Physics and Materials Challenges for ITER and fusion power

ZETA (UK), 1940 - 1950
Zero Energy Toroidal Assembly

JET (EU), 1980 - Joint European Torus

ITER (Earth), 2020 – International Thermonuclear Experimental Reactor

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Chair, Australian ITER Forum
Fusion, the power of the sun and the stars, is one option

“...Prometheus steals fire from the heaven”

On Earth, fusion could provide:

- Essentially limitless fuel, available all over the world
- No greenhouse gases
- Intrinsic safety
- No long-lived radioactive waste
- Large-scale energy production
• Achieve sufficiently high ion temperature $T_i$
  \[ \Rightarrow \text{exceed Coulomb barrier} \]
  density $n_D \propto \text{energy yield}$
  energy confinement time $\tau_E$

\[ \tau_E = \text{insulation parameter: e.g. time taken for a jug of hot water to lose energy to the surroundings} \]

• “Lawson” ignition criteria: Fusion power $> \text{heat loss}$
  
  \[ n_D\tau_E T_i > 3 \times 10^{21} \text{ m}^{-3} \text{ keV s} \]

• At these extreme conditions matter exists in the plasma state

\[ \approx 100 \text{ million } ^\circ \text{C} \]
The plasma state: the fourth state of matter

- plasma is an ionized gas
- 99.9% of the visible universe is in a plasma state

[Images of gas and plasma particles, motion of charged particles with and without magnetic field]

A Galaxy of Fusion Reactors.

- Fusion is the process that powers the sun and the stars
Toroidal Magnetic Confinement

• Magnetic fields cause charged particles to spiral around field lines. Plasma particles are lost to the vessel walls only by relatively slow diffusion across the field lines.

• Only charged particles \((D^+, T^+, He^+\ldots)\) are confined. Neutrons escape and release energy.

• Toroidal (ring shaped) device: a closed system to avoid end losses.

• The most successful Magnetic Confinement device is the TOKAMAK (Russian acronym for ‘Toroidal Magnetic Chamber’).
Components of a Tokamak
Fields lie in flux surfaces

- In an "perfect" tokamak field lines lie in flux surfaces
- If magnetic field sufficiently strong ions and electrons bound to flux surfaces
- Different flux surfaces are ~ thermally insulated
- Flux surfaces support pressure gradient
- Tokamaks maximise core pressure, needed to initiate fusion

$\Rightarrow$ bottle’s the plasma
How to obtain the extreme temperatures?

Ohmic heating: $\sigma \propto T^{3/2} \Rightarrow$ limited to $T \sim 3$ keV, additional heating needed, which also drives current:

- **Positive ion beams**: $E \sim 100$ keV
- **Negative ion beams**: $E \sim 1$ MeV
Progress in magnetically confined fusion

- **“Ignition” regime, \( Q \to \infty \): Power Plant.**

- **“Breakeven” regime:**
  \[ Q = \frac{P_{\text{out}}}{P_{\text{heat}}} \approx 1 \]
  Eg. Joint European Tokamak: 1983 - 
  1997: \( Q = 0.7 \), 16.1MW fusion
  1997 -: steady-state, adv. confinement geometries, metallic wall

- **“Burning” regime: ITER**
  \[ D^2 + T^3 \to He^4 (3.5 \text{ MeV}) + n^1 (14.1 \text{ MeV}) \]
  \[ Q > 5 \Rightarrow \text{ITER} \]
  \[ \geq P_{\text{heat}} \leq P_{\text{out}} \]
**BIG Experiments: ITER**

Fusion power = 500MW  
Power Gain (Q) > 10  
Temperature ~ 100 million °C  
Growing Consortium  

Construction +10 year  
operation cost ~$20 billion  
Fiscally, world’s largest science experiment

- Collaboration agreements with  
  - International Atomic Energy Agency  
  - CERN – world’s largest accelerator  
  - Principality of Monaco
ITER objectives

Programmatic
- Demonstrate feasibility of fusion energy for peaceful purposes

Physics
- Produce and study a plasma dominated by $\alpha$ particle (self) heating
- Steady-state power gain of $Q = 5$, higher $Q$ for shorter time
- “Grand Challenge” burning plasma science:
  - plasma self-organization, non-Maxwellian and nonlinear physics, confinement transitions, exhaust and fuelling control, high “bootstrap” (self-current driven) regimes, energetic particle modes, plasma stability.

