ITER contribution to closing DEMO Engineering and technology gaps (preliminary analysis)

Maurizio Gasparotto
Gianfranco Federici

and with the contribution of:

C. Bachmann (Cryostat and Vacuum Vessel), W. Biel (Diagnostics), S. Ciattaglia (Licensing), C. Damiani (Remote Handling), C. Day (Fuel Cycle), E. Diegele (Low Activation Structural Materials), T. Franke (Heating Systems), I. Ricapito (TBM) and L. Zani (Superconducting Coils).
OUTLINE

- Introduction;
- European DEMO (main objectives and parameters);
- What can we learn from ITER that is relevant for DEMO design and construction in the areas of: Project Organization, Licensing, Tokamak Components (Vacuum Vessel and Cryostat, Superconducting Coils, Divertor, Breeding Blanket), Remote Handling, Fuel Cycle, TBM, Heating Systems and Diagnostics;
- Conclusions
Some of the Engineering aspects and technologies adopted in ITER, that can be used in the design and construction of a DEMO reactor, will depend on the DEMO objectives.

In this presentation the European DEMO reactor, at present under definition, is used as reference (Presentation from G. Federici).

Of course considering that we are in the first period of the ITER construction and the DEMO design is not yet finalized, this is a “preliminary analysis” which has been prepared with the contribution of a number of European experts.
European DEMO main objectives and basic strategy

- Demonstrate production of electricity (several 100 MW);
- Achieve tritium self-sufficiency;
- Achieve adequate machine availability/reliability over a reasonable time span.

An important aspect to be considered is the timeline to develop the design and start the DEMO construction. This defines the time available to develop new technologies. One has to consider: (i) at least results of 10 years of ITER operation and (ii) the availability of tritium in the world to start DEMO operation. A reasonable assumption could be to start DEMO construction around 2035-2040, with the consequence of utilizing ITER results in Engineering and Technologies as much as possible.
The main parameters of DEMO, at present under discussion, are in the following range:

<table>
<thead>
<tr>
<th>Parameter</th>
<th>ITER</th>
<th>DEMO 1 A2.6</th>
<th>DEMO 1 A3.1</th>
</tr>
</thead>
<tbody>
<tr>
<td>R (m) =</td>
<td>6.2</td>
<td>9.0 (1.45)</td>
<td>9.0 (1.45)</td>
</tr>
<tr>
<td>a (m) =</td>
<td>2.0</td>
<td>3.5 (1.75)</td>
<td>2.9 (1.45)</td>
</tr>
<tr>
<td>b (m) =</td>
<td>3.4</td>
<td>5.6 (1.65)</td>
<td>4.6 (1.35)</td>
</tr>
<tr>
<td>Bmax (T) at superconductor=</td>
<td>12.0</td>
<td>9.9 (0.82)</td>
<td>12.0 (1.00)</td>
</tr>
</tbody>
</table>

Others DEMO parameters planned in the first phase (i.e. during the operation with the first Breeding Blanket) are:

<table>
<thead>
<tr>
<th>Parameter</th>
<th>ITER</th>
<th>DEMO 1 A2.6</th>
<th>DEMO 1 A3.1</th>
</tr>
</thead>
<tbody>
<tr>
<td>Heating Power (MW) =</td>
<td>50.0</td>
<td>50.0</td>
<td>50.0</td>
</tr>
<tr>
<td>Burn Time (h) =</td>
<td>0.11</td>
<td>2.0</td>
<td>2.0</td>
</tr>
<tr>
<td>Max d.p.a. on structural materials =</td>
<td>20.0</td>
<td>20.0</td>
<td>20.0</td>
</tr>
</tbody>
</table>
What can we learn from the organization of the project

ITER is the first fusion reactor with a complexity at level of nuclear plant.

Main lessons learned for DEMO with respect “project organization” will be in the fields of:

- Project organization structure;
- Responsibilities;
- Relation with the nuclear licensing and safety authority;
- Design Integration (interface control, etc.)
- Safety issues;
- Project Control;
- Quality Assurance;
- Documentations.
• **ITER** is defined, according to the French law, as INB “*Installation nucléaire de base*”.

• In order to get the license for the construction of the Safety Important Classified (SIC) Structures, Systems and Components, the Preliminary Safety Analysis Report (PSAR) has to be defined.

  This experience can be considered relevant also if DEMO will be built in another European Country.

• In 2012 ITER got the construction license with associated several tens of Commitments to be accomplished from ITER by a certain time, e.g.: Review some combinations of loads; further accidents to be analyzed, with the need in some case of further protection and mitigation systems; more warranties on safety aspects during operation (inspectability, tests, etc.)

