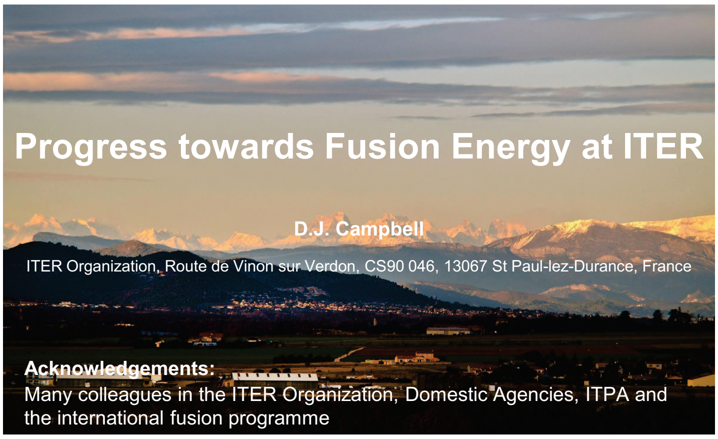

Progress towards Fusion Energy at ITER

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Acknowledgements:
Many colleagues in the ITER Organization, Domestic Agencies, ITPA and the international fusion programme

The views and opinions expressed herein do not necessarily reflect those of the ITER Organization.

What is ITER?

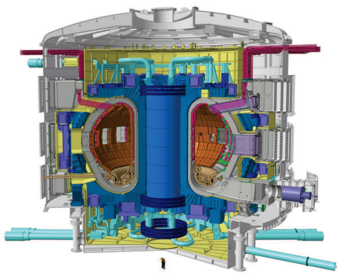
ITER is a major international collaboration in fusion energy research involving China, the EU (plus Switzerland), India, Japan, the Russian Federation, South Korea and the United States

- **The overall programmatic objective:**
  - to demonstrate the scientific and technological feasibility of fusion energy for peaceful purposes
- **The principal goal:**
  - to design, construct and operate a tokamak experiment at a scale which satisfies this objective
- **ITER is designed to confine a DT plasma in which α-particle heating dominates all other forms of plasma heating:**

$\Rightarrow$ a burning plasma experiment

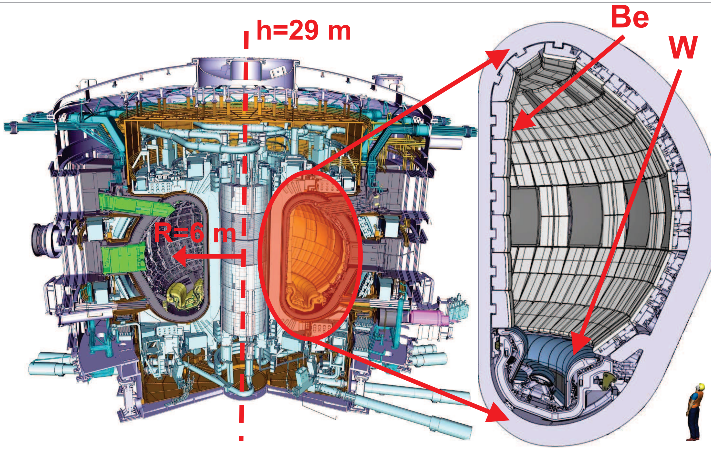
The ITER Mission

- **ITER Program Objective:**
  - to demonstrate the scientific and technological feasibility of fusion energy for peaceful purposes
- **Key Technical Goals:**
  - achieve extended burn of a DT plasma with dominant alpha-particle heating ($Q \geq 10$, ~500 s)
  - develop steady-state fusion power production as ultimate goal
  - integrate and test all essential fusion power reactor technologies and components
  - demonstrate safety and environmental acceptability of fusion



ITER tokamak

The ITER Tokamak



Synopsis

- **Fusion power production in ITER: the physics basis**
- **ITER construction status**
- **The ITER Research Plan**
- **Elements of ITER physics and technology research**

Plasma fusion performance

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

Fusion power amplification: $Q = \frac{\text{Fusion Power}}{\text{Input Power}} \sim n_i T_i \tau_E$

