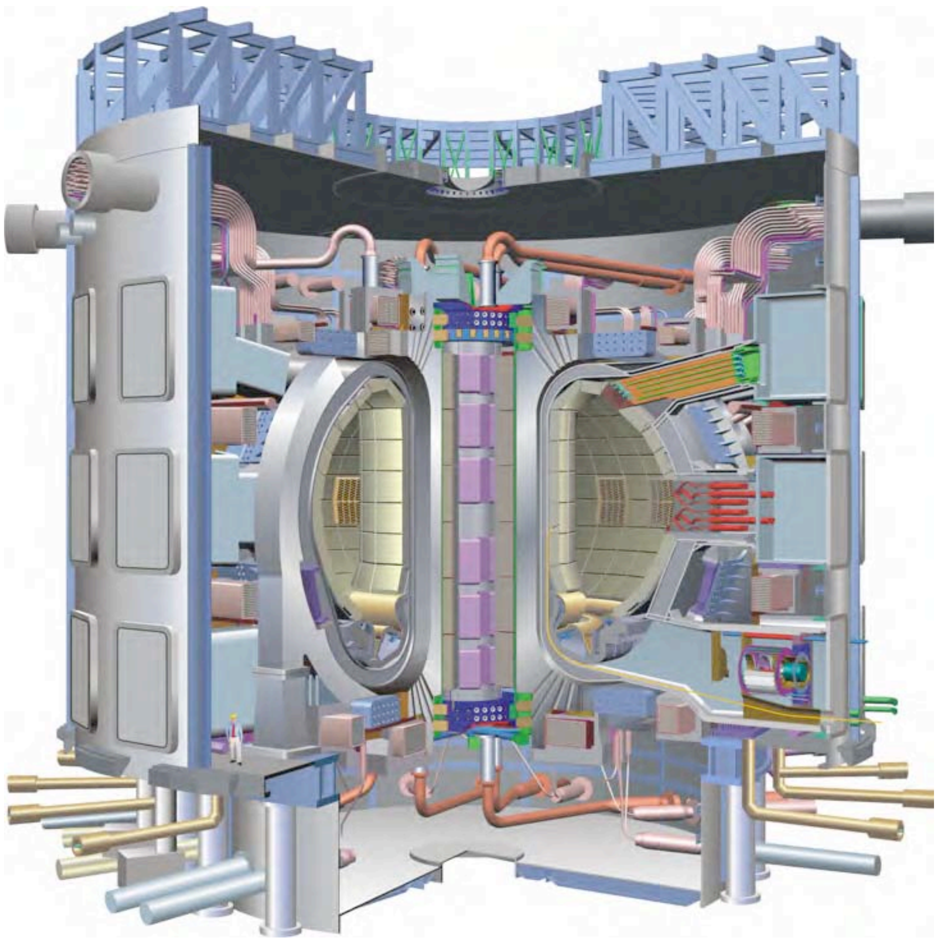
Nuclear Fusion:
ITER Project Update

Demonstrating the Scientific and Technological Feasibility of Magnetically-confined Fusion Power



Ned Sauthoff

Director, US ITER Project

DOE Princeton Plasma Physics Lab

EFI Members' Conference

Omni Orlando, Orlando Florida

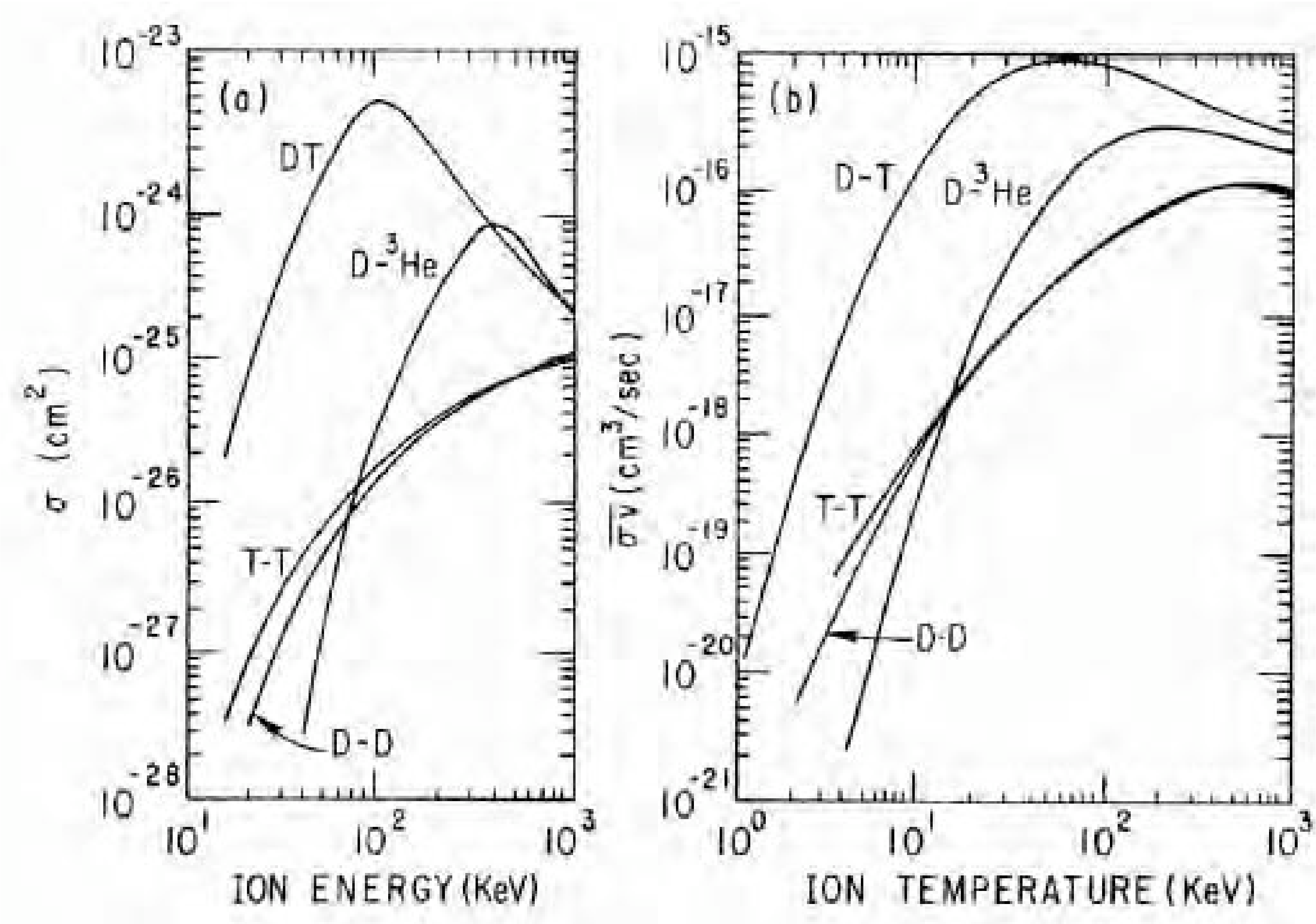
February 6 - 8, 2006

Magnetic Fusion Research is a World-wide Endeavor…

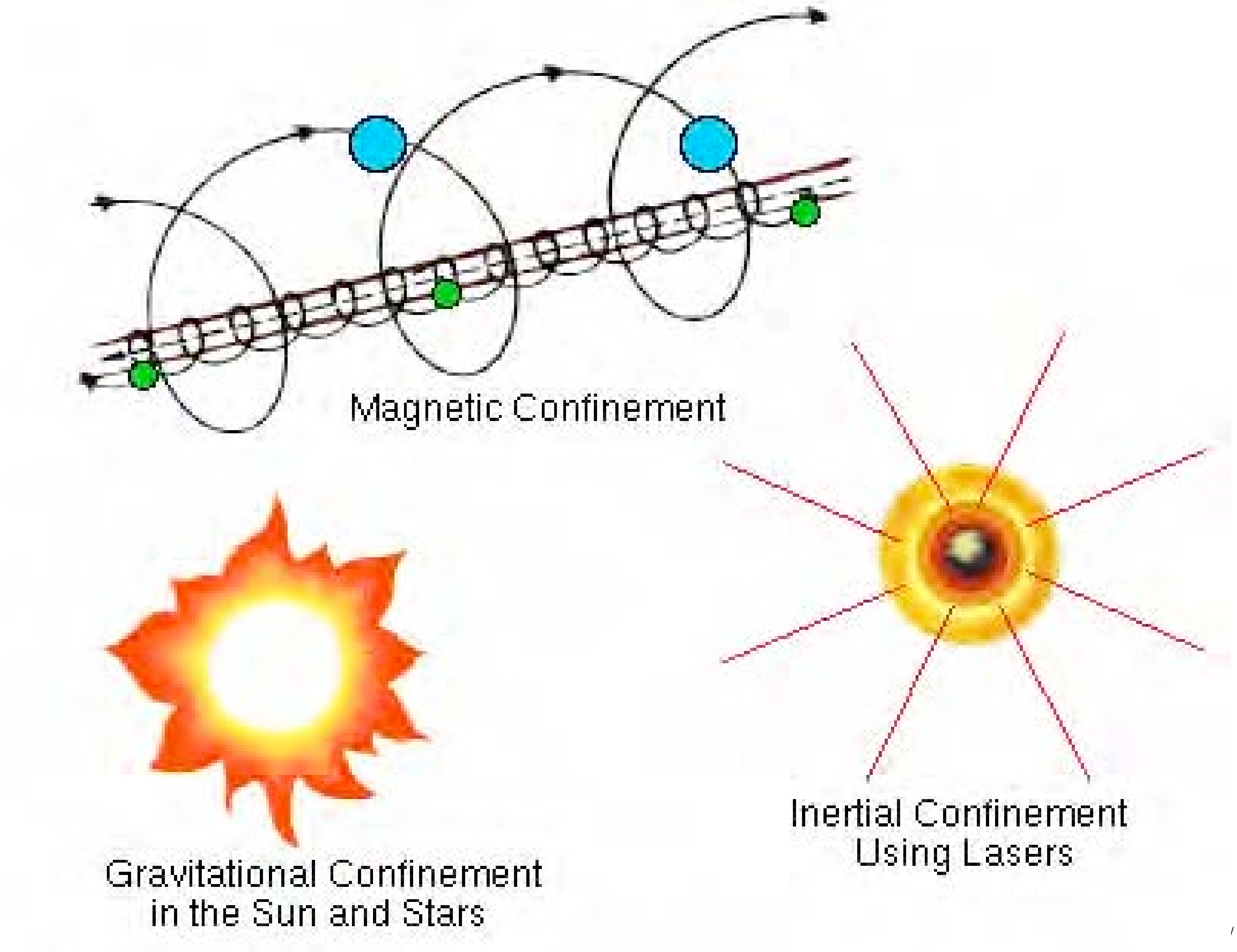
Roadmap

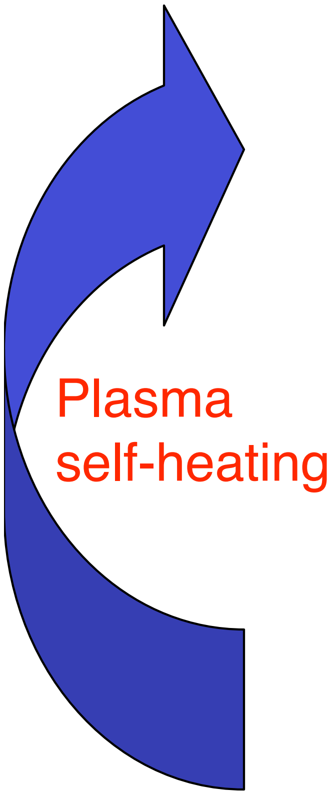
- **Overview of fusion and magnetic confinement systems**
- **Demonstrating the scientific and technological feasibility of fusion power through ITER**
  - Technical development
  - Organizational development

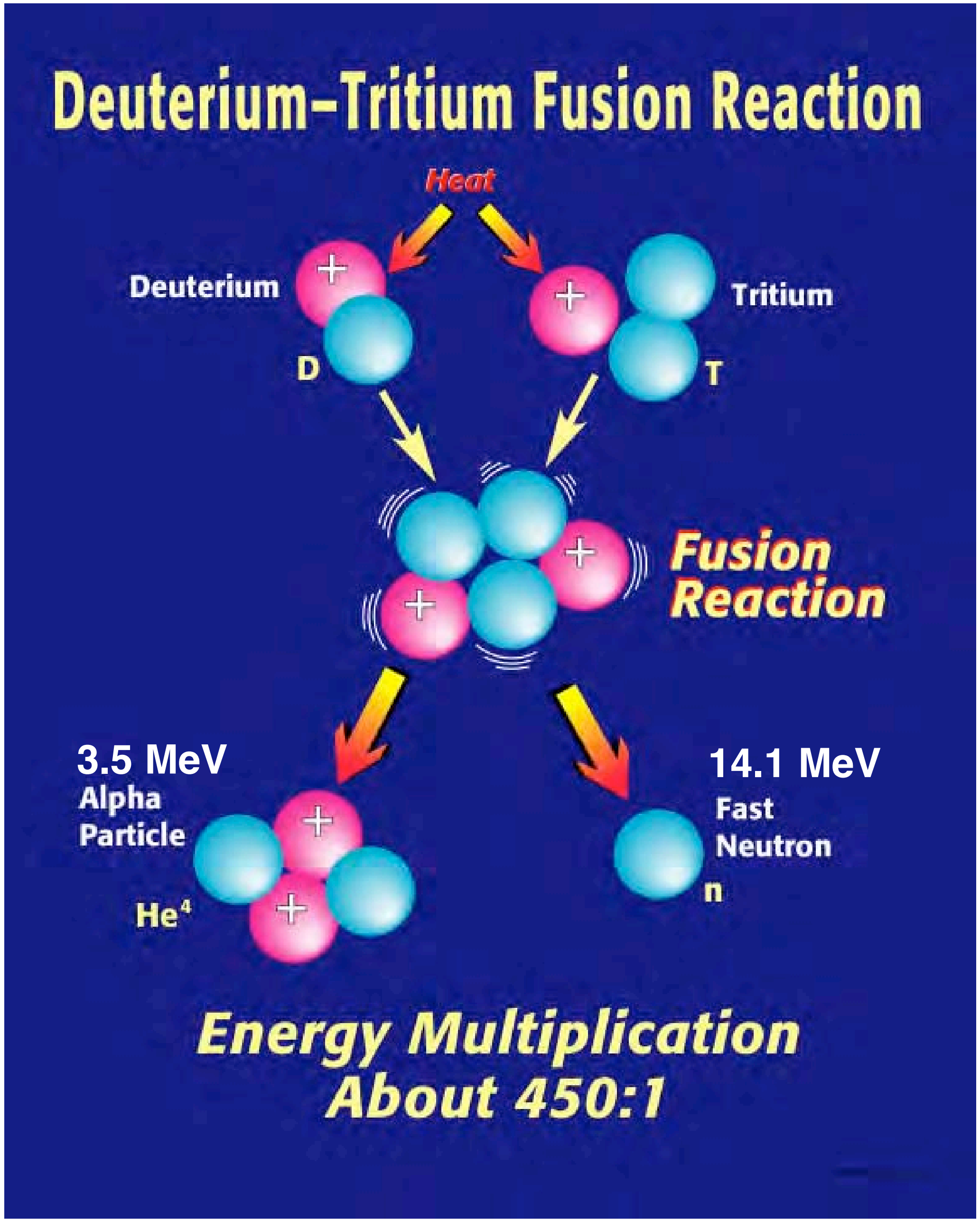
Relevant Fusion Reactions for Burning Laboratory Plasmas



