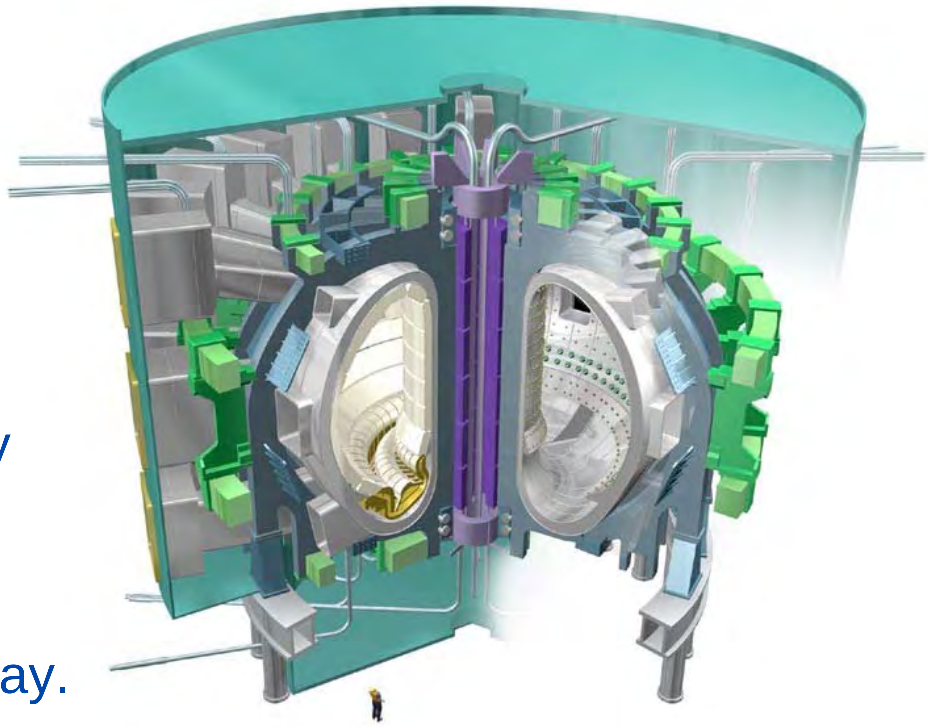
Nuclear Fusion and ITER

C. Alejaldre
ITER Deputy Director-General

Cursos de Verano UPM
Julio 2, 2007

ITER – the way to fusion power

- ITER ("the way" in Latin) is the essential next step in the development of fusion.
- Its objective: to demonstrate the scientific and technological feasibility of fusion power.
- The world's biggest fusion energy research project, and one of the most challenging and innovative scientific projects in the world today.



ITER – Key facts

- Designed to produce 500 MW of fusion power (tenfold the energy input) for an extended period of time
- Will bring together most key technologies needed for future fusion power plants
- 10 years construction, 20 years operation 5 years deactivation
- Cost: 5 billion Euros for construction, and 5 billion for operation and decommissioning

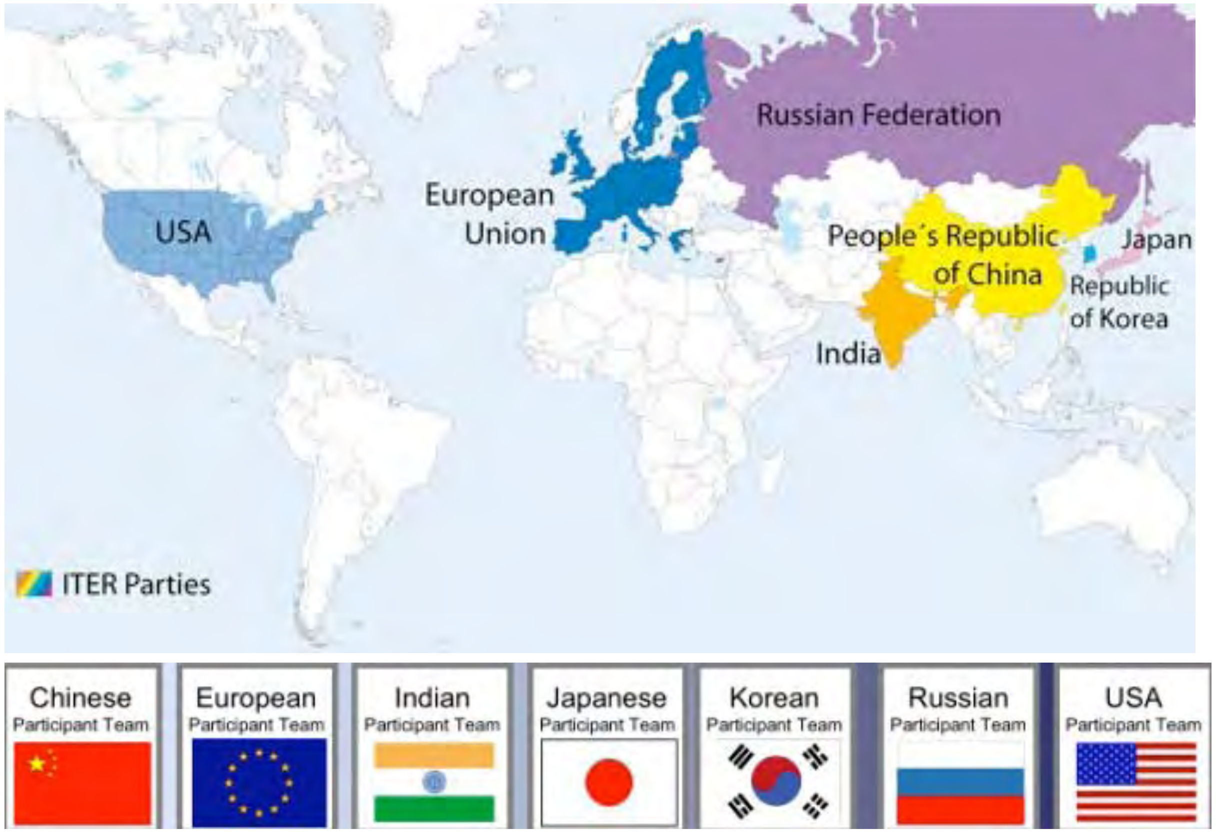
Cadarache Site

The current ITER building

ITER Collaboration

- For its size and cost and the involvement of virtually all the most developed countries, representing over half of today world's population ITER will become a new reference term for big science projects.

- The ITER project is one of the world's biggest scientific collaboration.



Outline

- Fusion fundamentals
- ITER technical overview
  - Description Project Situation
  - Staff, organization.
  - Planning
- Conclusions

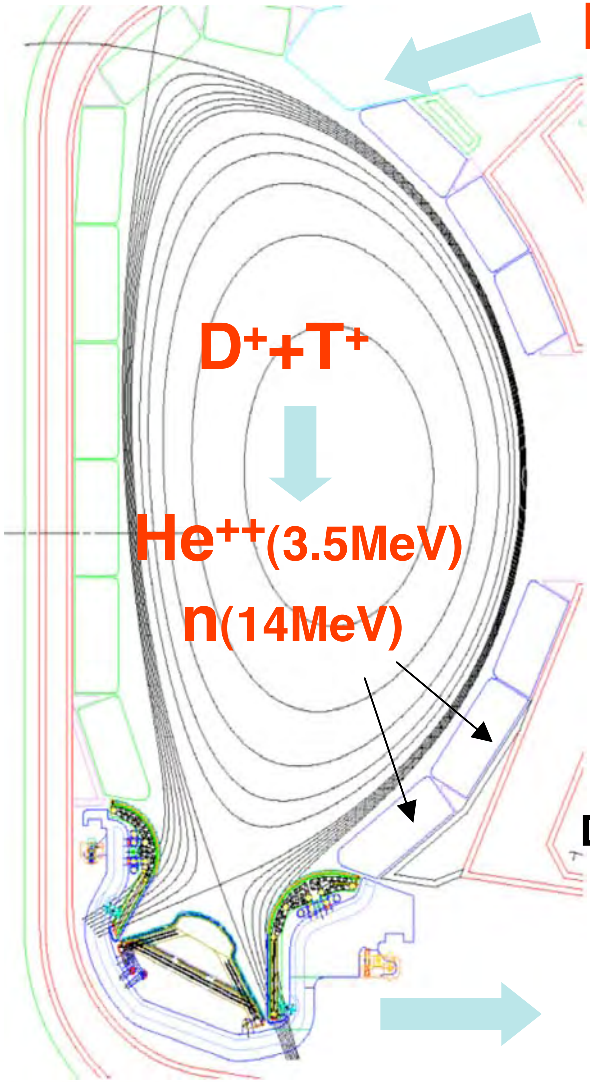
Fusion in Tokamak Plasma

Donut Shape Plasma

V: 830m^3
R/a: 6.2m /2m
Vertical elongation: 1.8 5
Triangularity: 0.45

-Density: 10^{20}m^{-3}
-PeakTemperature:17keV
-Fusion Power: 500MW

-Plasma Current : 15MA
-Toroidal field: 5.3T



D_2,T_2 Fuel

Blanket: neutron absorber

Power Plant
Li-->T
High temperature

Divertor: particle and heat exhaust

He, D_2,T_2, impurities

Fusion inherent feautures

- **Power: any disturbance will stop the plasma**
  - **"runaway" reaction is physically not possible**
- **After shutdown, residual heat is small and only in structural materials**
- **Fuel inventory small**
- **Low routine emissions and limited consequences of postulated accidental releases**
- **No long-lived radioactivity**
- **No materials with proliferation concerns**
- **No climate-changing emissions**

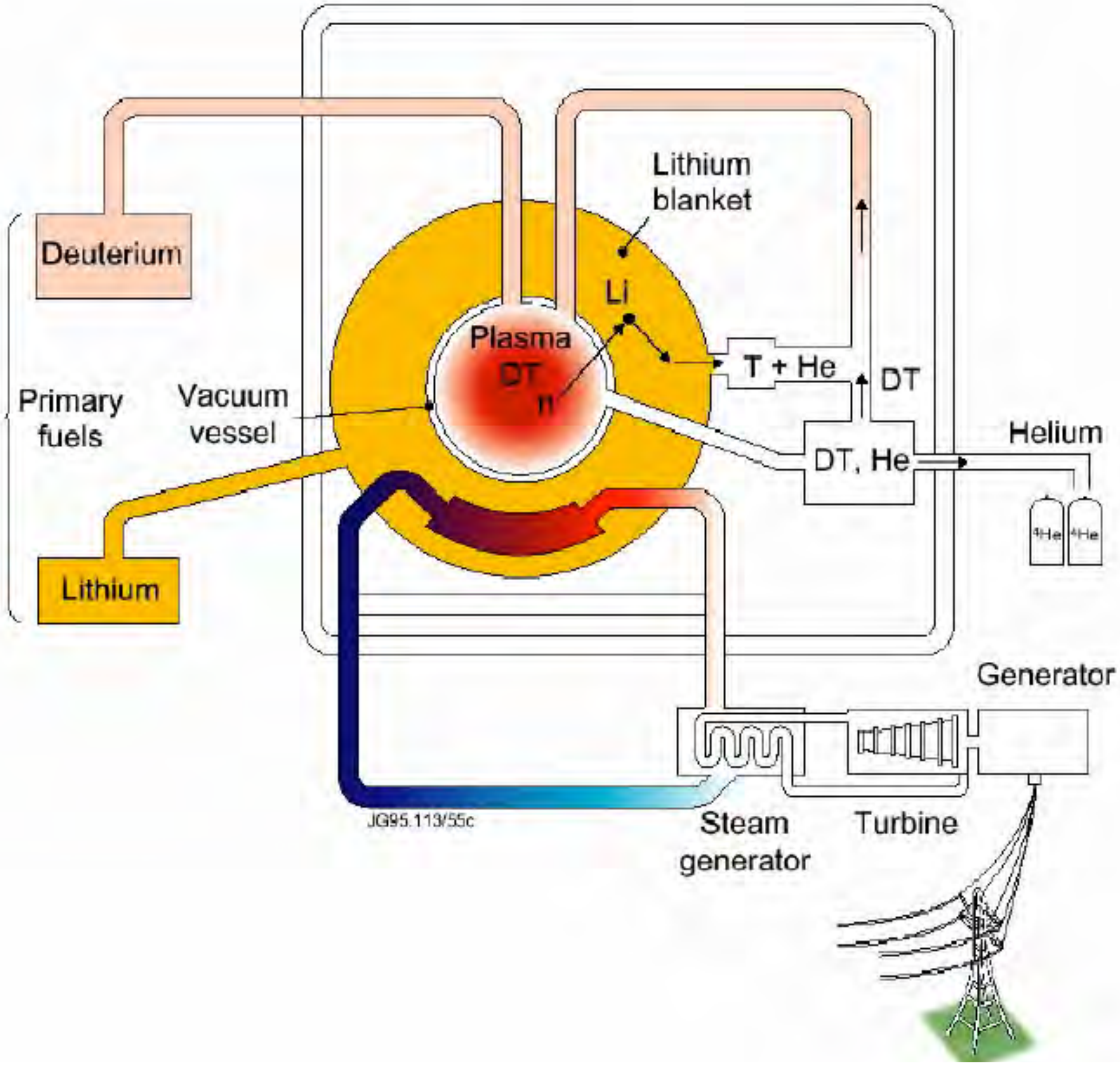
Confinement quality and Q

- Temperature (T_i): $1\text{-}2 \times 10^8$ °C (10-20 keV)
  (~10 × temperature of sun's core)
- Density (n_i): 1×10^{20} m^{-3} (~10^{-6} of atmospheric particle density)
- Energy confinement time (τ_E): few seconds
  (plasma pulse duration ~1000 seconds)

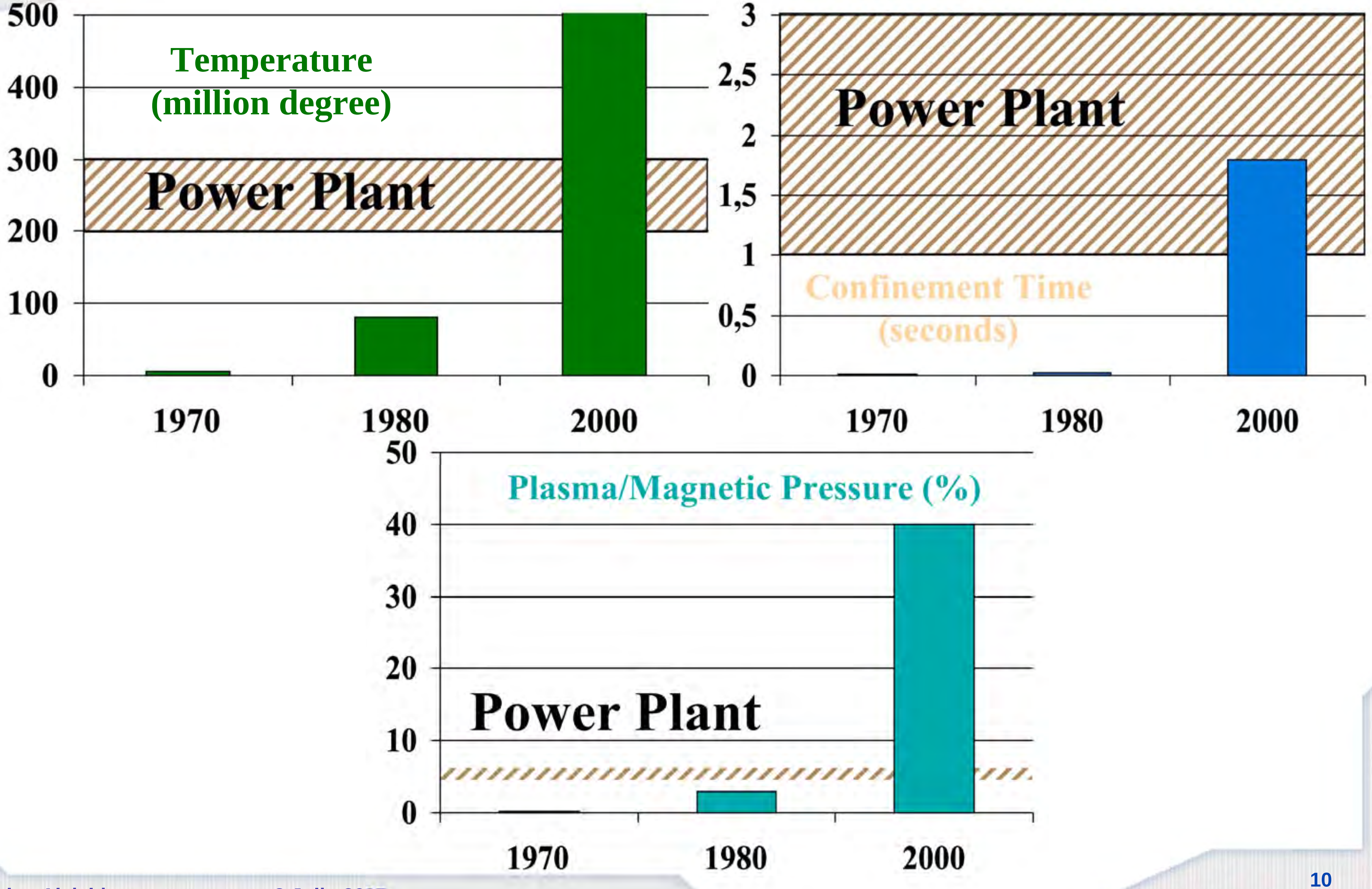
- **Fusion power amplification:** $Q = \dfrac{\text{Fusion power}}{\text{Input power}} \sim n_i T_i \tau_E$

