ITER and the road map towards fusion energy

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EFDA Close Support Unit Garching

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Nuclear Energy for New Europe 2005, Bled, Slovenia
Outline

• Introduction: fusion as a sustainable energy source; the conditions and challenges for the realisation of fusion energy
• ITER: Missions, Physics basis, Technological development
• Material research
• Electricity generating power plant conceptual study
• The role of fusion energy in future energy scenarios
Fusion reactions

- \( D + T \rightarrow \text{He}^4 (3.5 \text{ MeV}) + n (14.1 \text{ MeV}) \)
- \( D + D \rightarrow \text{He}^3 + n + 3.2 \text{ MeV} \)
- \( D + D \rightarrow T + H + 4.03 \text{ MeV} \)
- \( D + \text{He}^3 \rightarrow \text{He}^4 + H + 18.3 \text{ MeV} \)
- \( \text{Li}^6 + n \rightarrow T + \text{He}^4 + 4.8 \text{ MeV} \)

In a fusion reactor using D-T, T is regenerated in the reactor within the "tritium breeding blanket" through the reaction between Li and the fusion neutron.
Why do we develop fusion?

• Fusion could be a sustainable energy source:
  o Practically inexhaustible fuel source
  o No CO$_2$ emission
  o Waste
  o Accident analysis
Fuel

- Reserve of D: 1 D for 6700 of H
  (88 kg/a for a 1000 MW<sub>e</sub> power plant (PP))
- T: short lived radio isotope (13 years) but generated from reaction \( \text{Li}^6 + n \rightarrow \text{T} + \text{He}^4 \)
  (236 kg of Li<sup>6</sup>/ year for a 1000 MW<sub>e</sub> PP)
- Li reserve and resource:
  - Earth: 9 Mt reserve; >12 Mt resource (up to 21Mt)
  - Sea water: 170/billion; 2x10<sup>11</sup> tons
- Fuels are practically inexhaustible
CO$_2$ emission

- The production of energy from fusion does not generate any greenhouse gas
- Life cycle study

Ref. Tokimatsu et al 17th IAEA FEC
Waste (1)

• The fusion reaction D+T does not yield any radioactive daughter product (only a n and a He nucleus)
• The interaction of the energetic neutron (14 MeV) with nuclei will produce transmutation and hence yield radioactive daughter products
• But these products does not have extremely long life
Waste (2)
Waste (3)

- Calculation of radioactive life time and recycling limit of a fusion power plant

Ref. EU Fusion Power Plant Conceptual Study (PPCS), EFDA
## Waste (4)

<table>
<thead>
<tr>
<th>Activated material classifications</th>
<th>Contact dose rate after 50 y (mSv h(^{-1}))</th>
<th>Decay heat per unit volume after 50 y (W m(^{-3}))</th>
<th>Clearance index after 50 y</th>
</tr>
</thead>
<tbody>
<tr>
<td>PDW, Permanent Disposal Waste (Not recyclable)</td>
<td>&gt; 20</td>
<td>&gt;10</td>
<td>&gt; 1</td>
</tr>
<tr>
<td>CRM, Complex Recycle Material (Recyclable with complex RH procedures)</td>
<td>2 - 20</td>
<td>1 - 10</td>
<td>&gt; 1</td>
</tr>
<tr>
<td>SRM, Simple Recycle Material (Recyclable with simple RH procedures), Hands On Recycling for D &lt; 10 µSv h(^{-1})</td>
<td>&lt; 2</td>
<td>&lt; 1</td>
<td>&gt; 1</td>
</tr>
<tr>
<td>NAW, Non Active Waste (to be cleared)</td>
<td>&lt; 0.001</td>
<td>&lt; 1</td>
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According to ICRP and IAEA recommendation

Ref.: PPCS study, EFDA
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According to ICRP and IAEA recommendation

Ref.: PPCS study, EFDA
Accident (1)

- Accident sequences were assessed during the design phase of ITER and during the power plant conceptual study.
- No evacuation of the population: most severe conceivable accident driven by in plant energies lead to a dose of 18 mSv, below the threshold of 50 mSv for evacuation.