Plasma Confinement





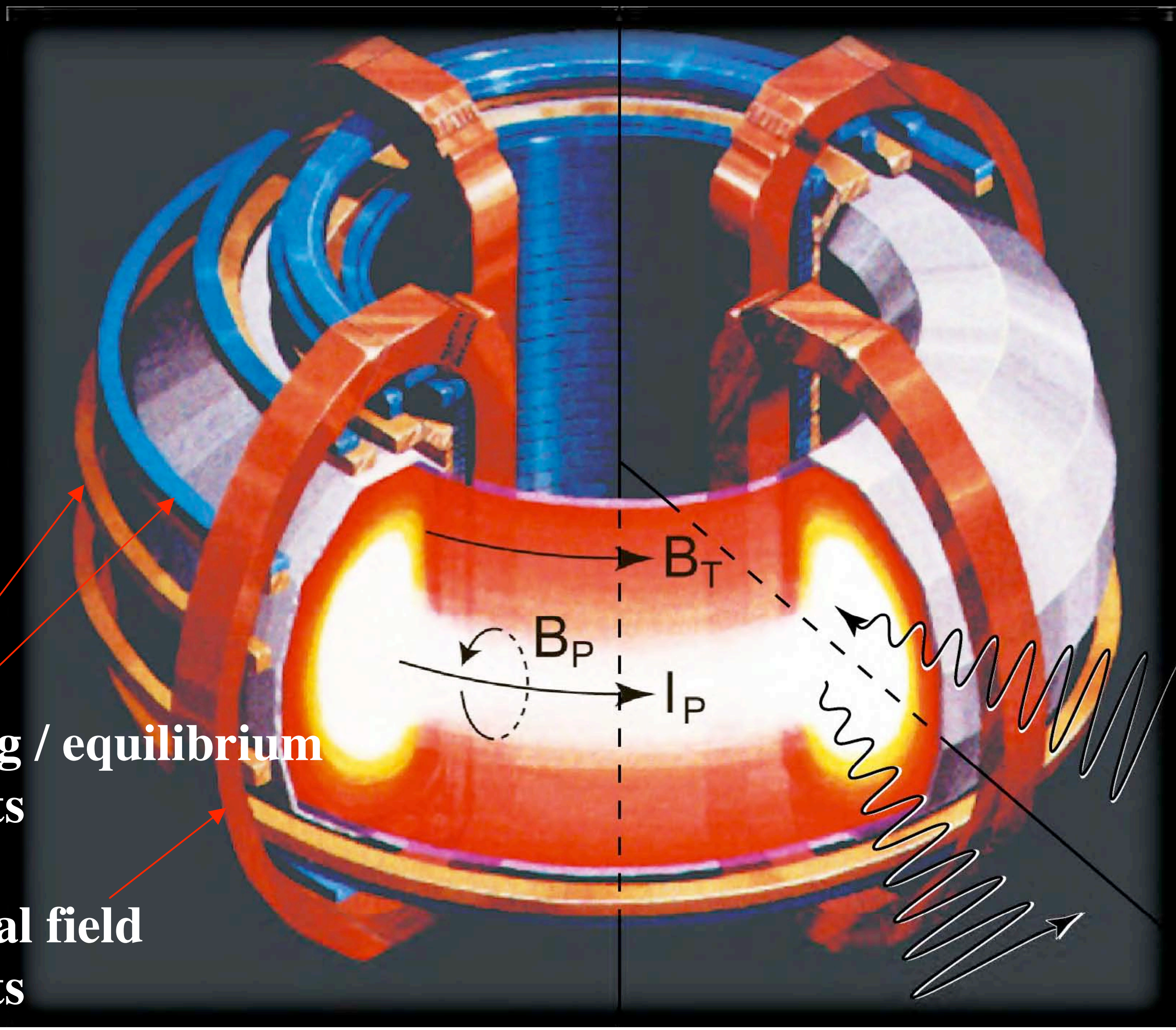


Key Science Topics of Burning Plasmas:

- Self-heating and self-organization
- Energetic Particles
- Size-scaling

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

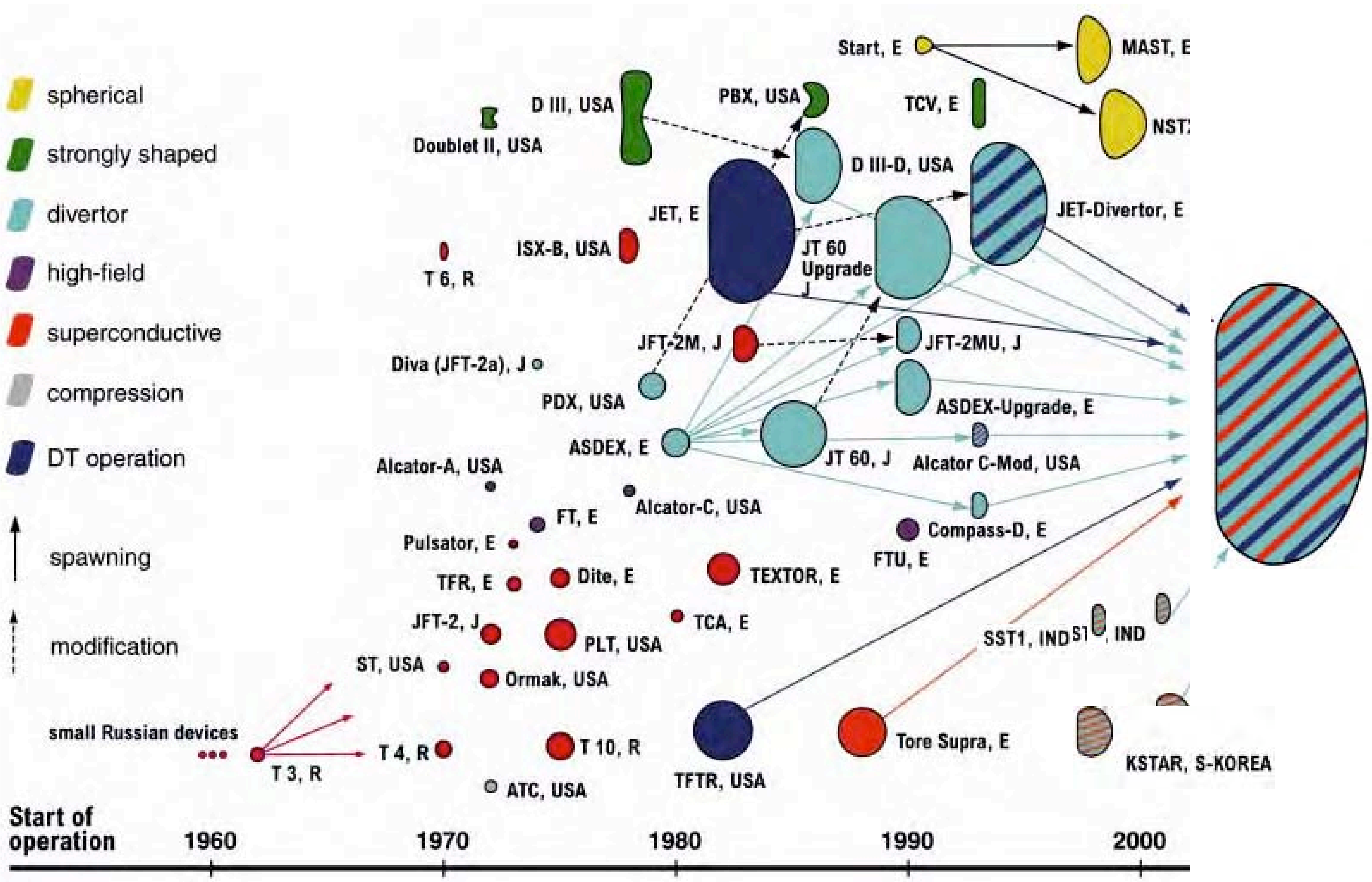
Toroidal plasmas and the tokamak configuration

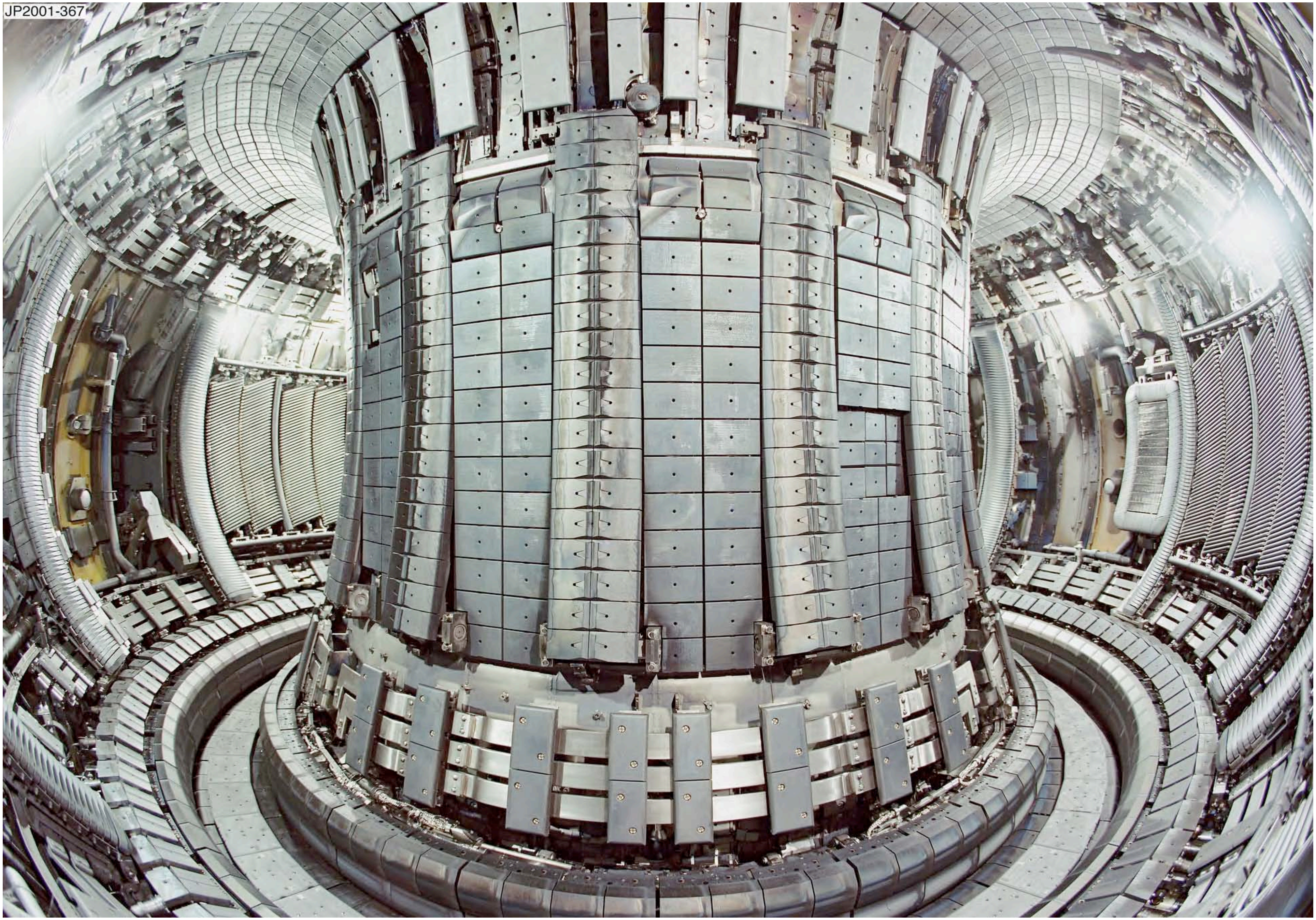


Shaping / equilibrium magnets

Toroidal field magnets

The range of worldwide tokamaks have provided the physics basis for ITER



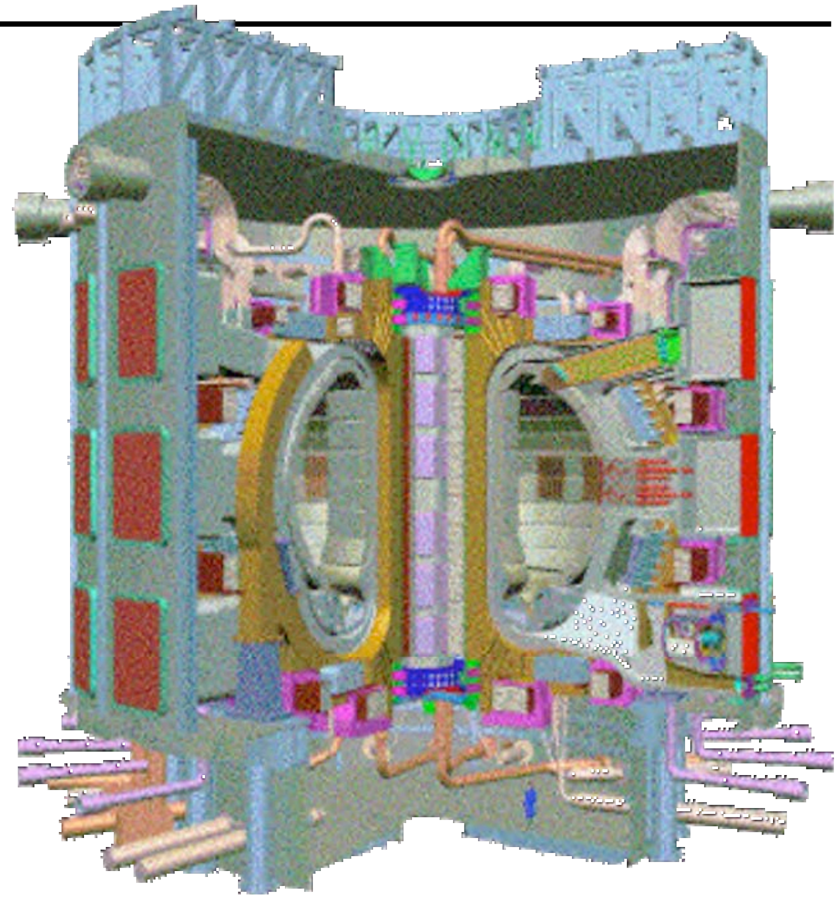


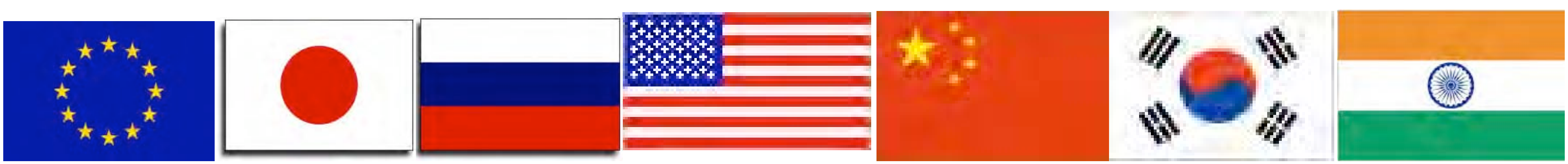
Joint European Torus (JET)

International Thermonuclear Experimental Reactor (ITER)

