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.

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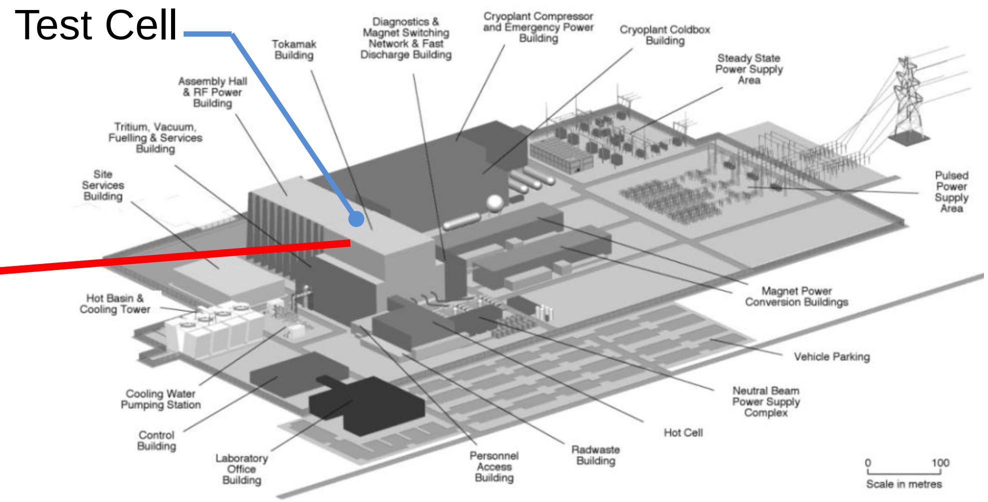
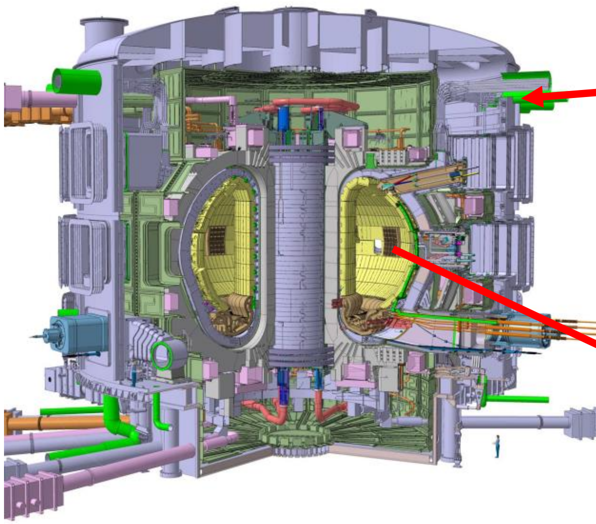
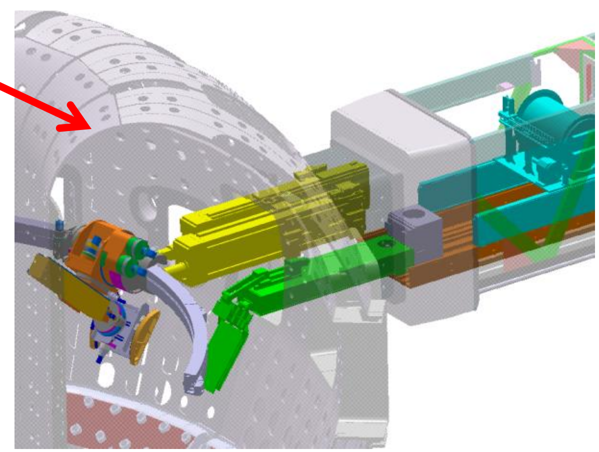
ITER's port-based maintenance is incompatible with high availability

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."

