ITER CRYOGENICS

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FRANCE

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Outline

• Introduction
• Cryogenics and superconductivity
• The ITER cryogenic system
• Key technological challenges
• Conclusions
• The overall programmatic objective:

to demonstrate the scientific and technological feasibility of fusion energy for peaceful purposes

• The principal goal: Q>10

to produce a significant fusion power amplification (tenfold the energy input):

input power 50 MW
output power 500 MW

• The Costs:

5 billion € for ten years of construction and 5 billion € for 20 years of operation and decommissioning

• The execution:

~90% of in kind contributions.

ITER is one of the most innovative and challenging scientific projects in the world today.
The Core of ITER

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

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

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

Cryostat
29 m high x 28 m dia.

Vacuum Vessel
9 sectors

Blanket
440 modules

Port Plug
heating/current drive, test blankets limiters/RH diagnostics

Torus
Cryopumps, 8

Divertor
54 cassettes

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: 23,350 t (cryostat + VV + magnets)
- shielding, divertor and manifolds: 7,945 t + 1,060 port plugs
- magnet systems: 10,150 t; cryostat: 820 t
Role of cryogenics

- High fields magnets
- HTS current leads
- Cryogenic pumping
- Reduction of specific project cost
- Save energy
Critical current density of superconductors

PF coils (4.2 K)
LHC magnets
CS and TF coils

Jc [A/mm²]

B [T]

Courtesy Ph. Lebrun
Sorption and desorption of gases at cryogenic temperatures
Phase Diagram of Helium

- SOLID
- HeII
- HeI
- CRITICAL POINT
- SUPERCRITICAL HELIUM
- GAS
- \( \lambda \) line

\[ T \, [K] \]
\[ P \, [kPa] \]

Courtesy Ph. Lebrun
## Helium as a cooling fluid

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<tr>
<th>Phase domain</th>
<th>Advantages</th>
<th>Drawbacks</th>
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<tr>
<td>Saturated He I</td>
<td>Fixed temperature&lt;br&gt;High heat transfer</td>
<td>Two-phase flow&lt;br&gt;Boiling crisis</td>
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<tr>
<td>Supercritical</td>
<td>Monophase&lt;br&gt;Negative J-T effect</td>
<td>Non-isothermal&lt;br&gt;Density wave instability</td>
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<tr>
<td>He II</td>
<td>Low temperature&lt;br&gt;High conductivity&lt;br&gt;Low viscosity</td>
<td>Second-law cost&lt;br&gt;Subatmospheric</td>
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</tbody>
</table>

Courtesy Ph. Lebrun
ITER cryogenics cooling principles

Cryoplant

Cooling power

Long lengths Cooling Distribution
SHe

Fix Temperature
HX
LHe

Heat Loads from magnet or cryopumps

SHe Supply

GHe Return

SHe Circulator

Cold Compressor

Heat exchanger

Cable in Conduit Cooling SHe

Heat Loads from magnet or cryopumps

P_{out}

P_{in}

m

T_{in}

T_{in}

P_{in}

P_{out}

m
>50 Cold Boxes, 3 km of cryolines, 4500 components

ITER cryogenics layout

Cryo production

end users
Magnets
Cryopumps
Thermal shields
Small users

utilities
Cooling water
Electric power
CODAC
Compressed Air
Vacuum

Cryo distribution
What does the ITER cryogenic system need?

- **Electric power**
  - about 30 MW; 22 GWh/month

- **Helium and nitrogen**
  - 24 t of He
dedicated LN2 refrigerator

- **Cooling and ventilation**
  - 2500 m³/h of water

- **Vacuum**
  - 10⁻² mbar

- **Controls:**
  - Networks, fieldbuses, PLC, SCADA

- **CRYO**
  - 65 kW @ 4.5 K
  - 1.3 MW @ 80 K

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Images show cooling towers, compressed air, and cryogenic equipment.
Birdseye view of ITER site
Main duties