"Scientific breakeven"	**Q = 1**	**(JET)**
"Self-heated plasma"	**Q ~ 10**	**(ITER)**
"Power Plant"	**Q ≥ 30**	**(DEMO)**

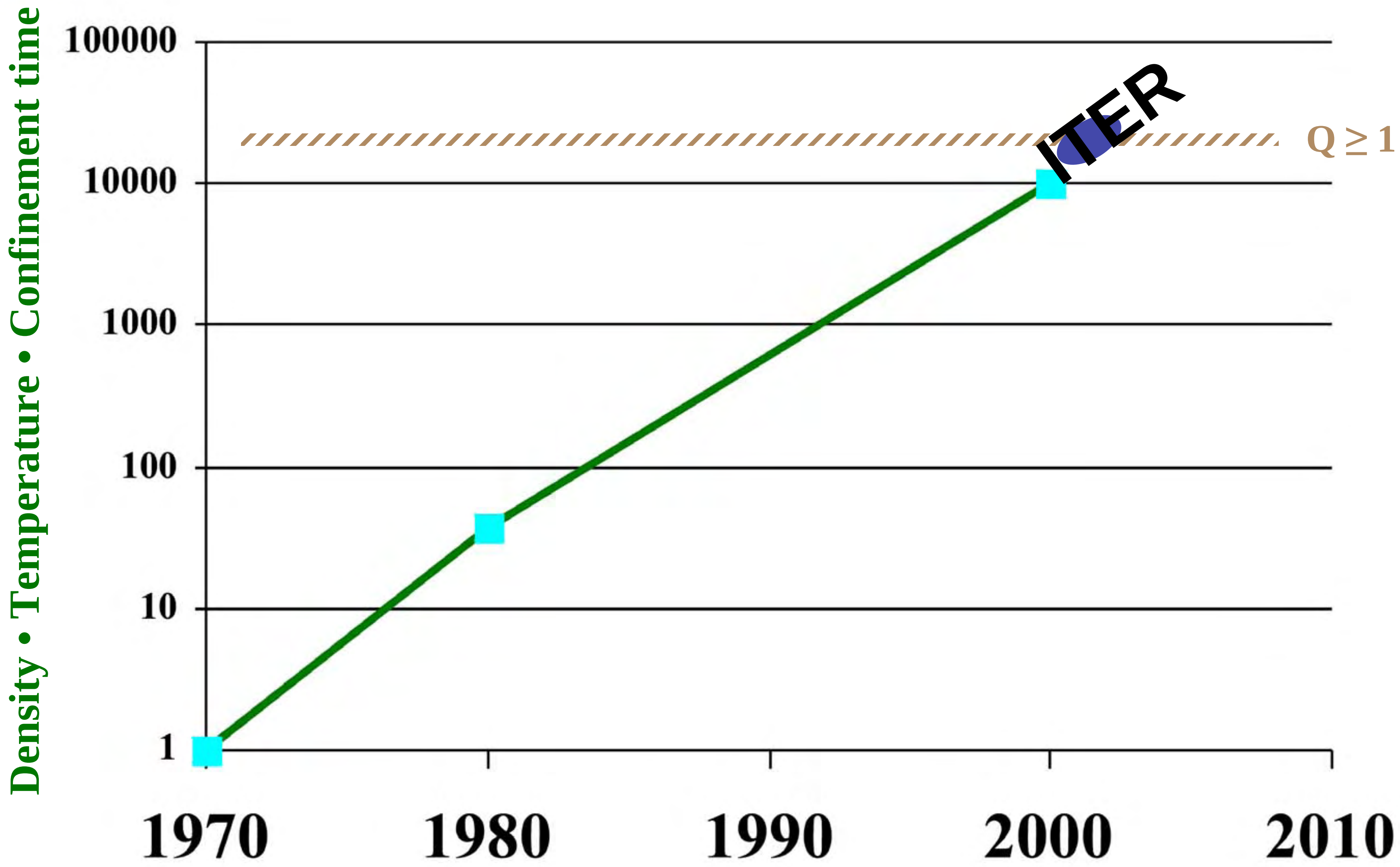
Power Reactor



Summary Results



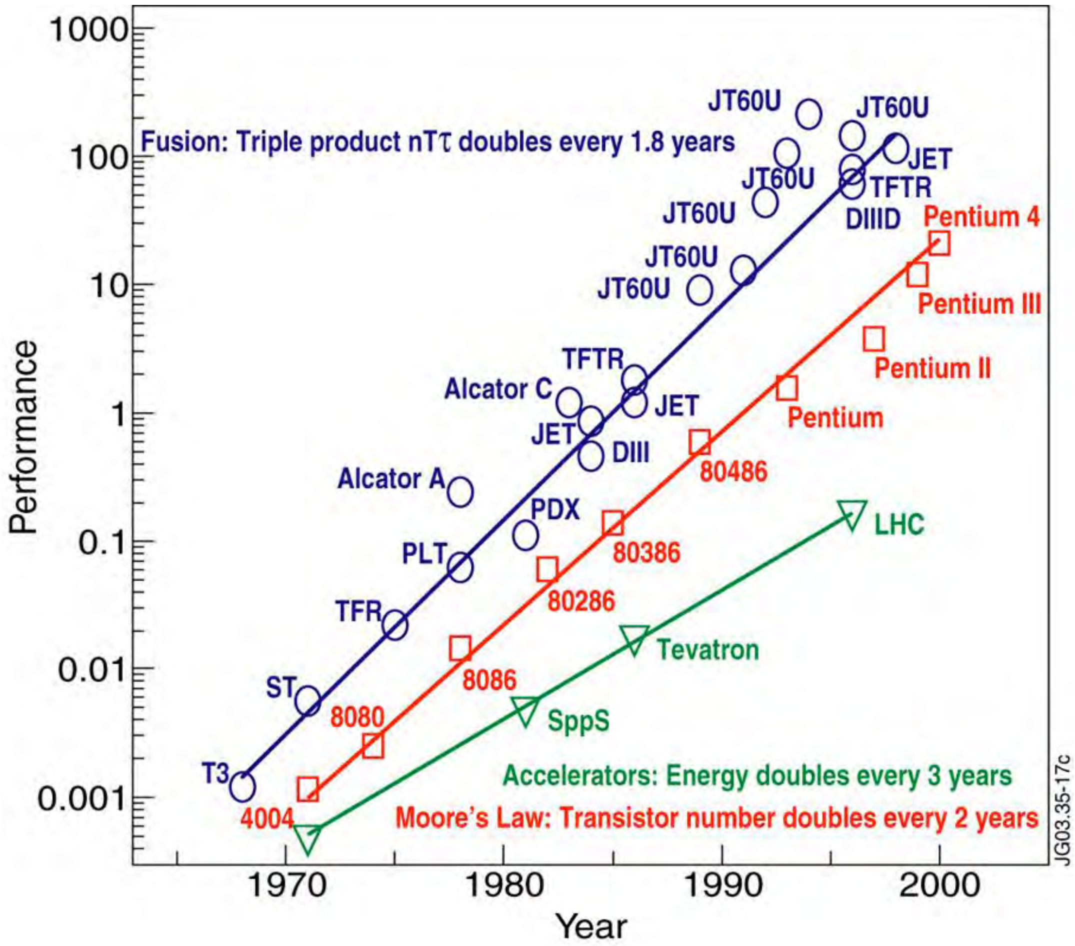
Globally



Density • Temperature • Confinement time
100000
10000
1000
100
10
1
ITER
Q ≥ 1
1970
1980
1990
2000
2010

Confinement Quality Scaling
Tokamak: a success story

- **Progress in fusion can be compared with the computing power performance**

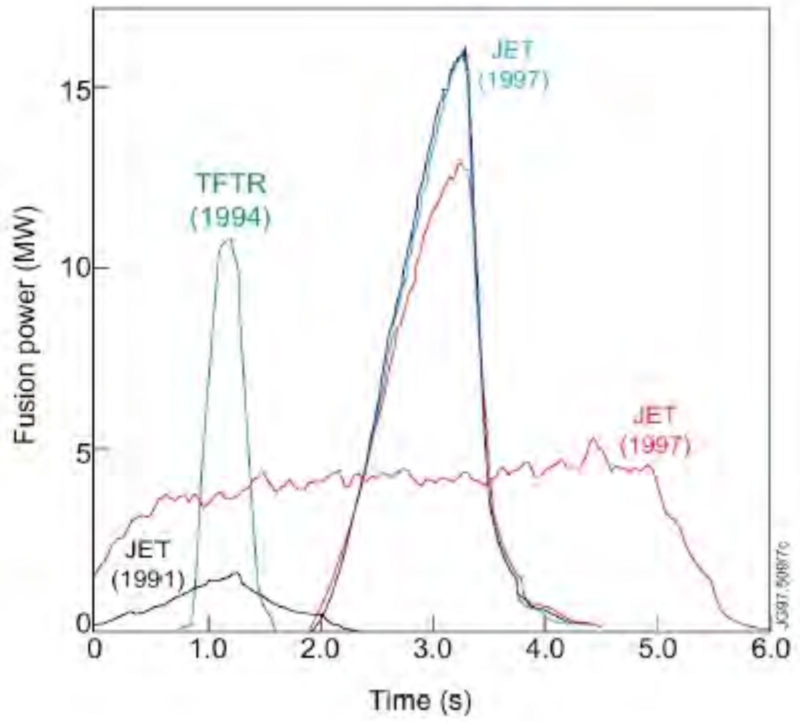


Fusion power production

- **Experiments in JET and TFTR have initiated the study of DT plasmas with significant fusion power:**
  - best JET results correspond to a fusion power production of 16MW

⇒ α-particle heating amounted to <15% of the input power to the plasma

$$f_\alpha = Q/(Q+5)$$



"All the News That's Fit to Print"

The New York Times

Late Edition

Weather: Rain likely today, strong easterly winds; rain ending late tonight. Partly cloudy and warmer tomorrow. Temperatures: today 43-47, tonight 40-45; yesterday 38-62. Details, page C30.

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ᴇxt of the Joint U.S.-Soviet Statement: 'Greater Understanding Achieved'

Special to The New York Times

EVA, Nov. 21 — Following is t of the joint Soviet-American ent at the end of the summit g today, as made public by the House:

iutual agreement, the President the United States, Ronald , and the General Secretary of itral, Committee of the Communist Party of the Soviet Union, Mi. Gorbachev, met in Geneva -21. Attending the meeting on side were Secretary of State P. Shultz; chief of staff, Dontegan; Assistant to the President obert C. McFarlane; Ambas- the U.S.S.R., Arthur A. Hart- ecial adviser to the President Secretary of State for Arms Paul H. Nitze; Assistant Sec- f State of European Affairs, L. Ridgway; Special Assist- he President for National Se- ffairs, Jack F. Matlock.

ding on the Soviet side were of the Politburo of the Cen- mmittee of the C.P.S.U., of Foreign Affairs Eduard ardnadze; First Deputy For- ister Georgi M. Korniyenko; ador to the United States, F. Dobrynin; head of the De- t of Propaganda of the Cen- mittee of the C.P.S.U., Alek- . Yakovlev; head of the De- t of International Informa- he Central Committee of the ., Leonid M. Zamyatin; t to the General Secretary of ntral Committee of the , Andrei M. Aleksandrov.

comprehensive discussions the basic questions of U.S.- lations and the current inter- situation. The meetings were d useful. Serious differences n a number of critical issues. acknowledging the differ- their systems and ap- to international issues, eater understanding of each ew was achieved by the two They agreed about the need ve U.S.-Soviet relations and national situation as a whole.

In this connection the two sides have confirmed the importance of an ongoing dialogue, reflecting their strong desire to seek common ground on existing problems.

They agreed to meet again in the nearest future. The General Secretary accepted an invitation by the President of the United States to visit the United States of America, and the President of the United States accepted an invitation by the General Secretary of the Central Committee of the C.P.S.U. to visit the Soviet Union. Arrangements for the timing of the visits will be agreed upon through diplomatic channels.

In their meetings, agreement was reached on a number of specific issues. Areas of agreement are registered on the following pages.

Security

The sides, having discussed key security issues, and conscious of the special responsibility of the USSR and the U.S. for maintaining peace, have agreed that a nuclear war cannot be won and must never be fought. Recognizing that any conflict between the U.S.S.R. and the U.S. could have catastrophic consequences, they emphasized the importance of preventing any war between them, whether nuclear or conventional. They will not seek to achieve military superiority.

Nuclear and Space Talks

The President and the General Secretary discussed the negotiations on nuclear and space arms.

They agreed to accelerate the work at these negotiations, with a view to accomplishing the tasks set down in the Joint U.S.-Soviet Agreement of Jan. 8, 1985, namely to prevent an arms race in space and to terminate it on earth, to limit and reduce nuclear arms and enhance strategic stability.

Noting the proposals recently tabled by the U.S. and the Soviet Union, they called for early progress, in particular in areas where there is common ground, including the principle of 50 percent reductions in the nuclear arms of the U.S. and the U.S.S.R. appropriately applied, we well as the idea of an interim I.N.F. agreement.

During the negotiation of these agreements, effective measures for verification of compliance with obligations assumed will be agreed upon.

Risk Reduction Cente

The sides agreed to study th tion at the expert level of cer reduce nuclear risk taking i count the issues and developm the Geneva negotiations. The satisfaction in such recent s this direction as the moderniza the Soviet-U.S. hot line.

Nuclear Nonprolifera

General Secretary Gorbach President Reagan reaffirme commitment of the U.S.S.R. a U.S. to the Treaty on the Nonpr ation of Nuclear Weapons and interest in strengthening to with other countries the nonpro tion regime, and in further enh the effectiveness of the treaty alia by enlarging its members

The U.S.S.R. and the U.S. re their commitment, assumed by under the Treaty on the Nonpro tion of Nuclear Weapons, to p negotiations in good faith on m of nuclear arms limitation and mament in accordance with A VI of the treaty.