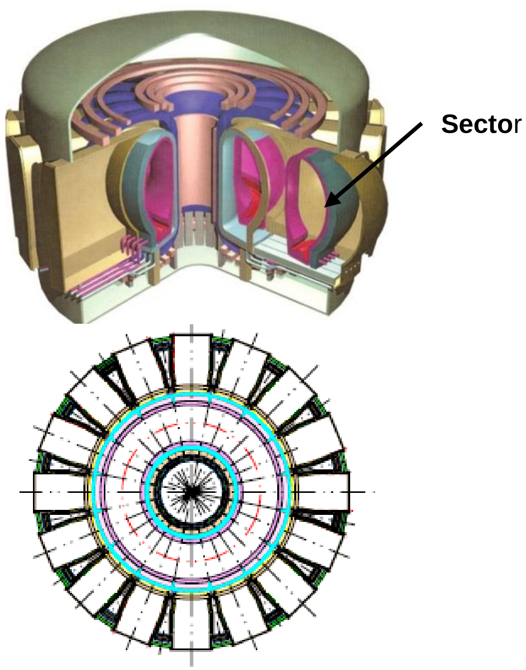
Final Report of the European Fusion Power Plant Conceptual Study, April, 2005

ITER incorporates port based maintenance

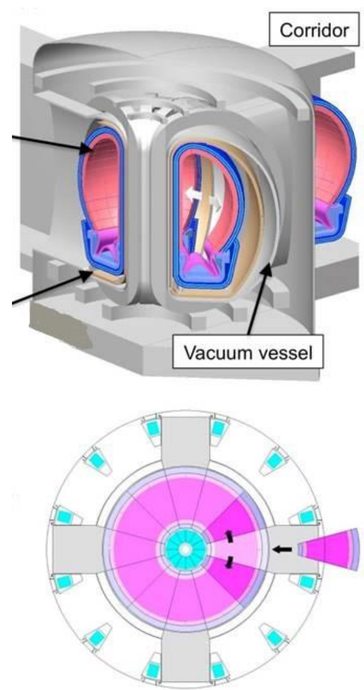
High availability designs require large openings to remove and replace large in-vessel modules

Multiple approaches have been studied, illustrating tradeoffs.