Ref.: PPCS study, EFDA
Accident (2)

- Beneficial aspects in case of loss of coolant accident (LOCA): delicate balance of conditions for fusion reactions, fuel inventory sufficient only for a few minutes of burn

Ref.: PPCS study, EFDA
Cross sections

1 keV is equivalent to $10^7 \,^0\text{K}$
Conditions for a fusion reactor (2)

• Power balance

\[ P_{\text{Fusion}} = \text{Power from fusion reactions} \]

\[ P_{\text{loss}} = \text{Power loss} \]

\[ P_{\text{out}} = \text{Electricity production} \]

\[ n \tau_E T > 5 \cdot 10^{21} \text{ m}^{-3} \text{s keV} \]

\[ n = \text{Particle density}, \quad T = \text{Temperature}, \quad \tau_E = \text{Energy confinement time in the plasma} \]
Conditions for a fusion reactor (1)

- Temperature in the range of 100 millions degree. At around $10^4$-$10^5$ °K, matter is in the plasma state, i.e. an ionized gas with global charge neutrality and dominated by collective effects.

  *The Sun is a thermonuclear reactor operating at about 10 millions degrees, using as fuel H*

- Creation and confinement of a plasma at $10^8$ °K:
  Confinement by magnetic field; heating by RF waves (170 GHz, 5 GHz, and 50 MHz in ITER) and by injection of energetic (1 MeV) neutral particles

  *In the Sun, confinement is insured by gravity*
Tokamak plasma confinement

- The plasma in a tokamak is confined by magnetic fields: toroidal field created by coils and poloidal field created by a current carried by the toroidal plasma
Fusion status (1)
Fusion status (JET) (2)
Fusion status: 50% D+ 50% T shots in JET (3)
Outline

• Introduction
• ITER: Missions, Physics basis, Technological development
• Material research
• Electricity generating power plant conceptual study
• The role of fusion energy in future energy scenarios
The ITER project

- International project with 6 Parties: EU (including Switzerland), China, Japan, Korea, Russia, USA
- India sent recently a request to become full Party
- Interest to join (through a Party): Brasil, Australia
- The decision to build ITER at the European site Cadarache was taken in June 2005
- Finalisation of negotiations regarding the ITER agreements
ITER

Central Solenoid
$\text{Nb}_3\text{Sn}$, 6 modules

Outer Intercoil Structure

Toroidal Field Coil
$\text{Nb}_3\text{Sn}$, 18, wedged

Poloidal Field Coil
$\text{Nb-Ti}$, 6

Machine Gravity Supports

Blanket Module
421 modules

Vacuum Vessel
9 sectors

Cryostat
24 m high x 28 m dia.

Port Plug (IC Heating)
6 heating
3 test blankets
2 limiters/RH rem.
diagnostics

Torus Cryopump
8

Divertor
54 cassettes
The tokamak ITER

Major radius $R$  6.2m

Minor radius $a$  2.0 m

Plasma current $I_p$  15 MA

Elongation  1.7

Plasma volume 837 m$^3$

Heating power  73 MW

$B_T$  5.3 T

Neutron flux  0.57 MW/m$^2$

Fusion power  500-700 MW

(thermal) during $> 400s$

Electrical power  500MW-

required  400 MVAr
Tritium in ITER

- T is supplied to ITER from external source (no internal breeding)
- 0.1g of T is burnt every 100 s for the production of 500 MW
- 25g/100 s will be injected to and pumped from the vessel due to high pumping speed required for plasma purity
- Tritium inventory: In vessel mobilizable = 1000 g, fuel cycle circulating inventory = 700 g, total site inventory < 3000 g
ITER design goals (1)

• Physics:
  • produce a plasma dominated by $\alpha$-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’ ($Q \geq 30$)
• Assessment by international community confirms the physics basis of ITER
ITER design goals (2)

• 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
  • demonstrate the safety characteristic of a fusion power plant
ITER scenario