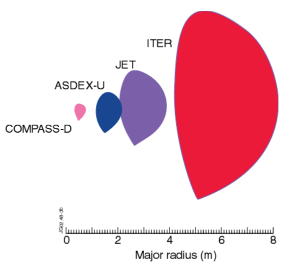
$\Rightarrow$ Present devices: $Q \leq 1$

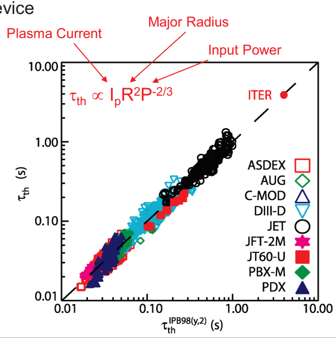
$\Rightarrow$ ITER: $Q \geq 10$

$\Rightarrow$ 'Controlled ignition': $Q \geq 30$

Plasma Confinement: τ_E Scaling

- **Turbulent transport in fusion plasmas difficult to predict quantitatively:**
  - so, we use scaling experiments to predict the level of energy confinement in ITER
  - H-mode turns out to be robust enough to provide the basis for the ITER design $\Rightarrow$ significant reduction in size of device

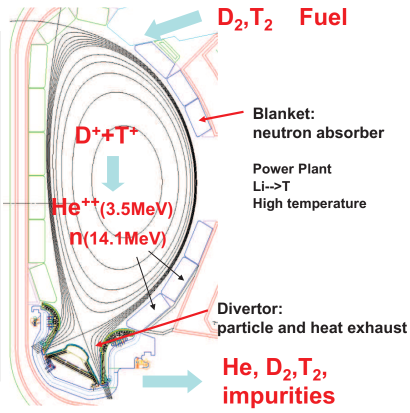




ITER: fusion power production

ITER Plasma:

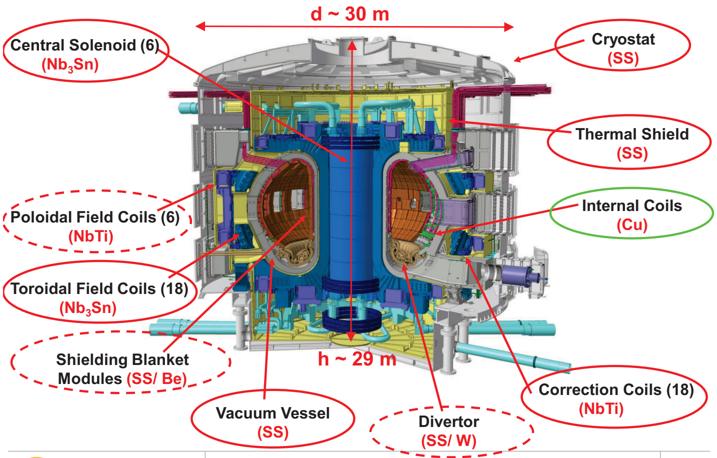
R/a:	**6.2 m /2 m**
Volume:	**830 m^3**
Plasma Current:	**15 MA**
Toroidal field:	**5.3 T**
Density:	**10^{20} m^{-3}**
Peak Temperature:	**2$\times$$10^8$ K**
Fusion Power:	**500 MW**
Plasma Burn	**300 - 500 s**
("Steady-state"	**~3000 s)**



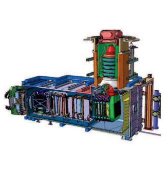
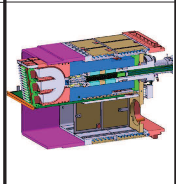
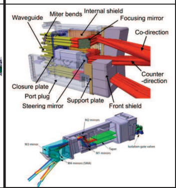
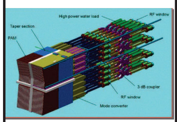
ITER is making a successful transition from detailed design to construction

- Large scale prototyping of major components is preparing the ground for series manufacture
- Significant manufacturing activities and construction work are already underway in several critical path areas
- In November 2012, the French Government authorized the creation of the *installation nucléaire de base ITER*
- Substantial expansion of on-site construction activities is planned in the coming months