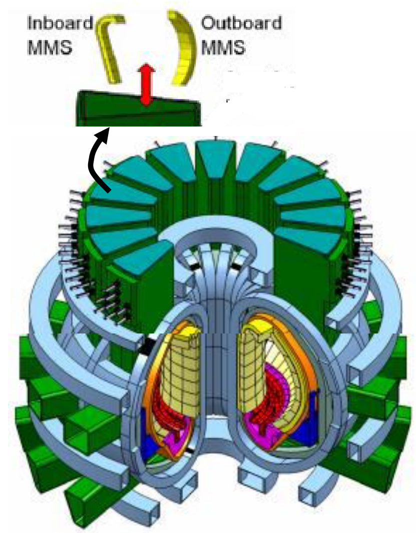
U.S. ARIES-AT



JAEA, DEMO



EU multi-module concept



16-port vertical maintenance

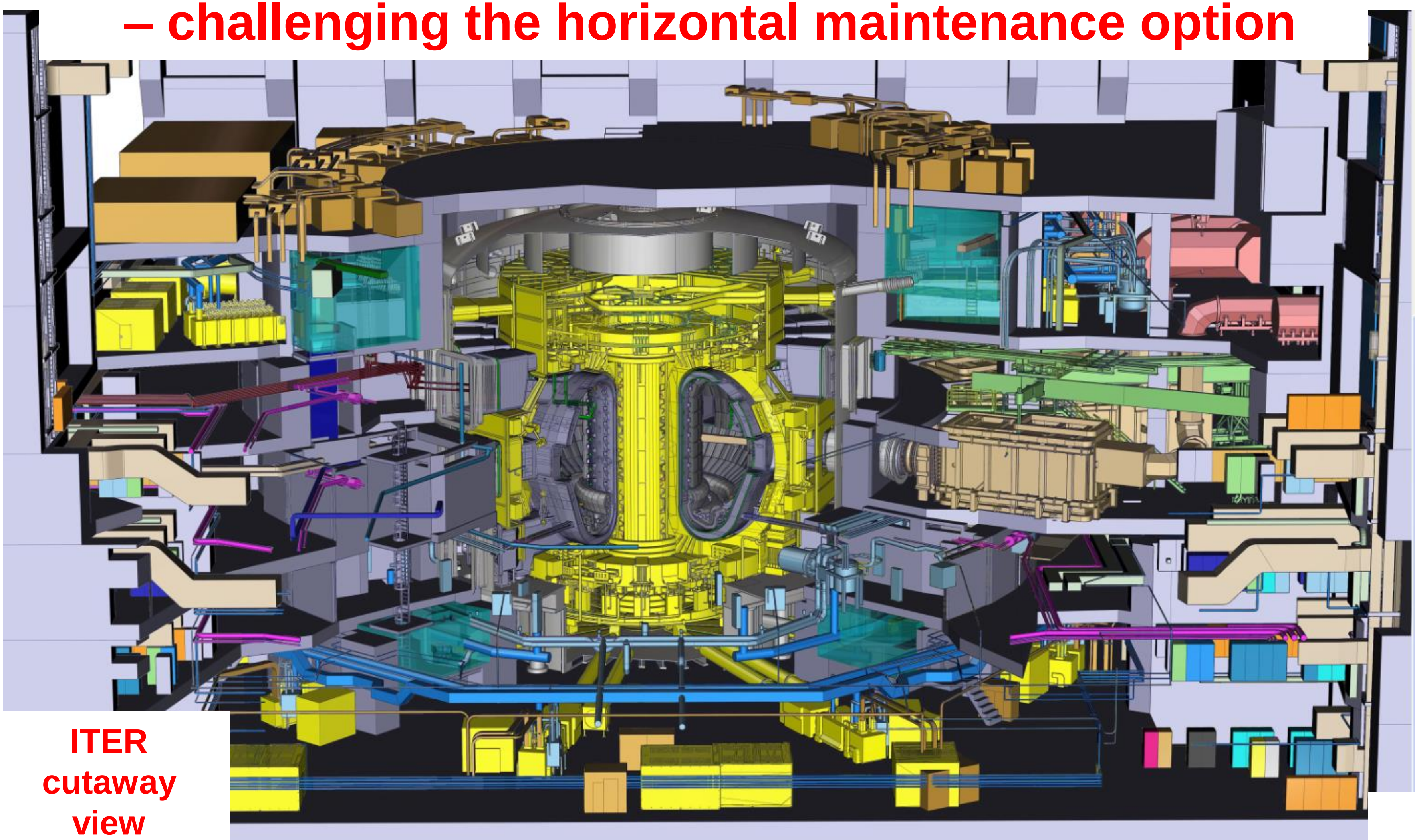
U.S. ARIES-AT:
16 radially extended TF coils
Toroidal segmentation
16 modules
16-port horizontal removal

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

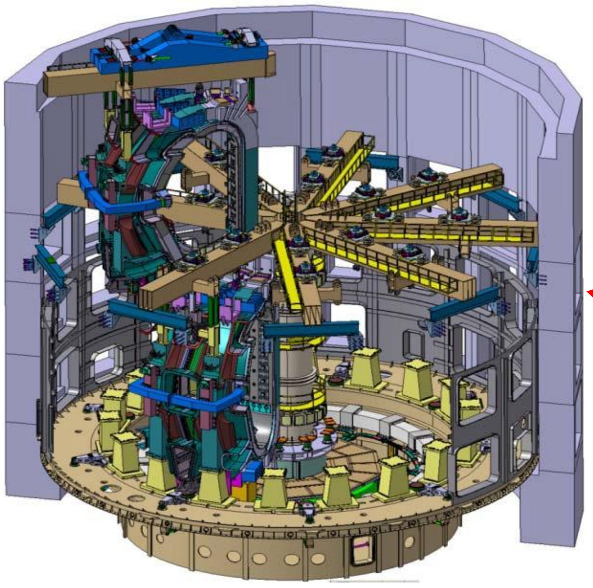
– challenging the horizontal maintenance option