Technology
- Demonstrate integrated operation en-route to a power plant
- Investigate crucial materials issue:
  - First wall neutron flux loading $> 0.5$ MW/m$^2$
  - Average fluence $> 0.3$ MW years/m$^2$
- Test tritium breeding blanket for a demonstration reactor ( DEMO )

The first wall of a fusion reactor has to cope with the ‘environment from hell’ so it needs a “heaven sent surface”.
ITER in detail

Plasma conditions:
- 15MA Ip, plasma current
- 2.0m, 6.2m Minor (a), major (R) radius
- 500MW Total Fusion power
- 73MW Auxiliary heating, current drive
- 837 m³ Plasma Volume
- 5.3T Toroidal field @6.2m

<table>
<thead>
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### BIG Science: plasma performance

#### Fusion power amplification:

\[ Q = \frac{\text{Fusion Power}}{\text{Input Power}} \sim n_i T_i \tau_E \]

- **Present devices:** \( Q \leq 1 \)
- **ITER:** \( Q \geq 10 \)
- ’Controlled ignition’: \( Q \geq 30 \)

#### Temperature - \( T_i \):

1-2 \( \times \) \( 10^8 \) K (10-20 keV)

set by cross-section

\(~10\ \times \) temperature of sun’s core

#### Energy confinement time - \( \tau_E \):

Few seconds \( (\propto \text{current} \times \text{radius}^2) \)

set by turbulence and magnetic geometry

(plasma pulse duration \(~1000s)\)

#### Density - \( n_i \):

1 \( \times \) \( 10^{20} \) m\(^{-3}\)

determined by ignition criterion

\(~10^{-6}\) of atmospheric particle density
Toroidal Plasma Confinement: H-mode

- Plasma energy and particle transport is driven by turbulence.
- It is found that the plasma confinement state ($\tau_E$) can bifurcate:
  - two distinct plasma regimes, a low confinement (L-mode) and a high confinement (H-mode), result.
  - this phenomenon has been shown to arise from changes in the plasma flow in a narrow edge region, or pedestal.

![Diagram showing confinement time vs. input power and plasma temperature vs. normalized radius.](Image)

**JET**
Design determined by physics & technology

- **Stability considerations** set magnetic topology
  - Field pitch \( q \) = toroidal / poloidal rotation of field lines
  - \( q \propto \frac{1}{l_p} \), changes across plasma
  - Generally higher \( q \) is more stable

- **Materials Limits**
  - Superconducting NbTi or NbSn \( B_c \leq 10 \text{T} \)
  - Divertor ablation limits during ELM’s
  - Required neutron flux loading \( P \sim 0.5 \text{MWm}^{-2} \)

Radial Tokamak build

<table>
<thead>
<tr>
<th>OH coil</th>
<th>TF coil</th>
<th>shield</th>
<th>plasma</th>
<th>shield</th>
<th>TF coil</th>
</tr>
</thead>
<tbody>
<tr>
<td>( R_{\text{coil}} )</td>
<td>( R )</td>
<td>( \delta_{BS} )</td>
<td>( a )</td>
<td></td>
<td></td>
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Fold design objectives, \( \tau_E \) scaling magnetic stability, materials limit

\~ \text{ITER class machine}

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<tr>
<th>Fusion Power ( P_f )</th>
<th>~ 500 MW</th>
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<td>( n_{DT} )</td>
<td>( 10^{20} \text{ m}^{-3} )</td>
</tr>
<tr>
<td>( R_c, \delta_{BS}, a, R )</td>
<td>3.2, 1.0, 2.0, 6.2</td>
</tr>
<tr>
<td>( l_p )</td>
<td>15 \text{ MA}</td>
</tr>
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Plasma Physics Challenges

• Production and study of a plasma dominated by self heating. **Burning Plasma Physics**.

• New instabilities in burning plasmas: possibilities of energetic particle modes driven by beam ions, fusion $\alpha$s could “short-circuit” heating of thermal plasma.

• Edge Localised Modes: Control of field lines that erupt through plasma edge.

• Better disruption mitigation (e.g. massive gas puff injection).

• Real time mode control and identification.

• Measurement and “integrated modelling” of plasmas under extreme conditions.