• Basic:
  – Cool-down of the cryostat and torus cryopumps
  – Gradual cool-down and filling of the magnet system and the 80 K thermal shield in about one month
  – Cool-down of the NB cryopumps, pellet units and gyrotrons
  – Maintain magnets and cryopumps at nominal temperatures over a wide range of operating modes with pulsed heat loads due to nuclear heating and magnetic field variations
  – Accommodate periodic regeneration of cryopumps
  – Accommodate resistive transitions and fast discharges of the magnets and recover from them in few days

• Additional
  – Ensure high flexibility and reliability
  – Low maintenance
## Cryogenic capacity & loads

- **LHe cryoplant:** 65 kW equivalent @ 4.5 K
  - Cooling of the superconducting magnet system, HTS current leads
  - Cooling of cryo-pumps with high regeneration frequency and small users
- **LN2 cryoplant:** 1300 kW @ 80 K
  - Thermal shielding, LHe cryoplant pre-cooling
- **Helium inventory:** 24 t

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<tr>
<th>Type of load</th>
<th>Temperature level</th>
<th>Averaged value</th>
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<tr>
<td>Nuclear heating</td>
<td>4.2 K</td>
<td>3.2 kW</td>
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<tr>
<td>Variable heat load (AC losses &amp; Eddy currents)</td>
<td>4.2 K</td>
<td>16.4 kW</td>
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<tr>
<td>Static heat loads</td>
<td>4.2 K</td>
<td>8.1 kW</td>
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<tr>
<td>SHe circulating pumps and cold compressors</td>
<td>4.2 K</td>
<td>11.4 kW</td>
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<tr>
<td>Cryopumps system and small users</td>
<td>4.5 K</td>
<td>6.5 kW + 0.07 kg/s</td>
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<tr>
<td>HTS current leads</td>
<td>50 K</td>
<td>0.15 kg/s</td>
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<tr>
<td>LHe plant precooler</td>
<td>80 K</td>
<td>500 kW</td>
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<tr>
<td>Thermal shields and cryopumps baffles</td>
<td>80 K</td>
<td>800 kW (Baking)</td>
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</table>
Operation scenarios

- Cooldown in one month
- Uninterrupted operation in order to maximize machine availability
  - The Tokamak will be operated during two 8-hour shifts
  - The third shift will be used to recover nominal cryogenic conditions, for short interventions and to regenerate the cryopumps up to 470 K
- The large dynamic loads prevent full redundancy but allow continuous and uninterrupted operation without plasma
- Short maintenance periods of few days every two weeks
- Major shutdowns every 16 months
- RAMI analysis to improve the design and requirements for spares
Main cryogenic sub-systems

The ITER cryogenic system consists of two main sub-systems:

**Cryoplant:**

the LHe (JF) and the LN2 plants combined with the 80 K helium loop (EU)

**Cryo Distribution, Cold Termination and Valve Boxes:**

Main Cryo Distribution Boxes with helium circulating pumps for cooling of magnets and cryopumps (IN)

System of cryogenic transfer lines (IN) located inside the Tokamak building, between the Tokamak and Cryoplant buildings and inside the cryoplant building

Cold Termination Boxes (CN) for the Magnets

Cold Valve Boxes to feed the (EU) Cryopumps and (KO) Thermal Shields

Cold Valve Box (US) for the Pellet Injection System
Cryoplant architecture

1 – Cold process boxes of LHe Plant
2 – Cold process boxes of LN2 Plant
3 – Cold boxes of 80 K He loop
4 – Auxiliary LN2 box of 80 K He loop
5 – Helium gas purifier and recovery compressors
6 – LN2 Tank
7 – Warm 1.8 MPa He tanks
8 – 80 K He Quench tanks
9 – Cryoplant termination box
10 – LHe tank