<table>
<thead>
<tr>
<th>Time (s)</th>
<th>t_{SCF}</th>
<th>t_{SOB}</th>
<th>(~400s)</th>
<th>600</th>
<th>700</th>
<th>900</th>
<th>1600</th>
</tr>
</thead>
<tbody>
<tr>
<td>Begin pulse</td>
<td>Current Rampup</td>
<td>Burn</td>
<td>End Pulse</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>P_{fuel}</td>
<td>Ip</td>
<td>\phi_{SH}</td>
<td>DT Refuel</td>
<td>n_e</td>
<td>f_{He}</td>
<td>P_{add}</td>
<td></td>
</tr>
</tbody>
</table>

Plasma Initiation
ITER performances (1)

\[
\tau_{E}^{H98(y,2)} = 0.0562 I^{0.93} B^{-0.15} n_{19}^{0.41} P^{-0.69} R^{1.97} \kappa_{a}^{0.78} \epsilon^{0.58} M^{0.19}
\]
ITER Performances (2)

\[ \tau_E = H_{H98(y,2)} \tau_{E}^{h98(y,2)} \]

ITER has a large operating domain to achieve \( Q = 10 \)
ITER Performances (3)

Long pulse or steady state operation

Steady-state operation
\( Q = 2, \frac{\langle n_e \rangle}{n_G} = 0.57 \)

Inductive operation point
\( \frac{\langle n_e \rangle}{n_G} = 0.85 \)

High Q operation

- \( R/a = 6.35 \text{ m} / 1.85 \text{ m}, \beta_N \leq 2.5 \)
- \( R/a = 6.35 \text{ m} / 1.85 \text{ m}, \beta_N = 2.0 \)
- \( R/a = 6.20 \text{ m} / 2.00 \text{ m}, \beta_N \leq 2.5 \)
- \( R/a = 6.20 \text{ m} / 2.00 \text{ m}, \beta_N < 2.0 \)
- \( R/a = 6.20 \text{ m} / 2.00 \text{ m}, \beta_N \leq 2.0, \frac{\langle n_e \rangle}{n_G} = 1.0 \)
Technology

- No show stopper regarding specific technology or the integration of the whole device
- Critical components were identified and industrial size mock-up developed by all international Parties: the so called 7 Large Projects were successfully completed
- Specific development was undertaken by the EU party in all areas: development of heating systems, of the vacuum vessel construction, of high heat flux components, of low temperatures superconducting cables, high temperatures superconducting current leads, tritium breeding concepts, remote handling, tritium pumps…
7 Large projects

CENTRAL SOLENOID MODEL COIL
- Radius 3.5 m
- Height 2.8m
- $B_{\text{max}} = 13$ T
- $W = 640$ MJ
- $0.6$ T/sec

REMOTE MAINTENANCE OF DIVERTOR CASSETTE
- Attachment Tolerance ± 2 mm

DIVERTOR CASSETTE
- Heat Flux >15 MW/m², CFC/W

TOROIDAL FIELD MODEL COIL
- Height 4 m
- Width 3 m
- $B_{\text{max}} = 7.8$ T
- $I_{\text{max}} = 80$ kA

VACUUM VESSEL SECTOR
- Double-Wall, Tolerance ±5 mm
- HIP Joining Tech
- Size : 1.6 m x 0.93 m x 0.35 m

BLANKET MODULE
- 4 t Blanket Sector
- Attachment Tolerance ± 0.25 mm

EU role in the 7 Large projects

- EU has taken a significant share in the technology development for ITER in general and in the 7 Large projects in particular

EU participation

- CSMC 10%
- TFMC 100%
- VV Sector 15%
- Blanket Module 50%
- Divertor Cassette 25%
- Blanket Remote Handling 15%
- Divertor Remote Handling 90%
Safety and environmental aspects (1)

- The ITER design considered various safety aspects based on IAEA and ICRP recommendations, on the concept of As Low As Reasonably Achievable.
- Example of LOCA calculations.
Safety and environmental aspects (2)

- Even in the worst case, hypothetical accident, the limit of 50 mSv (public evacuation limit) is not reached.
- The safety studies confirm that the operation of ITER is safe because of, among other factors, the character of fusion reactions.
Construction Schedule