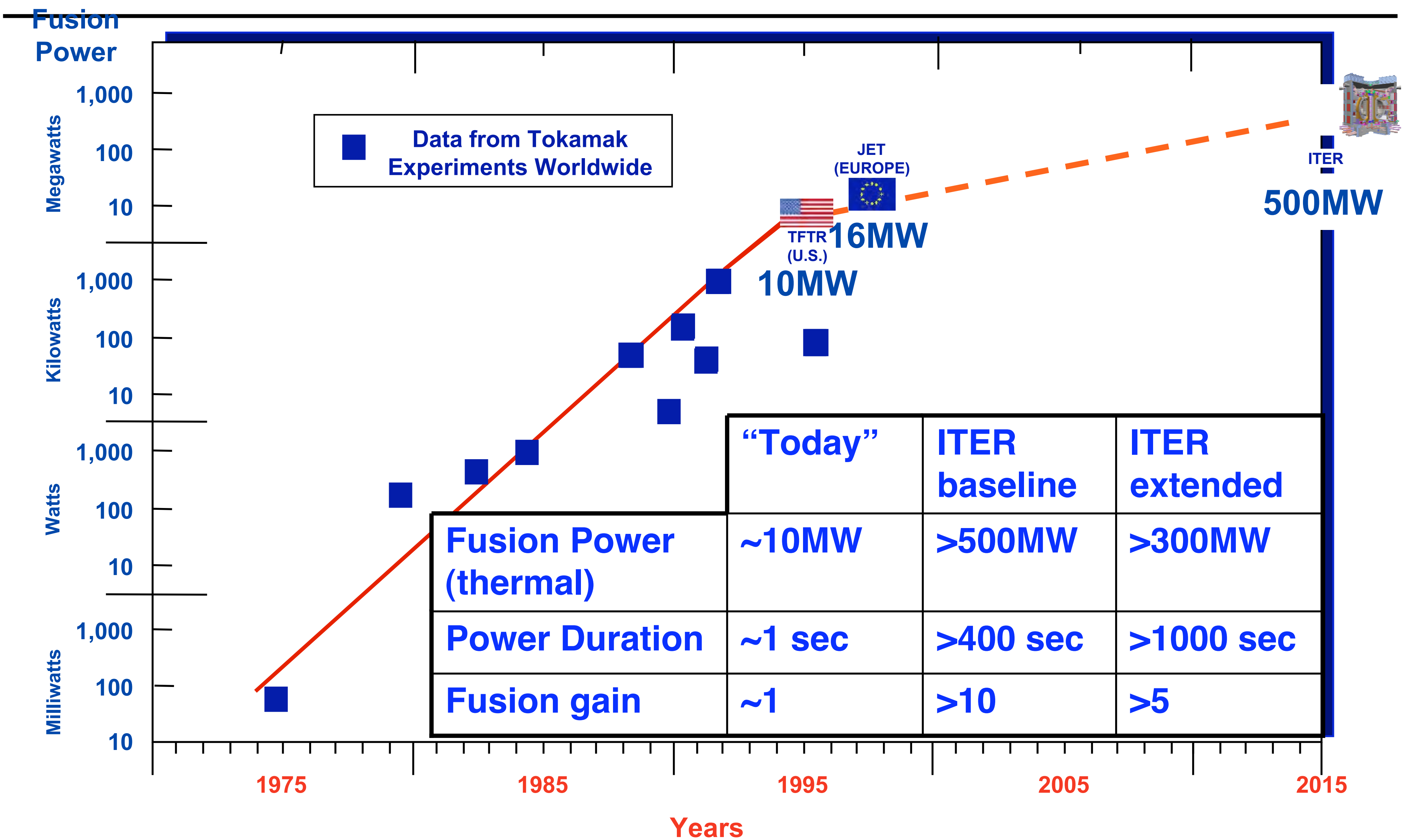
ITER's Mission:

To Demonstrate the Scientific and Technological Feasibility of Fusion Energy





ITER's fusion performace in context

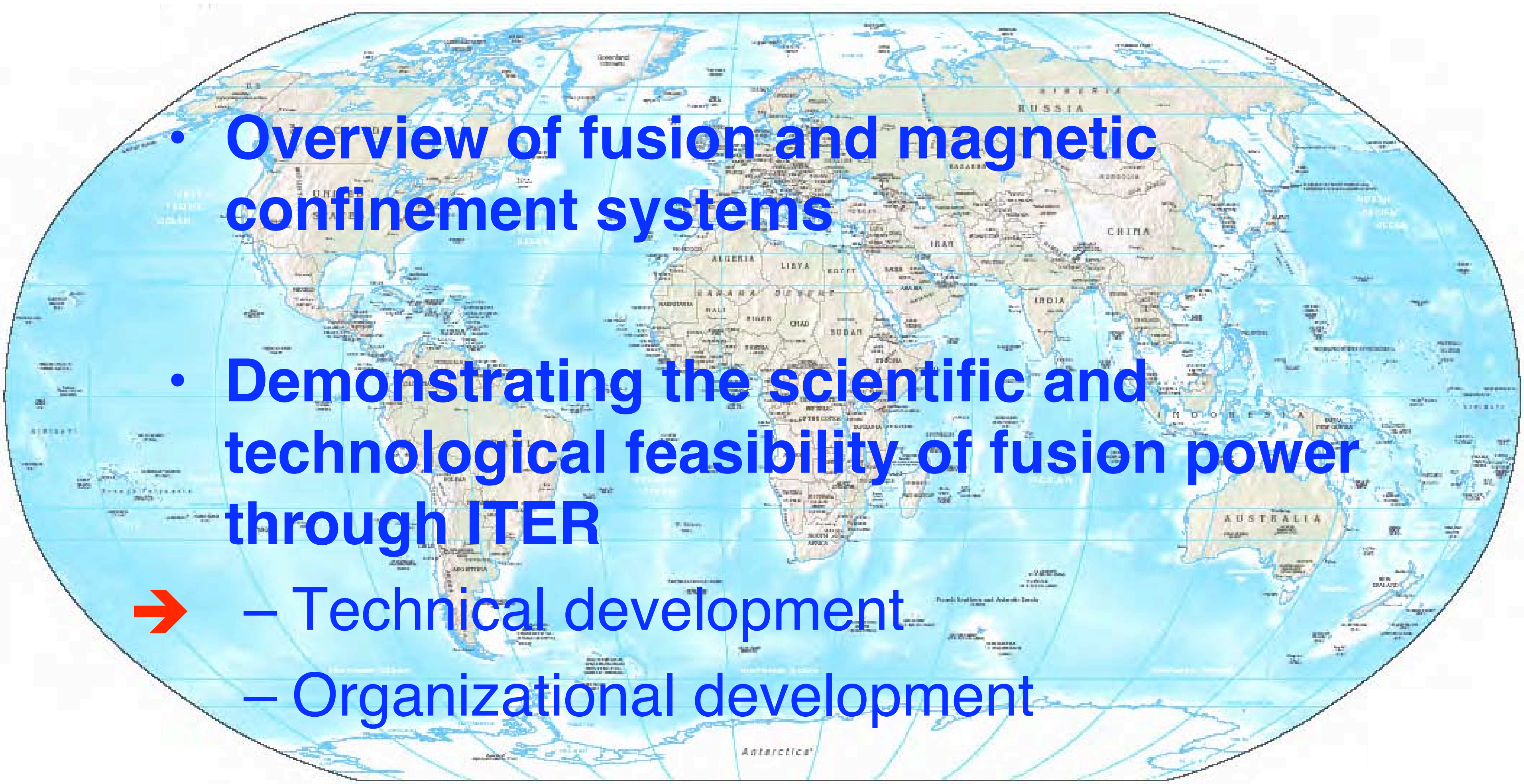


	"Today"	ITER baseline	ITER extended
Fusion Power (thermal)	~10MW	>500MW	>300MW
Power Duration	~1 sec	>400 sec	>1000 sec
Fusion gain	~1	>10	>5

ITER's Physics and Technology Objectives

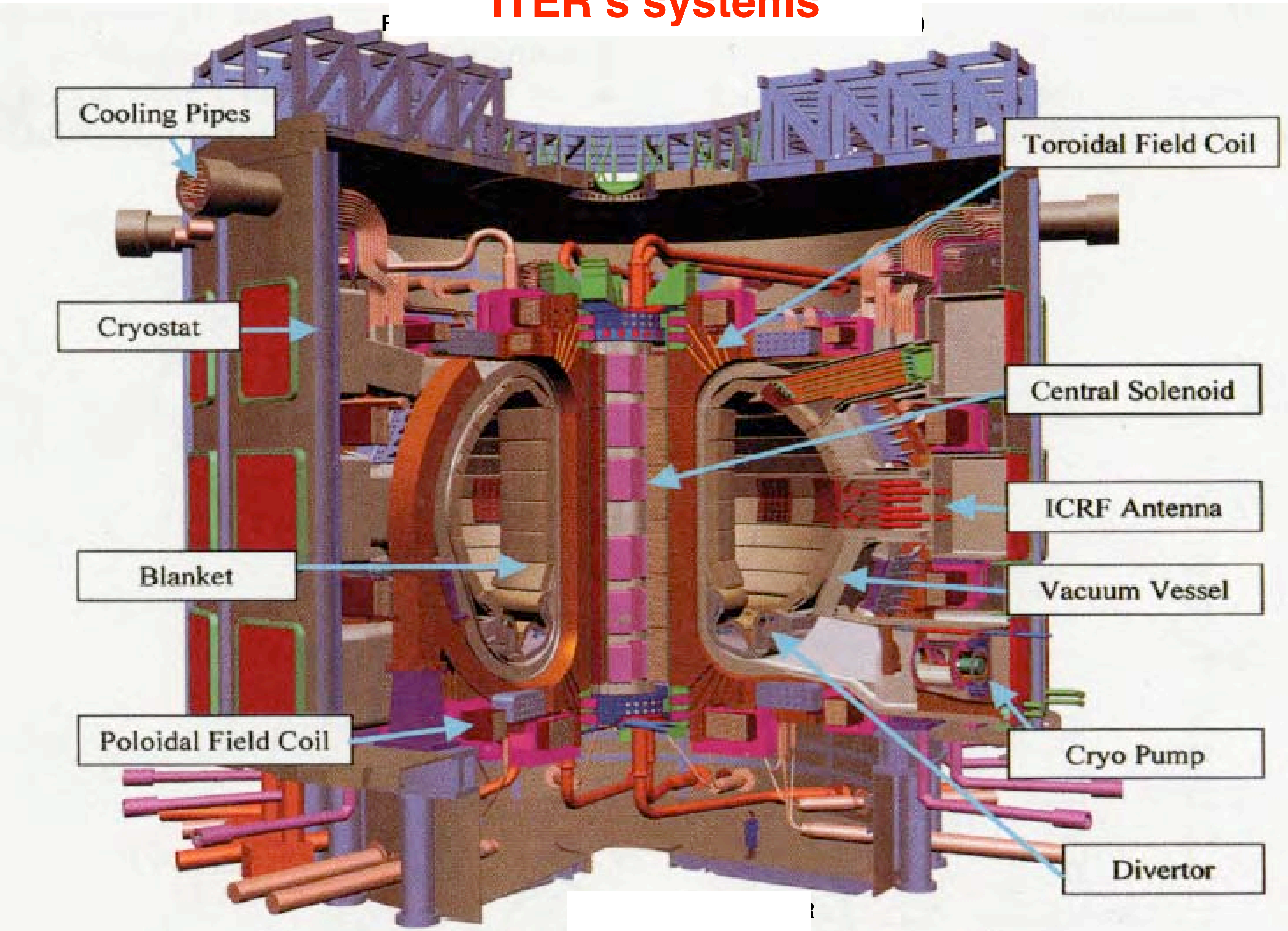
- **Physics:**
  - Produce and study a plasma dominated by α-particle heating
  - $P_{fusion} \sim 10 \times P_{external}$ ($P_{alpha} \sim 2 \times P_{external}$) for ≥ 300s
  - $P_{fusion} \sim 5 \times P_{external}$ ($P_{alpha} \sim P_{external}$) for steady-state
  - retain the possibility of exploring "controlled ignition" ($Q \geq 30$)
- **Technology:**
  - demonstrate integrated operation of technologies for a fusion power plant, except for material and component developments
  - average neutron wall load ≥ 0.5 MW/m^2 and average lifetime fluence of ≥ 0.3 MW years/m^2
  - test concepts for a tritium breeding module

Roadmap



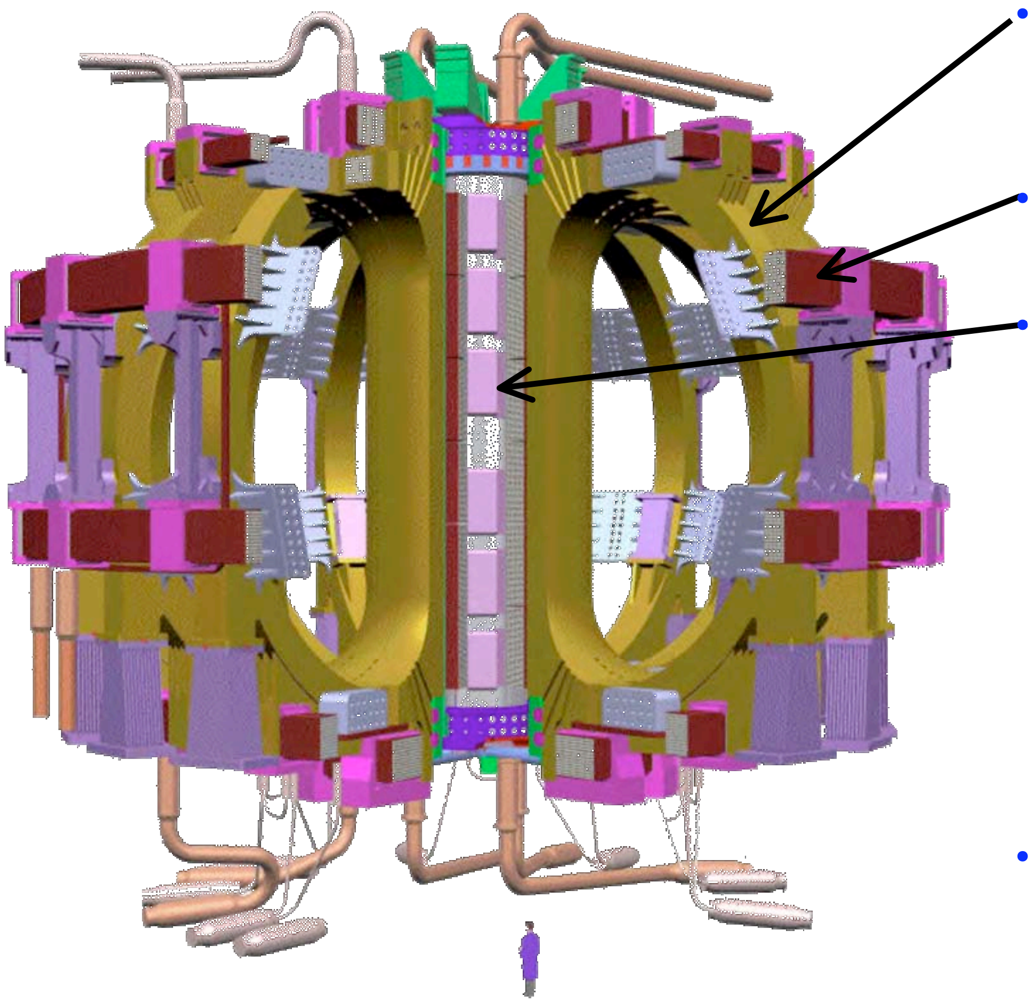
- **Overview of fusion and magnetic confinement systems**
- **Demonstrating the scientific and technological feasibility of fusion power through ITER**
  - ➔ – Technical development
  - – Organizational development

ITER's systems



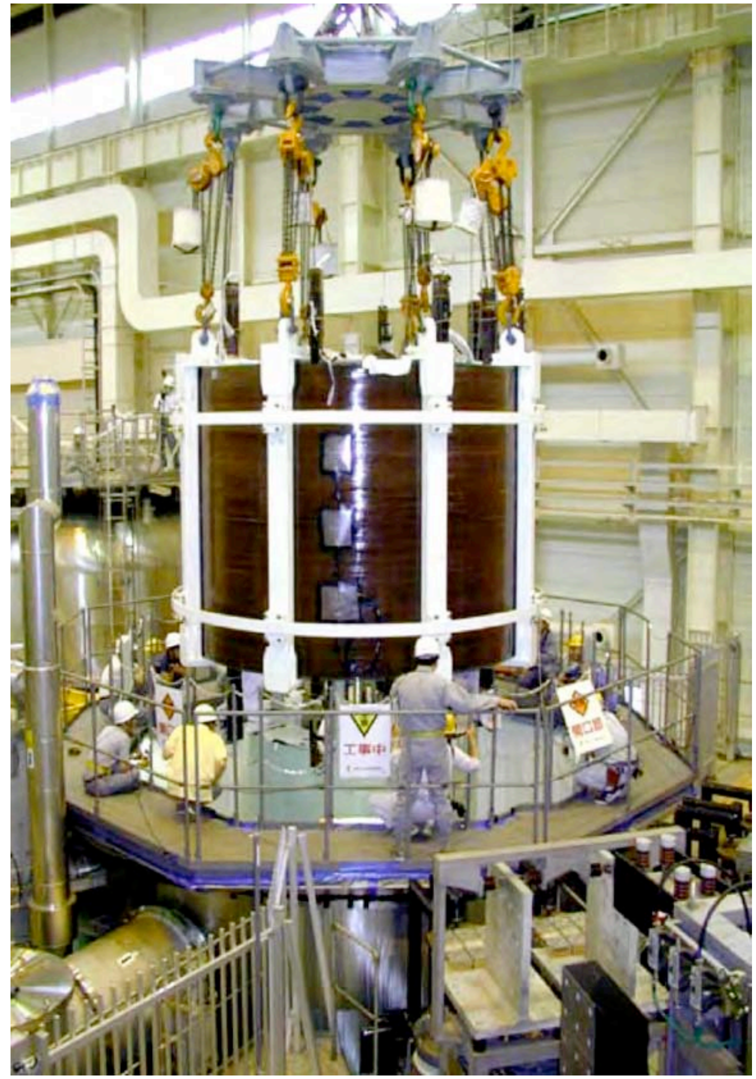
Magnets

ITER's Magnet system



- Nb3Sn toroidal field (TF) coils produce confining/stabilizing toroidal field
- NbTi poloidal field (PF) coils position and shape plasma
- modular Nb3Sn central solenoid (CS) coil induces current in the plasma
- Magnet system weighs ~ 8,700 t.

