# Technological and Engineering Challenges of Fusion

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# Outline

The European "Fast-Track" Approach to Fusion

Milestones to be met and Required Achievements

Reference Fusion Development Scenario

Alternative Scenarios

Conclusions

# The Fast-Track

Growing demand for energy worldwide ⇒ "fast-track" strategy, with one step only between ITER and a commercial Fusion Power Plant.

- King panel in 2001.
- Lackner et al. paper in 2002.
- Euratom/UKAEA association report in 2005.

Significant similarities in the conclusions and in the time-schedules (between 39 and 43 years until start of operation of first FPP).

All 3 analysis essentially focused on physics; technology issues essentially limited to materials and blanket.

# The Fast-Track (continued)

| | ITER operations | | DEMO operations | | |
|---|---|---|---|---|---|
| t = 0 | | t = 20 | | t ≈ 36 | |
| ITER construction | DEMO design | DEMO construction | PROTO design | PROTO const. | Reactor design |
| | 10 | 10 | 10 | TBD | TBD |

Fusion Fast Track Experts 'Tentative' Two-Step Roadmap

| | ITER operations and decativation | | | DEMO operations | |
|---|---|---|---|---|---|
| t = 0 | | | t = 23 | | t ≈ 39 |
| ITER construction | | DEMO design | DEMO construction | Reactor design | Reactor const. |
| 8 | 7 | 8 | 8 | 9 | TBD |

K Lackner et al 'Reference' One-Step Roadmap

| | ITER operations | | DEMO operations | |
|---|---|---|---|---|
| t = 0 | | t = 18 | | t = 31 |
| ITER construction | DEMO design | DEMO const. | Reactor design | Reactor const. |
| 8 | 10 | 8 | 6 | 7 |

K Lackner et al 'Accelerated' One-Step Roadmap

| | ITER operations | | DEMO operations | |
|---|---|---|---|---|
| t = 0 | | t = 16 | | t = 33 |
| ITER const. | DEMO design | DEMO const. | Reactor design | Reactor const. |
| 8 | 8 | 8 | 11 | 6 |

UKAEA 'Reference' One-Step Roadmap

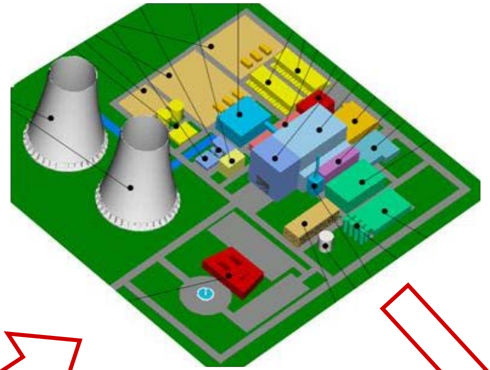
| | ITER operations | | DEMO operations | |
|---|---|---|---|---|
| t = 0 | | t = 19 | | t = 29 |
| ITER const. | DEMO design | DEMO const. | R$^{ctor}$ des. | Reactor const. |
| 8 | 10 | 9 | 4 | 6 |

UKAEA 'Variant' One-Step Roadmap

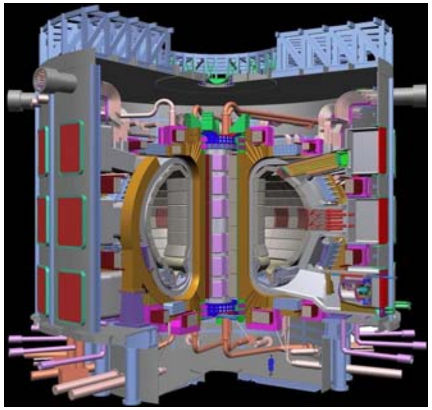
Comparison of EU fast-track scenarios

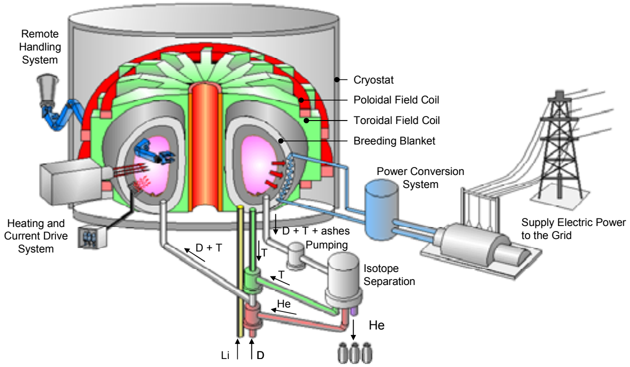
# The Fast-Track (continued)

DEMO objectives defined implicitly: to bridge the gap between ITER and the first FPP



**DEMO**






**ITER**: scientific and technological (partially) feasibility of fusion

**Fusion Power Plant**: economically acceptable, safe and environmentally friendly

# Overall Objectives to be Satisfied for "Fusion Maturity"

Qualification of all fusion-specific, reactor-relevant systems (requires prototype testing in relevant conditions).