ITER International Organization

LICENSE TO CONSTRUCT

TOKAMAK ASSEMBLY STARTS

FIRST PLASMA

YEAR

2005

2006

2007

2008

2009

2010

2011

2012

2013

2014

2015

2016

ITER International Organization

License to Construct

TOKAMAK ASSEMBLY Starts

First Plasma

ITER

7/6/05
### Operation Schedule

<table>
<thead>
<tr>
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</thead>
<tbody>
<tr>
<td>FIRST PLASM</td>
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<tr>
<td>Full field, current, and H/CD power</td>
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<td></td>
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</tr>
<tr>
<td>Short DT burn</td>
<td>Q = 10</td>
<td>500 MW</td>
<td>400 s</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
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<tr>
<td>Full non-inductive current drive</td>
<td></td>
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</tbody>
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#### PLASMA AND PERFORMANCE

- **2014**: Integrated Commissioning
- **2015**: Commission machine with plasma. Heating and CD Expts. Reference scenarios in H.
- **2016**: Commission with neutrons. Reference scenarios in D. Short DT burn
- **2017**: Develop full DT high Q. Develop non-inductive aimed at Q = 5. Low duty.
- **2018**: Improve operation. High duty.

#### BLANKET TESTING

- **Electromagnetics. Hydraulics.**
- **Neutronics. Validate**
- **Short-term T breeding. Thermo-mechanics.**
- **On-line tritium recovery. High grade heat generation**

#### Equivalent accumulated nominal burn pulses

<table>
<thead>
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<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>2014</td>
<td>1</td>
<td>750</td>
<td>1750</td>
<td>3250</td>
<td>5750</td>
<td>8750</td>
<td>11750</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

#### Nominal burn:

- 400 s/500 MW / 0.77 MWm\(^{-2}\) on outboard surface

#### Neutron fluence:

- 0.12 MWam\(^{-2}\) for the first 10 years

#### Tritium consumption:

- 4.7 kg
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The “Broader Approach”

- The European Fusion Programme is energy oriented, aiming towards the realisation of a DEMO Reactor
- In this frame, the realisation of ITER is only one important element of the programme
- This view is shared by Japan
- A more global vision of the programme (“the Broader Approach”) is developed
- The Broader Approach includes a vigorous physics programme to advance the physics optimisation towards DEMO and the advance of the science and technology of materials for a fusion reactor
Material science and technology

- Materials for fusion must be low activation and retain their mechanical and thermal properties under irradiation.

**Nuclear reactions**
- Production of impurities (He, H)

**Cascades**
- Production of vacancies and interstitials

**Diffusion processes**
- Formation of the final microstructure

---

Time [s]

- $10^{-16}$
- $10^{-13} - 10^{-8}$
- $10^{-6}$
Characterisation of irradiation damage

- Dpa = displacement per atom

<table>
<thead>
<tr>
<th>MWy/ m²</th>
<th>n.m⁻²</th>
<th>dpa (Fe)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>1.4 \times 10^{25}</td>
<td>9.5</td>
</tr>
<tr>
<td>0.3 –1 (ITER)</td>
<td>0.4 – 1.4 \times 10^{25}</td>
<td>2.8 – 9.5</td>
</tr>
<tr>
<td>3 –4 (DEMO reactor)</td>
<td>4 – 5.6 \times 10^{25}</td>
<td>28 – 76</td>
</tr>
<tr>
<td>10 – 15 (REACTOR)</td>
<td>14 – 21 \times 10^{25}</td>
<td>95 – 143</td>
</tr>
</tbody>
</table>

- He production: 10 ppm/ dpa
- H production: 40 ppm/ dpa

Need of suitable neutron sources: energy = 14 MeV and high fluence
Material for fusion reactor

- Criteria:
  - Specific radioactivity
  - Radioactive decay heat
  - Half-life radio nuclides
  - Waste disposal

Candidate materials presently under development have a chemical composition based on low activation elements: Fe, Cr, V, Ti, W, Ta, Si, C
Steel of the 9Cr type such as EUROFER 97: 8.9 wt.% Cr, 1.1 wt.% W, 0.47 wt.% Mn, 0.2 wt.% V, 0.14 wt.% Ta, 0.11 wt.% C, Fe for the balance. Oxide (Yttria) dispersion strengthened (ODS) steel. SiC\textsubscript{f} in SiC matrix, Va alloys
Application in other fields