Central Solenoid Model Coil



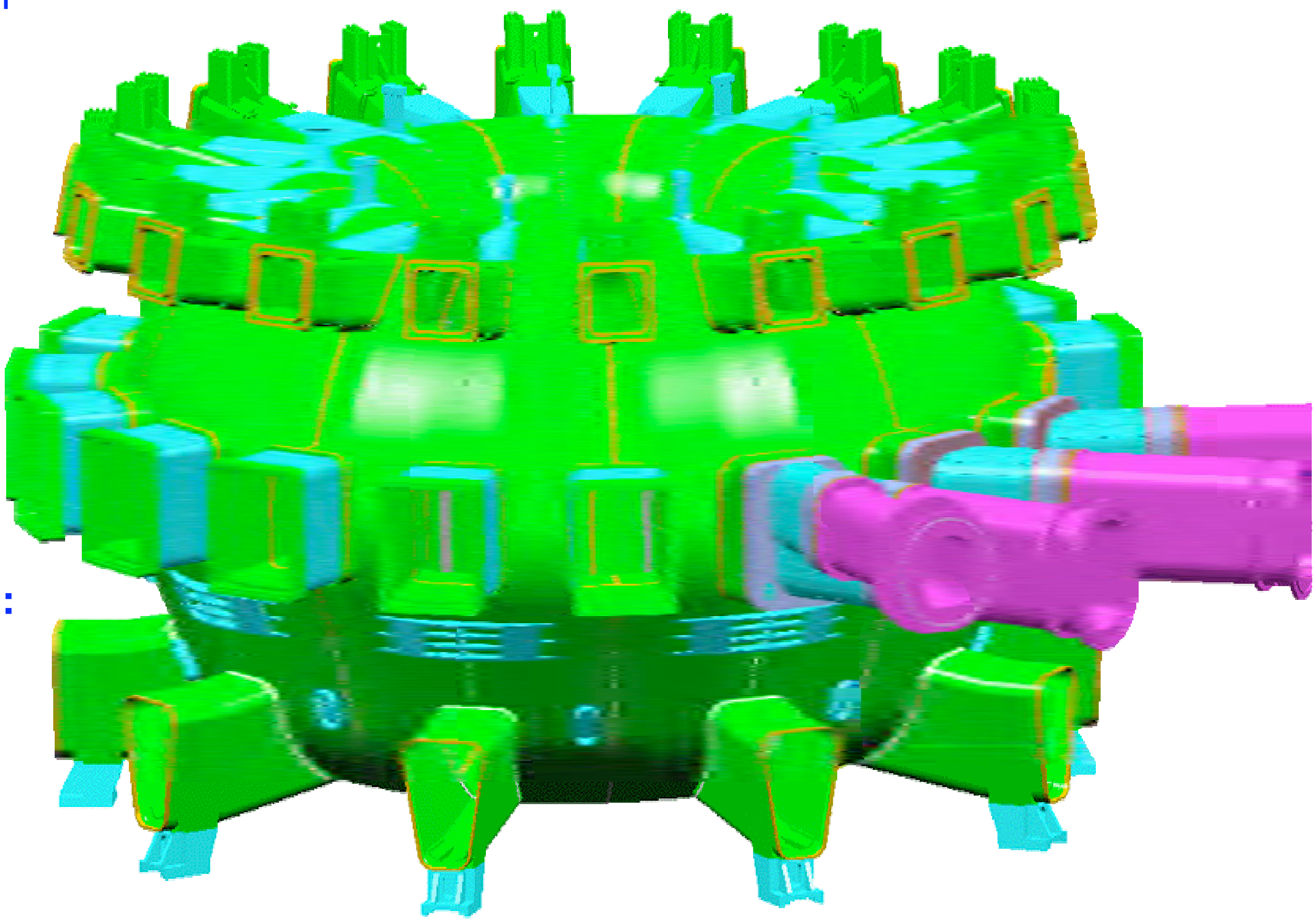
Max. field 13.5T, max. current 46kA, stored energy 640MJ
(max. in Nb_3Sn)

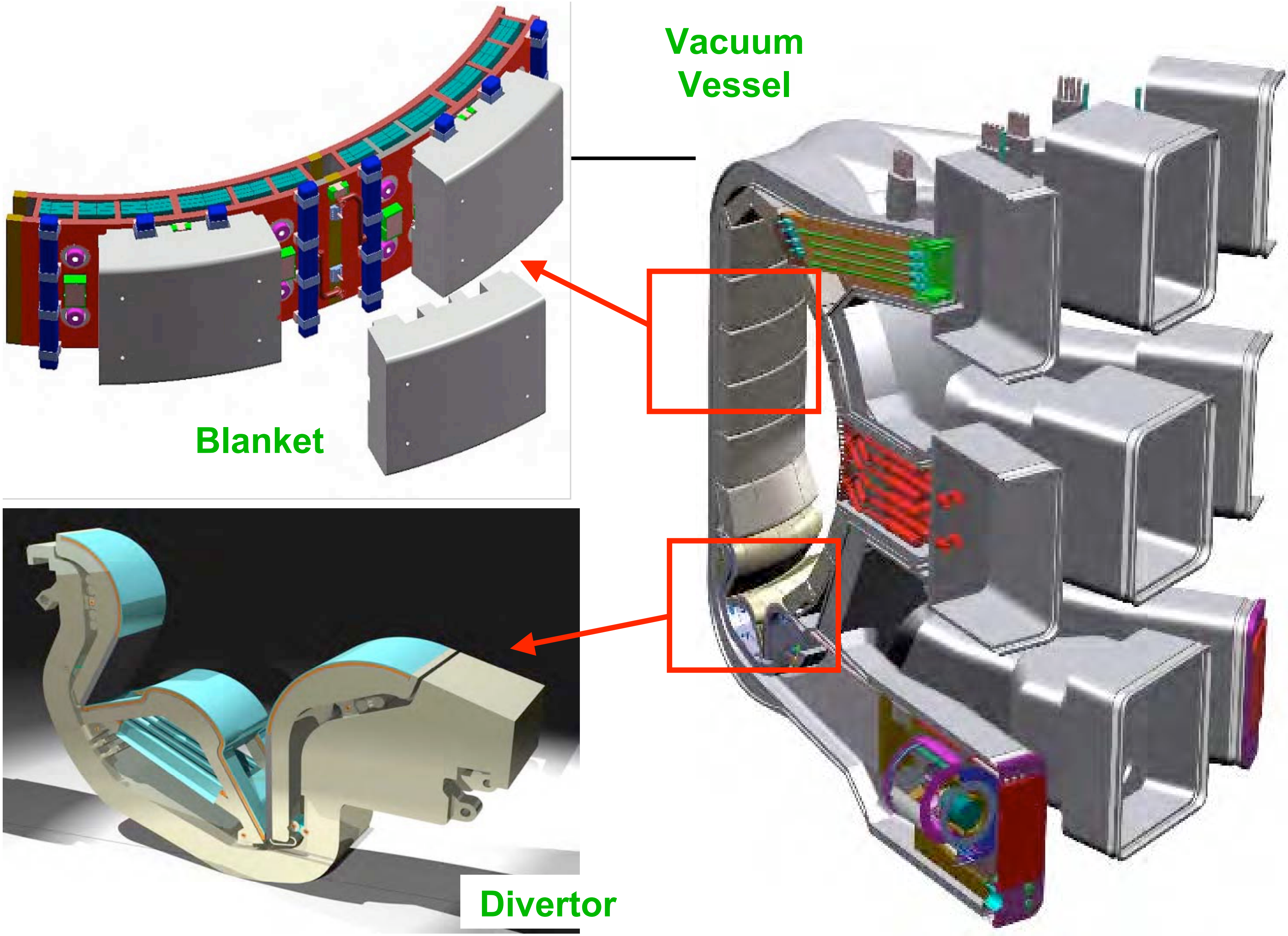
Ramp-up 1.2T/s (goal 0.4) and rampdown rates of -1.5T/s (goal -1.2) in insert coils, and 10,000 cycle test.

Power-handling

Plasma Vacuum Vessel

- **Primary function**
  - high quality vacuum for the plasma
  - first confinement barrier to radioactive materials
- **Double wall**
- **Water cooled**
- **Many ports for access:**
  - Diagnostics
  - Maintenance
  - Heating systems
  - Fuelling/Pumping
  - Inspection
  - Test Blankets




Vacuum
Vessel
Blanket
Divertor

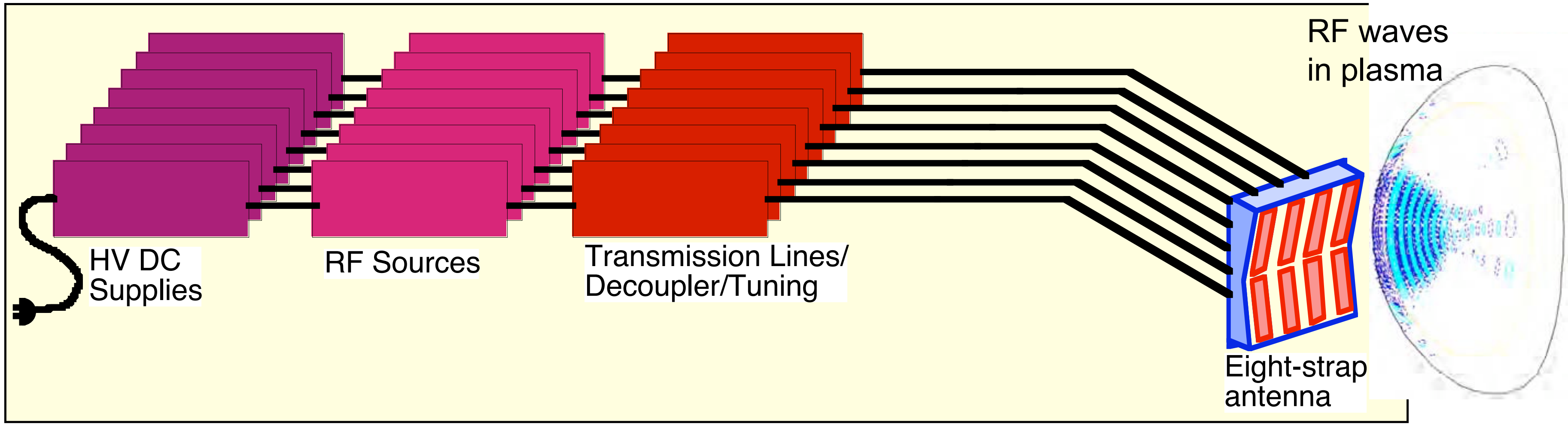
Plasma control, heating, current drive

What is the ITER ICH system and what does it do?

- **What it is:**
  - 20 MW plasma heating system
  - One antenna with multiple current straps
  - RF sources, each one feeding a current strap
  - Tuning elements for a frequency range of 35-65 MHz

- **What it will be used for:**
  - Tritium ion heating
  - Minority (He, D) ion heating
  - Plasma current drive near plasma center
  - Plasma current drive off center (ie. at the sawtooth inversion radius)

ITER Ion Cyclotron Heating (ICH) system block diagram



Electron Cyclotron System Configuration

(24) 1 MW, 170 GHz Gyrotrons

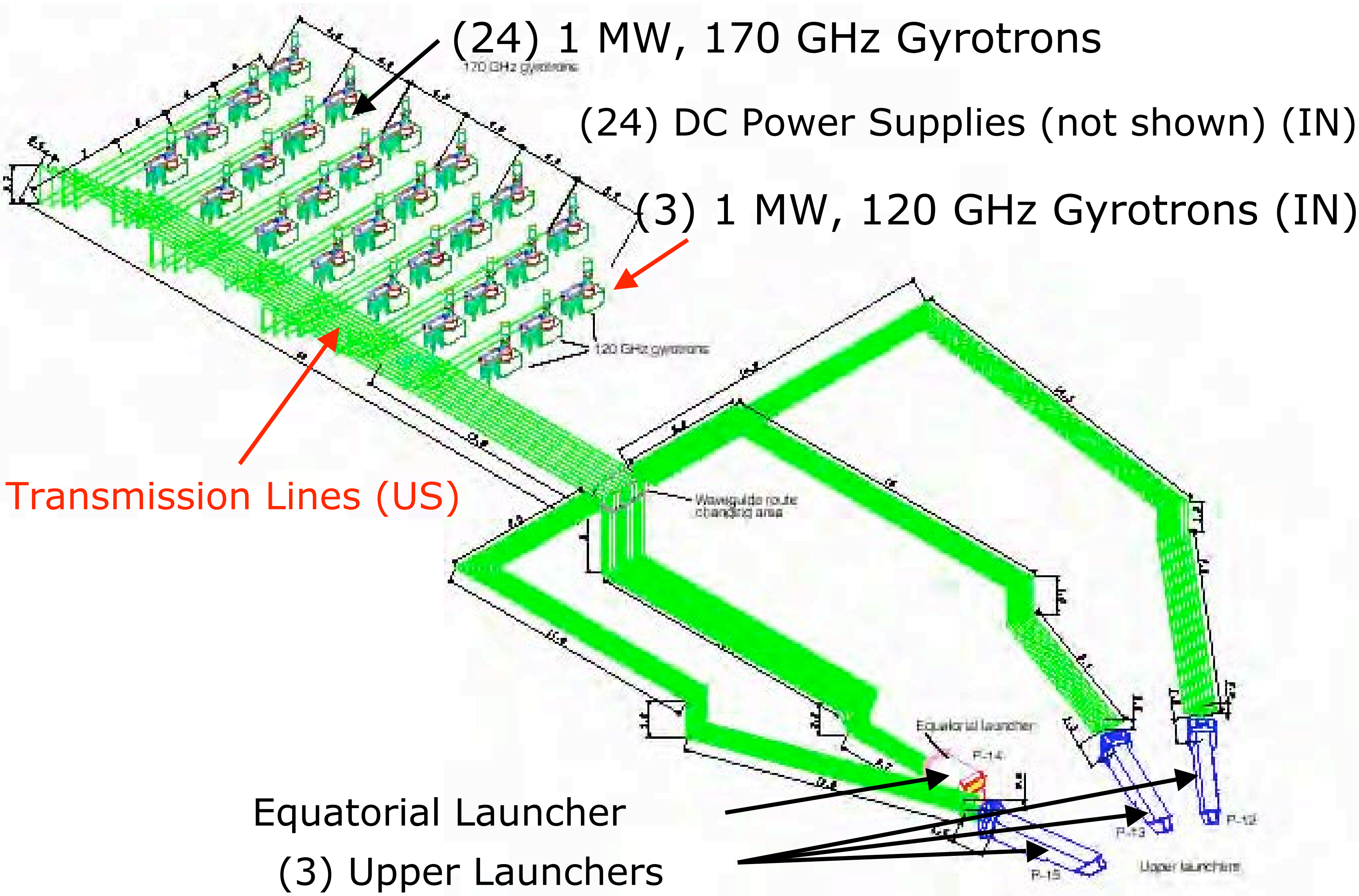
(24) DC Power Supplies (not shown) (IN)