Validation of the reactor architecture and qualification of the remote-handling procedures (in particular for the complete replacement of internal components – blanket & divertor).

Qualification of structural materials for the internal components.

# Milestones to be met prior to FPP Construction

Qualified physics basis.

Qualification of in-vessel components, (manufacture and process performances).

Qualification of H&CD systems.

Qualification of tritium systems.

Demonstration of remote handling procedures and validation of the overall reactor architecture.

Qualification of materials for blanket (>120dpa) and divertor (>50dpa).

Qualification of ex-vessel components and systems if and when required (e.g. HTS, He-cooled BoP).

# Milestones to be met prior to DEMO Construction

Demonstration of physics scenario for DEMO/Reactor with a full tungsten First Wall.

Qualification of DEMO/Reactor relevant PFCs (made of tungsten).

Validation of blanket functional performance.

Validation of divertor functional performance.

Qualification of materials (>80dpa), including welding, brazing and hipping.

Qualification of tritium technology.

Demonstration of feasibility of H&CD systems.

Demonstration of accumulated body of experience in the use of remote handling systems in ITER maintenance.

# DEMO Availability

Qualification of prototypical reactor-relevant systems for in-vessel components: 50dpa before start of FPP design, 100dpa before FPP licensing/start of operation.

Neutron wall loading of $2MW/m^2$.

8 years are required for the qualification (50dpa) with an availability of 33% (6 years with 50%).

Replacement of internal components during shutdown at the end of Phase 1 operation.

# DEMO Availability (continued)

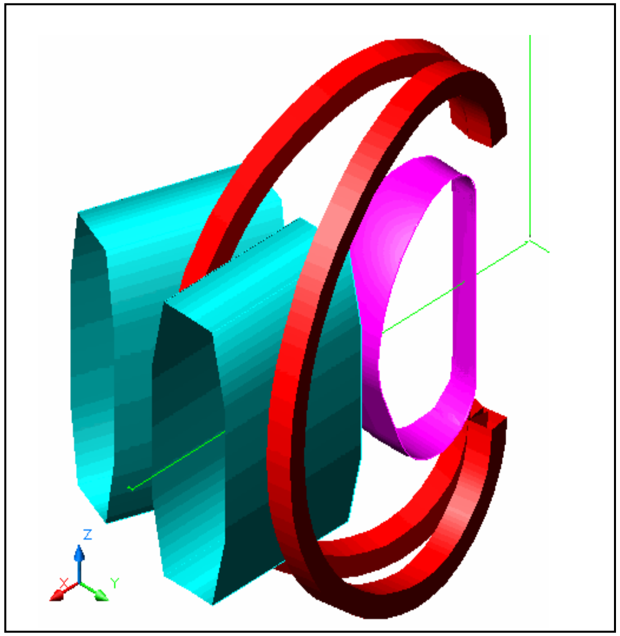
To be “qualified”, reactor-relevant systems will have had to operate reliably and in relevant conditions for a duration comparable to their expected lifetime. For a number of systems this can only be achieved in DEMO because of the neutron flux required.

Individual systems need to operate with a much higher availability than the DEMO target availability. Assuming 10 independent systems, a 90% availability is required for each individual system to achieve an overall availability of around 33%.

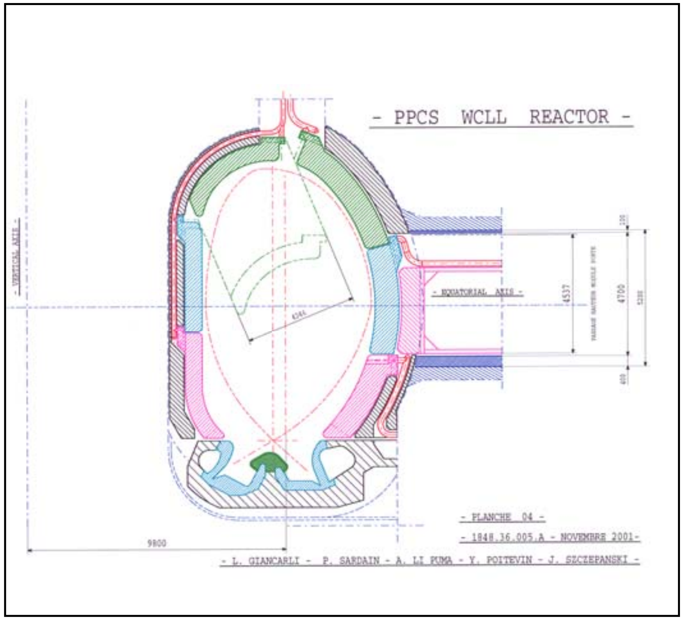
# DEMO Availability (continued)

ITER scheme for scheduled replacement of in-vessel components not reactor relevant: too many modules (>400).