Advanced fission reactors Gen IV

- Oxide dispersion strengthened steels
- Refractory metals and alloys
- Intermetallic alloys
- C/C, SiC, SiC/SiC ceramic composites

Fusion reactor

- Reduced activation ferritic/martensitic steels
- Oxide dispersion strengthened steels
- Refractory metals and alloys
- Vanadium alloys
- SiC/SiC ceramic composites

Accelerator Driven System (ADS) demonstrator

- Reduced activation ferritic/martensitic steels
- Oxide dispersion strengthened steels
IFMIF (1)

- International fusion material irradiation facility IFMIF: a neutron source capable of simulating the fusion neutron with high flux
- IFMIF is the key infrastructure for fusion material science
IFMIF (2)

D^+ Beam (10MW)

D^+ Accelerator

Liquid Li Target

Li Free Surface

Specimens

High flux region (20 dpa/y) is 0.5 l

--> Small sample test technology
IFMIF (3)
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Power plant conceptual studies (PPCS) (1)

- Define the parameters of a fusion power plant, the underlying physics assumption, the key technologies
- Assess the safety and environmental impacts
- Assess the economics of the fusion plant
- PPCS assume a tokamak reactor

Ref. PPCS report from EFDA
<table>
<thead>
<tr>
<th>Parameters</th>
<th>ITER</th>
<th>PPCS A</th>
<th>PPCS B</th>
<th>PPCS C</th>
<th>PPCS D</th>
</tr>
</thead>
<tbody>
<tr>
<td>R (m) (R/a)</td>
<td>6.2 (3.1)</td>
<td>9.55 (3)</td>
<td>8.6 (3)</td>
<td>7.5 (3)</td>
<td>6.1 (3)</td>
</tr>
<tr>
<td>Elongation</td>
<td>1.75</td>
<td>1.7</td>
<td>1.7</td>
<td>1.9</td>
<td>1.9</td>
</tr>
<tr>
<td>B_T (T)</td>
<td>5.3</td>
<td>7</td>
<td>6.9</td>
<td>6</td>
<td>5.6</td>
</tr>
<tr>
<td>Density (10^{20} m^{-3}) [(n/\pi n_G)^{1/2}/I_p]</td>
<td>1-1.4 (0.85)</td>
<td>1.1 (1.2)</td>
<td>1.2 (1.2)</td>
<td>1.3 (1.5)</td>
<td>1.4 (1.5)</td>
</tr>
<tr>
<td>I_p (MA)</td>
<td>15 -17</td>
<td>30.5</td>
<td>28</td>
<td>20.1</td>
<td>14.1</td>
</tr>
<tr>
<td>&lt;T_{i_\perp} (keV)</td>
<td>8.1</td>
<td>22</td>
<td>20</td>
<td>16</td>
<td>12</td>
</tr>
<tr>
<td>Heating Power (MW)</td>
<td>70</td>
<td>246</td>
<td>270</td>
<td>112</td>
<td>71</td>
</tr>
<tr>
<td>Q</td>
<td>10</td>
<td>20</td>
<td>13.5</td>
<td>30</td>
<td>35</td>
</tr>
<tr>
<td>Fusion Power (MW)</td>
<td>400 -500 MW</td>
<td>5000</td>
<td>3600</td>
<td>3410</td>
<td>2530</td>
</tr>
<tr>
<td>\beta_n = \beta aB_T / I_p</td>
<td>1.77</td>
<td>2.8; 3.5</td>
<td>2.7; 3.4</td>
<td>3.4; 4.0</td>
<td>3.7; 4.5</td>
</tr>
<tr>
<td>H_H</td>
<td>1</td>
<td>1.2</td>
<td>1.2</td>
<td>1.5</td>
<td>1.5</td>
</tr>
</tbody>
</table>

\[ \tau_E = H_H \tau_E^{H98(y,2)} \]