(3) 1 MW, 120 GHz Gyrotrons (IN)

Transmission Lines (US)

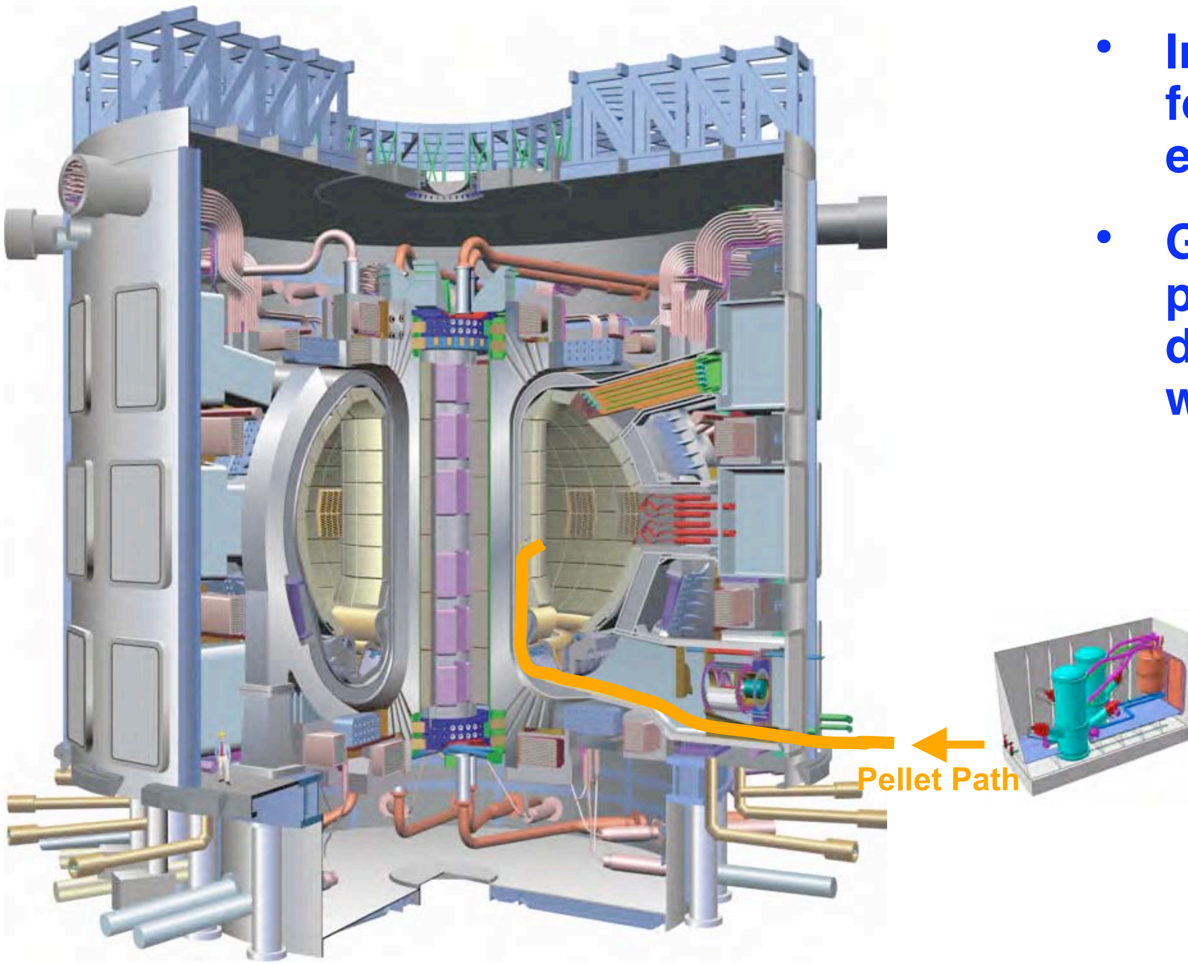
Equatorial Launcher

(3) Upper Launchers



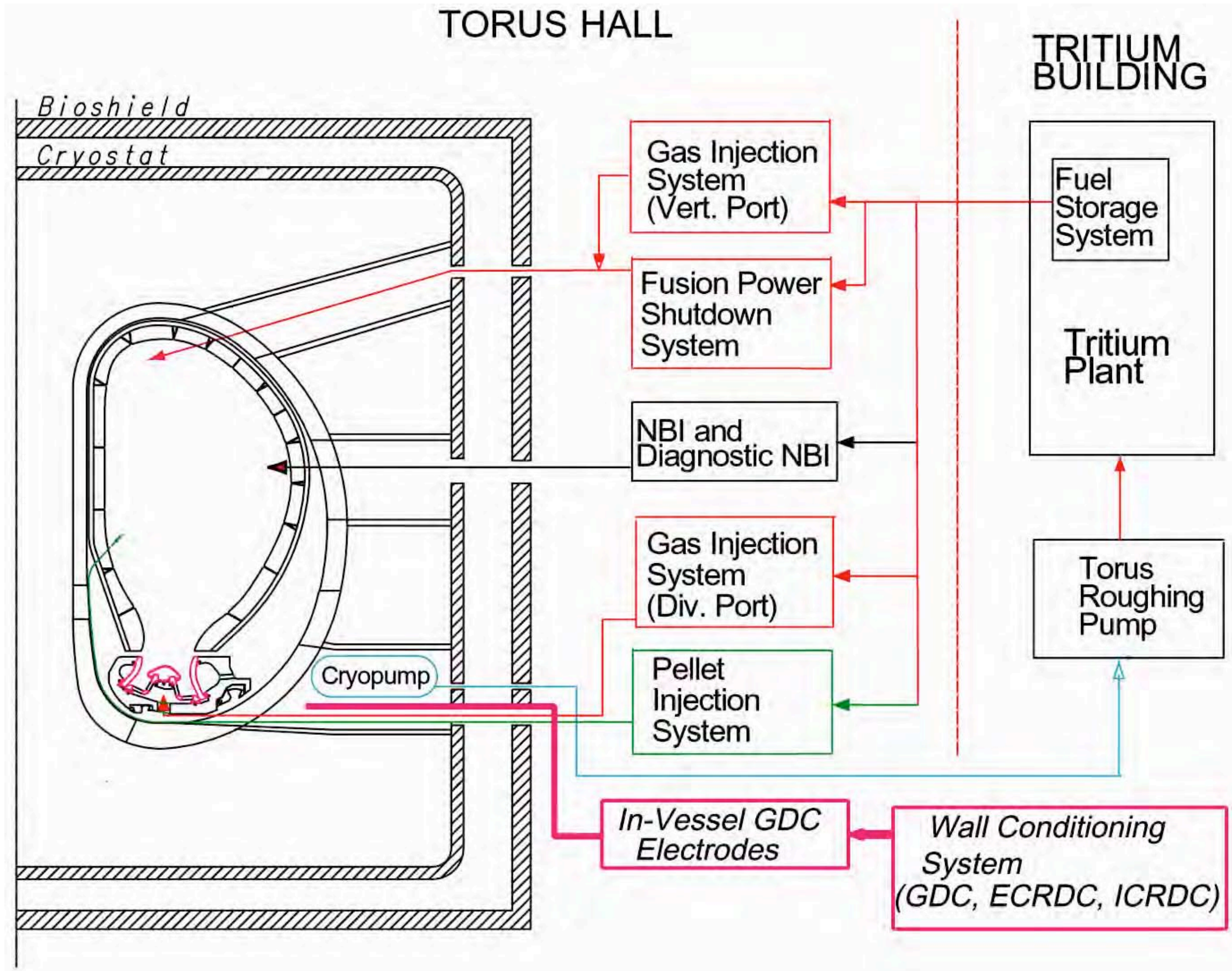
Fuelling and exhaust processing

High Field Side Launch will be Utilized



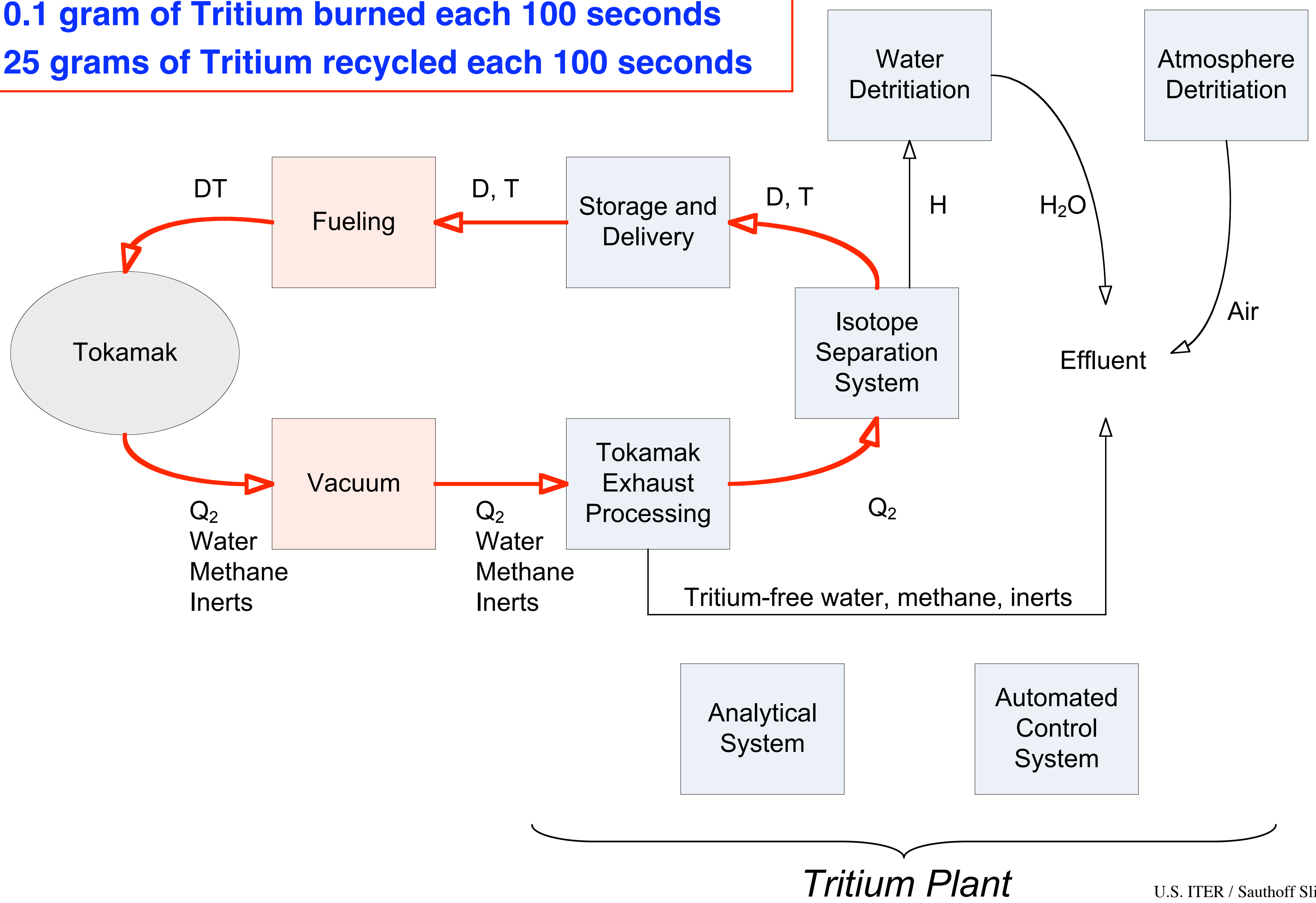
- Inside wall pellet injection for deep fueling and high efficiency.
- Guide tubes bring the pellets through the divertor ports to the inner wall.

ITER Pumping and Fueling Systems

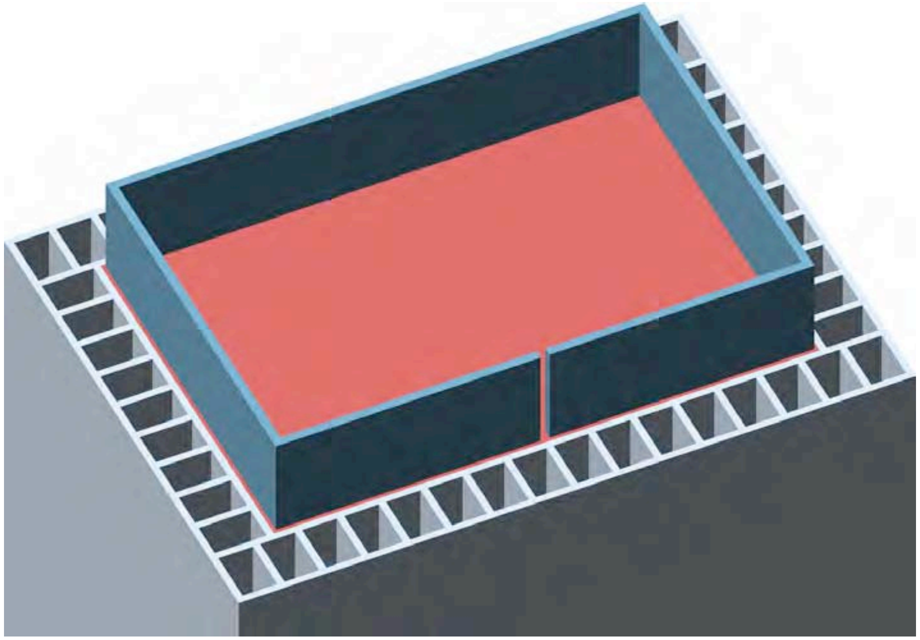


The ITER Tritium Plant is essentially a small chemical processing plant consisting of seven systems

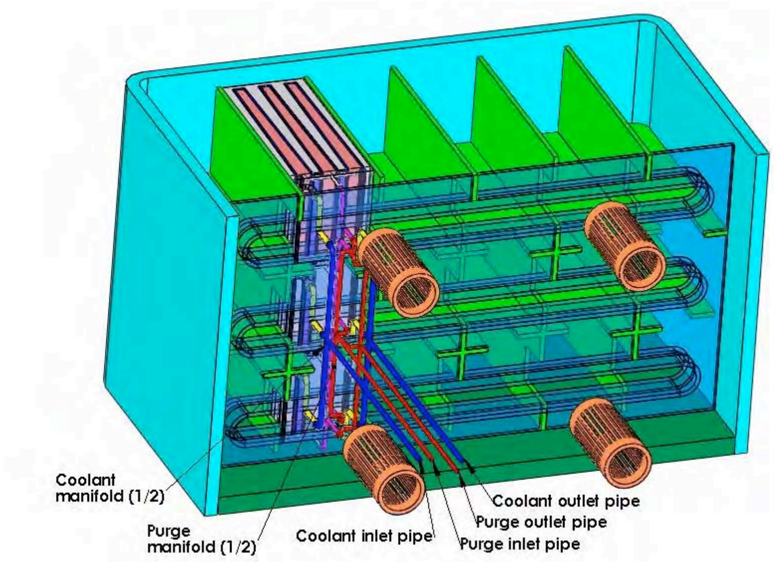
- ~ 0.1 gram of Tritium burned each 100 seconds
- ~ 25 grams of Tritium recycled each 100 seconds



