Designing Fusion Machines for High Availability

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What will DEMO look like?

High availability is a key ingredient in defining the DEMO configuration and achieving fusions economic goal

- COE is proportional to \((\text{Availability})^{-1}\)
- Rapid removal/replacement of limited-life in-vessel components is a necessary condition for high availability.
- DEMO will need to show that a fusion plant can operate with high availability, as its last step before full-scale electricity production.
- Availability drives *fundamental* design choices for DEMO.
ITER’s port-based maintenance is incompatible with high availability

ITER was designed to demonstrate the scientific feasibility of fusion energy.

“The ITER maintenance approach used for a power plant design results in an availability barely above 50%, which is unacceptable.”

Final Report of the European Fusion Power Plant Conceptual Study, April, 2005
High availability designs require large openings to remove and replace large in-vessel modules

Multiple approaches have been studied, illustrating tradeoffs.

**U.S. ARIES-AT**
- 16 radially extended TF coils
- Toroidal segmentation
- 16 modules
- 16-port horizontal removal

**JAEA, DEMO**
- 12 radially extended TF coils
- Toroidal segmentation
- 12 modules
- 4-port horizontal removal

**EU multi-module concept**
- 16 tight-fitting TF coils
- Toroidal & radial segmentation
- 64 modules
- 16-port vertical removal
Heating systems, diagnostics and services surround a fusion device

– challenging the horizontal maintenance option
As with ITER, vertical installation will be used to assemble DEMO – setting the stage for vertical maintenance

The building space above the device is set by machine assembly requirements

Assembly within the tokamak pit

ITER tokamak building
The EU vertical maintenance design represents one option under consideration for DEMO.

The multi-module maintenance concept incorporates 16 tight fitting TF coils with 64 split blanket segments.

Designed for a Single-null plasma

Blanket segments attached inclined bending bars and toroidal lower rings.

Large ports cut the continuity of a poloidal blanket module
A second vertical maintenance option is introduced with enlarged TF coils

Developed for the PPPL-AT pilot plant and now detailed in K-DEMO

- Limited piping at the top
- VV
- Blanket
- Semi-permanent Inboard Shield structure

EU multi-module vertical maintenance concept

- Enlarged TF coil for expanded VV maintenance space
- Self-supporting hot ring structure
- Gravity support
- Major piping services from below
- Upper port pipe connections
- Blanket
- Shield
- Single null divertor port access
A graded TF design helps to offset the cost of the enlarged coil size

A two-conductor design results in a lower cost, TF coil for K-DEMO

Low field winding (low-cost conductor)

High field winding (premium conductor)

Inboard leg winding detail

Outboard leg winding detail

TF shown with quarter section cut

Local rib structure

Low field winding
In-vessel segmentation concept provides alignment, labyrinth gap shielding and disruption load support.

Three blanket and four divertor segments per TF coil.

Semi-permanent inboard shield used for alignment, disruption load support and shielding for gaps between modules.
K-DEMO
- 6.8-m $R_0$
- 200 - 600 MW $P_{\text{net}}$
- Steady State
K-DEMO incorporates high-availability design features

- Vertical maintenance access
- PF designed for vertical access
- Enlarged TF for expanded VV space
- Port set for Aux equipment and RM
- Lower PF/machine access
- Double-null divertor
- Machine support at the base
- Major coolant supply from below
Magnetic system components evolved from ITER experience

- Cryostat
- ITER style inboard TF support system
- Outer shell supporting TF overturning forces
- Stacked plates for TF and machine support
- ITER developed PF design and sized CD’s
- Different TF winding scheme but ITER experiences
K-DEMO Poloidal Field coil arrangement satisfies performance goals with large vertical openings

System Parameters

- \( R = 6.8 \) m, \( DN \)
- \( a = 2.1 \) m
- \( \kappa_x = 2.0 \)
- \( \delta_x = 0.625 \)
- \( B_T = 7.4 \) T

Operating Space

- Low \( P_{elec} \sim 200-300 \) MW
  - \( \beta_N^{total} \leq 3.0 \)
  - \( I_p = 11-12 \) MA
- High \( P_{elec} \sim 500-600 \) MW
  - \( \beta_N^{total} \leq 4.15 \)
  - \( I_p = 12-14 \) MA
A test cell built to initially assemble the device also accommodates vertical maintenance.

Device core shown integrated within a test cell.

Space allows replacement of half of the blanket modules simultaneously.
To achieve DEMO availability goals....

A rich set of designs need to be established to maximize the chance of success – no solution is perfect.

The vertical maintenance design being developed for K-DEMO is showing promise...

The EU vertical and the JA 4-port horizontal maintenance concepts also have advantages.

Further developed integrated designs of all options is needed to ensure that high availability can be achieved, compatible with component requirements and cost objectives.
A Pilot Plant can demonstrate net electricity and Prototype a DEMO maintenance scenario

Providing an intermediate step with reduce risks on the path to DEMO

**K-DEMO 6.8-m device**
- $P_{\text{elec}} \sim 200\text{-}600 \text{ MW}, \ TBR > 1$
- $P_{\text{fus}} = 2181 \text{ MW}, < W_n > 2.09 \text{ MW/m}^2$

**PPPL 4.0-m AT Pilot Plant**
- $Q_{\text{engr}} \geq 1, \ TBR > 1$
- $P_{\text{fus}} = 674 \text{ MW}, < W_n > 2.2 \text{ MW/m}^2$
Rapid removal and replacement of limited-life in-vessel components is a necessary condition for high availability.

Success depends on tradeoffs among some very fundamental machine design choices:

- Number and size of TF coils.
- In-vessel segmentation scheme and defined access for module removal.
- Provision for ease of alignment and gap shielding that is compatible with plasma disruption support.
- Auxiliary interfaces that enhances in-vessel module removal.
- Routing of in-vessel services that fosters ease of maintenance.
- Defined poloidal field coil arrangement compatible with large openings for maintenance access.

A range of concepts need to be studied and compared.

Prototyping a DEMO-relevant maintenance concept in an intermediate (pilot-scale) fusion device also should be considered.