Alternatives proposed to date, large sector (eg ARIES) and large modules (PPCS), not proven.




Drivers for in-vessel maintenance:
1) # of components
2) parallel work
3) logistics




**A MAJOR R&D effort is required in this area.**

# H&CD

| System | $\gamma_{CD}(A \cdot W^{-1} \cdot 10^{20} m^{-2})$ | $\eta_{plug}$ | $\rho$ |
|---|---|---|---|
| LHCD | 0.3? | 0.6? | >0.8 |
| ECCD | Te(keV)/160? | 0.45? | All? |
| NBCD | 0.6?<br>0.2 near edge? | 0.6? | <? |
| ICCD | Te/100? | 0.5? | <0.2? |

Best future possible performances for candidate CD systems

In the PPCS, figures corresponding to best possible performances for NBI were considered, irrespective of the CD system ($\gamma_{CD}$=0.6 and $\eta_{plug}$=60%).

In the on-going DEMO study less optimistic numbers are being considered. However, no system except the NBI is likely to achieve them.

**A MAJOR R&D effort is required in this area.**

# IFMIF

The objective of IFMIF is the testing of fusion materials under reactor-relevant conditions to characterise their use in fusion power plant.

IFMIF does not appear critical in the reference scenario if it can be assumed that one irradiation campaign is sufficient for material qualification.

However, this assumption may be optimistic and more than one campaign may be required.

# ITER

The reference scenario assumes that the DEMO physics will be confirmed during the first phase of ITER operation (currently within Phase 2 of ITER operation).

A key part of the second phase of ITER operation would be to validate the DEMO physics in the presence of a tungsten FW.

The qualification of all key systems required for DEMO should also take place during (or in parallel with) the second phase of operation.