**EUROPEAN FUSION DEVELOPMENT AGREEMENT**
## Parameters (2)

<table>
<thead>
<tr>
<th></th>
<th>Mode I A</th>
<th>Mode I B</th>
<th>Mode I C</th>
<th>Mode I D</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Fusion Power (MW)</strong></td>
<td>5000</td>
<td>3600</td>
<td>3410</td>
<td>2530</td>
</tr>
<tr>
<td><strong>Blanket Power (MW)</strong></td>
<td>4845</td>
<td>4252</td>
<td>3408</td>
<td>2164</td>
</tr>
<tr>
<td><strong>Divertor Power (MW)</strong></td>
<td>894</td>
<td>685</td>
<td>583</td>
<td>607</td>
</tr>
<tr>
<td><strong>Heating Power (MW)(\eta)</strong></td>
<td>246 (0.6)</td>
<td>270 (0.6)</td>
<td>112 (0.7)</td>
<td>71 (0.7)</td>
</tr>
<tr>
<td><strong>Pumping Power (MW)</strong></td>
<td>110</td>
<td>375</td>
<td>87</td>
<td>12</td>
</tr>
<tr>
<td><strong>Gross electric Power (MW)</strong></td>
<td>2066</td>
<td>2157</td>
<td>1696</td>
<td>1640</td>
</tr>
<tr>
<td><strong>Net electric power (MW)</strong></td>
<td>1546</td>
<td>1332</td>
<td>1449</td>
<td>1527</td>
</tr>
<tr>
<td><strong>Plant efficiency</strong></td>
<td>0.31</td>
<td>0.36</td>
<td>0.42</td>
<td>0.6</td>
</tr>
</tbody>
</table>
### Parameters (3)

<table>
<thead>
<tr>
<th></th>
<th>Mode 1 A</th>
<th>Mode 1 B</th>
<th>Mode 1 C</th>
<th>Mode 1 D</th>
</tr>
</thead>
<tbody>
<tr>
<td>Average n load (MW/m²)</td>
<td>2.2</td>
<td>2.2</td>
<td>2.2</td>
<td>2.4</td>
</tr>
<tr>
<td>Divertor peak heat load (MW/m²)</td>
<td>15</td>
<td>10</td>
<td>10</td>
<td>5</td>
</tr>
<tr>
<td>Coolant</td>
<td>Water</td>
<td>He</td>
<td>LiPb/He</td>
<td>LiPb</td>
</tr>
<tr>
<td>$T_{in}/T_{out}$ (°C) Blankest</td>
<td>285/325</td>
<td>300/500</td>
<td>480/700</td>
<td>700/1100</td>
</tr>
<tr>
<td>$T_{in}/T_{out}$ (°C) Divertor</td>
<td>140/167</td>
<td>540/720</td>
<td>540/720 (He)</td>
<td>600/900</td>
</tr>
</tbody>
</table>

**Upper operating temperature:**
- Ferritic Steel: 550 °C
- ODS Steel: 650 °C (To be tested)
- Nano composite Ferritic Steel: 800 °C (To be tested)
- SiCf/SiC: larger than 1000 °C (To be tested)
- Refractory metal: W (for divertor and armor on the first wall)

**He cooling:** also of interest for nuclear power plant
Breeding blanket

<table>
<thead>
<tr>
<th>Breeding blanket</th>
<th>Mode 1A</th>
<th>Mode 1B</th>
<th>Mode 1C</th>
<th>Mode 1D</th>
</tr>
</thead>
<tbody>
<tr>
<td>n multiplier and breeder</td>
<td>17L i-Pb (n multiplier and T breeder)</td>
<td>Be (Diam: 1 mm) Li₄SiO₄ (Diam: 0.25 - 0.63 mm) Li₂TiO₃ (Diam: 1 mm)</td>
<td>17L i-Pb (n multiplier and T breeder)</td>
<td>17L i-Pb (n multiplier and T breeder)</td>
</tr>
<tr>
<td>Coolant</td>
<td>Water</td>
<td>He</td>
<td>Dual coolant 17L i-Pb He</td>
<td>17L i-Pb</td>
</tr>
</tbody>
</table>

