vessel surface
3. Coils around blanket modules
4. Mid-plane port-plug coils
5. On TF, above/below mid-plane
6. Coils on upper/lower port plugs

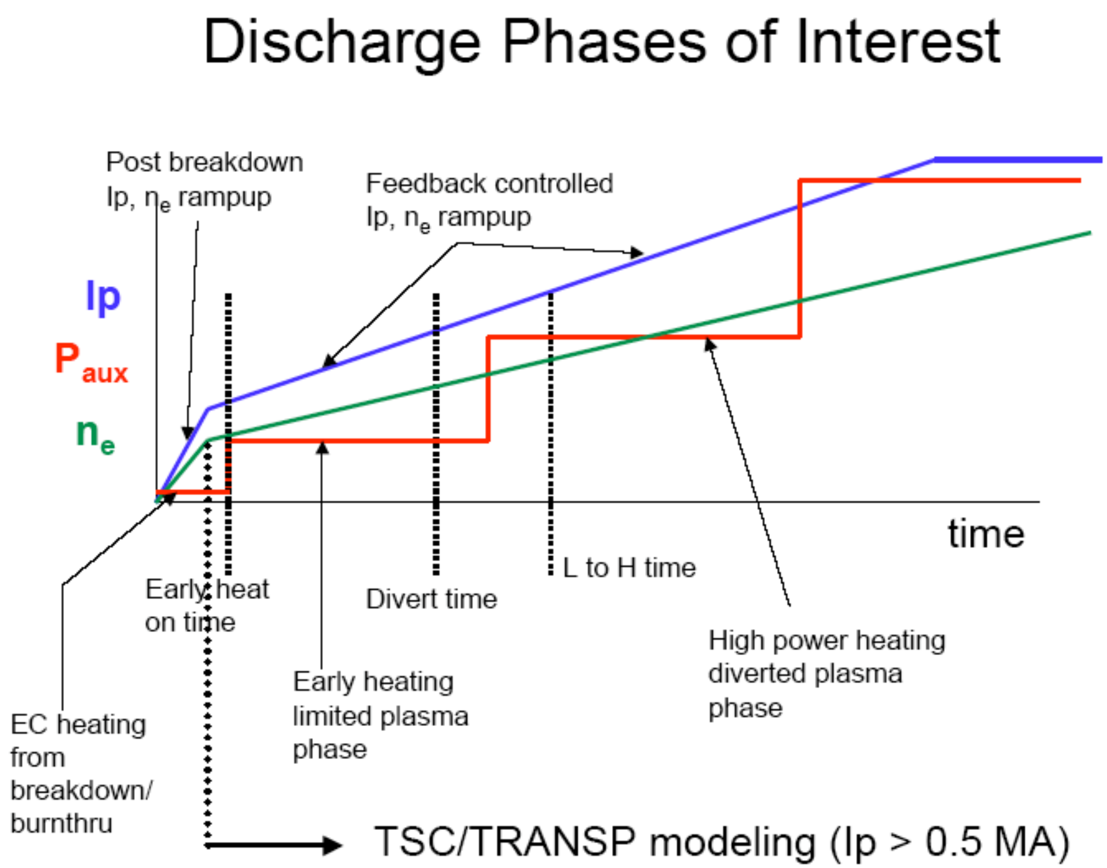


Example: Startup flexibility for ITER

USBPO

Integrated Scenarios USBPO Topical Group

- **Main issue**
  - Can ITER produce target plasma suitable for advanced regimes (hybrid, steady-state)?



- **Objective:** Demonstrate range of safety factor (current) profiles that can be produced using:
  - heating/CD timing
  - density ramping
  - divert time
  - L-H mode transition time

Example: Alpha particle/fast ion issues for ITER

USBPO

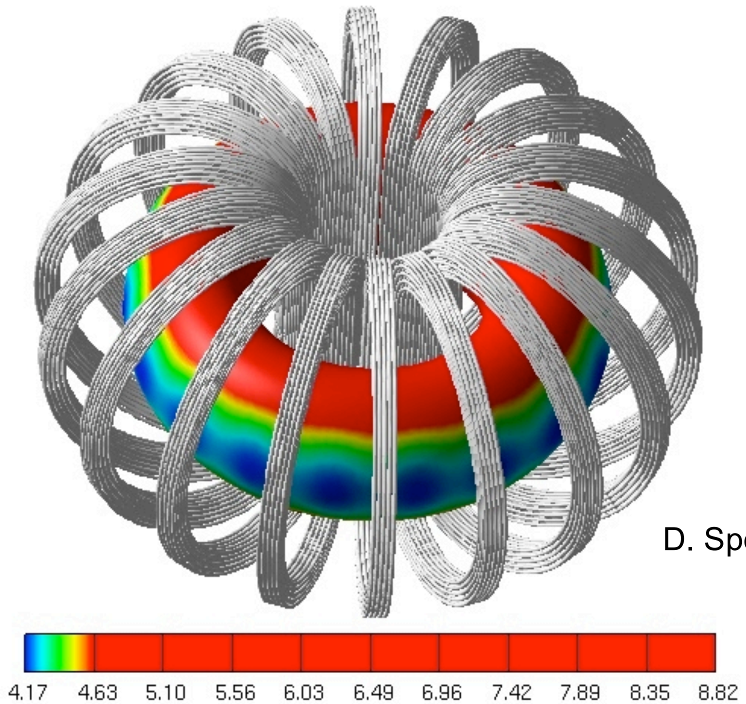
Energetic Particles USBPO Topical Group

Activity #1:

- Quantify flux and localization of fast ion loss in ITER in presence of ripple and Alfvén eigenmodes

Activity #2:

- Assess capabilities and needs in fast ion and Alfvén eigenmode diagnostics



D. Spong

- **ITER β=0 equilibrium with TF ripple**
  - Finite beta analysis needs PF currents
  - Include ferritic inserts

FINAL LESSON:
Be prepared to learn more lessons

References for burning plasmas

USBPO

- *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)

- *Plasma Physics and Fusion Energy*, J. P. Freidberg (Cambridge Univ Press, 2007)

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

ACKNOWLEDGEMENTS: M. Bell, D. Campbell, R. Fonck, R. Hazeltine, G. Janeschitz, G. Navratil, N. Sauthoff, E. Synakowski, and USBPO team