The two sides plan to conti promote the strengthening of t ternational Atomic Energy A and to support the activities agency in implementing safeg as well as in promoting the pe uses of nuclear energy.

They view positively the pract regular Soviet-U.S. consultatio nonproliferation of nuclear wea which have been businesslike constructive, and express their i to continue this practice in the fu

Chemical Weapons

In the context of discussin curity problems, the two sides

firmed that they are in favor of a general and complete prohibition of chemical weapons and the destruction of existing stockpiles of such weapons. They agreed to accelerate efforts to conclude an effective and verifiable international convention on this matter.

The two sides agreed to intensify bilateral discussions on the level of experts on all aspects of such a ...

ministries and departments in such fields as agriculture, housing and protection of the environment have been useful.

Recognizing that exchanges of views on regional issues on the expert level have proven useful, they agreed to continue such exchanges on a regular basis.

The sides intend to expand the pro-

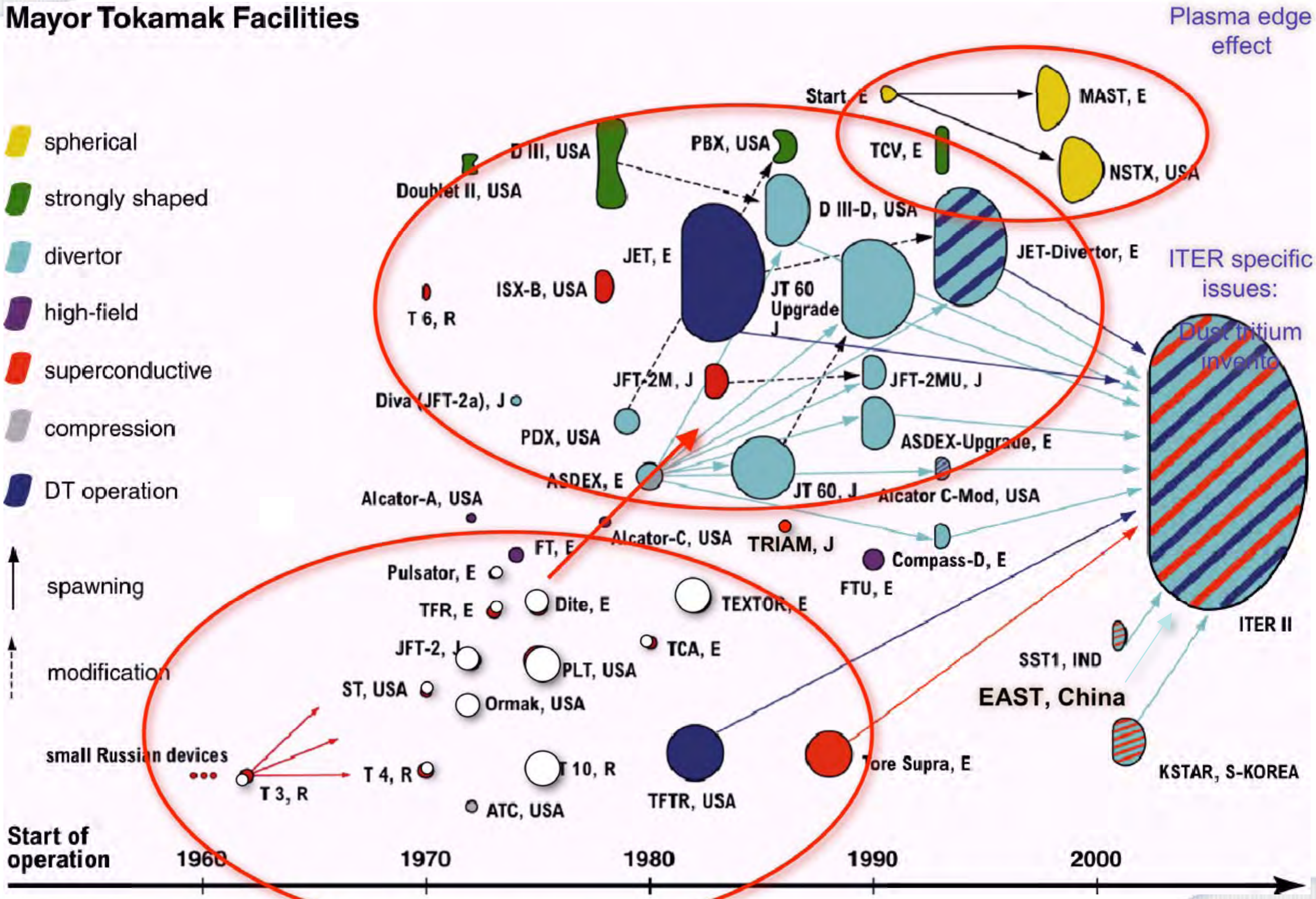
— a global task — through joint research and practical measures. In accordance with the existing U.S.-Soviet agreement in this area, consultations will be held next year in Moscow and Washington on specific programs of cooperation.

Exchange Initiatives

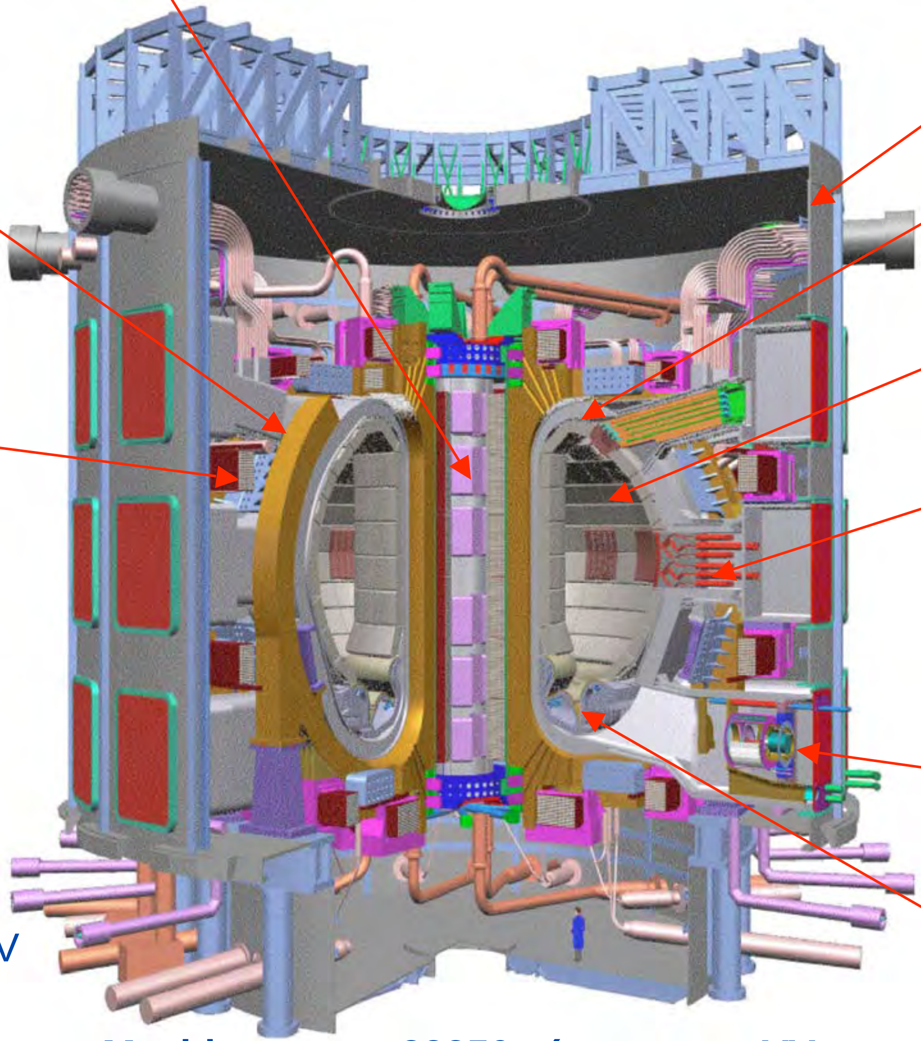
Fusion Research

The two leaders emphasized the potential importance of the work aimed at utilizing controlled thermonuclear fusion for peaceful purposes and, in this connection, advocated the widest practicable development of international cooperation in obtaining this source of energy, which is essentialy inexhaustible, for the benefit for all mankind.

ITER, one of a kind, but not the first fusion facilitiy



The core of ITER



Major plasma radius 6.2 m

Plasma Volume: 840 m^3

Plasma Current: 15 MA

Typical Density: 10^{20} m^{-3}

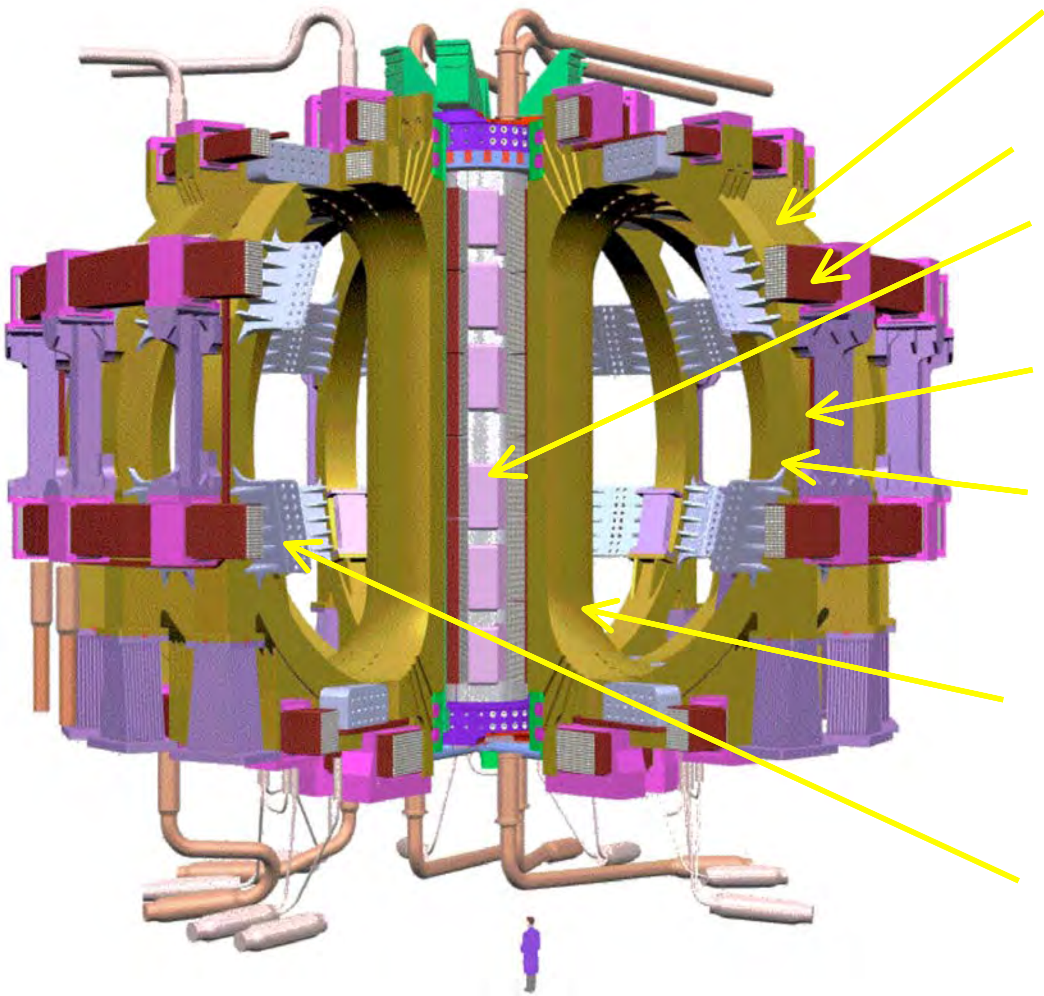
Typical Temperature: 20 keV

Fusion Power: 500 MW

Machine mass: 23350 t (cryostat + VV + magnets)

- shielding, divertor and manifolds: 7945 t + 1060 port plugs
- magnet systems: 10150 t; cryostat: 820 t