ITER – Tokamak Core Components

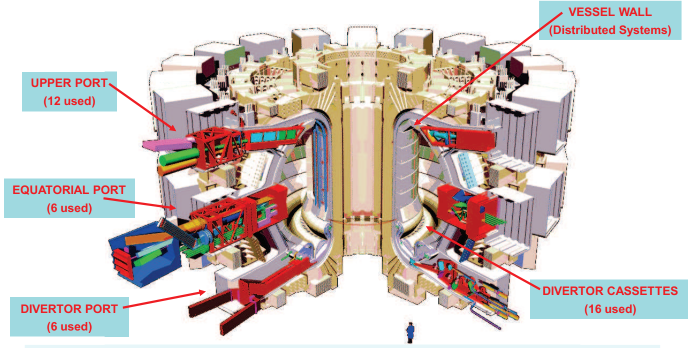


ITER heating and current drive systems

NB	IC	EC	LH
Neutral Beam - 1 MeV	Ion Cyclotron 40-55MHz	Electron Cyclotron 170GHz	Lower Hybrid ~5 GHz
			
33MW* +16.5MW#	20MW* +20MW#	20MW* +20MW#	0MW* +40MW#
Bulk current drive limited modulation	Sawtooth control modulation < 1 kHz	NTM/sawtooth control modulation up to 5 kHz	Off-axis bulk current drive

*Baseline Power
#Possible Upgrade

Analyzing the Plasma - ITER Diagnostics



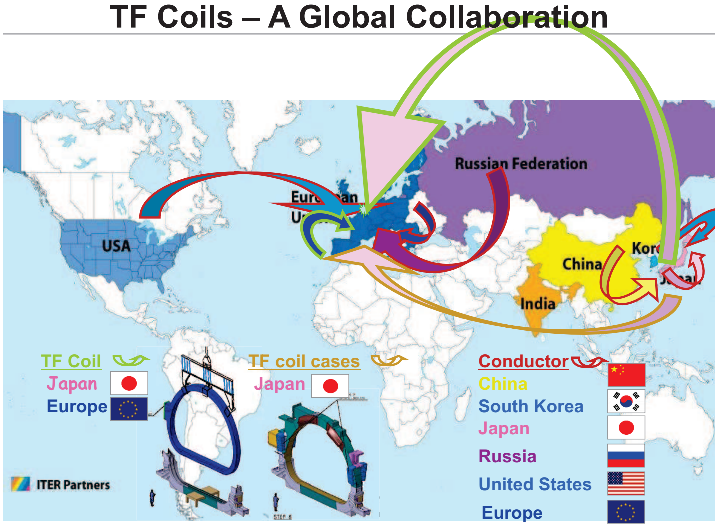
- About 40 large scale diagnostic systems are foreseen:
  - Diagnostics required for protection, control and physics studies
  - Measurements from DC to γ-rays, neutrons, α-particles, plasma species
  - Diagnostic Neutral Beam for active spectroscopy (CXRS, MSE ….)

ITER – A Major International Collaboration

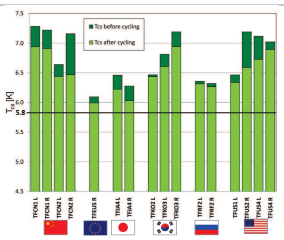
- 90% of ITER components will be supplied "in-kind" by the Members through their Domestic Agencies

- This approach necessitates the integration of ITER management, design and procurement activities across the globe