Difference images from $D^\alpha$ camera of MAST plasmas.
Materials Choices for ITER

- **Be first wall (~700m²):**
  - low heat flux
  - Chosen due to low Z, low plasma impurities

- **W-clad divertor elements (~100m²):**
  - Chosen due to low sputtering (plasma impurities) and to limit tritium codeposition effects (safety and operation).
  - *melt layer loss during ELMs and disruptions*
  - *W dust production a radiological hazard*
Materials Challenges Beyond ITER

**fusion devices:**
- ASDEX-U
- JET
- ITER
- DEMO

**heat removal:**
- passively cooled PFCs
- actively cooled PFCs
  - water
  - He, liquid metal

**tritium fuel:**
- increased T inventory
- \( n \)-induced material degradation

**life time fluence:**
- 0 dpa
- 10\(^{-9} \) dpa
- 1 dpa
- 100 dpa

- Motivation for the International Fusion Materials Irradiation Facility
(Un)expected Challenges

- 90% of ITER components will be supplied “in-kind” by the Members through their Domestic Agencies
- Quality compliance essential otherwise machine won’t fit together

**Components:**
- Cryostat
- Thermal Shield
- Vacuum Vessel
- Blanket
- Divertor
- Central Solenoid (6)
- Poloidal Field Coils (6)
- Correction Coils (18)
- Toroidal Field Coils (18)
- Feeders (31)
(Un)expected Challenges

- Design finalisation and cost.
- Diverse cultures and management approaches amongst members
- Broad range of expectations
- Delays

2005 2010 2015 2020 2025 2030 2035 2040 2045 2050

- Site
- Machine assembly
- 1st ITER plasmas

2005

2010

2015

2020

2025

2030

2035

2040

2045

2050

supporting R&D

ITER

materials testing facility (IFMIF)

demonstration power-plant (DEMO)

commercial power-plants
ITER Construction at St Paul lez Durance

- Tokamak Complex
- PF Coil Winding Building
- Cryostat Workshop (IN)
- 400 keV Substation
- ITER Headquarters
Resting on the 493 columns of the Tokamak Pit seismic system, a basemat (1.5-m. thick) will support the 400,000-ton Tokamak Complex buildings. Walls construction is ongoing on the lowest basement level of the building.
Assembly Building

October 2015
The PF Coils Building

Too large to be transported by road, 4 of the 6 Poloidal Field Coils (ring-shaped magnets) will be assembled by Europe in this facility.
The Cryostat Workshop

The Cryostat Workshop, under India's responsibility, was inaugurated in November 2014. Procured by India, the giant “thermos” (30 m. x 30 m.) that encloses the ITER Tokamak will be assembled here.

4 billion euros worth of contracts already engaged in construction on-site.
Manufacturing is ongoing

7 billion euros worth of contracts already engaged in components and systems manufacturing worldwide
<table>
<thead>
<tr>
<th>Date</th>
<th>Description</th>
</tr>
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<tbody>
<tr>
<td>14 Jan. 2015:</td>
<td>US-procured transformer (90 t.)</td>
</tr>
<tr>
<td>20 March 2015:</td>
<td>Europe-procured detritiation tank (20 t.)</td>
</tr>
<tr>
<td>2 April 2015:</td>
<td>Europe-procured detritiation tank (20 t.)</td>
</tr>
<tr>
<td>20 April 2015:</td>
<td>US-procured transformer (90 t.)</td>
</tr>
<tr>
<td>7 May 2015:</td>
<td>2 US-procured drain tanks (79 t.)</td>
</tr>
<tr>
<td>Expected 21 May:</td>
<td>US-procured transformer (90 t.)</td>
</tr>
</tbody>
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Installation of First Large Scale Components

First 400 kV Main Transformer (4 delivered out of 7):
In kind contribution of US DA, fabricated in South Korea, installed by EU DA
First Plasmas have arrived!

June 2015
Summary

- Introduced fusion power and toroidal magnetic confinement
- Outlined next step project, ITER
  - Physics and materials challenges
  - Machine scaling
  - ITER completion timeline
- Timeline beyond ITER and global R&D
- Australian fusion R&D
- Strategic planning for Australian engagement in ITER – key feature will be Memorandum of Understanding between ANSTO and ITER International Organisation on participation in the International Tokamak Physics Activity

Australian ITER Forum
www.ainse.edu.au/fusion
Wendelstein 7-X

- Aim: evaluate the main components of a future fusion reactor built using stellarator technology.
- 06/07/2015: full test of toroidal field coils at 12.8kA current, cooled to 4K (-269°C), producing 3T on-axis.
- 02/07/2015: electron beam in full vacuum field