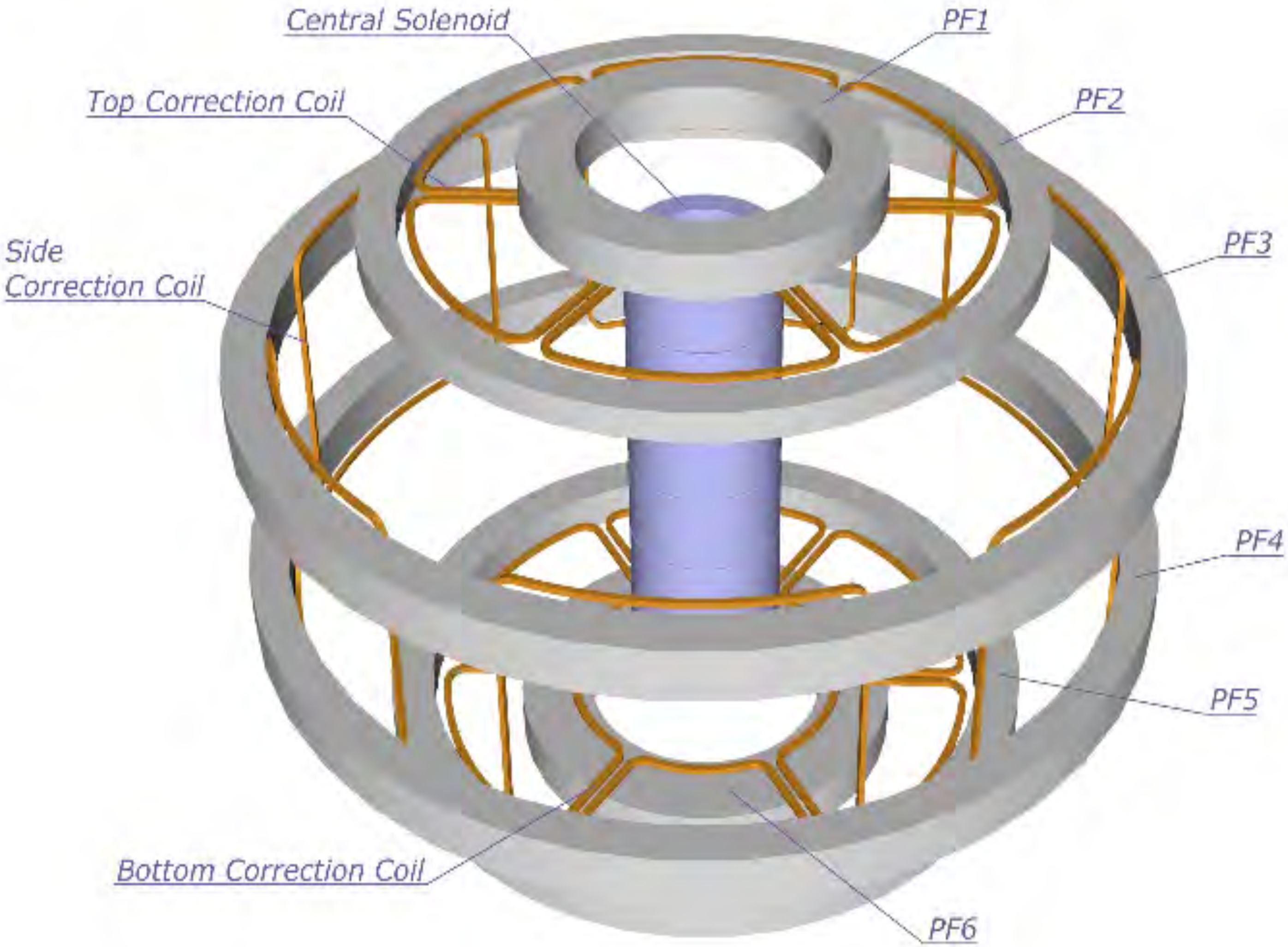
Magnet System

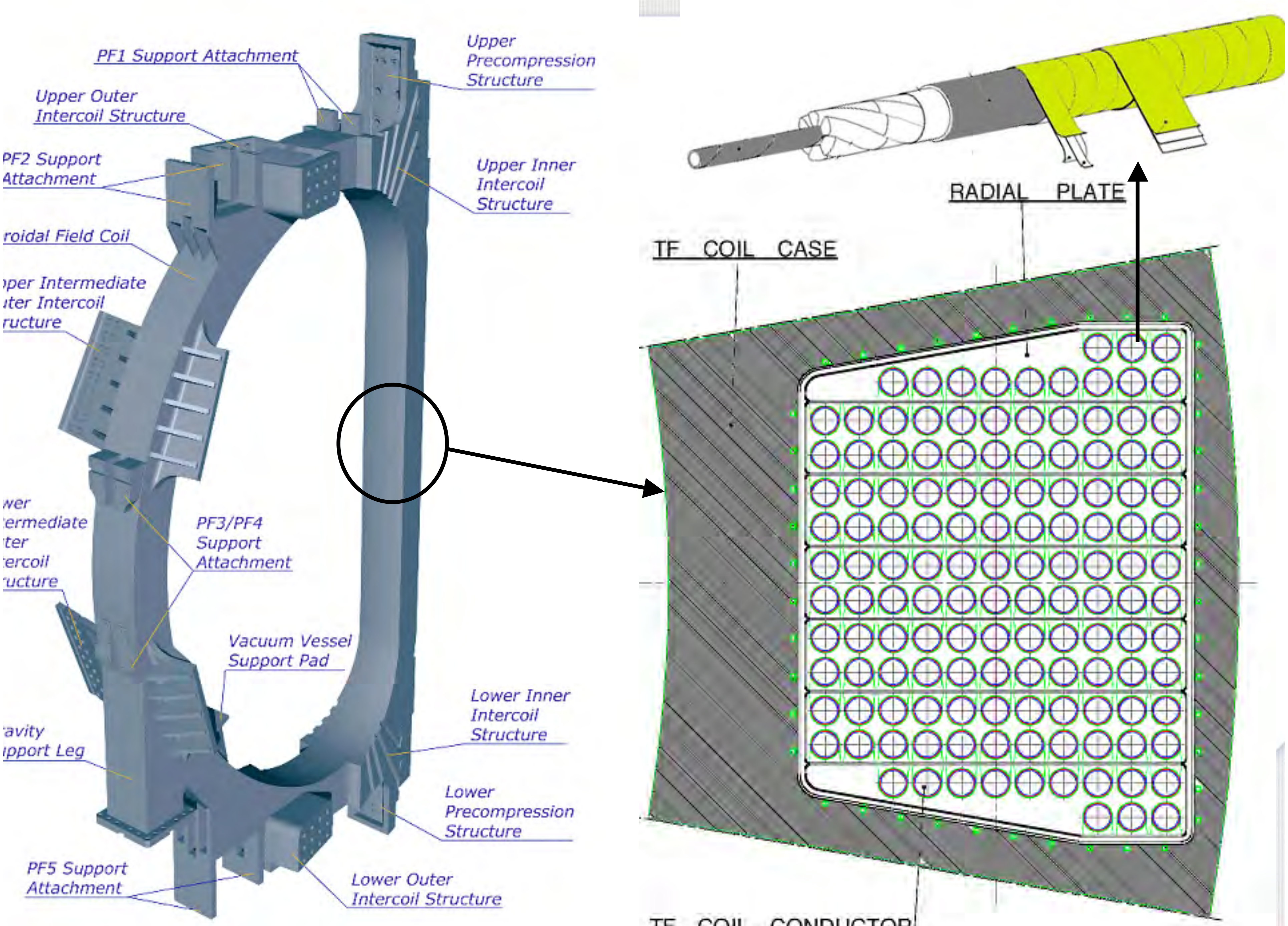


- Superconducting. Nb_3Sn toroidal field (TF) coils produce confining/stabilizing toroidal field;
- NbTi poloidal field (PF) coils position and shape plasma;
- Modular Nb_3Sn central solenoid (CS) coil induces current in the plasma.
- Correction coils correct error fields due to manufacturing/assembly imperfections, and stabilize plasma against resistive wall modes.
- TF coil case provides main structure of the magnet system and the machine core. PF coils and vacuum vessel are linked to it. All interaction forces resisted internally.
- TF coil inboard legs wedged together along their side walls and linked at top and bottom by two strong coaxial rings which provide toroidal compression
- On the outboard leg, out-of-plane support provided by intercoil structures integrated with TF coil cases.

◆Magnet system weighs ~ 8,700 t.

Poloidal Field system

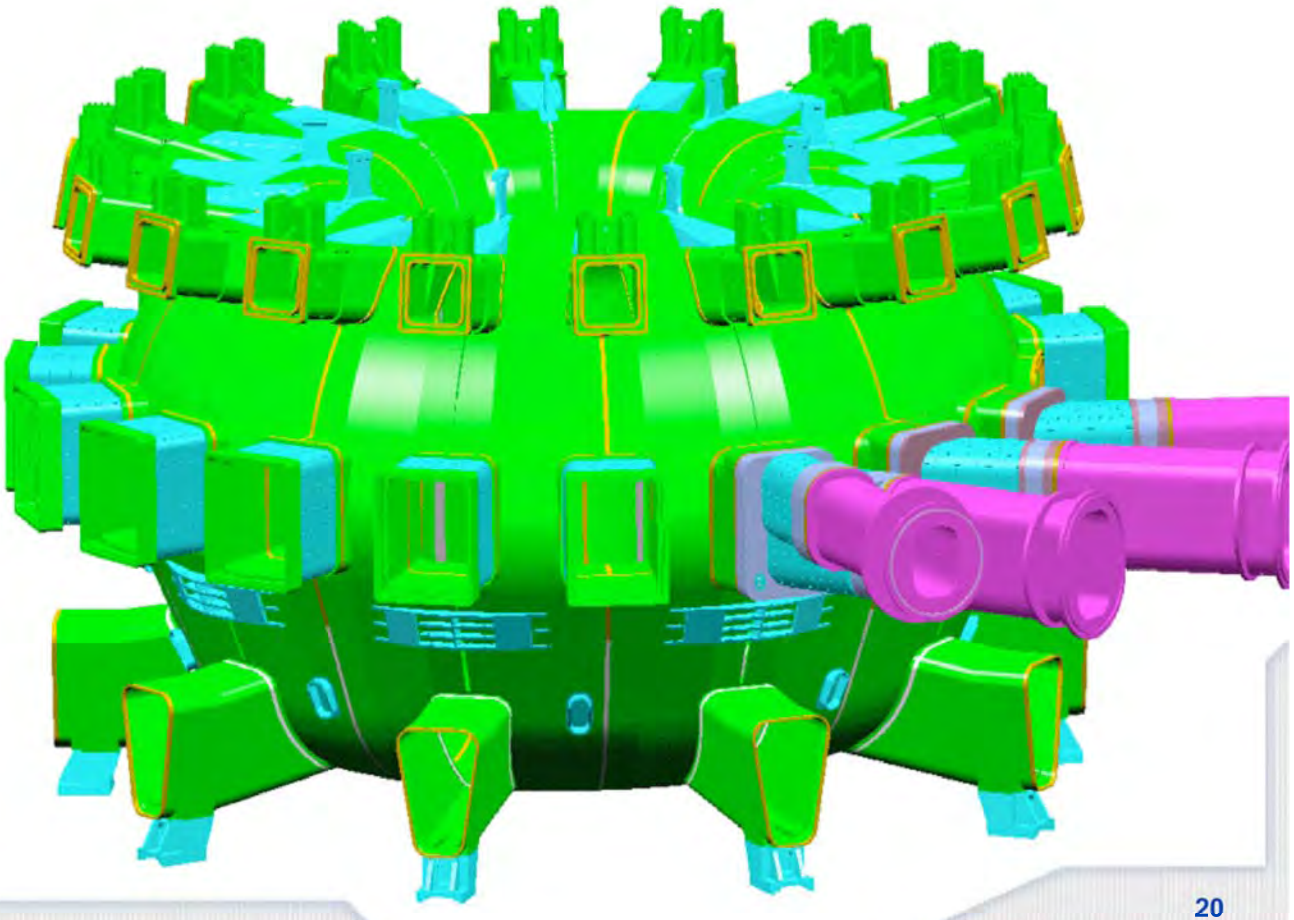



PF1 Support Attachment
Upper Precompression Structure
Upper Outer Intercoil Structure
PF2 Support Attachment
Upper Inner Intercoil Structure
roidal Field Coil
pper Intermediate
uter Intercoil
ructure
wer
ermediate
ter
ercoil
ucture
PF3/PF4 Support Attachment
Vacuum Vessel Support Pad
Lower Inner Intercoil Structure
avity
pport Leg
Lower Precompression Structure
PF5 Support Attachment
Lower Outer Intercoil Structure
RADIAL PLATE
TF COIL CASE
TF COIL CONDUCTOR

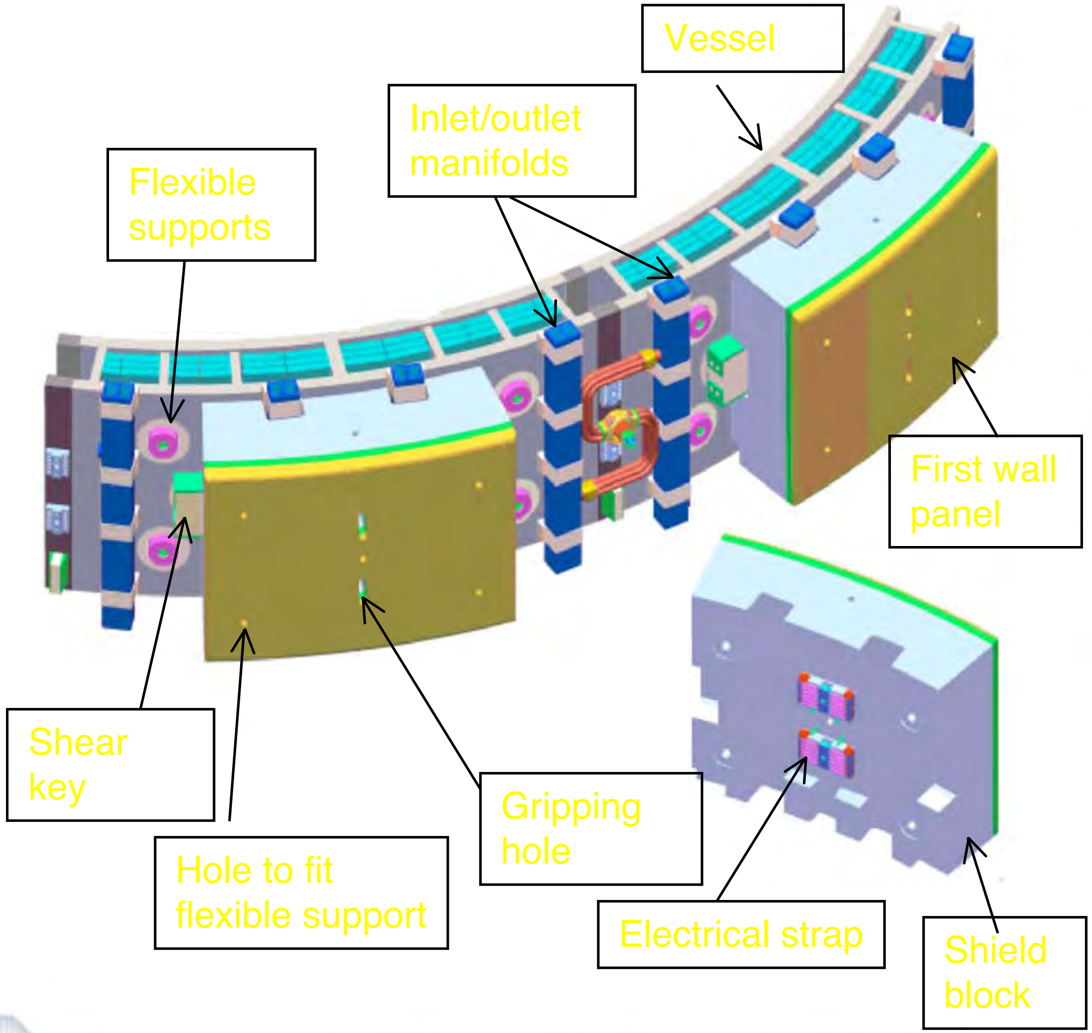
Plasma Vacuum Vessel

- Primary function
  - high quality vacuum for the plasma
  - first confinement barrier to radioactive materials

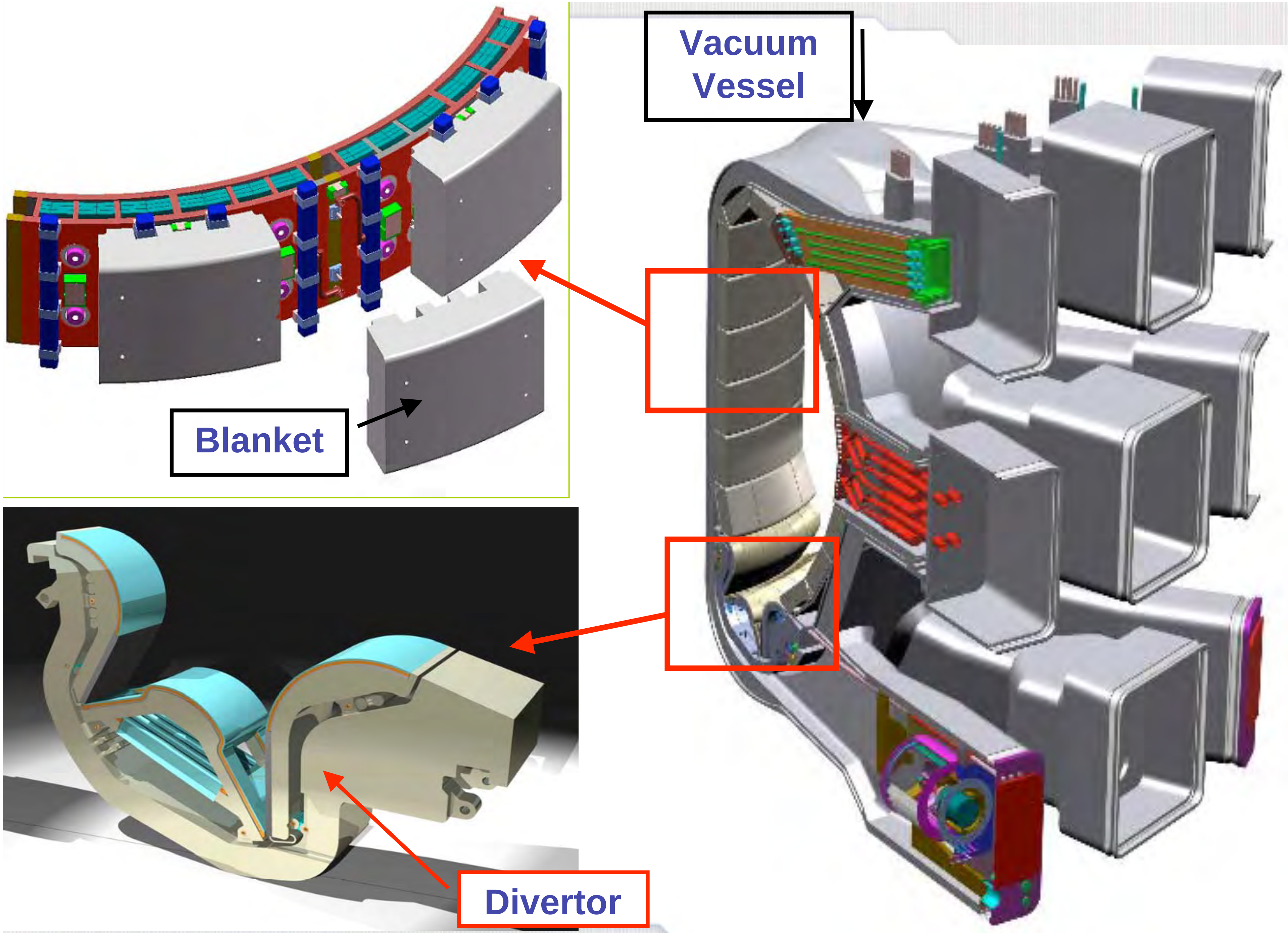
- 9 x 40° vessel sectors.
- Many ports for access:
  - -Diagnostics
  - -Maintenance
  - -Heating systems
  - -Fuelling/Pumping
  - -Inspection
  - -Test Blankets
- Double wall
- Water cooled



Blanket



- 440 blanket modules with detachable faceted first wall (FW) with Be armour on a water-cooled copper substrate, attached to a SS shielding block.
- Blanket cooling channels are mounted on the vessel.
- Design strongly affected by need to resist electromagnetic forces.
- Initial blanket acts solely as a neutron shield, and tritium breeding experiments are carried out on test blanket modules inserted and withdrawn at radial equatorial ports.