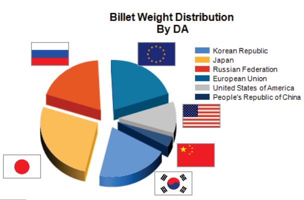
TF Coils – A Global Collaboration



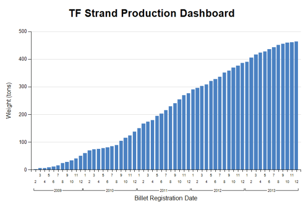
TF Conductor Production



TF Qualification Sample Summary

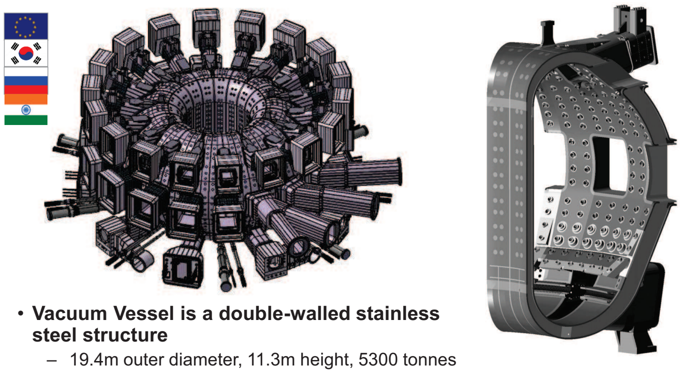


- All TF conductor qualification samples were manufactured at CRPP and enabled supplier qualification in all 6 DAs involved in TF conductor production
- Currently, virtually all of required >500t of Nb_3Sn strand has been produced around the world



TF Strand Production Summary

Vacuum Vessel Manufacturing Contracts Awarded

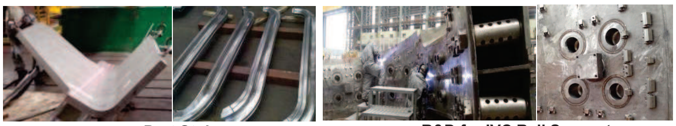


- Vacuum Vessel is a double-walled stainless steel structure
  - 19.4m outer diameter, 11.3m height, 5300 tonnes
  - provides primary tritium confinement barrier
- VV sector, port and in-wall shielding PAs signed (EU, KO, RF, IN)
  - industrial contracts awarded in each area by corresponding DA

ITER Vacuum Vessel Prototyping

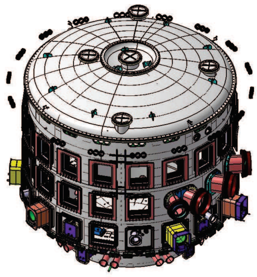
Fabrication of Upper Segment (PS2)

Welding of Centering Keys and Inter-Modular Keys

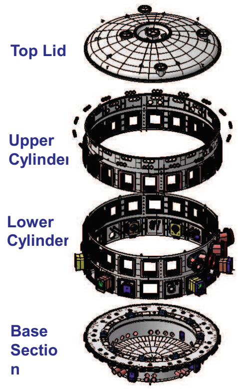


Port Stub — R&D for IVC Rail Support

Cryostat



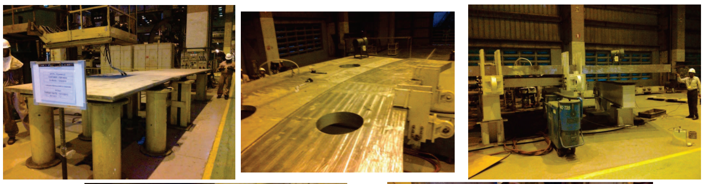
- 304L Stainless steel
  40 – 180 mm thick
- Diameter: 29.4 m/ Height: 29 m
- Weight ~3500 tonnes
- Base pressure < 10^{-4} mbar
- Transfers loads to tokamak complex floor



- **IN-DA signed PA September 2011**
- **Contract awarded in August 2012**

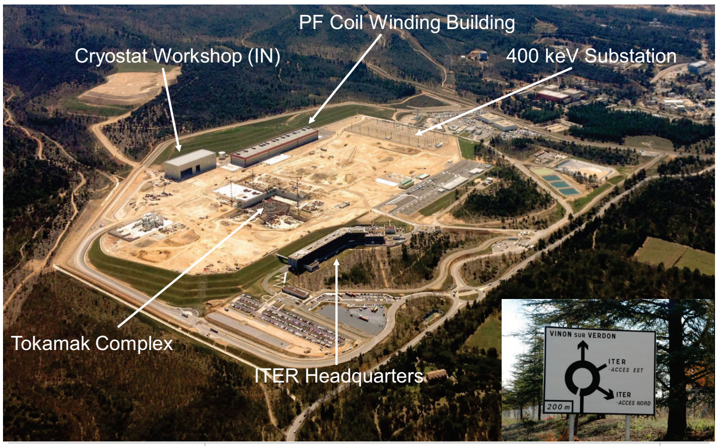
40° Prototype Cryostat Base Section

Cryostat pedestal ring- top plate 200 mm and skirt plate 105 mm thick welded together