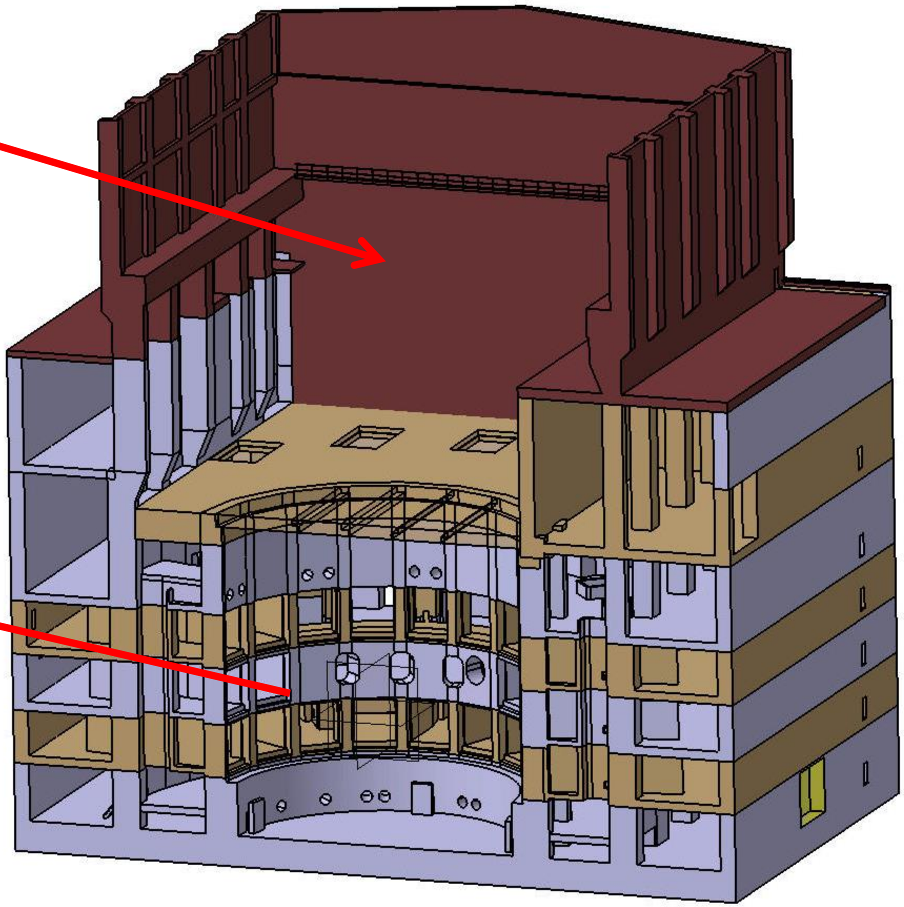
ITER cutaway view

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

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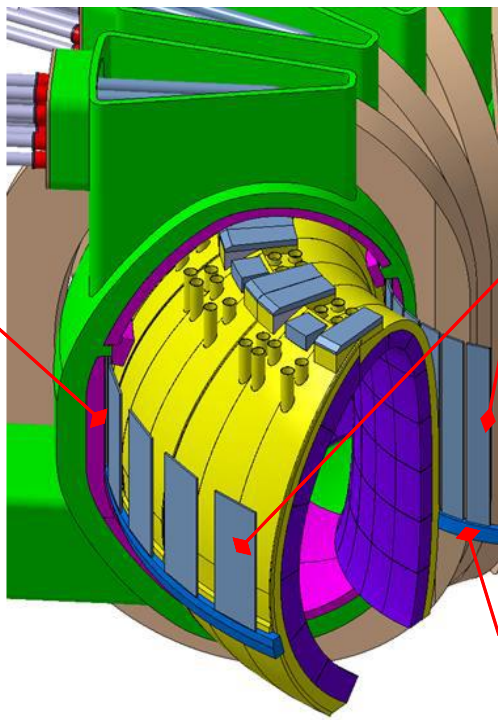
The EU vertical maintenance design represents one option under consideration for DEMO