Tritium-breeding: Test Blanket Modules



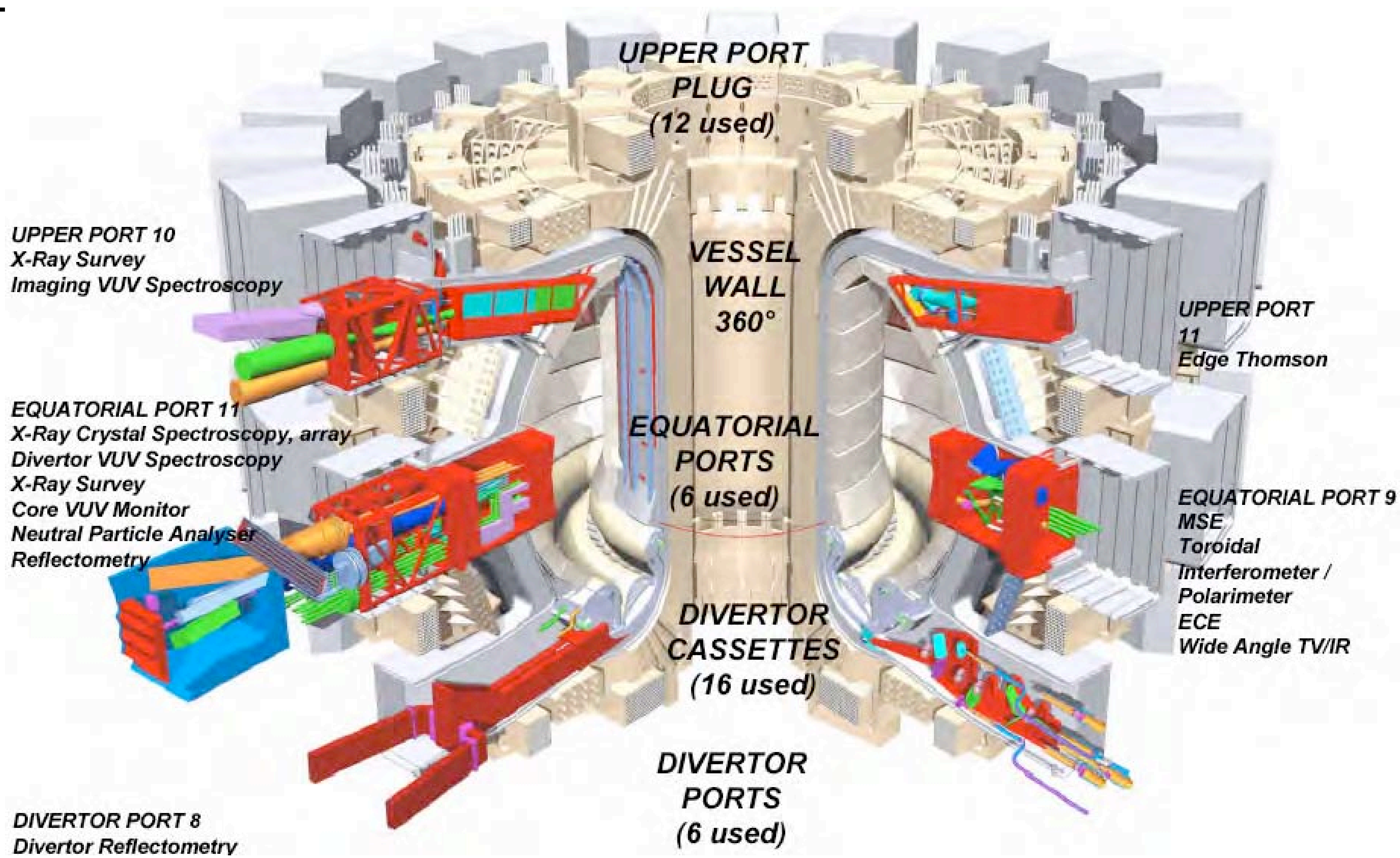
Dual Coolant Lead- Lithium TBM



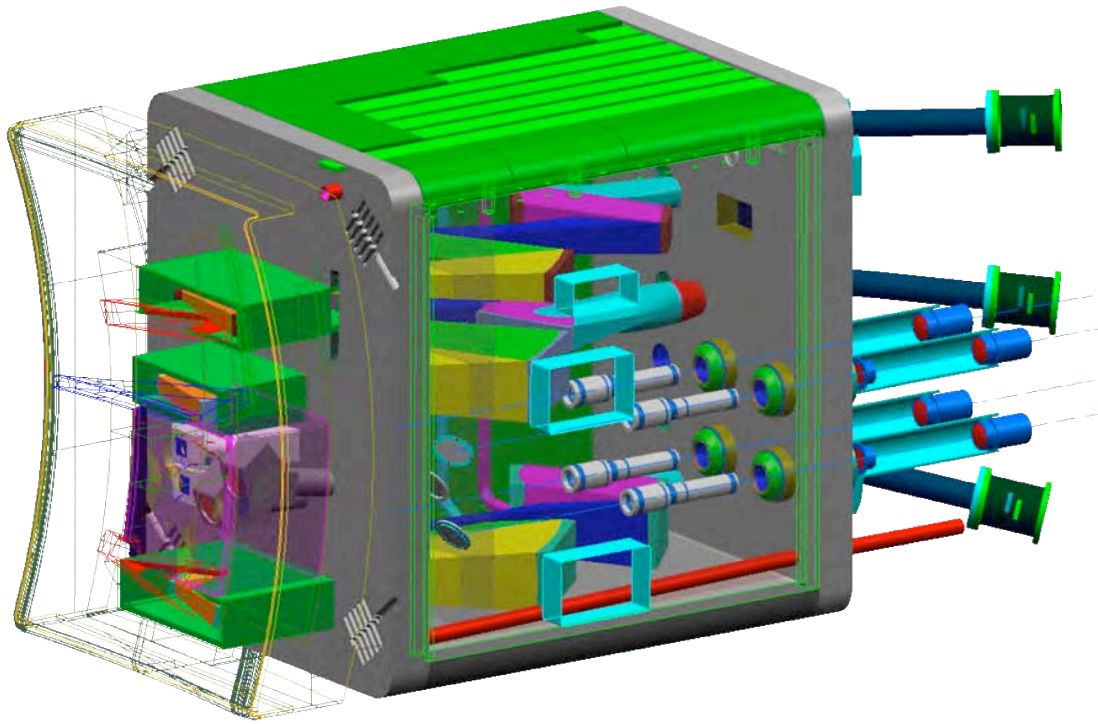
Schematic view of three solid breeder thermomechanics unit cell test articles housed inside the EU's Helium-cooled pebble bed box

Diagnostic instrumentation

Instrumentation is key to science on ITER

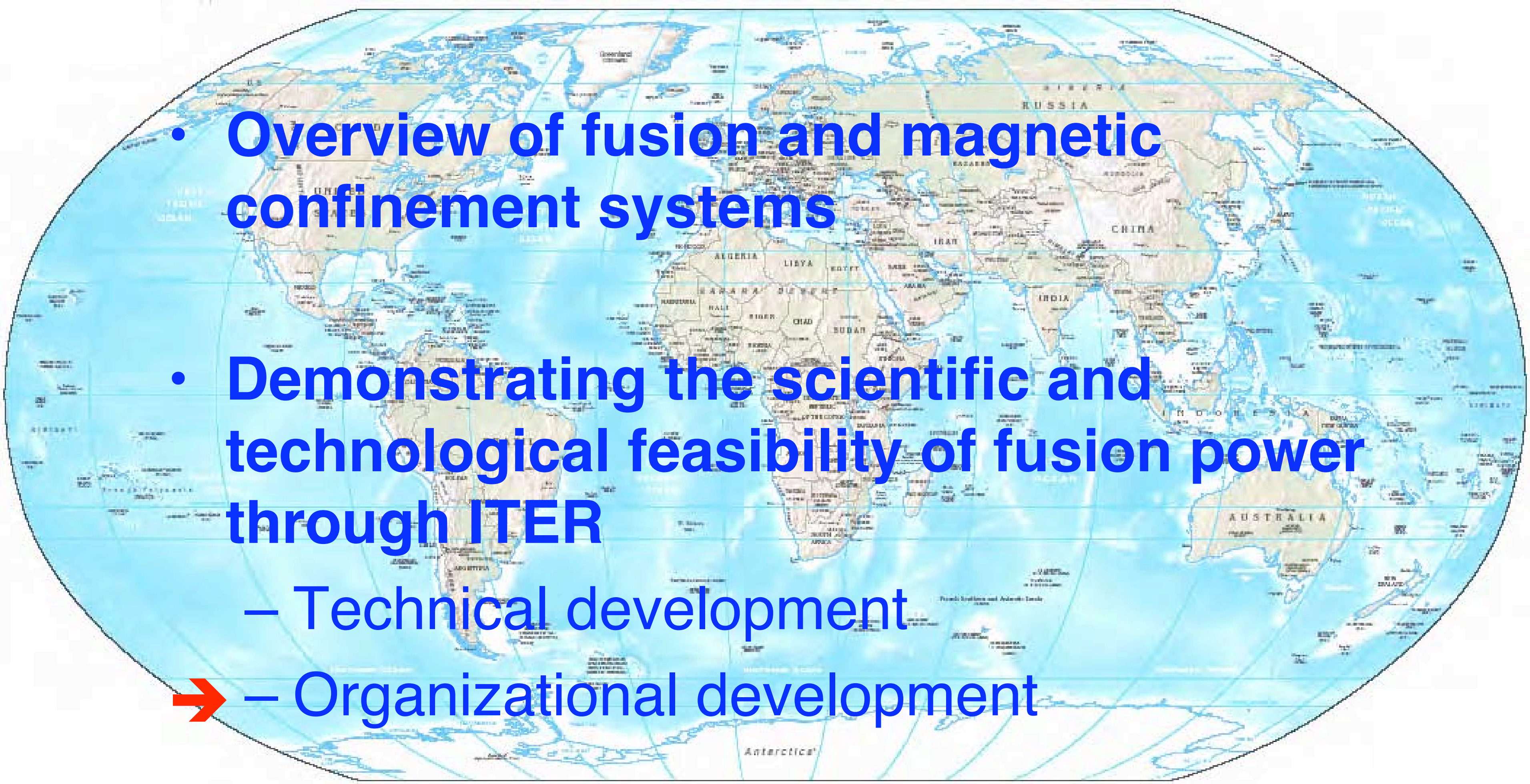


Diagnostic Port Plugs



- **Design constraints**
  - Intermingling of numerous labyrinths, many with precision optics
  - Provide access while limiting neutron streaming
  - Provide attachments and cooling to blanket shield modules

Roadmap



- **Overview of fusion and magnetic confinement systems**
- **Demonstrating the scientific and technological feasibility of fusion power through ITER**
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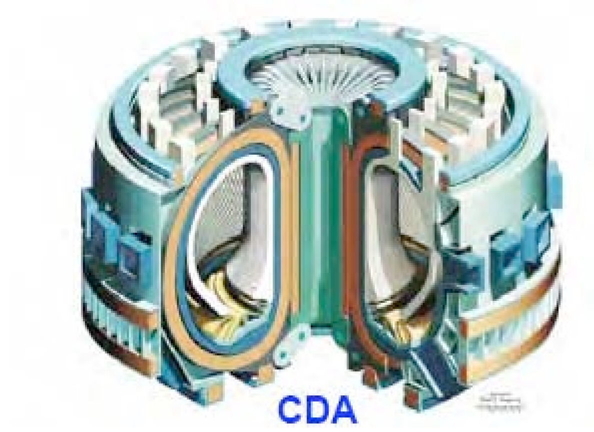
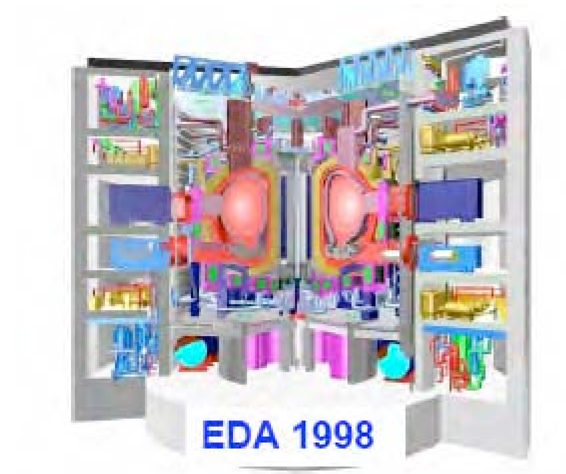
Early ITER Activities (1988-1998)

1988-90
- Europe, Japan, USSR and US conduct Conceptual Design Activity (CDA)



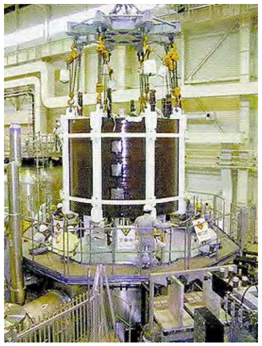
1992
- Engineering Design Activity (EDA) starts with three co-centers (EU, Japan, US)

1998
- Initial EDA period ends with final design report



ITER Technology was developed between 1992 and 1998

CENTRAL SOLENOID MODEL COIL

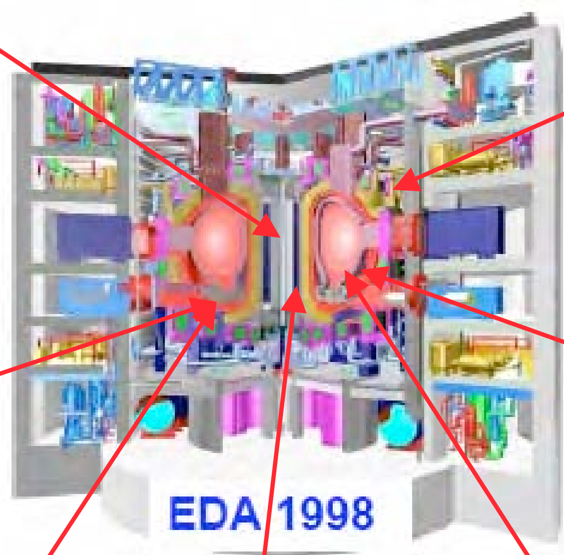


Radius 3.5 m
Height 2.8m
B_{max}=13 T
W = 640 MJ
0.6 T/sec

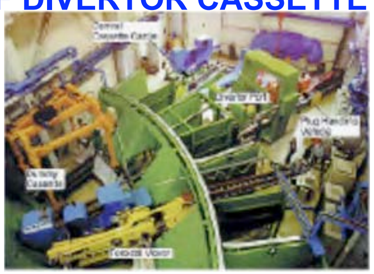
R&D Activities completed by July 2001.