Cryostat pedestal ring- bottom plate (180 mm & side plates (120 & 80 mm thick being welded

ITER Construction at St Paul-lez-Durance



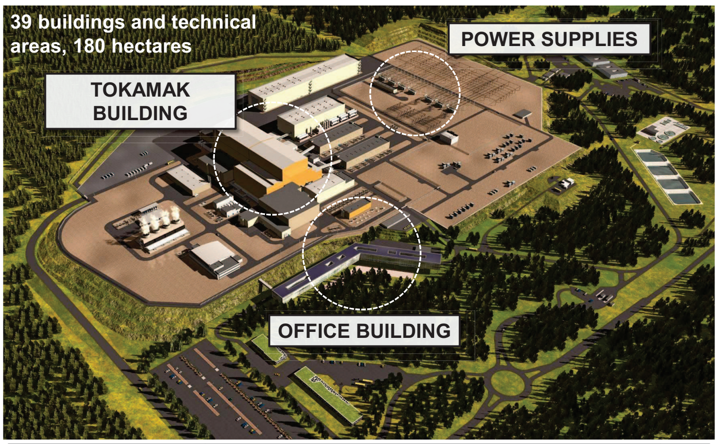
ITER Construction at St Paul-lez-Durance

ITER Construction at St-Paul-lez-Durance

Construction of Assembly Hall begins

B2 slab complete and cranes in place for Tokamak Complex construction

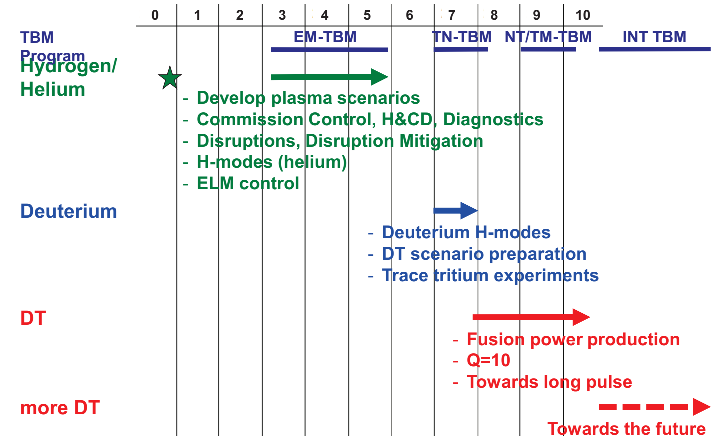
ITER Site Overview (~2020)



ITER Research Plan – Rationale

- **The ITER Research Plan has been developed to analyze the programme towards high fusion gain DT operation:**
  - allows programme logic to be developed and key operational challenges to be identified and addressed during ITER construction
  - supports planning of installation and upgrade programme accompanying operation
  - provides insight into principal physics risks impacting on experimental programme
    ⇒ R&D priorities in current research programmes
  - encourages exploration of issues in burning plasma physics which are likely to be encountered on route to Q = 10 and beyond

ITER Research Plan – Structure



Research Plan Structure and Activities

1. **Non-active operation:**
   - plasma operation to ~3.5 MA to establish initial divertor operation
   - disruption loads, disruption detection, avoidance and mitigation
   - development of plasma operation to ~7.5 MA/ 2.65 T
   - H-mode operation and ELM Control
   - demonstration of 15 MA/ 5.3 T operation
2. **Nuclear operation:**
   - development of deuterium H-modes and preparation of DT scenarios
   - initial DT operation to short-pulse Q=10
3. **Subsequently, long-pulse Q=10 scenarios and 'advanced' operational scenarios will be developed, including non-inductive steady-state operation**