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

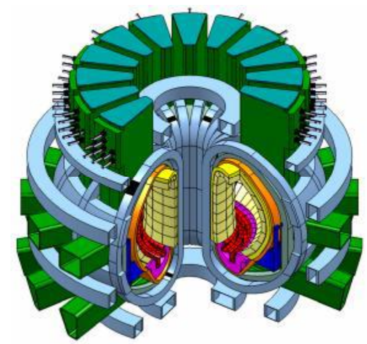
Designed for a Single-null plasma



Shield

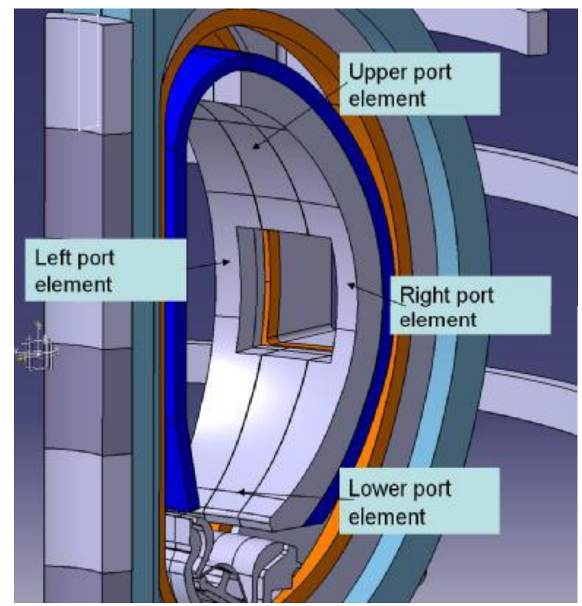
Vertical bending bars

Toroidal Mid Rings



Blanket segments attached inclined bending bars and toroidal lower rings.

Large ports cut the continuity of a poloidal blanket module



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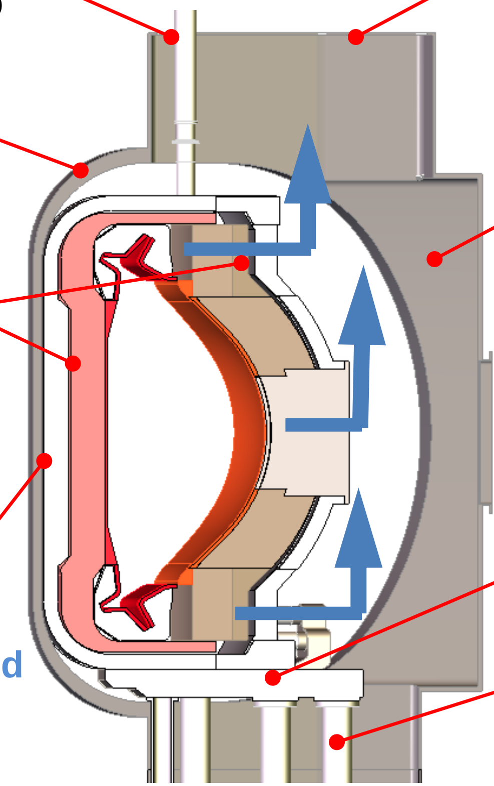
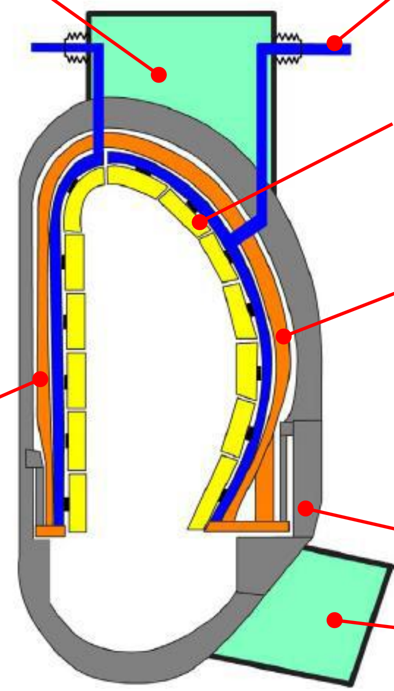
A second vertical maintenance option is introduced with enlarged TF coils