Vacuum
Vessel
Blanket
Divertor

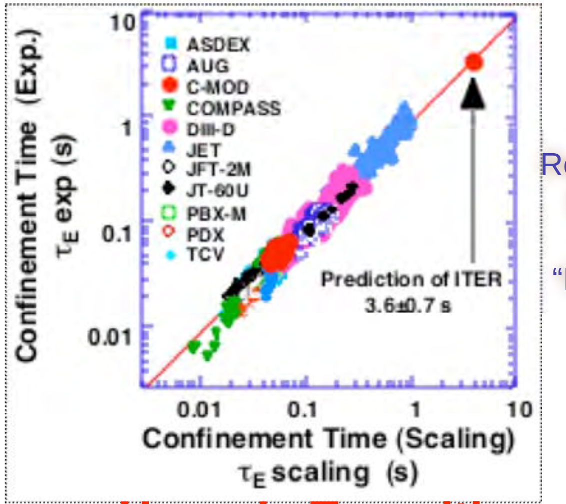
ITER Physics R&D

The World Tokamak Research Efforts Have Been Concentrated on Establishing ITER Physics Basis.

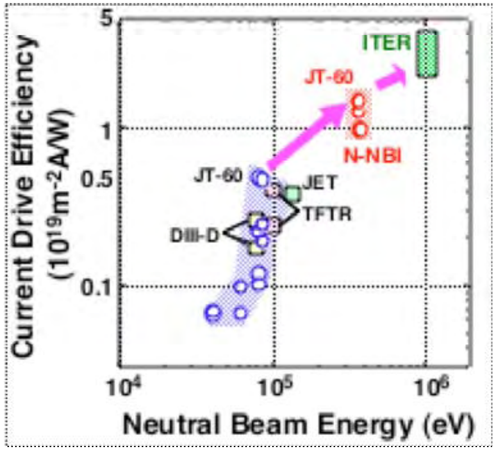
Review paper "ITER Physics Basis" (500 pages,NF1999)
http://www.iop.org/EJ/abstract/0029-5515/39/12/301)

"Progress in ITER Physics Basis" (500 pages, NF2007)

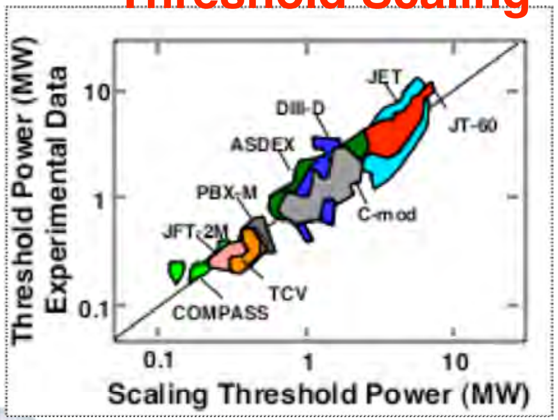
Energy Confinement Scaling

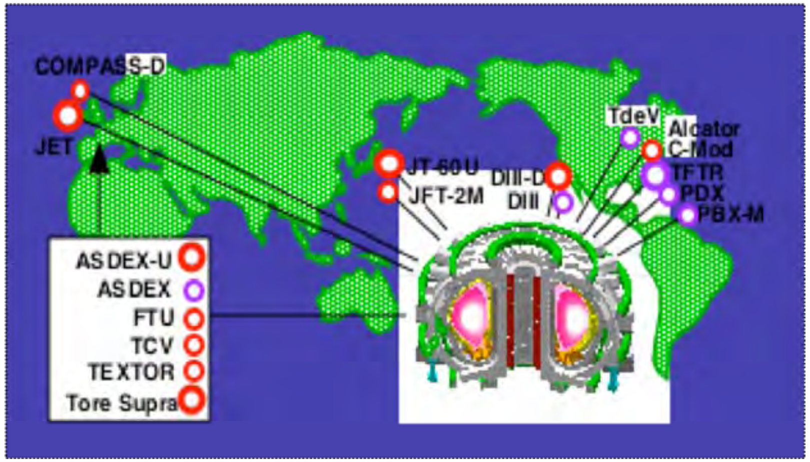


Current Drive

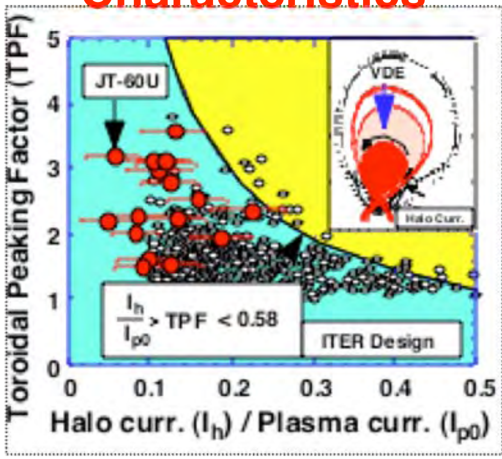


H-mode Transition Threshold Scaling





Halo Current Characteristics

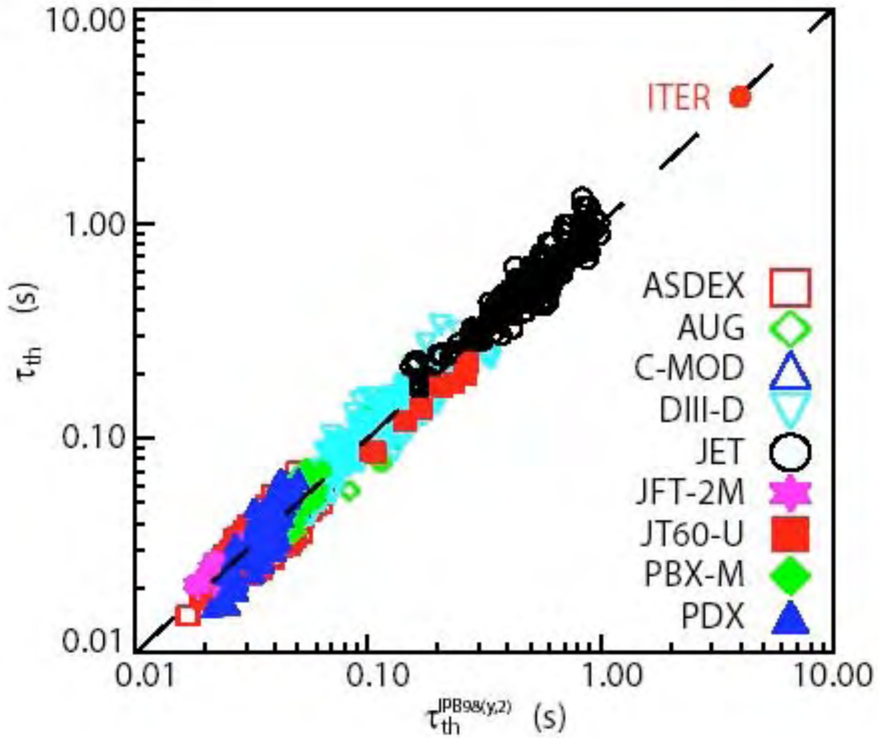


Plasma energy confinement

- **An international collaboration has assembled an extensive database of experimental results which provides the prediction of the energy confinement time, τ_E, in ITER:**

$$\tau_E \propto I_p R^2 \times Power^{-2/3}$$

  - confinement times based on scaling prediction correspond to H_H=1
  - predicted energy confinement time of 3.9s (±15%)



Long pulses – Current Drive
Tore Supra results

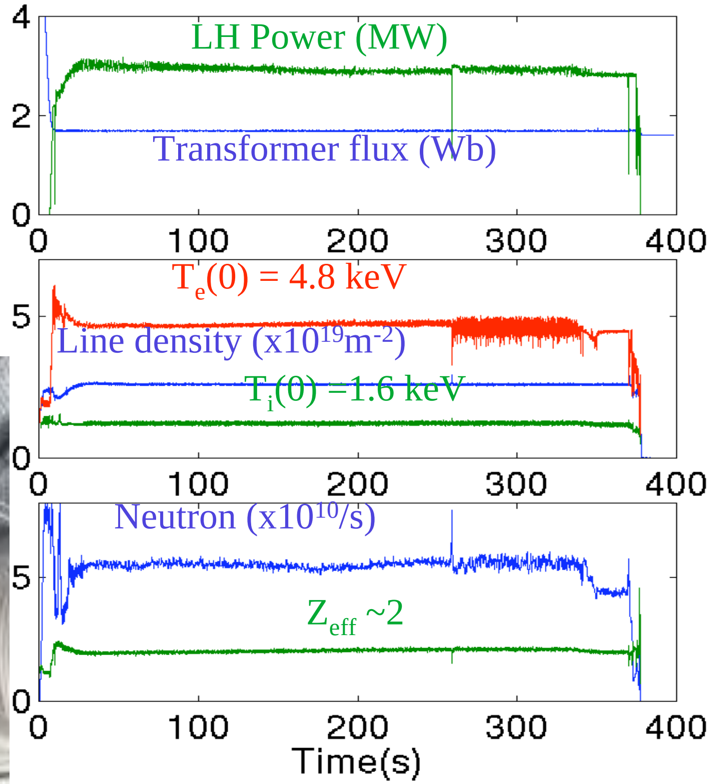
e.g. Tore Supra (CEA-Cadarache)

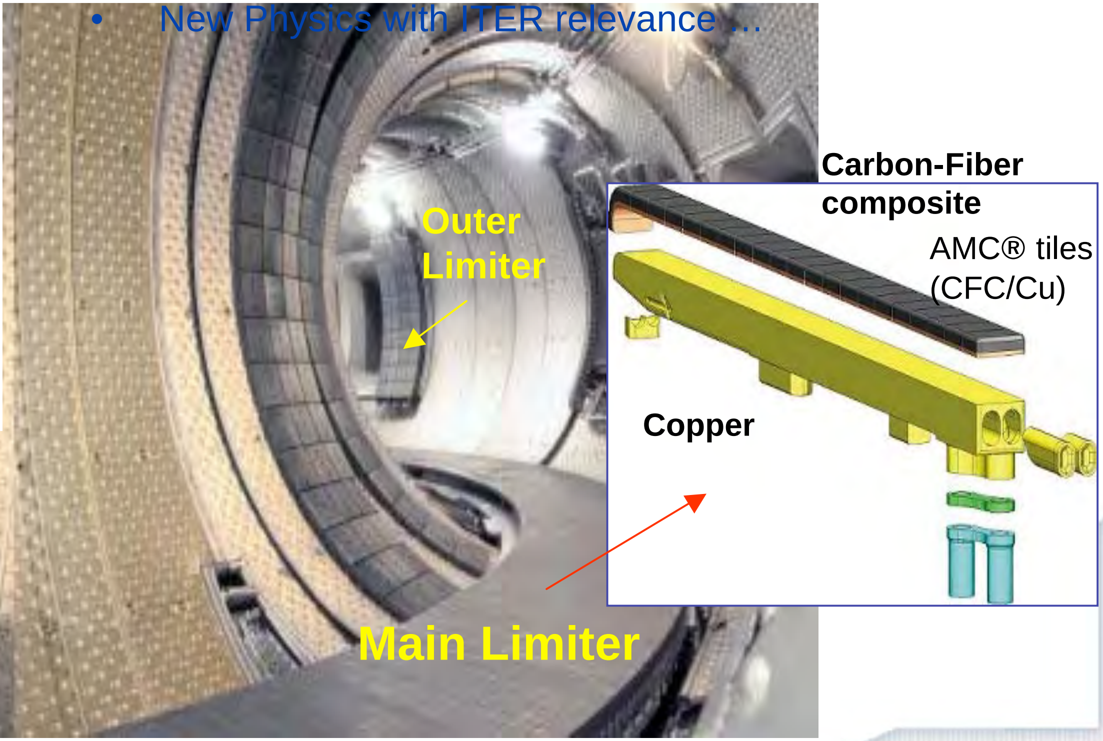
Actively cooled Plasma Facing Components tested up to 10 MW/m²

World records (over 6 minute pulses)

Long pulse non inductive discharges (V~0, Ip = 0.5 MA, feed back control of plasma current on LH power, 360 s, 1 GJ):

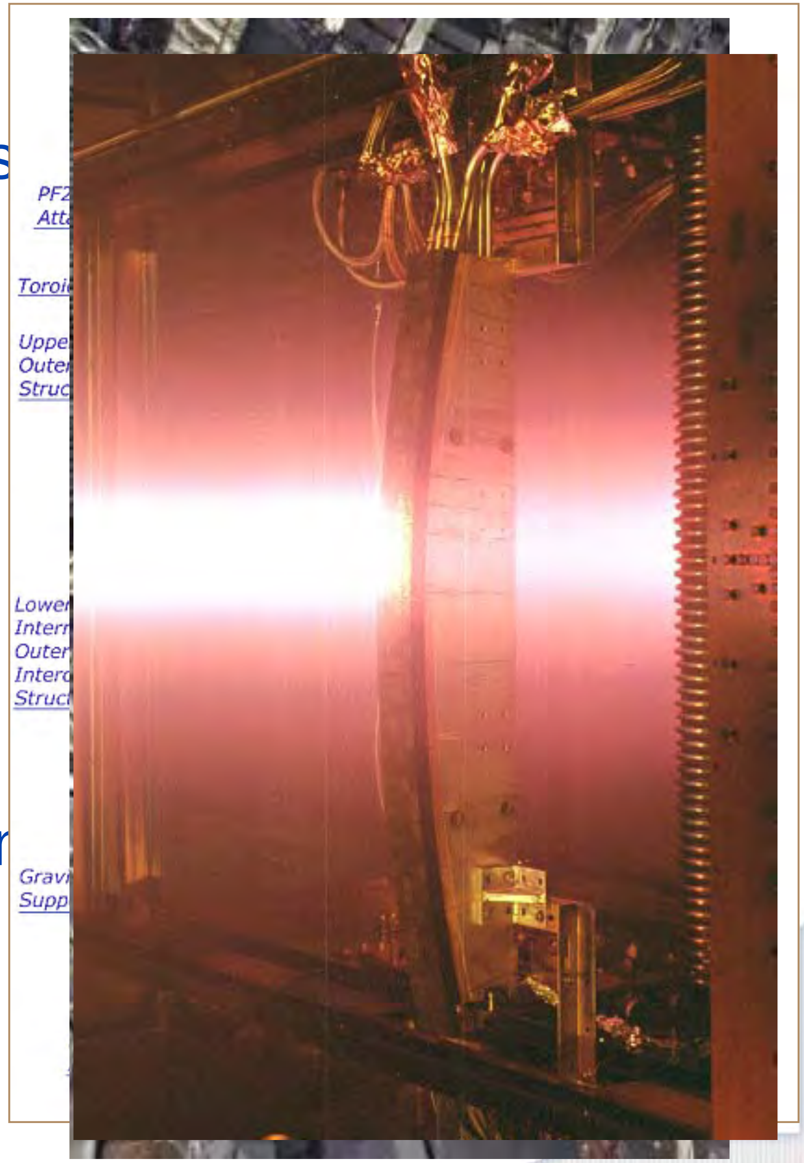
- Constant wall temperature
- New Physics with ITER relevance ...