VACUUM VESSEL SECTOR

Double-Wall, Tolerance ±5 mm



REMOTE MAINTENANCE OF DIVERTOR CASSETTE

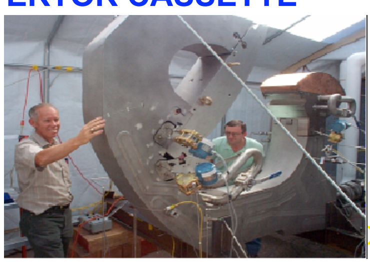


Attachment Tolerance ± 2 mm

BLANKET MODULE

HIP Joining Tech
Size : 1.6 m x 0.93 m x 0.35 m

DIVERTOR CASSETTE



TOROIDAL FIELD MODEL COIL

Height 4 m
Width 3 m
B_{max}=7.8 T
I_{max} = 80kA

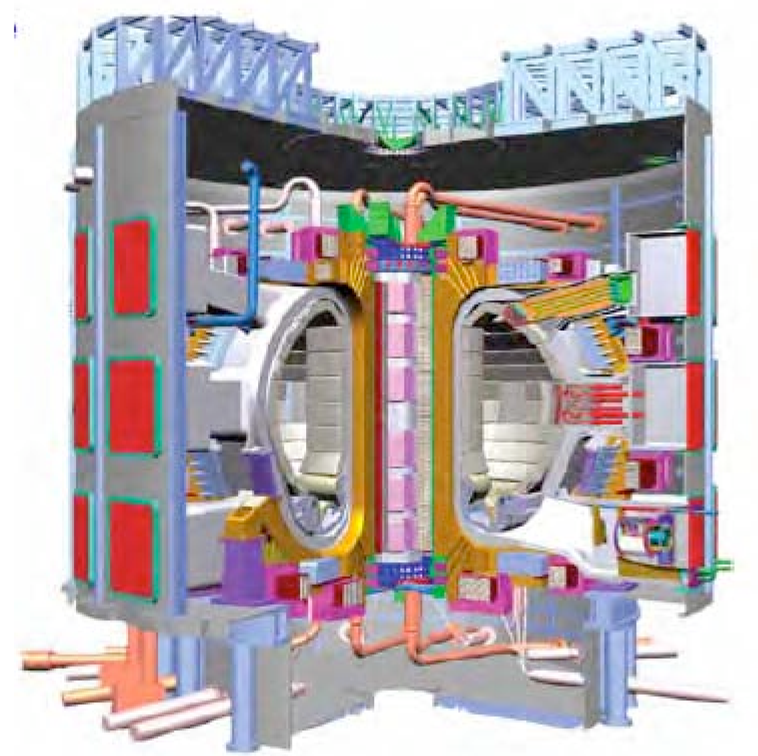
REMOTE MAINTENANCE OF BLANKET

4 t Blanket Sector
Attachment Tolerance ± 0.25 mm

Intermediate ITER Activities (1998-2001)

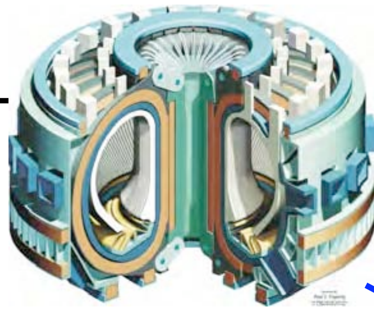
1998
- US withdraws from ITER at Congressional direction;
  EDA Extension starts with EU, JA and RF pursuing lower-cost, more advanced design including systematic studies of a range of aspect ratios

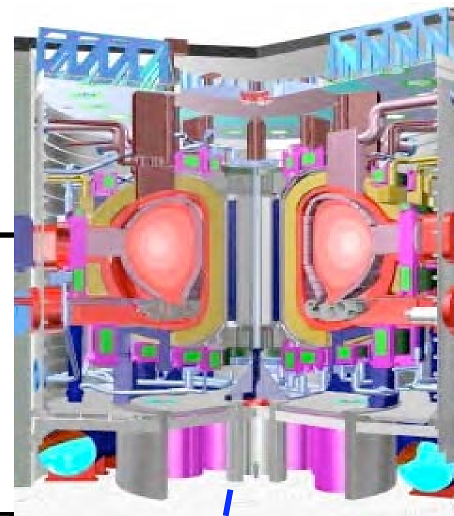
2001
- EDA ends with de-scoped design

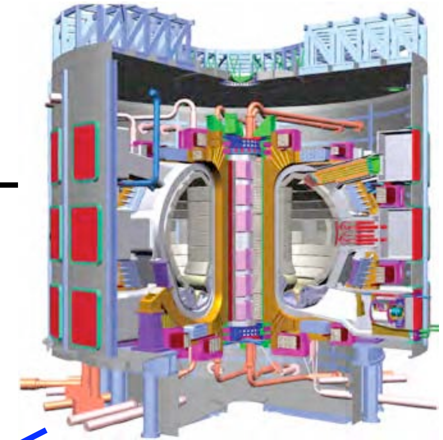


EDA 2001

Evolution of the ITER design







	CDA 1990	EDA 1998	EDA 2001
Plasma major radius (m)	6.0	8.1	6.2
Plasma half width at mid-plane (m)	2.1	2.8	2.0
Toroidal magnetic field on axis (T)	4.85	5.6	5.3
Nominal maximum plasma current (MA)	22	21	15
Nominal fusion power (MW)	1000	1500	500
Q (= $P_{fusion}/P_{heating}$) (reference plasma)		infinity	>= 10
Q (= $P_{fusion}/P_{heating}$) (steady-state)		>= 5	>= 5
Nominal inductive pulse length (s)	>200	>1000	>400
Average neutron wall load (MW/m^2)	~1.0	~1.0	0.57
Neutron fluence (MW years/m^2)		1.0	>= 0.3

ITER Activities (2001 – 2002)

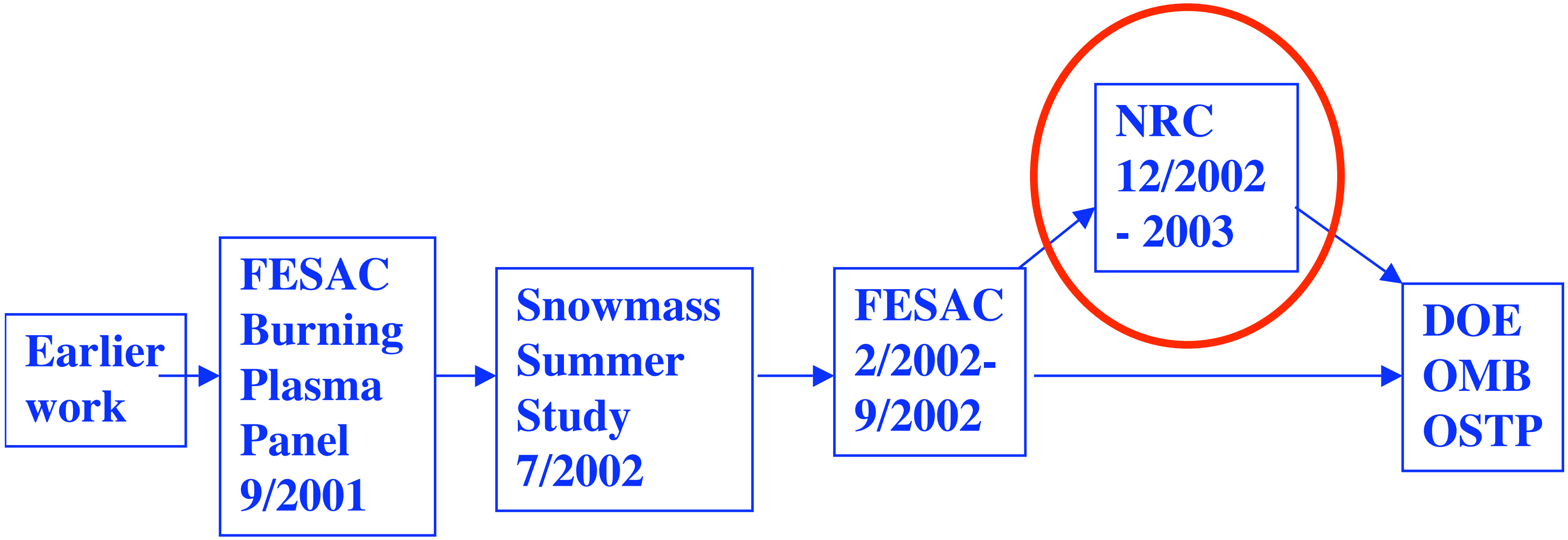
2001

- ITER Coordinated Technical Activities / Transitional Arrangements started with
  EU, JA, RF, and CA
- Intent was short duration, transition to ITER construction.
  - Select site – CA, EU, and JA offers made.
  - Negotiate Agreement
  - Complete Design

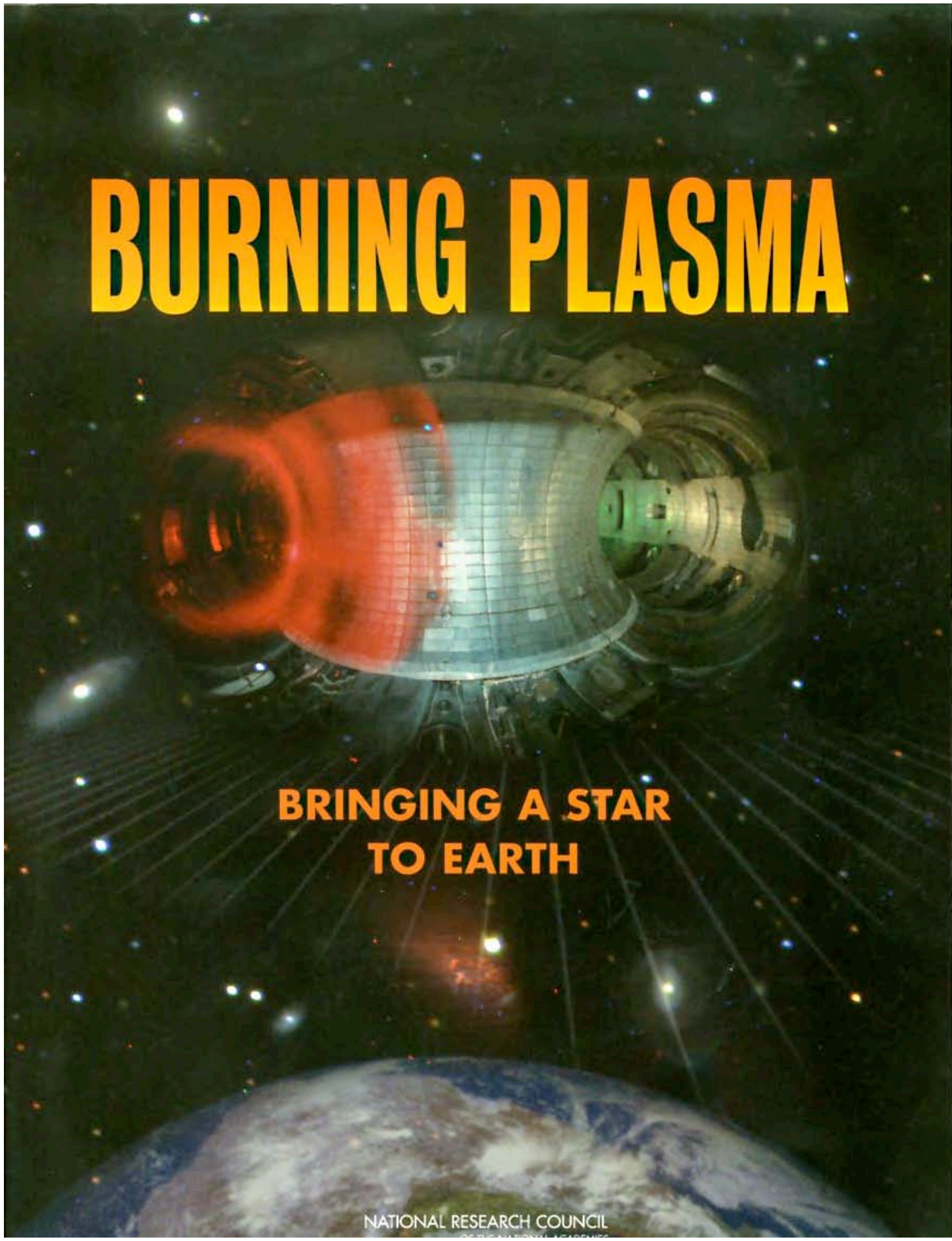
2002

- Joint Assessment of Sites carried out by Parties
- US Snowmass Fusion Summer Study
- US DOE/SC Review of ITER (Value) Cost Estimate (11/02)

The path to the US decision on Burning Plasmas and participation in ITER negotiations



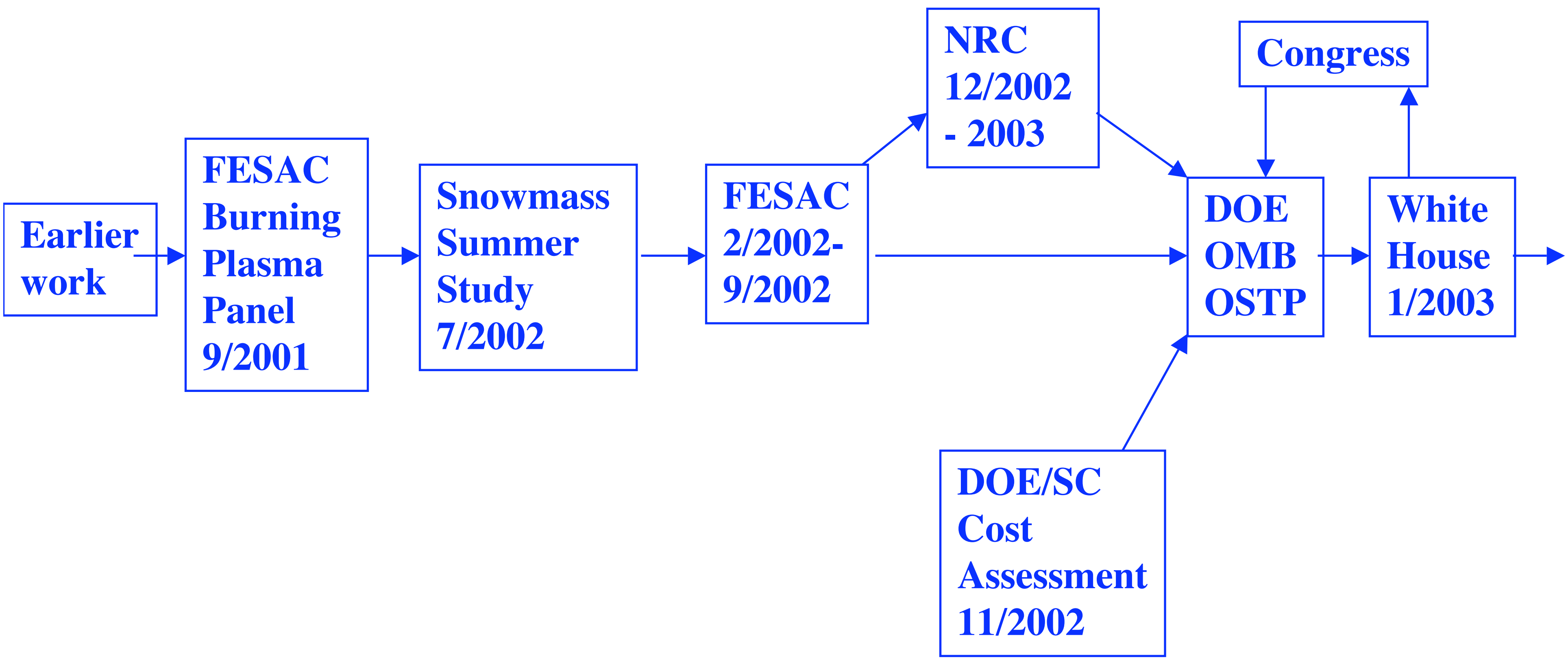
NRC Burning Plasma Report



- The United States should participate in ITER.
  If an international agreement to build ITER is reached, fulfilling the U.S. commitment should be the top priority in a balanced fusion science program.

- The United States should pursue an appropriate level of involvement in ITER, which at a minimum would guarantee access to all data from ITER, the right to propose and carry out experiments, and a role in producing the high-technology components of the facility consistent with the size of the U.S. contribution to the program.

The path to the US decision on Burning Plasmas and participation in ITER negotiations



US decision on joining ITER Negotiations (1/30/03)

“Now is the time to expand our scope and embrace international efforts to realize the promise of fusion energy.