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

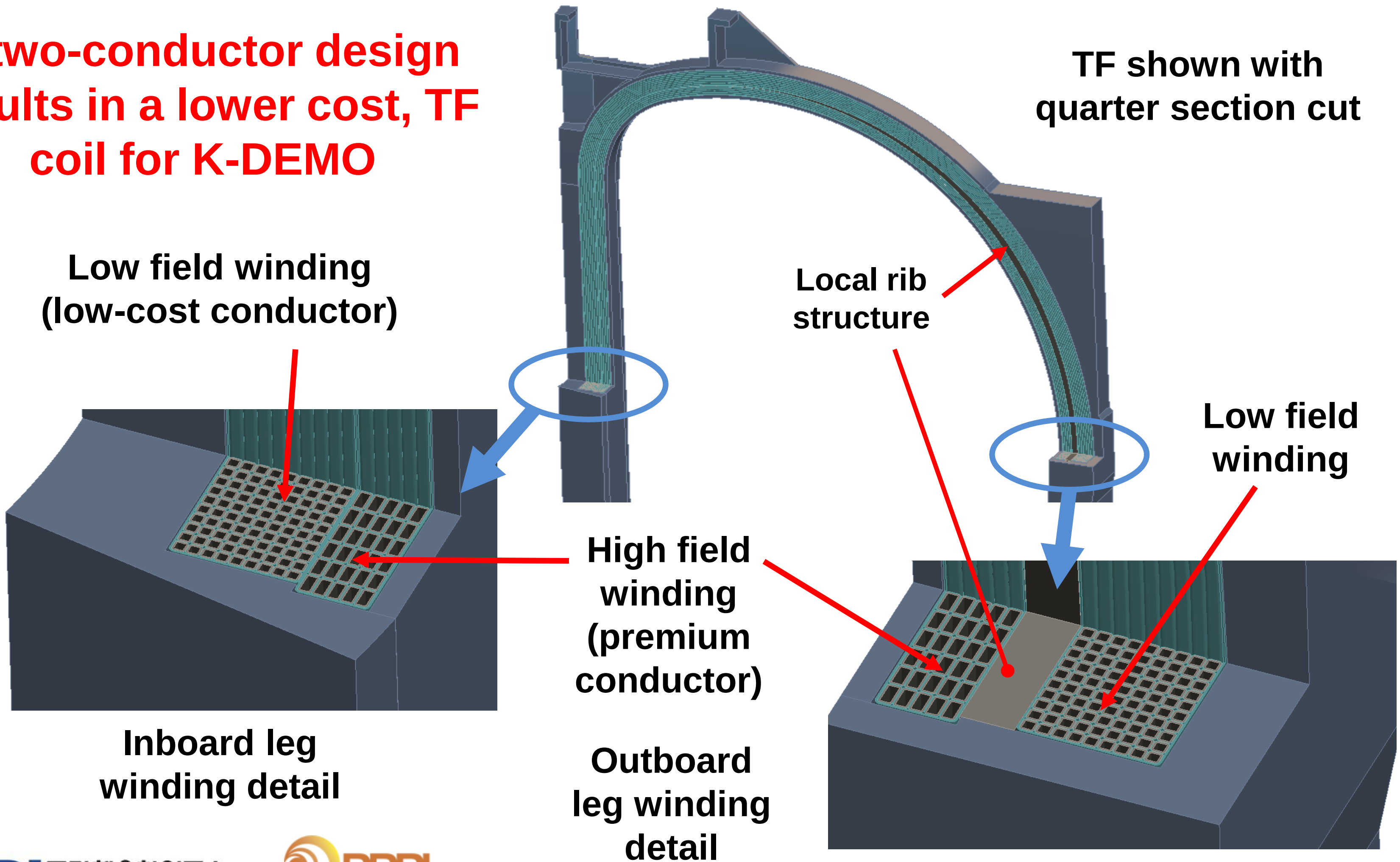


EU multi-module vertical maintenance concept

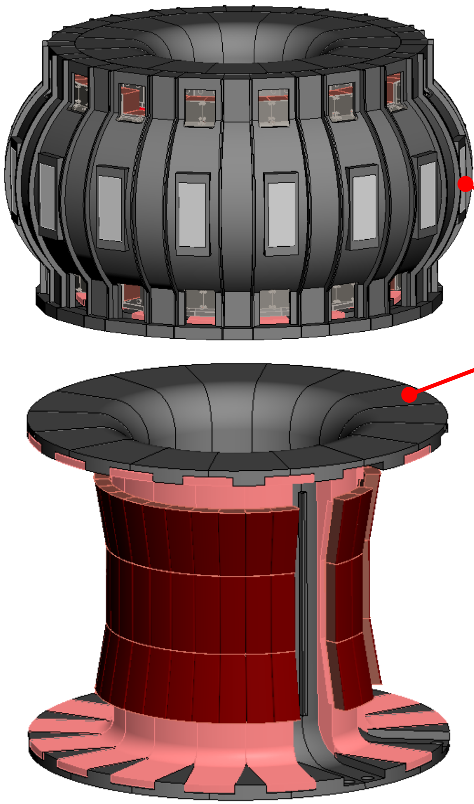


A graded TF design helps to offset the cost of the enlarged coil size