EUROPEAN FUSION DEVELOPMENT AGREEMENT
Outline

• Introduction: The conditions and challenges for the realisation of fusion energy
• ITER: Missions, Physics basis, Technological development
• Material research
• Electricity generating power plant conceptual study
• The role of fusion energy in future energy scenarios
Economics (1)

\[
\text{Plant cost}
\]

\[
\text{Specific cost (€/W)}
\]

<table>
<thead>
<tr>
<th>Plant Model</th>
<th>A</th>
<th>B</th>
<th>C</th>
<th>D</th>
</tr>
</thead>
<tbody>
<tr>
<td>Specific cost</td>
<td>6</td>
<td>4</td>
<td>2</td>
<td>2</td>
</tr>
</tbody>
</table>

\[
\text{Fusion Power} \quad 5000 \quad 3600 \quad 3410 \quad 2530 \quad \text{MW}
\]

\[
\text{coefficient} \propto \left( \frac{1}{A} \right)^{0.6} \frac{1}{\eta_{\text{th}}^{0.5}} \cdot P_{e}^{0.4} \beta_{N}^{0.4} \left( \frac{n}{n_{G}} \right)^{0.3}
\]
Economics (2)

- External Costs [mEuro/kWh]
- External Costs [mEuro/kWh]

- Global Warming
- Other
- Sum

- CCGT
- Fission
- Wind
- Fusion

- Coal
- Gas
- Nuclear fission
- Biomass
- Photovoltaics
- Wind
- Fusion
Fusion and the energy mix

Pre industrial level of CO$_2$: 280 pppm; Now: 360 ppm

![Bar chart showing energy mix for EU and India with CO$_2$ targets and year projections.](chart.png)
Conclusions (1)

• Fusion progresses have been significant
Conclusions (2)

- The decision to build ITER opened a new era for the achievement of fusion as an energy source.
- A fusion programme must also continue to include physics (preparation of the exploitation of ITER, physics basis basis for a demonstration reactor) and a vigorous programme on material science and technology.
- The training of the physicists and engineer is also a priority of the programme, in view of its long term character.
• Energy will be the challenge of the 21st Century if we want to avoid:

Fusion (and fission) will have its role in the energy mix.

From W. Schroppel, PSCC 2005
ITER Performances (4)

- Q = 10 operation scenario

\[ Q=10 \text{ for } 400\text{s at } 15\text{MA} \ (q_{95}=3) \]

\[ P_{RF} = 7 \text{ MW}, \ P_{NB} = 33 \text{ MW} \]
ITER Performances (5)

- Steady state operation: Issue to drive the plasma current

\[ Q = 6 \]
\[ P_{\text{fusion}} = 360 \text{ MW} \]
\[ I_P = 9 \text{ MA} \]
\[ P_{\text{LH}} = 29 \text{ MW} \]
\[ P_{\text{NB}} = 30 \text{ MW} \]
\[ I_{\text{CD}} / I_P = 52\% \]
\[ I_{\text{BS}} / I_P = 48\% \]
ITER Performances (6)

• High Q operation

Figure 4.4.1-7 Evolution of Plasma Parameters for High-Q Operation
$I_p = 17$ MA, $<n_e> = 1.1 \times 10^{20}/m^3$ ($<n_e>/n_G = 0.81$) and $\tau_{He}^* / \tau_E = 5$. a) $Q = 45$, b) $Q = \infty$
Example of development projects (1)

- High current (80 kA) high field (12 T) superconducting Nb$_3$Sn cable
- High Tc 70 kA current leads
Example of development projects (2)

- High heat flux components (3 MW/m²) from Be/CuCrZr
- Welding and HIPPing technologies
- Tritium compatible cryopump
- Development of Tritium plant for ITER
- Water detritiation system
- Remote handling system
Mechanical effects

Hardening (H)
Loss of ductility (LD)
Loss of fracture toughness
Loss of creep strength
Swelling

Change in the
Ductile to Brittle Transition temperature
DBTT

9Cr type of steel

Hardening (H)
Loss of ductility (LD)
Loss of fracture toughness
Loss of creep strength
Swelling

Ttest = Tirrad.

Hardening (H)
Loss of ductility (LD)
Loss of fracture toughness
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Swelling

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