Risk Assessment ⇒ Key R&D Needs

- **Top 12 risks associated with plasma operation and their potential consequences have been identified; mitigation strategies (and implications) have been developed – top 6 are:**
  - Disruption loads and effectiveness of disruption mitigation
  - Uncertainty in H-mode power threshold scaling
  - Effectiveness of ELM mitigation schemes
  - Vertical stability control limited by excessive noise (or failure of in-vessel coils)
  - Availability of reliable high power heating during non-active phase of programme (⇒ H-mode access)
  - Acceptable "divertor" performance with tungsten PFCs over required range of plasma parameters

ITER reference plasma scenarios

- **The set of DT reference scenarios in ITER is specified via illustrative cases in the *Project Requirements*:**

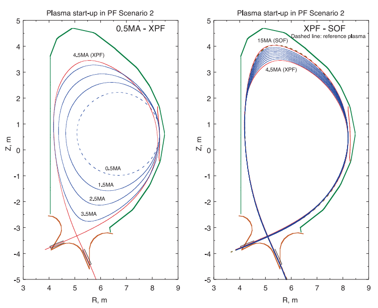
⇒ Design Basis plasma scenarios

Parameter	Inductive Operation	Hybrid Operation	Steady-State Operation
Plasma Current, I_p (MA) Safety Factor, q_{95}	15 3.0	13.8 3.3	9 5.3
Confinement Time, τ_E (s)	3.4	2.7	3.1
Fusion Power, P_{fus} (MW) Power Multiplication, Q	500 10	400 5.4	360 6
Burn time (s)	300 – 500	1000	3000

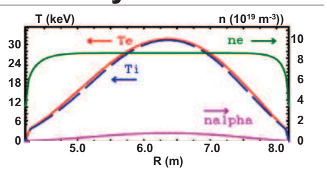
ITER Plasma Scenario - ELMy H-mode

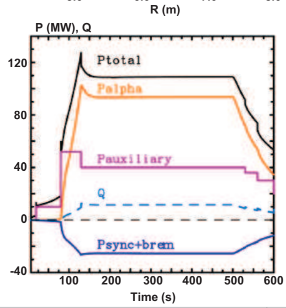
A Q ≥ 10 scenario with:

I_p=15 MA, P_{aux}=40 MW, P_{fus}~500 MW



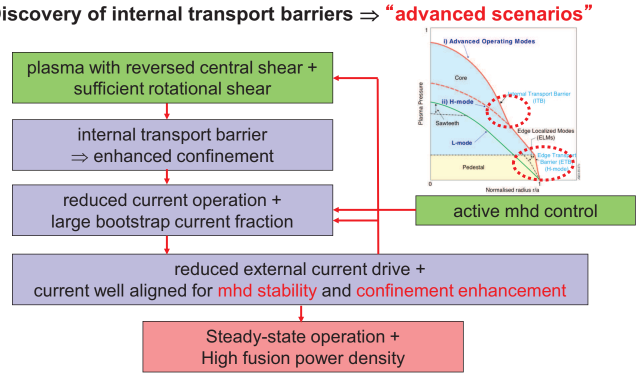
Current Ramp-up Phase





Steady-State Operation

- **Discovery of internal transport barriers ⇒ "advanced scenarios"**



- **But development of an integrated plasma scenario satisfying all reactor-relevant requirements remains challenging**

What's different about ITER physics and operation ?