Quench line

50 K LHe
4.6 – 4.8 K
80 – 100 K

LHe
4.6 – 4.8 K
80 – 100 K

50 K LHe
4.6 – 4.8 K
80 – 100 K
Cryodistribution architecture

- Cryolines from cryoplant building

- CCB
- Str-ACB
- TF-ACB
- CS-ACB
- PF-ACB
- CP-ACB

- 4.6 K SHe Supply
- 4.8 K GHe Return
- 4.5 K LHe Supply
- 50 K GHe Supply

- SHe Circulator
- Cold Compressor
- Heat exchanger

- System of long cryogenic lines for cryogenic users inside the Tokamak building

- LHe bath

- 3 CVBs of magnet Structures
- 9 CTBs of TF Coils
- 6 CTBs of CS Coils
- 11 CTBs of PF&CC Coils
- 14 CVBs of Cryopumps for Cryostat, Torus&PIS, NB
Coping with large pulsed heat loads

Without active control of the cooling loop

With active control of the cooling loop

~ 6000 t of Structures

used as thermal damper
Layout of cryo distribution boxes and cryolines inside Tokamak building

>50 Cold Boxes, 3 km of cryolines, 4500 components
Cryoline in the low pipe chase

Low pipe chase
Complex layout and maintainability

Water cooling modules
Cryoline
Auxiliary Cold Boxes

Diameter of ACB - 4.3 m.
Height ~ 6 m.
Key technological components

- Key cryodistribution components such as
  - Cold circulators
  - Cold compressors
- Cryoplant pulse mode operation with unprecedented load variation
  (cryogenic system are usually operated in quasi-steady state)
Layout of the Cold Termination Boxes for magnets
The components of a magnet cold termination box

- Cryostat lower vertical wall
- Bio-shield
- S-bend Box
- Coil Terminal Box
- Cold Helium distribution valves
- Vacuum Barrier Neck
- In-Cryostat Feeder
- CFT (Cryostat Feed-through)
- CICC joints
- Electrical Isolators for bus bars
- HTS Current leads
- Dry Box
- 1 Auxiliary Cold Box (ACB)
- 3 Cryolines
- 14 Cold Valves Boxes (CVBs)
- 36 Cryopumps cryojumpers
- 3 PIS cryojumpers
- 8 Torus Cryopumps
- 2 Cryostat Cryopumps
- 4 Neutral Beam Cryopumps
- 3 Pellet Injectors System (PIS)
- 470 K box
- Cryogenic Guard Vacuum System (CGVS)
Torus cryo-pumping

~100 m$^3$s$^{-1}$ pumping speed
Cryopump arrangement in the cryostat

Thermal shield

Cryopump

Cryostat
Thermal Shield Cooling System (TSCS)

Provide full redundancy of the system (2004, DDD)

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<tr>
<th>Sub-system</th>
<th>Quantity</th>
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<tr>
<td>(1) Manifold/Supply Line</td>
<td>Set</td>
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<td>(2) U-bend Box</td>
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<td>(3) Valve Box</td>
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<td>(4) Water Cooler</td>
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<td>(5) Electrical Heater</td>
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Technological challenges and variants under study

• Analysis of technical variants compatible with the requirements and basic design principles are presently under study
  – Simplification of the layout and improvement of performances, reliability and availability or reduction of investment and operation costs
  – Review and update of heat loads
  – Lowering of operating temperature to accommodate conductors and physics requirements

a) Large dynamic loads handling
  ✓ Pulse mitigation by temporary by-pass of the structure load
  ✓ Speed control of the cold circulators and temperature adaptation to load requirements
  ✓ Use of liquid helium storage buffering and complex process control
  ✓ Independent temperature control and subcooling capabilities

b) Helium management and cold quench tank temperature level

c) Optimal size, number of cold boxes and parallel operation (flow sharing)

d) Thermodynamic cycle optimization for the refrigerators

e) Developments of technology and engineering solutions for key components (e.g. SHe circulating pumps and heat exchangers)

f) Tritium containment and control
Cryogenics planning

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Conclusions

• ITER is a tremendous technical, managerial and scientific adventure exploring and pushing forward the frontiers of our knowledge.

• The ITER cryogenic system is one of the key component of the future machine

• It will be the second largest cryogenic system in the world with an installed cooling power of 65 kW at 4.5 K and 1300 kW at 80 K

• The cryogenic system is a technological but also an industrial challenge to develop efficient and industrially available components for future reactors

• Successful collaboration among ITER Organization, the Domestic Agencies and industry will be a key element for the successful completion of the project