• The lesson learned is that the level of details and integration of the DEMO design, before the definition of the PSAR, should be more advanced in all the systems, especially auxiliary ones to avoid later problems during component manufacturing.
Data and lessons expected on DEMO from ITER during construction, commissioning and operation

<table>
<thead>
<tr>
<th>From ITER Fabrication &amp; Construction</th>
<th>From ITER Commissioning and Operation</th>
</tr>
</thead>
<tbody>
<tr>
<td>• Improvement in the Nuclear Safety Culture and on the relation with Nuclear Safety Authority (e.g. Inspections);</td>
<td>• Validation of models, and reduction of uncertainties, e.g:</td>
</tr>
<tr>
<td>• Optimization of Fabrication and Construction Quality Assurance plan and Control plan;</td>
<td>o Stresses</td>
</tr>
<tr>
<td>• Optimization of Maintenance and Inspection plans</td>
<td>o Dust production rate model and inventory control</td>
</tr>
<tr>
<td></td>
<td>o H permeation/retention and distribution in VV, BB, Vacuum System and Fuel Cycle;</td>
</tr>
<tr>
<td></td>
<td>• Improvement of the reliability data on components and systems;</td>
</tr>
<tr>
<td></td>
<td>• Qualification of components in a tokamak environment;</td>
</tr>
<tr>
<td></td>
<td>• Optimization of Maintenance procedures and spare part policy.</td>
</tr>
</tbody>
</table>
## Vacuum Vessel - Similarities

<table>
<thead>
<tr>
<th>Similarities</th>
<th>Functions</th>
<th>Technology</th>
<th>Design</th>
</tr>
</thead>
<tbody>
<tr>
<td>Functions</td>
<td>• First confinement barrier</td>
<td>• Austenitic steel</td>
<td>• Double shell with ribs</td>
</tr>
<tr>
<td></td>
<td>• Contribution to radiation shielding</td>
<td>• Welded structure</td>
<td></td>
</tr>
<tr>
<td></td>
<td>• Support in-vessel components</td>
<td>• Actively cooled (water)</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>• Neutron shielding plates in interspace between shells</td>
<td></td>
</tr>
</tbody>
</table>

### Mock-up of the VV inboard

ITER VV

3rd IAEA DEMO Programme Workshop - Hefei 11-14 May 2015 - M. Gasparotto
Cryostat

No essential differences regarding requirements, design and technology of the DEMO cryostat compared to ITER.

<table>
<thead>
<tr>
<th>Functions</th>
<th>Technology</th>
</tr>
</thead>
<tbody>
<tr>
<td>• Provide vacuum for SC coils</td>
<td>• Conventional vessel</td>
</tr>
<tr>
<td>• Support tokamak</td>
<td>• Welded structure</td>
</tr>
<tr>
<td>→ Pedestal ring: Safety important (SIC)</td>
<td>• Austenitic steel</td>
</tr>
</tbody>
</table>

ITER Tokamak

ITER Cryostat
Superconducting coils - Construction phase

- Production strand / conductor performances – better definition of achievable tolerances;

- $\text{Nb}_3\text{Sn}$ conductor samples: resilience regarding performances, degradation versus cycling and stability in transient field;

- Conductor hydraulic performances before winding;

- Feedback on winding manufacture and on assembly difficulties (\textit{TF system in particular}).
Superconducting coils - Operation phase

- Coil stability against transients (PF, CS);
- Nb$_3$Sn coils (TF, CS): resilience against EM loads (fatigue stresses);
- Quench Protection System behaviour (e.g. optimization to avoid fast discharges due to spurious signals);
- Insulation behaviour during operation (coils, feeders) (e.g. irradiation effect during high voltage discharges);
- Feedback on cryoplant power balance;
Divertor Technology

- All the technologies developed in ITER to build the Water Cooled Monoblock concept can be adopted in the divertor DEMO construction;
- The divertor cassette concept could be utilized in DEMO.
Main objectives and implementation of the Test Blanket Module (TBM) programme

- Validation of the structural integrity under combined loads.
- Tests of the integral performance of the blanket system.
- In particular validation of predictions (computational tools) on: Neutronics, Thermo-mechanics, Magneto-hydrodynamics (MHD), Electromagnetic and Thermal behaviour, Tritium breeding; Tritium inventory and recovery; Power extraction.

TBM sets in Equatorial Port #16 and TBS equipment in Port Cell
Contribution of TBM Programme to DEMO BB

- Development, with European Industry, of large heats (> 30 tons/heat) and products (thick plates, tubes...) of Reduced Activation Ferritic-Martensitic (RAFM) steel.

- Development and qualification of various joining technologies including “diffusion bounding”.

- Development of special rules for RAFM steels in Structural Design Criteria and its inclusion into a nuclear code (RCC-MRX).

- Development and qualification in ITER (at low dose rate) of:
  - the structural material and critical fabrication technology with EUROFER,
  - functional materials (Li₄SiO₄, Li₂TiO₃, Be-alloy pebbles, Pb-16Li, anti-permeation/corrosion coatings).