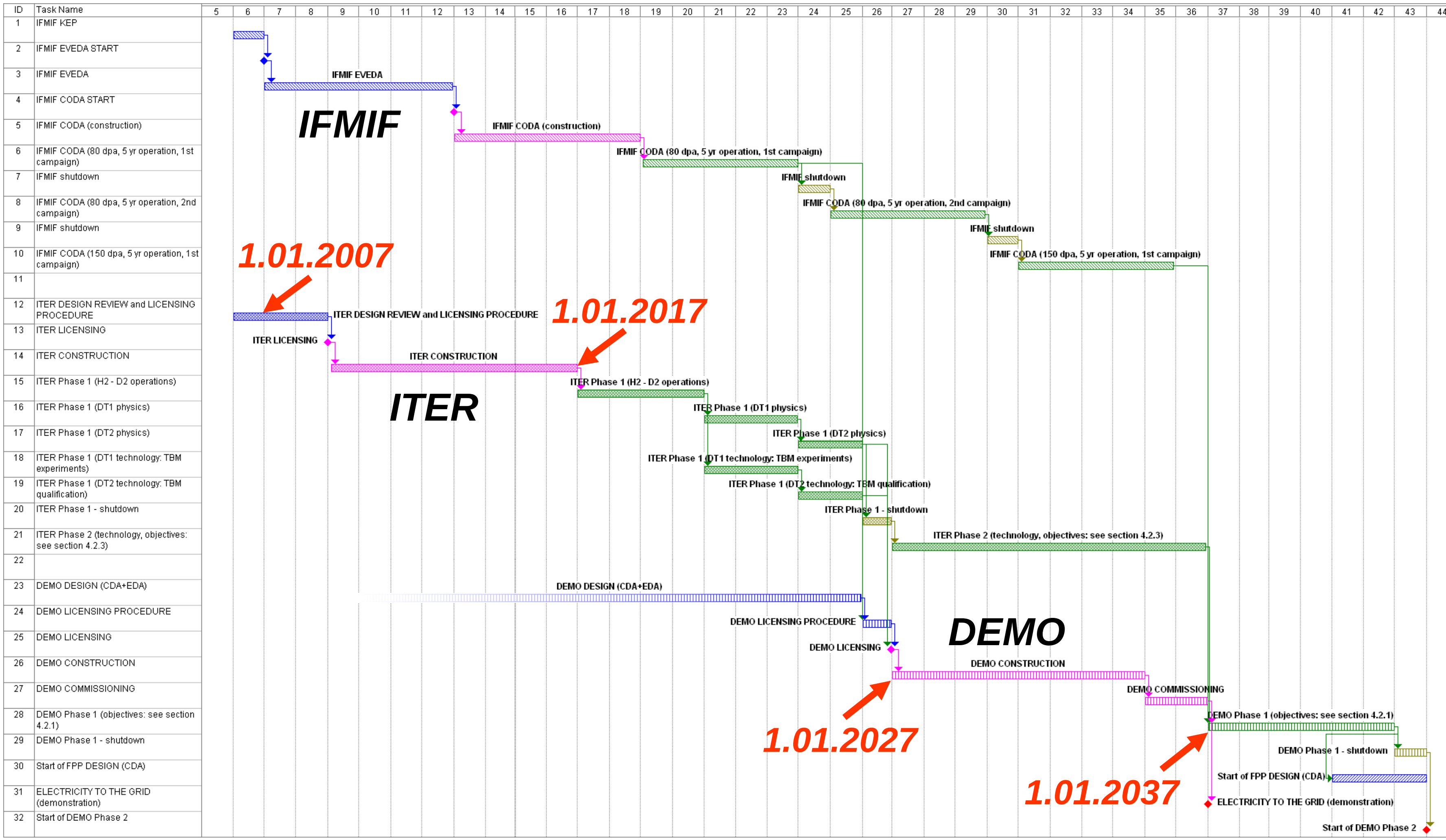
# Reference Fusion Development Scenario

DEMO design and licensing (10 years) starting immediately after completion of ITER construction.

DEMO construction (8 years) followed by DEMO commissioning (2 years).

DEMO Phase 1 operation (8 years with average availability of 33%) followed by 1 year DEMO shutdown.

# Reference Fusion Development Scenario



# Alternative Scenario Reduction of Risks

Mitigation of risks associated with timely achievement of the objectives required for the reference scenario.

Non-technical risks (e.g. programmatic decisions not being made in time) are difficult to mitigate.

Technical risks can be assessed and mitigated with programmes of supporting work, e.g. with facilities for:

- Development and qualification of H&CD systems.
- Development and qualification of DEMO and FPP-relevant Remote Handling procedures.
- Testing of in-vessel components in relevant neutronics conditions.
- Ad-hoc facility for High Temperature Superconductive magnets
- …

# Alternative Scenario
# Acceleration of the Programme

To accelerate the reference programme a new paradigm is required. This implies:

- Dropping the main condition underlying the reference scenario i.e. where DEMO construction starts after establishing the DEMO/reactor physics basis at the end of ITER Phase 1 operation.

- A reduction of the objectives of the reference DEMO (steady state, “high” availability and demonstration of economic acceptability).

# Alternative Scenario EDEMO

"Early DEMO": EDEMO.

EDEMO objectives:

- "Simpler" physics basis than that considered for the Reference DEMO.
- Reduction of some technological restraints:
  - Loads on the plasma facing components (divertor and FW).
  - Power required for H&CD.

Both of these can be achieved by considering a pulsed rather than steady-state device.

# Alternative Scenario EDEMO (continued)

Example of a pulsed EDEMO:

- Large, pulsed tokamak device conceived as a reactor.
- Pulse length at least 5 hours (preferably 10 hours) with a dwell time of 15 minutes or less.
- Utilise current ITER technology as far as possible.
- Water-cooled device, hence inefficient in terms of thermodynamics.
- Operation with limited availability.

Design work could start immediately.

Construction could be expected to start in 10 years and operations in 20 years.

Benefits of building such a device require careful consideration.

# Conclusions

Challenges of the Reference Scenario ("fast track"):

- DEMO physics critical issues to be resolved during ITER Phase 1 operation.
- DEMO construction to start after completion of ITER Phase 1, in parallel with the validation of the DEMO physics during ITER Phase 2 with a full tungsten first wall and divertor.
- ITER will have to achieve a number of engineering objectives during Phase 2 (validation of in-vessel components, tritium technology,…).

DEMO will have to operate with a relatively high average availability, even during Phase 1.

Steady-state operation of a power plant plasma remains a significant challenge (in particular H&CD).

# Conclusions (continued)

## Alternative Scenarios

- Firstly, one should consider how to mitigate the risks associated to the reference scenario.

- An acceleration of the reference scenario is possible with an EDEMO device, but this implies that the objectives of the reference DEMO be considerably reduced.
- EDEMO could be a pulsed machine, using current ITER technology as far as possible.
- The benefits of such a device in the overall fusion development scenario need to be carefully evaluated before considering such a step.