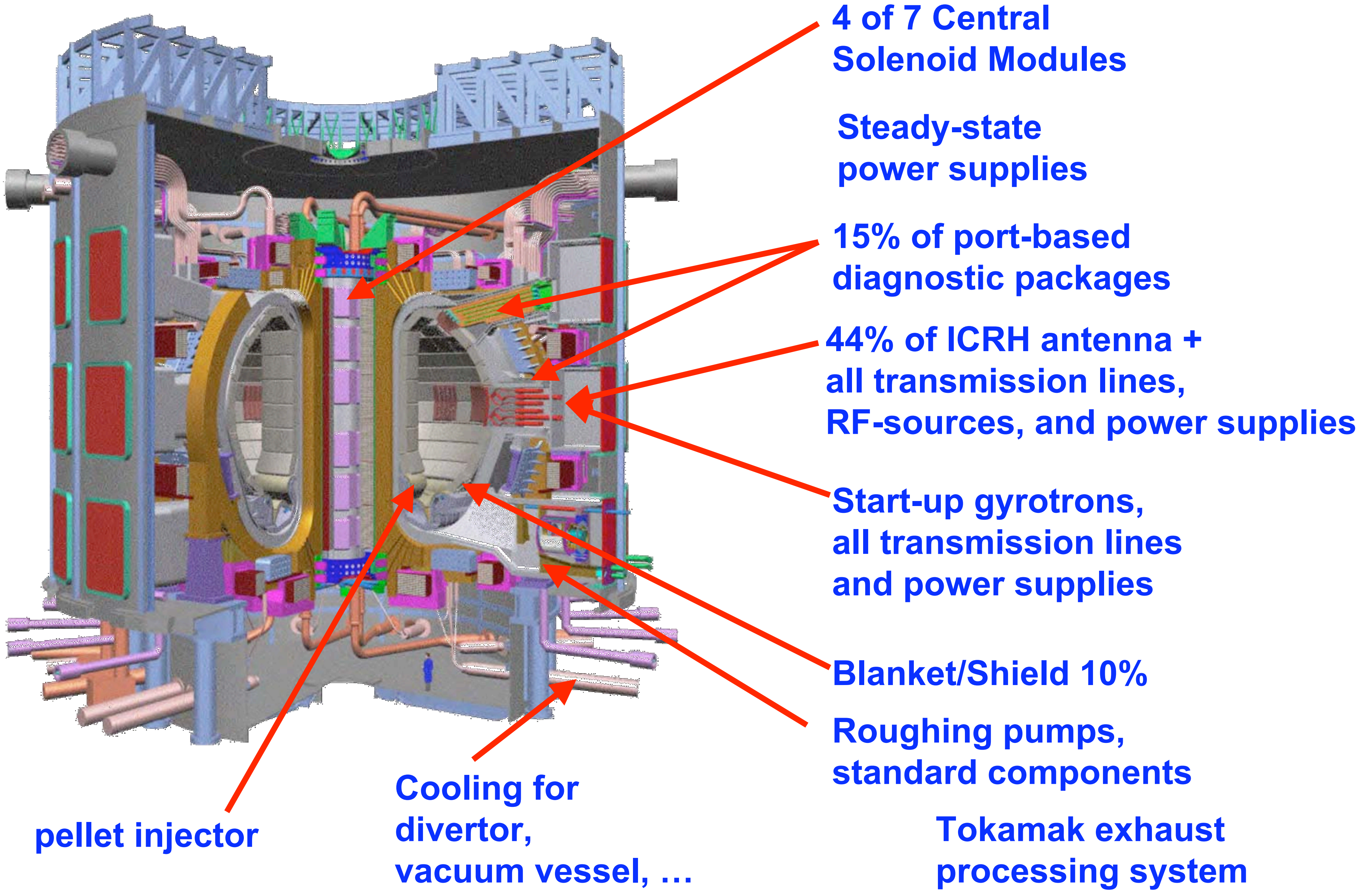
Now it is time to take the next step on the way to having fusion deliver electricity to the grid.

Therefore, I am pleased to announce today, that <u>President Bush has decided that the United States will join the international negotiations on ITER</u>.”

U.S. ITER Activities (2003)

2003
- U.S., Korea, and China join negotiations
- U.S. negotiating limits established – 6/03
- Intense working level discussions (Munich, Tokyo, Abingdon, Beijing)
- Agreement advanced; some difficult issues remain
- Ministerial Meeting (12/03) ends with site stalemate

U.S. provisional "in-kind contribution" scope



Recent U.S. ITER Activities (2004 - 2005)

2004

- Technical comparisons of candidate sites
- Explorations of broader approaches
- High-level site discussions in Vienna
- EU/JA bilateral site negotiations begin

2005

- U.S. Contributions to ITER in FY06 Budget with Total Project Cost of $1.122B
- EU and JA negotiate
- Site Decision (6/28)
- Director General selected (12/05)

Evolution of the Site Selection

France
(Cadarache)

Spain
(Vandellòs)

Nov 26, 2003

EU site
(Cadarache)

Withdrew
6/28/05

Japan
(Rokkasho)

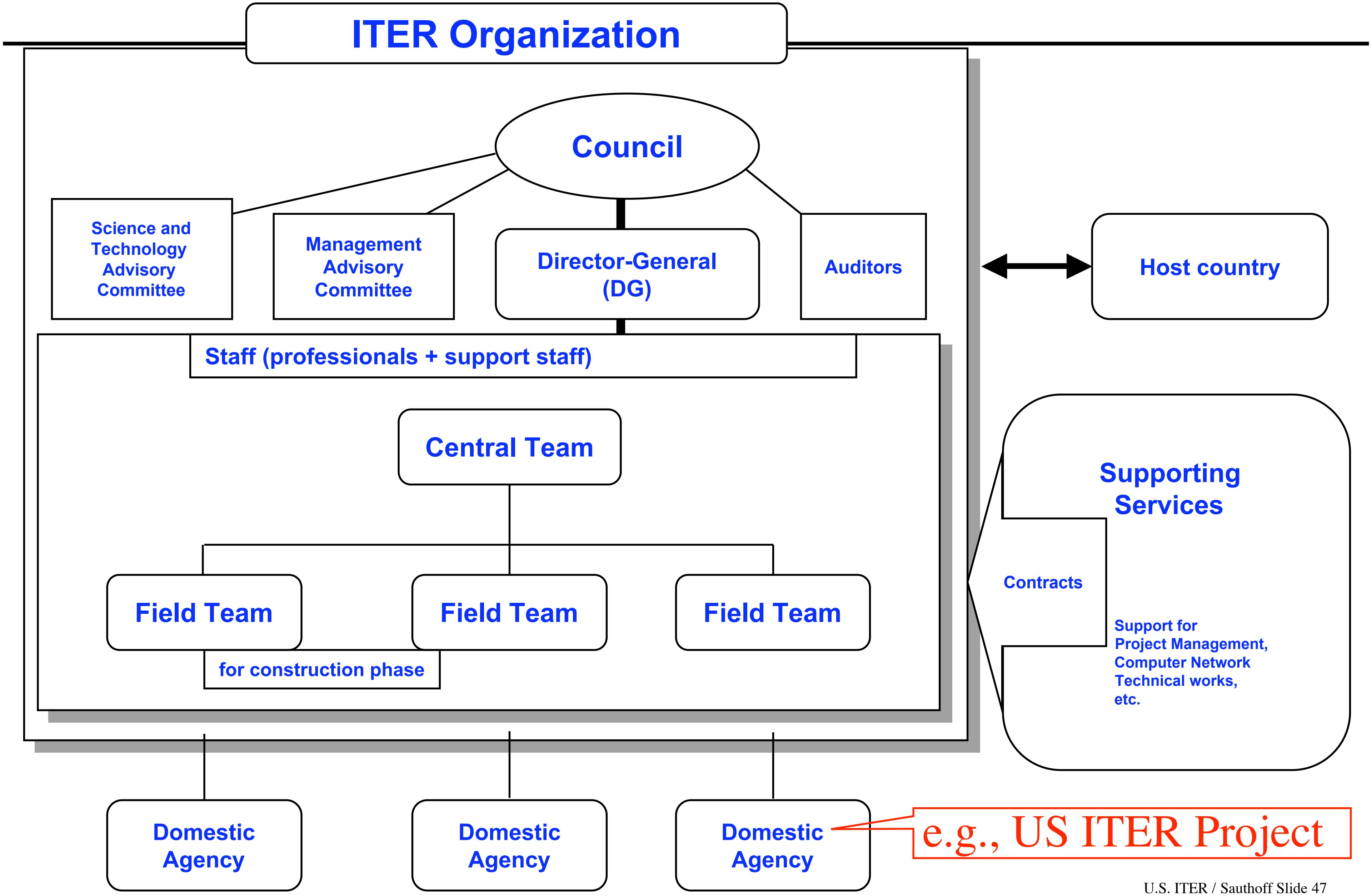
Withdrew
12/03

Canada
(Clarington)

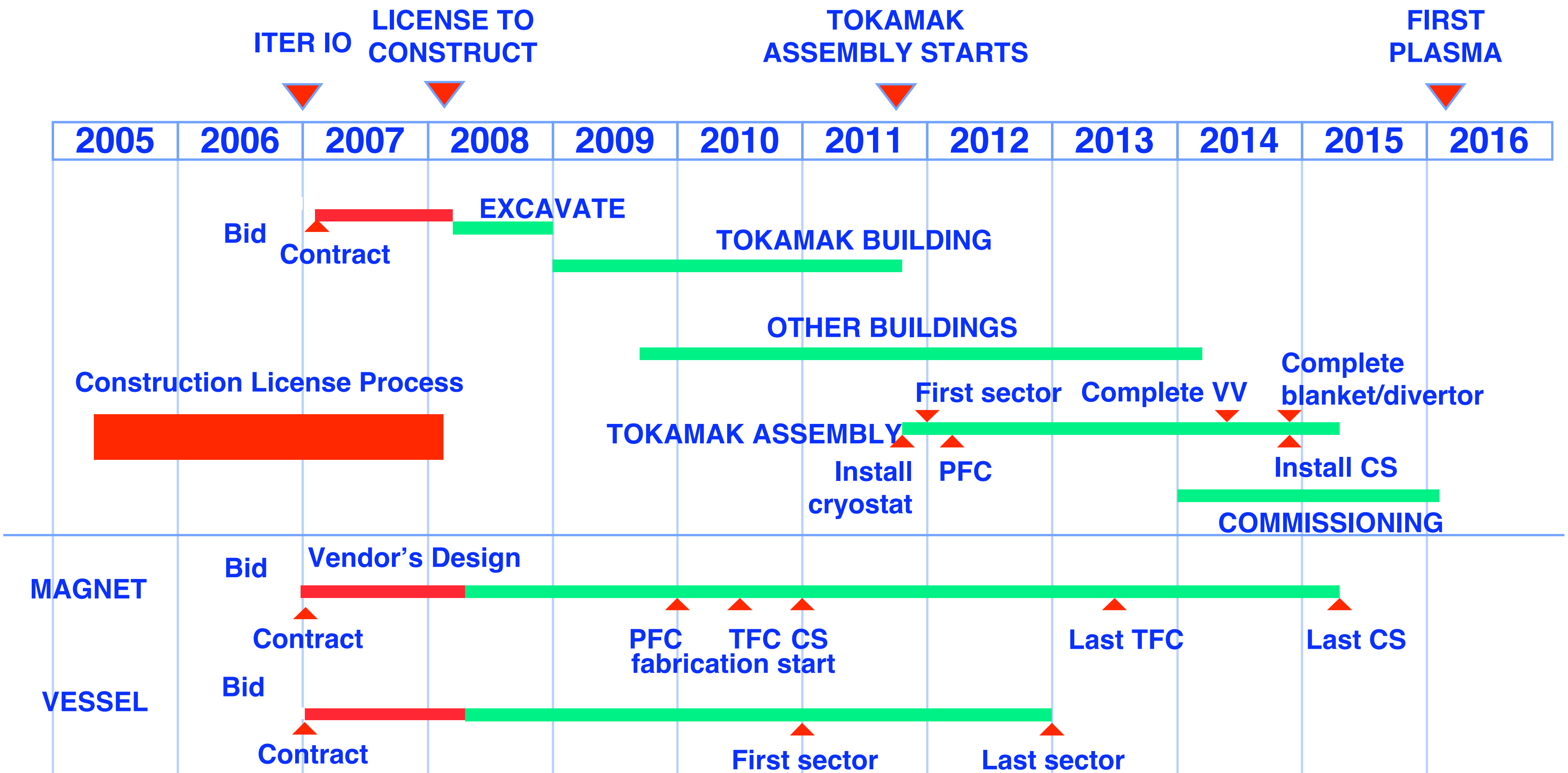
Evolution of ITER Management

- **Selection of Director General Nominee Kaname Ikeda**
- **Management Structure**
  - NSSG working group identified Director General / Principal Deputy concept and corresponding roles/qualifications
  - EU is soliciting candidates for Principal Deputy DG
  - DGN issued a draft structure and invited parties to provide candidates for Deputy DG's;
    US responded with suggestions

Highest Level Management Structure

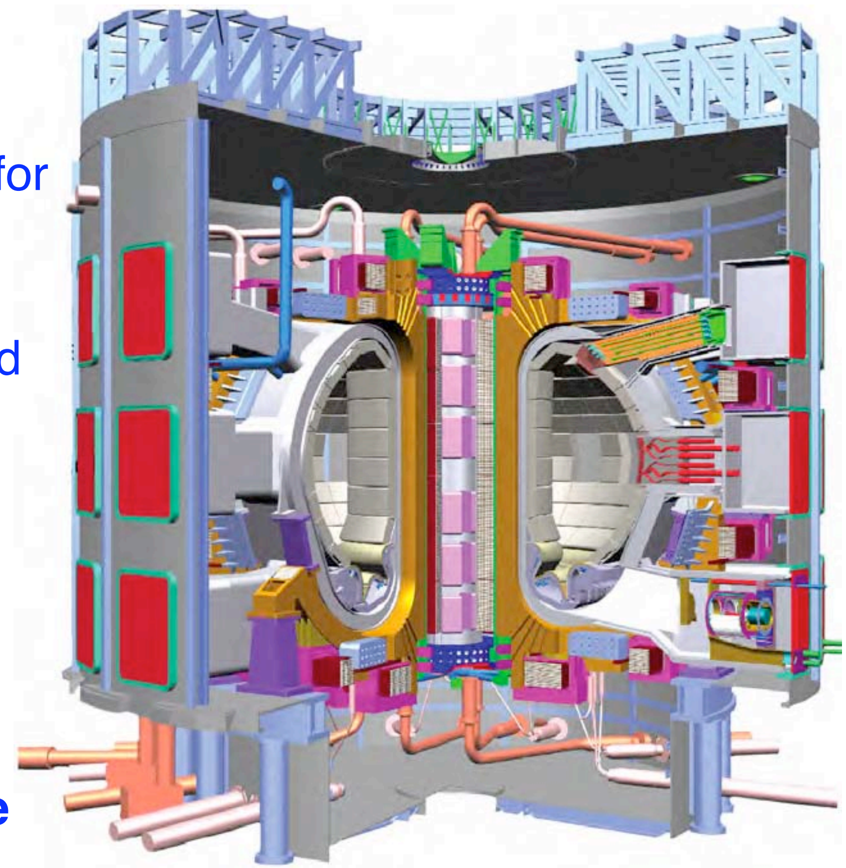


Schedule


ITER IO
LICENSE TO CONSTRUCT
TOKAMAK ASSEMBLY STARTS
FIRST PLASMA
2005
2006
2007
2008
2009
2010
2011
2012
2013
2014
2015
2016
Bid
Contract
EXCAVATE
TOKAMAK BUILDING
OTHER BUILDINGS
Construction License Process
First sector
Complete VV
Complete blanket/divertor
TOKAMAK ASSEMBLY
Install cryostat
PFC
Install CS
COMMISSIONING
MAGNET
Bid
Vendor's Design
Contract
PFC
TFC
CS
fabrication start
Last TFC
Last CS
VESSEL
Bid
Contract
First sector
Last sector

The Bottom Line….

- **Scientific and technological assessments have affirmed**
  - the significance of burning plasma science
  - the readiness of the tokamak as a vehicle for the study of toroidal magnetically-confined self-heated plasmas.
  - the scientific and technological benefits and readiness of ITER



- **The world fusion community is striving to start the construction of ITER to enable burning plasma research.**

- **ITER should serve as a major facility for the study of reactor-scale long-pulse toroidal plasmas, providing burning plasma science and technology research opportunities in the 2015-2035 period.**