- Development of technologies and instrumentation related to tritium extraction

More details to be given in Topics 3 discussion.
Many loops and experimental devices have been designed and constructed in EU for supporting the TBM programme. They constitute a high value patrimony also for supporting the Breeding Blanket design development.
Remote Handling (RH)

From the ITER experience DEMO will benefit on the:

- Development of fusion-relevant nuclear grade RH technologies including intensive use of virtual reality and force feedback manipulator in remote control;
- Definition of nuclear fusion plant layout and logistic adapted to the nuclear maintenance (in tokamak and in hot cell);
- Engineering effort made for the design of the various RH systems (in areas like divertor handling, tooling, cask-based transportations, hot cells systems and processes, advanced vision system, etc.);
- Huge gain in industrial experience (never made at this scale and complexity).
Remote Handling: Divertor Cassette Movers

- The remote handling is performed by movers equipped with end-effectors, force feedback manipulator arms, special tooling, cameras etc.
Remote Handling: In-Vessel Viewing System

In-Vessel Viewing System (IVVS) layout

The IVVS resides in the primary vacuum.

- Scanning based on an amplitude modulation laser radar (LADAR).
- 2D and 3D pictures from intensity and phase shifting measurements.
Remote Handling: The Multi-Purpose Deployer

- To access all in-vessel surfaces
- Handling capacity 2T (long), 4T (short)
- Relative accuracy ±10mm
- Tools and service exchange inside the cask

In-vessel tasks:
- Dust accumulation monitoring & removal
- Tritium monitoring
- VV In-Service inspection and leak localisation
- Rescue of RH equipment
The tritium plant systems

DEMO

- Advanced tritium plant architecture with a primary and a secondary tritium plant loop in order to minimise batchwise cryogenic isotope separation (i.e. T inventory).
- Other technologies developed from the ones adopted in ITER.
The injection system

**DEMO**

- Gas puffing technology will very much rely on ITER solutions.
- Pellet injection has to be improved with respect ITER:
  1. Pellet source (extruder) will be ITER-type
  2. Extension of the ITER acceleration technology to double-stage gas
  3. Pellet guiding systems for the DEMO injection velocities (~ 1 km/s) have to be developed.
ITER Heating System concepts applicable to DEMO with minor modifications

A) NB system
1) NB Injector components in case \( E_{\text{beam}} \leq 1\text{MeV} \) with modified Cs ion source;
2) NB Test Facilities PRIMA, ELISE;
3) 1MV HV Power supplies, High Voltage Deck and Transmission Lines.

B) IC system
1) Generator with Final Power Amplifiers with modified frequencies compared to ITER;
2) Coaxial Transmission Lines;
3) Main antenna components.

C) EC system
1) Gyrotrons with similar or modified output frequencies depending on final choice of \( B_t \);
2) Main Gyrotron components (e-gun collector, cavity, SC magnet, RF system);
3) Corrugated Waveguide, Polarizers;
4) Chemical vapour deposition windows as 1\textsuperscript{st} confinement T-barrier;
5) EC Test Facility.
General developments expected from ITER

- Experience from remote maintenance of diagnostic components;
- Experience on in-situ calibration strategies in a nuclear environment;
- Developments towards a comprehensive integrated data analysis + model based plasma control system;
- Progress on disruption prediction, avoidance and mitigation.

Specific developments and results expected from ITER

- Experience with microwave diagnostics under conditions of high plasma temperature and high EC stray radiation;
- Feasibility of IR interferometry/polarimetry;
- Experience with neutron/gamma diagnostics under conditions of high flux densities and multiple neutron scattering;
- Experimental validation of first mirror and secondary optics lifetime for spectroscopic and optical systems;
- Magnetic diagnostics: validation of radiation hard sensors;
- Safety related diagnostics: feasibility of dust and fuel retention measurements.

A number of open issues remain for DEMO (see Poster from W. Biel)
ITER will provide important lessons with respect:

- Management of contracts,
- Design changes and non conformities,
- Metrology,
- Assembly procedures,
- Achievable tolerances,
- Tests to be performed during construction and assembly,
- Implementation and integration of the CoDaC system,
- Local commissioning of single systems,
- Commissioning of the machine.
Conclusions (1)

- This preliminary analysis has demonstrated that ITER will provide a substantial contribution to the DEMO organization, design and construction.
- Important lessons will be learned on the organization of the project, relation with the safety and licensing authority, interaction with the industries and on the assembly and commissioning phases.
- Some DEMO components can be built using the same design concept and fabrication technologies adopted in ITER (Vacuum Vessel, Cryostat, Superconducting Coils...).
- Materials and fabrication technologies adopted in ITER components can be used also in DEMO (Divertor, TBM, H&CDs).
Conclusions (2)

- Many computational models will be validated during ITER operation allowing to reduce the uncertainties in DEMO design and operation (Safety, TBM...).
- ITER construction will provide important information on the achievable tolerances and assembly procedures.
- ITER operation will provide important information on the reliability of components and adopted technologies and on the maintenance processes.
- A number of facilities used to test ITER components are also available to test DEMO prototypes.
Thank you for your attention