Technology Challenges

- Unprecedented size of the super-conducting magnet and structures
- Remote Handling systems.
- Extremely high heat fluxes in first wall components
- Materials under neutron irradiation
- Plasma Heating Systems



ITER Design and Technology have been developed

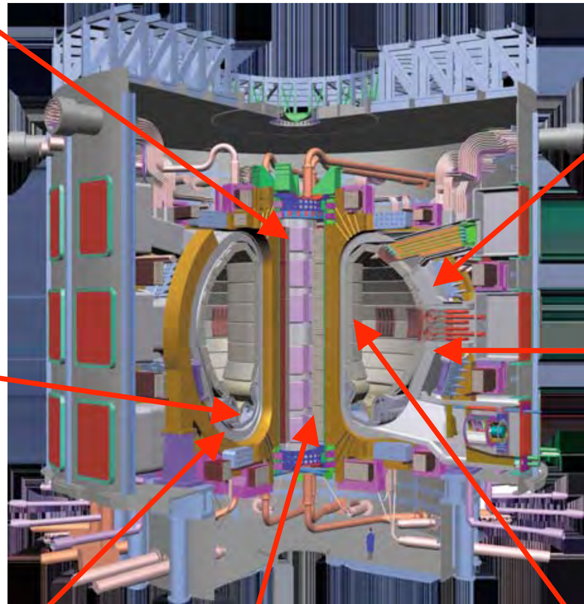
Completed R&D Activities by July 2001.

CENTRAL SOLENOID MODEL COIL

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

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

Heat Flux 20 MW/m^2

TOROIDAL FIELD MODEL COIL

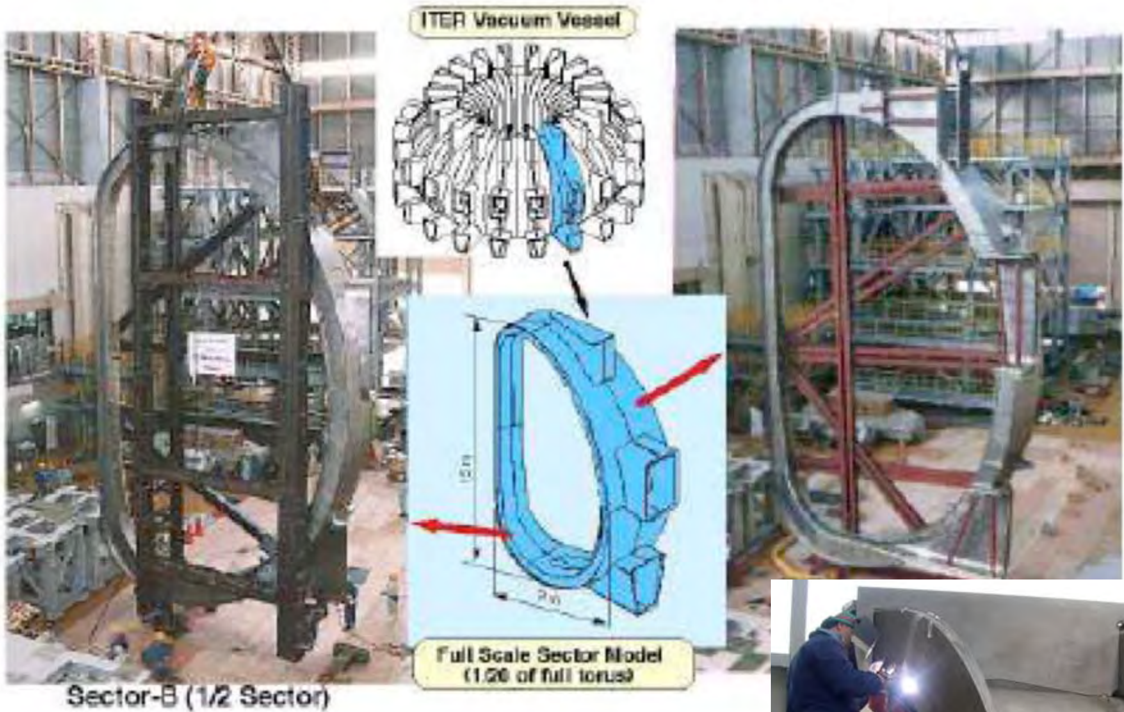
Height 4 m
Width 3 m
B_{max}=7.8 T

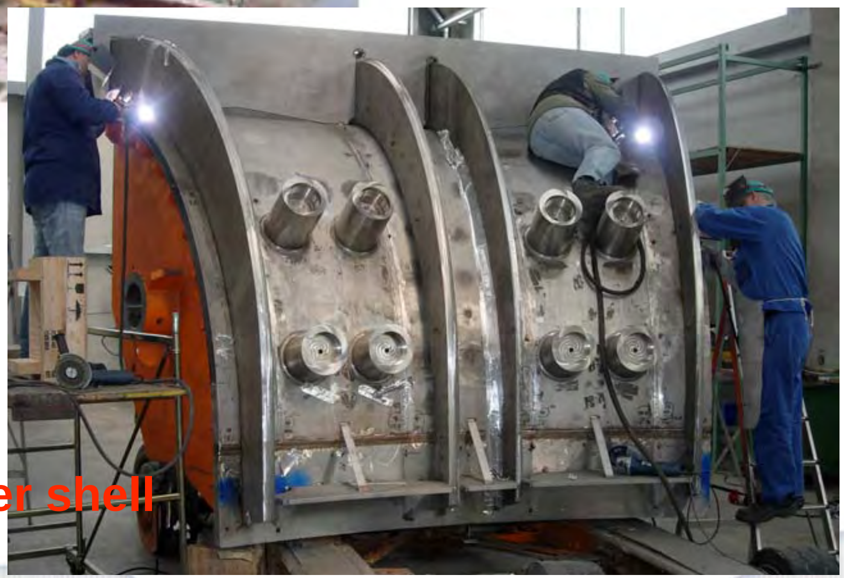
REMOTE MAINTENANCE OF BLANKET

4 t Blanket Sector
Attachment Tolerance ±0.25 mm

ITER Vacuum Vessel

Vacuum Vessel Sector Assembly

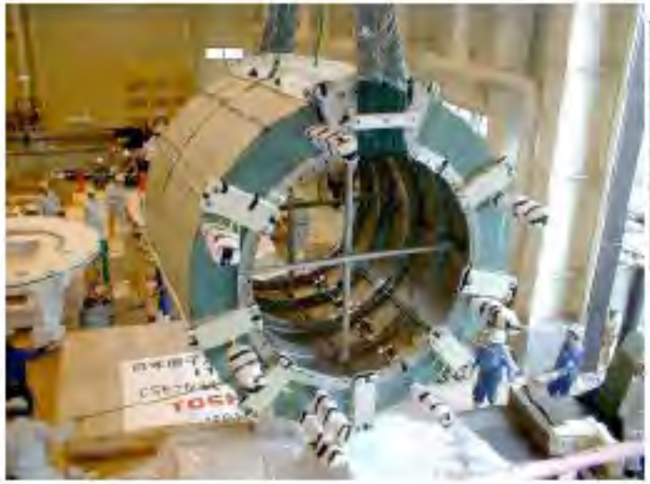




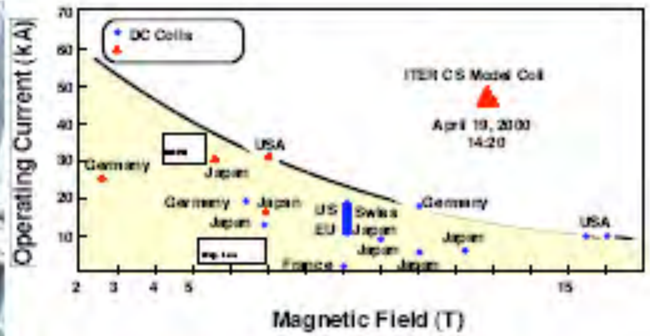
Electron Beam welding on the inner shell

ITER Central Solenoid

CS MC Outer Module



CS MC Performance

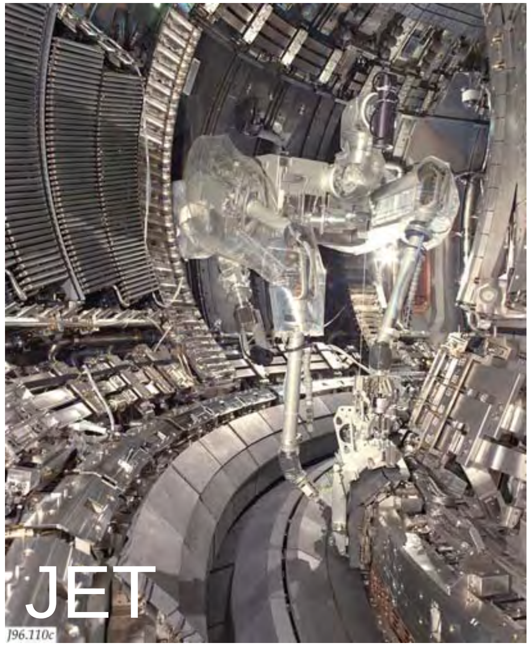


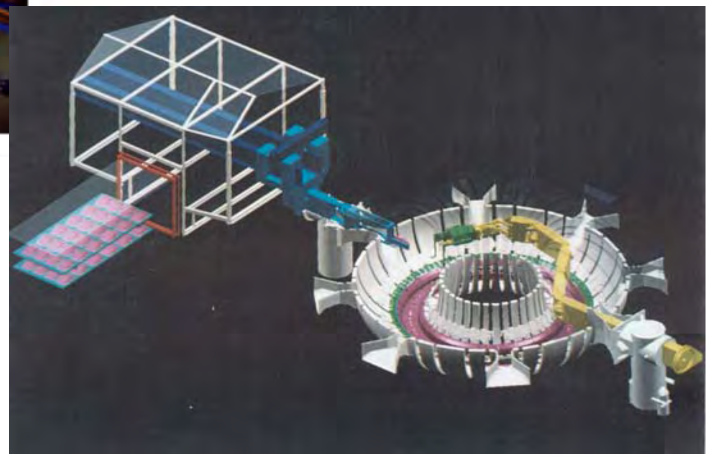
The CS MC has achieved its design magnetic field of 13T

CS conductor (Incoloy jacket)

ITER Divertor Remote Handling

Divertor Remote Handling Test Platform

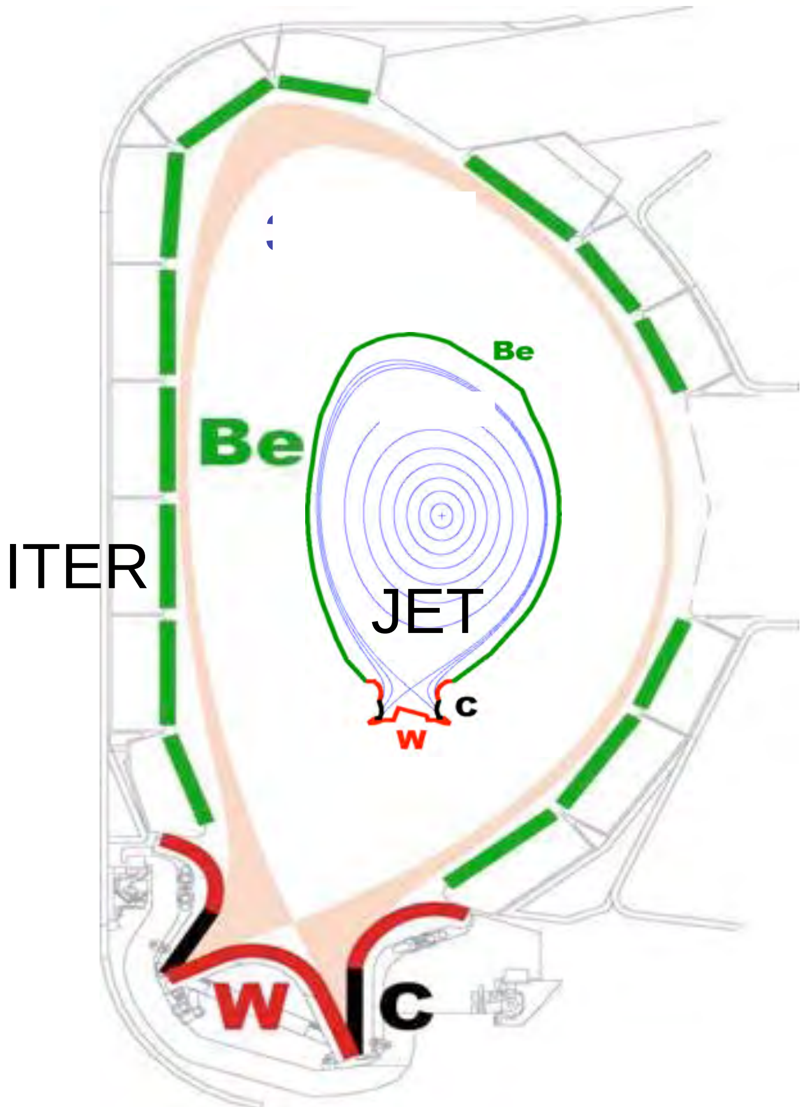




Preparing ITER operation on present tokamaks

The ITER like Wall experiment JET (>2009)

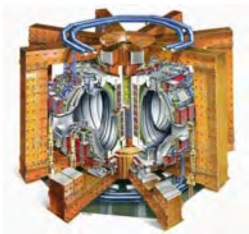
- Materials of ITER plasma facing components will be installed in JET (2008-2009)
- ITER relevant safety issues (T inventory with Be and W; dust from W and Be etc.)
- Progressing the plasma scenarios in the most relevant conditions: **a key step in support to ITER**



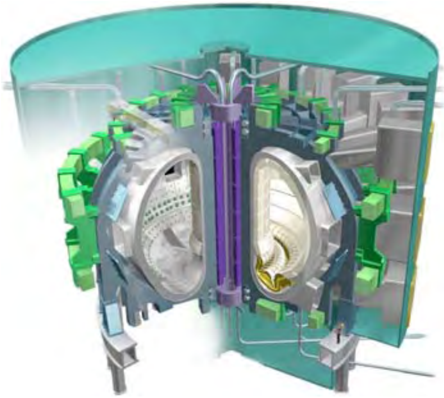
The ITER design is based largely on the success of JET and other tokamaks: high confidence in extrapolation