- **Burning plasma: self-heated by α-particles**
  - non-linearity in total heating power due to dependence on plasma profiles
  - MHD: sawtooth stabilization by α-particles, fast particle modes
- **Plasma control (position, shape, fuelling, heating, stability, exhaust)**
  - time constant for position control is >1s ⇒ very easy to damage plasma-facing components (e.g. on inner wall of vacuum chamber)
  - very complex control matrix
- **Very high stored energy**
  - disruptions, ELMs, melting of metallic PFCs
- **High plasma current (15 MA for Baseline Q = 10 scenario)**
  - runaway electron damage of PFCs, huge disruption forces
- **High ion fluence (integrated plasma flux) to PFCs**
  - erosion of PFCs and migration of wall material, dust formation

Conclusions

- **Since the establishment of the ITER Baseline in July 2010, the ITER project has moved fully into the Construction Phase**
  - on-site construction of the Tokamak Complex is underway
  - Domestic Agencies have launched large scale manufacturing contracts for many major components
  - extensive prototyping is ongoing in preparation for series manufacture
  - there has been substantial progress in design and R&D for In-Vessel Components, Plasma Auxiliary Systems, Remote Handling, TBM etc
- **ITER Organization has been authorized to establish the *installation nucléaire de base ITER***
- **An extensive international collaboration is active in pursuing physics R&D for ITER in support of the preparations for ITER operation**
- **Successful exploitation of ITER will realize the limitless possibilities of fusion energy, and open new areas of research in fusion plasma physics and fusion technology, including tritium breeding**

Thank you for your attention

Backup Slides

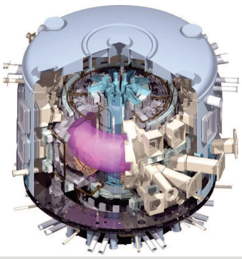
Plasma Control

- **A magnetically confined plasma is a complex state**
  - it cannot be created and sustained without a sophisticated feedback control system
- **Free energy which is available within the plasma tends to generate turbulence and magnetohydrodynamic instabilities (mhd) which reduce plasma confinement quality**
  - great effort is expended within plasma control to sustain a high quality plasma capable of producing significant fusion power
- **In a thermonuclear plasma with significant fusion power, additional control requirements are imposed in ensuring the fusion power can be sustained for extended periods**
  - failures of the control system lead to conditions which tend to reduce fusion power or extinguish the plasma
- **At this stage of R&D, significant (uncontrolled) excursions in fusion power appear unlikely (ie burn point is stable)**
  - measures exist to control and suppress such excursions

Plasma Control on ITER

- **Ensure that physics objectives of any discharge are met**
- **Provide first level of machine protection (other levels above)**

Measurements:
>50 systems
thousands of data channels

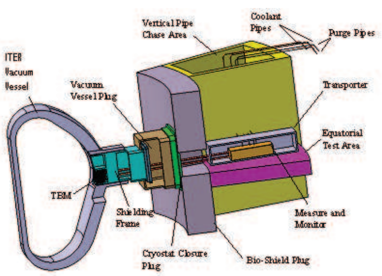


Actuators:
Magnets,
Heating and current drive systems,
Fuelling and pumping
~20 in total

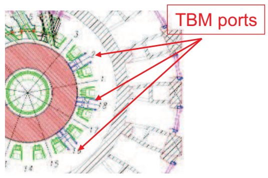
Plasma Control System (PCS)
~20 parameters controlled simultaneously
timescales from 1 ms to several seconds
(blink of an eye ~50-80 ms)
Requires state of the art control schemes

Test Blanket Modules - Tritium Breeding

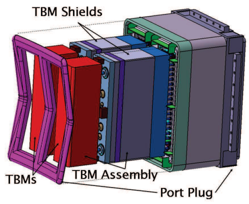
$n + {}^{6}Li \rightarrow T + {}^{4}He + 4.8MeV$
$n + {}^{7}Li \rightarrow T + {}^{4}He + n - 2.47MeV$



Three dedicated stations for testing up to six tritium breeding concepts



TBM Port Plug (exploded view)



Component Transport

For heaviest components: vacuum vessel sectors, toroidal field coils, poloidal field coil 1 and 6
Road upgrades from south coast to Cadarache complete and paid for by regional funding (115 M€)
ITER itinerary ~104 km by road + 32 km by barge

Component Transport

- **352 wheel test convoy carrying 800 ton load (33 m long, 9 m wide, 10 m high) trialled in September 2013 and March/April 2014**
  - 2 power generators developing 730 horse power

Crossing Etang de Berre (32 km)

Journey lasts 4 nights