ITER prepares for the demonstration reactor DEMO

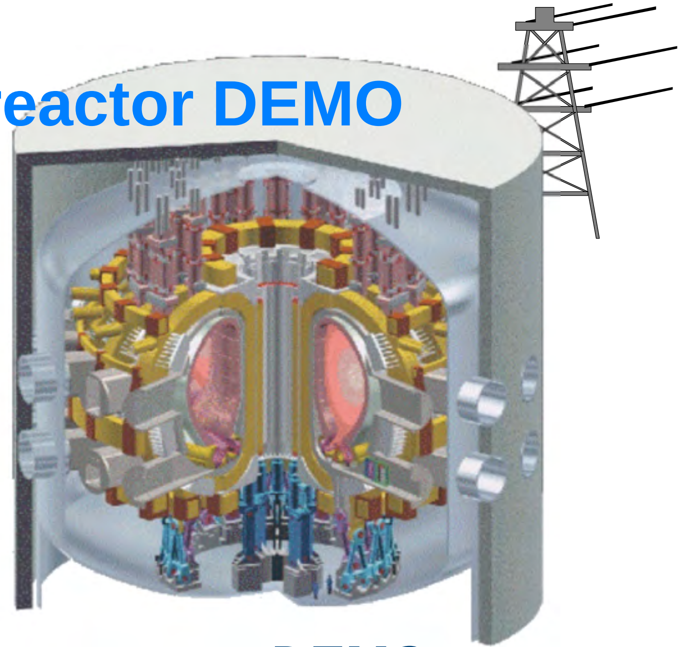
Tore Supra
$25\ m^3$
$\sim 0\ MW_{th}$



JET
$80\ m^3$
$\sim 16\ MW_{th}$



ITER
$800\ m^3$
$\sim 500\ MW_{th}$



DEMO
$\sim 1000 - 3500\ m^3$
$\sim 2000 - 4000\ MW_{th}$

- Dominant self heating -----------------

Fusion in Tokamak Plasma

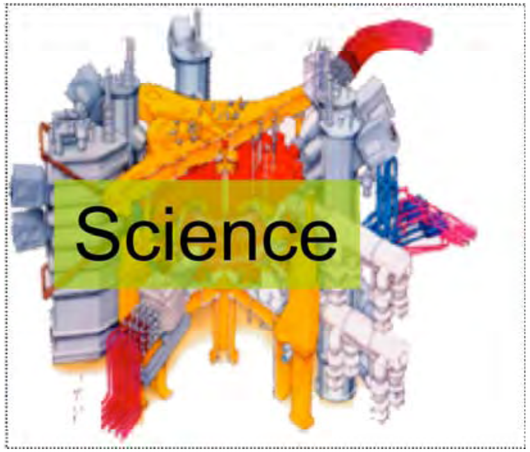
Deuterium + Tritium = Helium (3.5 MeV) + neutron (14MeV)

(Deuterium from water, Tritium produced from Lithium with neutron collision)

Energy: 1 g of fusion fuel = 8 tonnes of oil

JET(EU), JT-60(Japan)

Plasma research



Plasma Volume	~ $100m^3$
Fusion Power	~ 16 Mega Watt (JET)
Temperature	~ 520 Million C (JT60)
Pulse length	~ a few seconds
Cu magnets	

ITER

Long burn, Integration of fusion tech.,

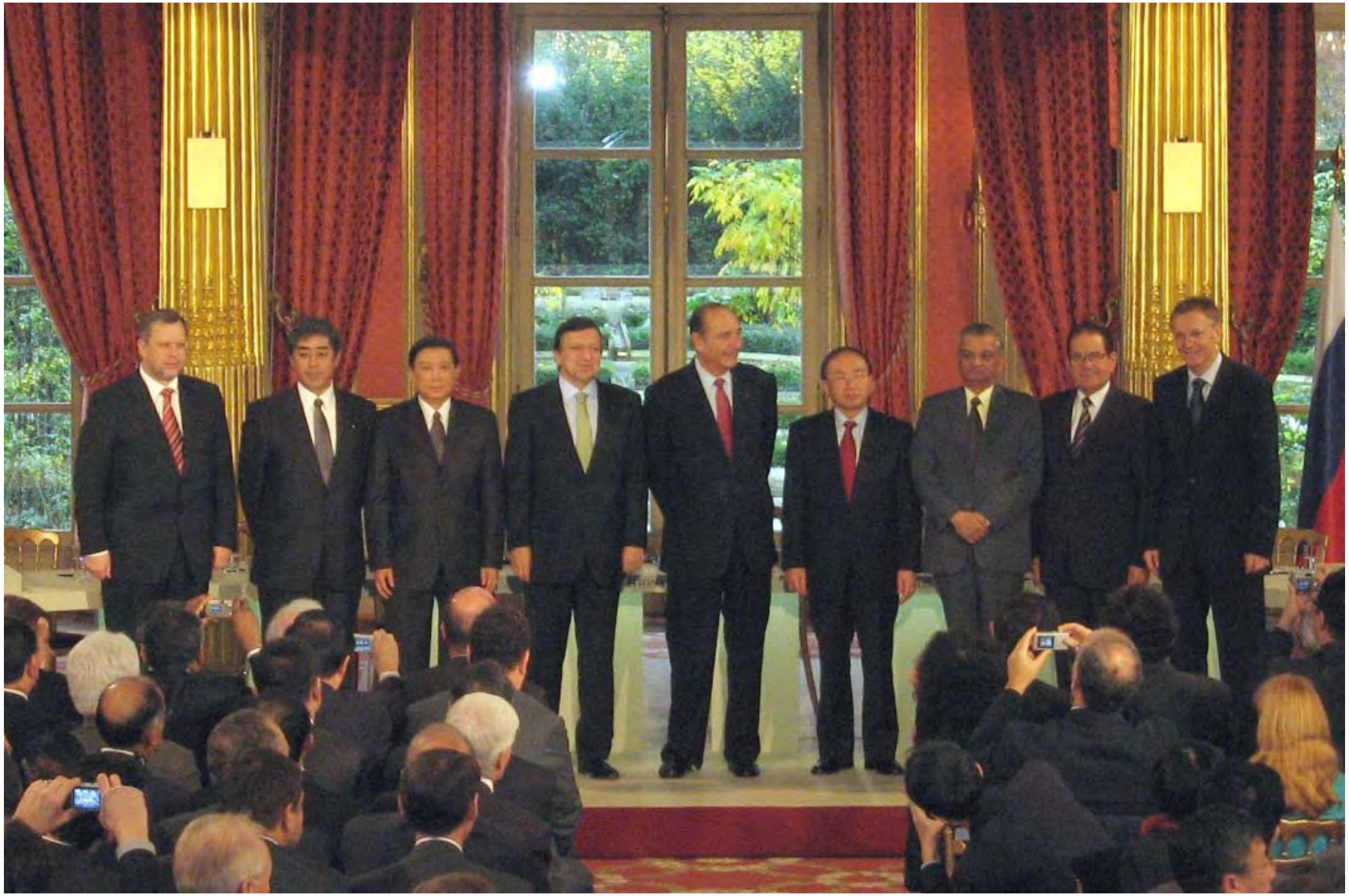
Test of tritium production

850 m^3
500 MW
200 - 300 M°C
400s -> steady state
SC magnets

Electricity - generating power plant including tritium production

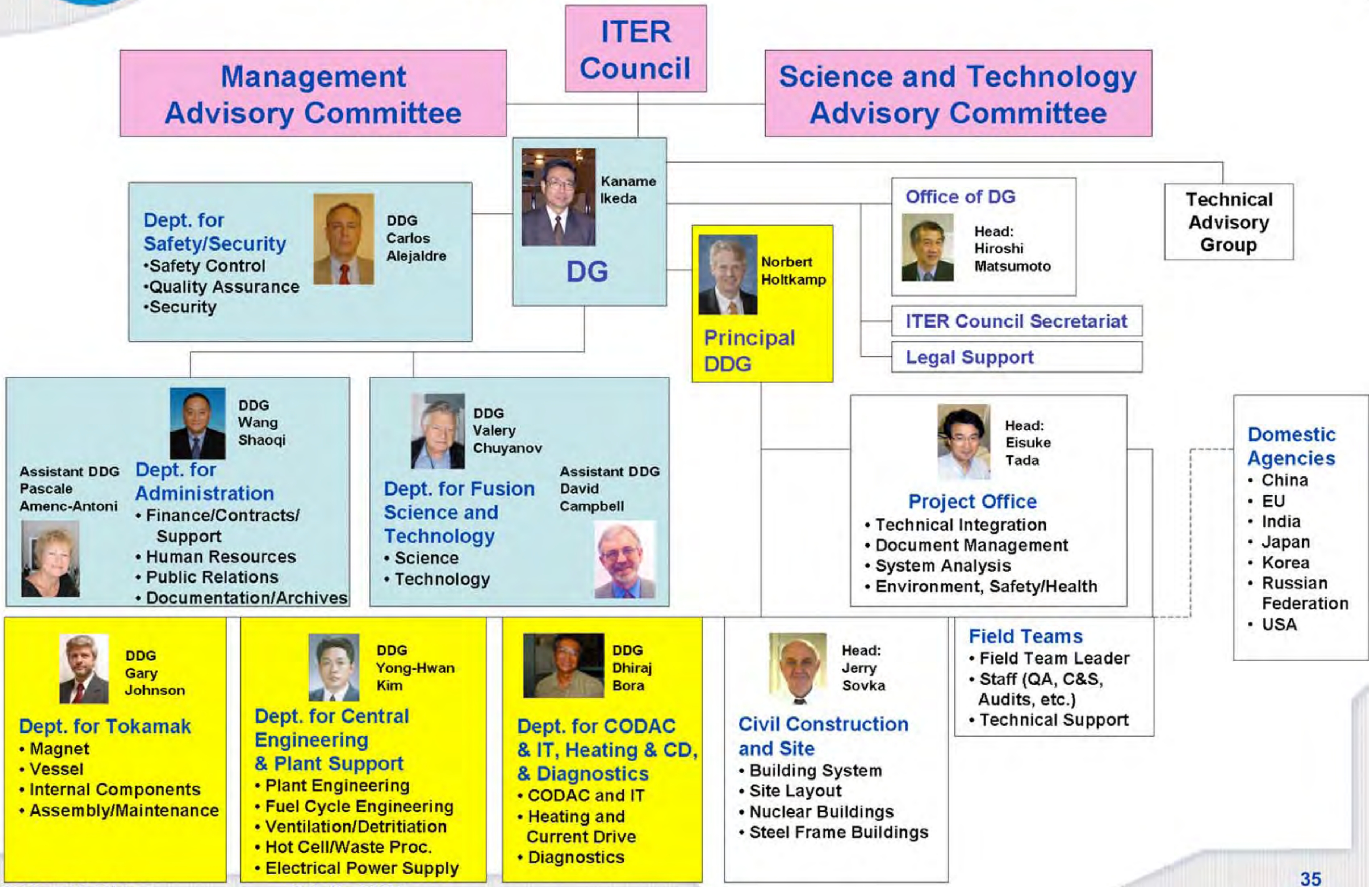
similar size
3000 MW
200 - 300 M°C
steady state

Mutual trust is our greatest asset

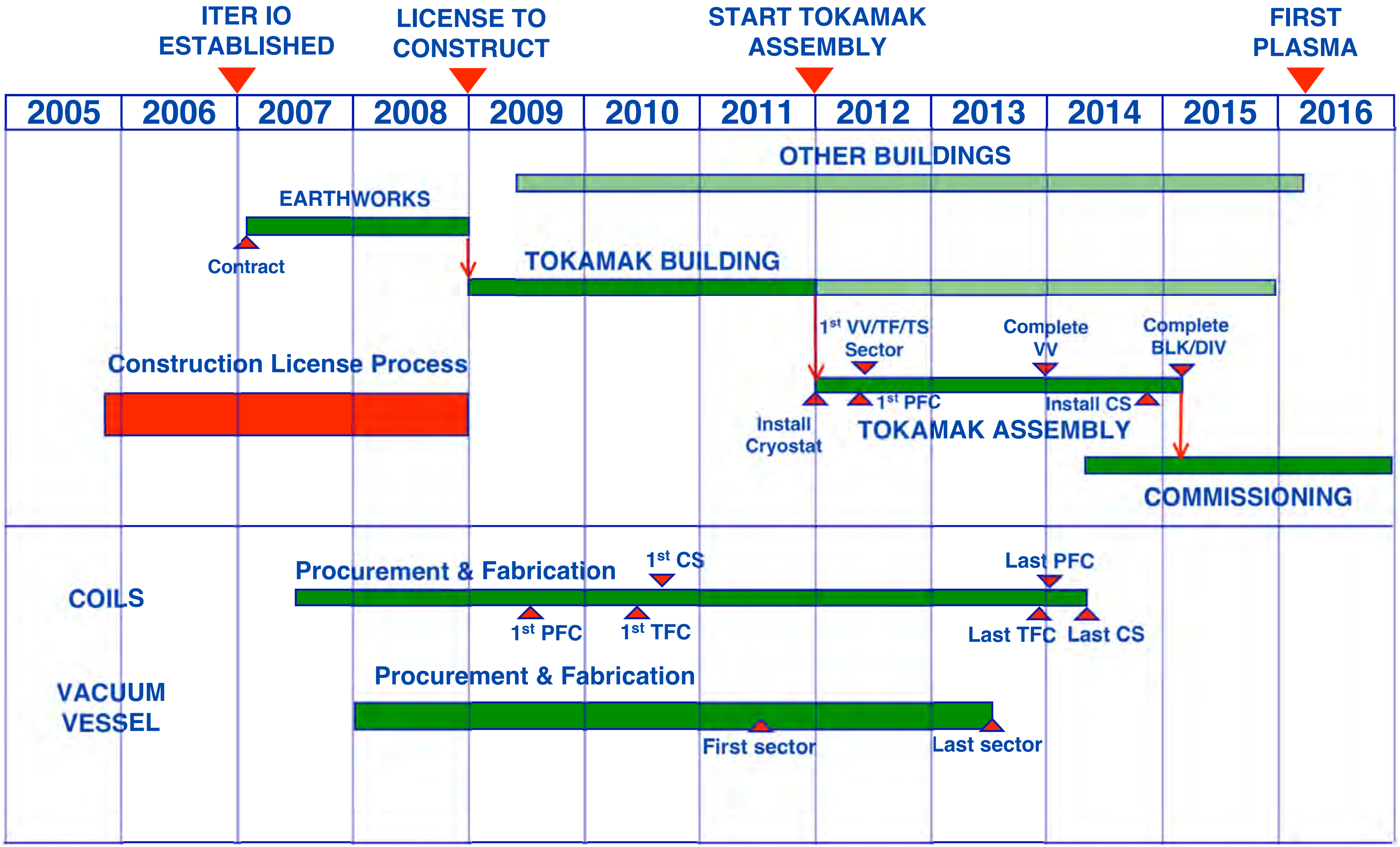


Ceremony ITER Agreement Signature, Elysee Palace, 21 November 2006

ITER Organization

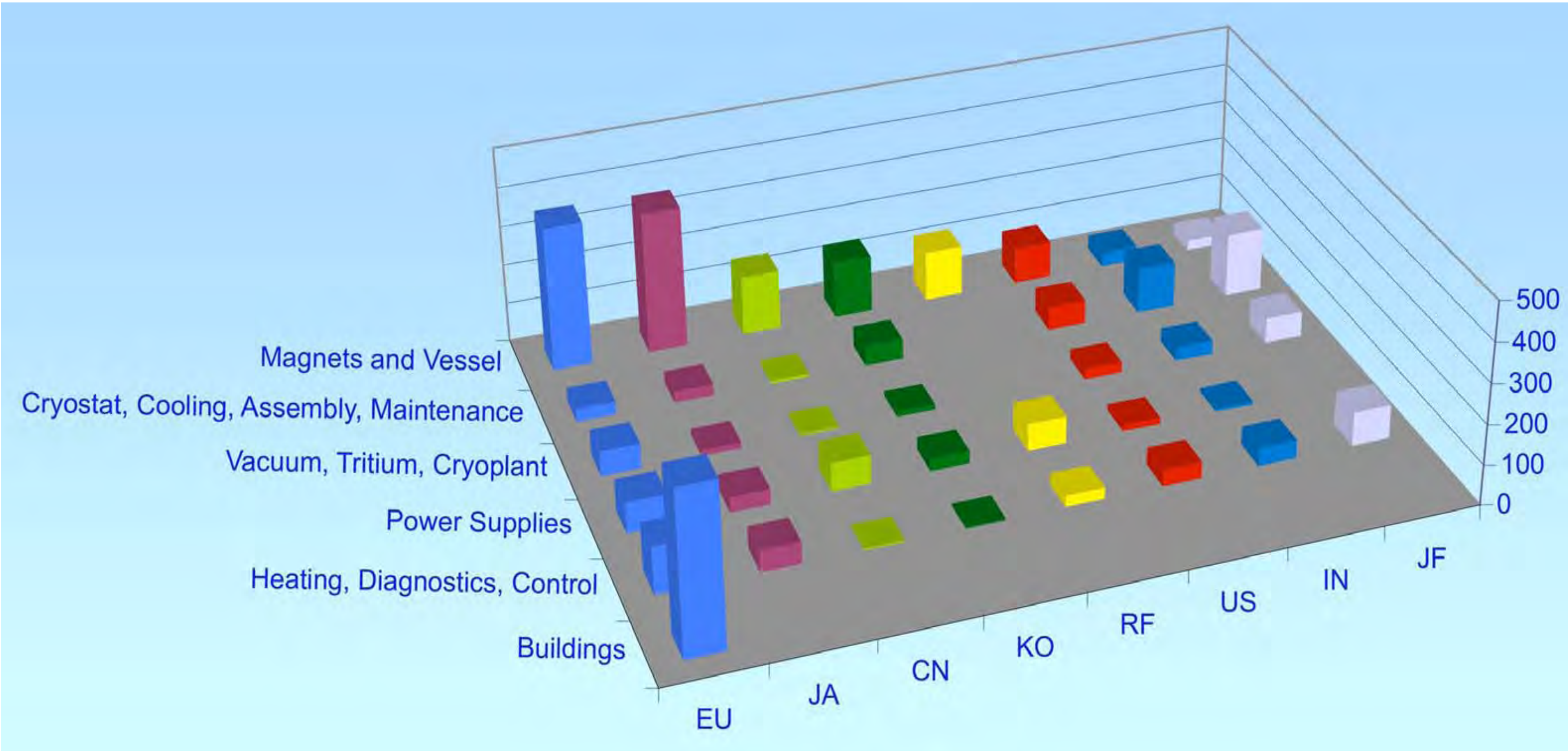


Project Schedule

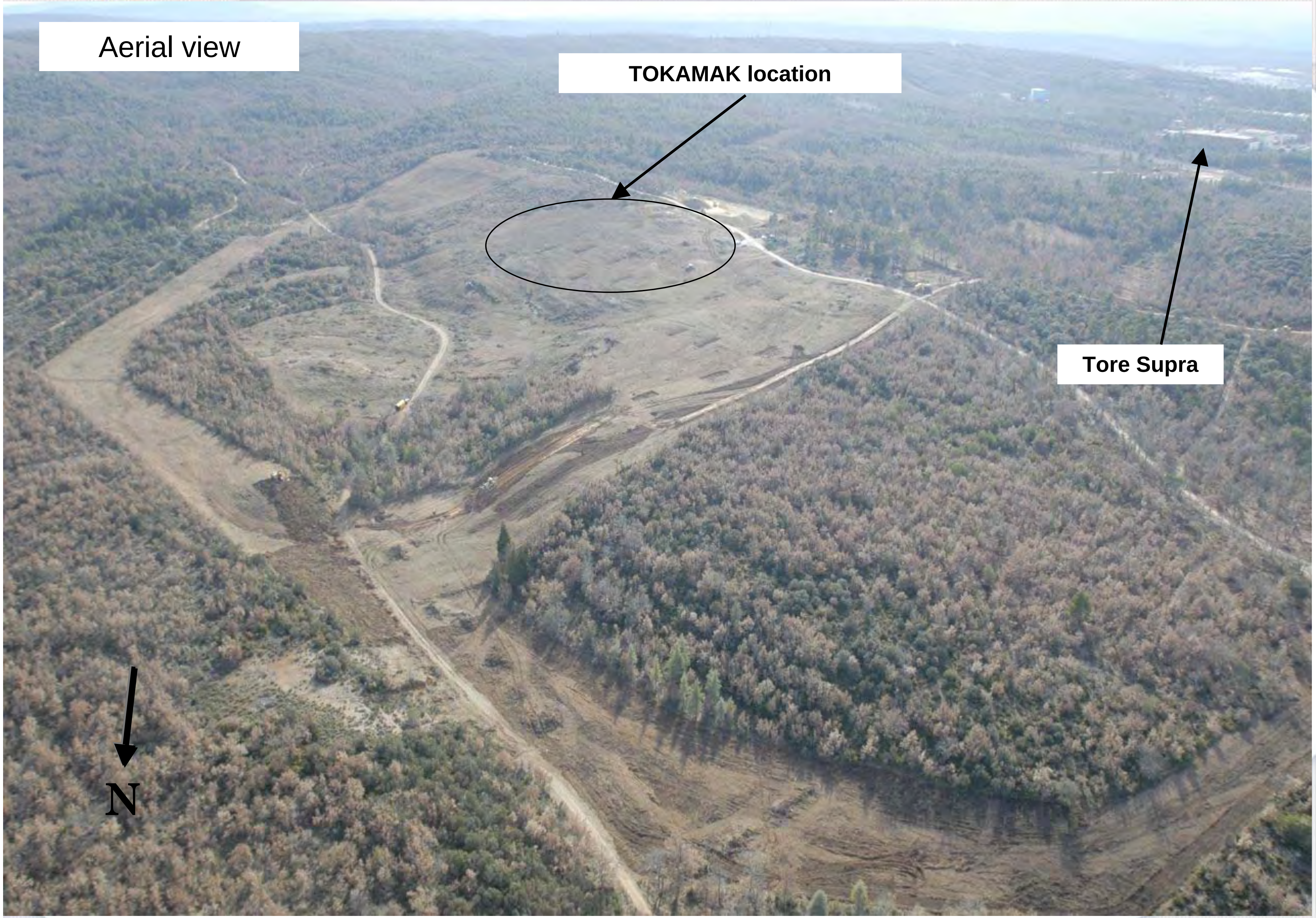


Procurements in kind

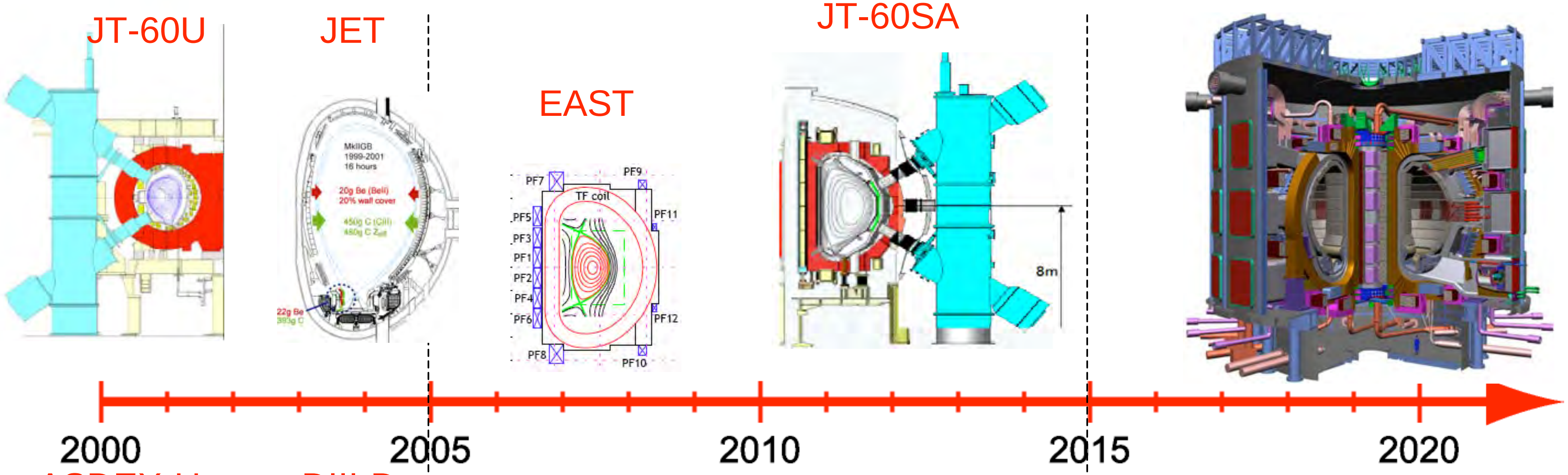
A unique feature of ITER is that almost all of the machine will be constructed through *in kind* procurement from the Parties

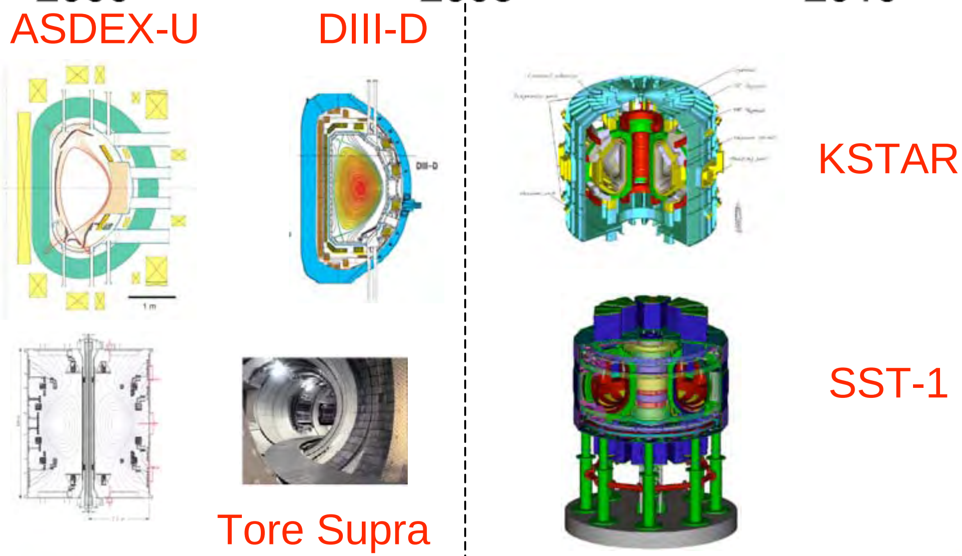


The site - artist's view


Aerial view
TOKAMAK location
Tore Supra
N

ITER and accompanying devices





Current Devices

- **Confinements**
- **Plasma wall interactions**
- **MHD stability control**

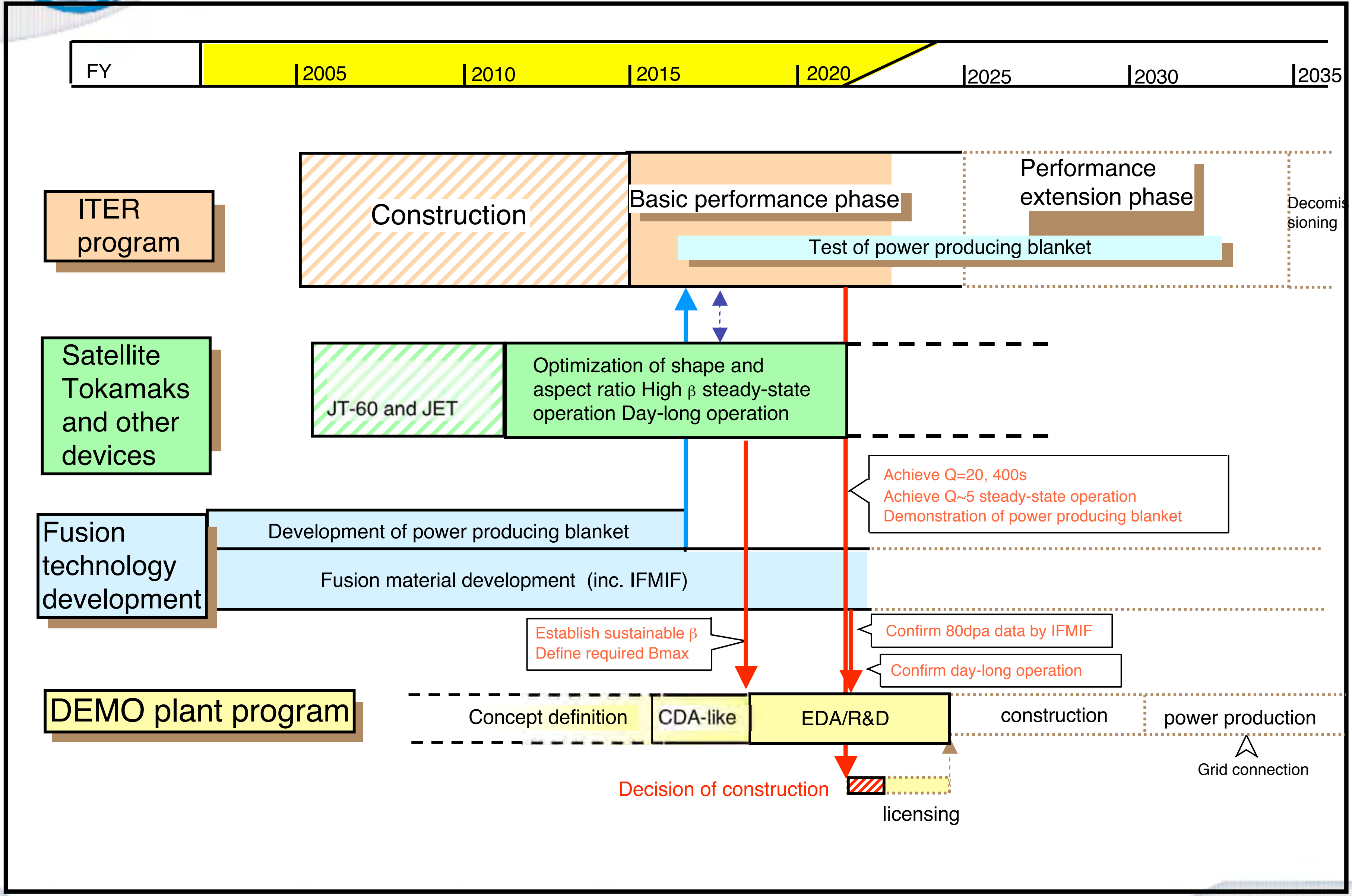
EAST, KSTAR, SST-1, TS

- **Long pulse operation**

JT-60 SA

- **Advanced stability scenarios**

Roadmap for Early Realization of Fusion Power



Conclusions

- ITER is one of the most challenging and innovative scientific projects in the world today

- Almost all of the machine will be constructed through *in kind* procurements, demanding a very high level of international cooperation

- The ITER Organization is building up quickly at Cadarache, with strong support of the ITER Parties

- ITER will demonstrate the scientific and technological feasibility of fusion as an energy source .