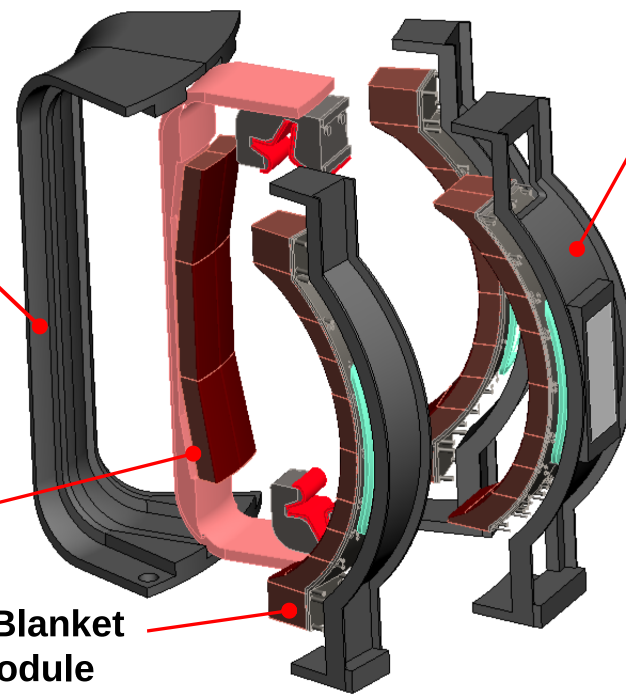
A two-conductor design results in a lower cost, TF coil for K-DEMO



In-vessel segmentation concept provides alignment, labyrinth gap shielding and disruption load support

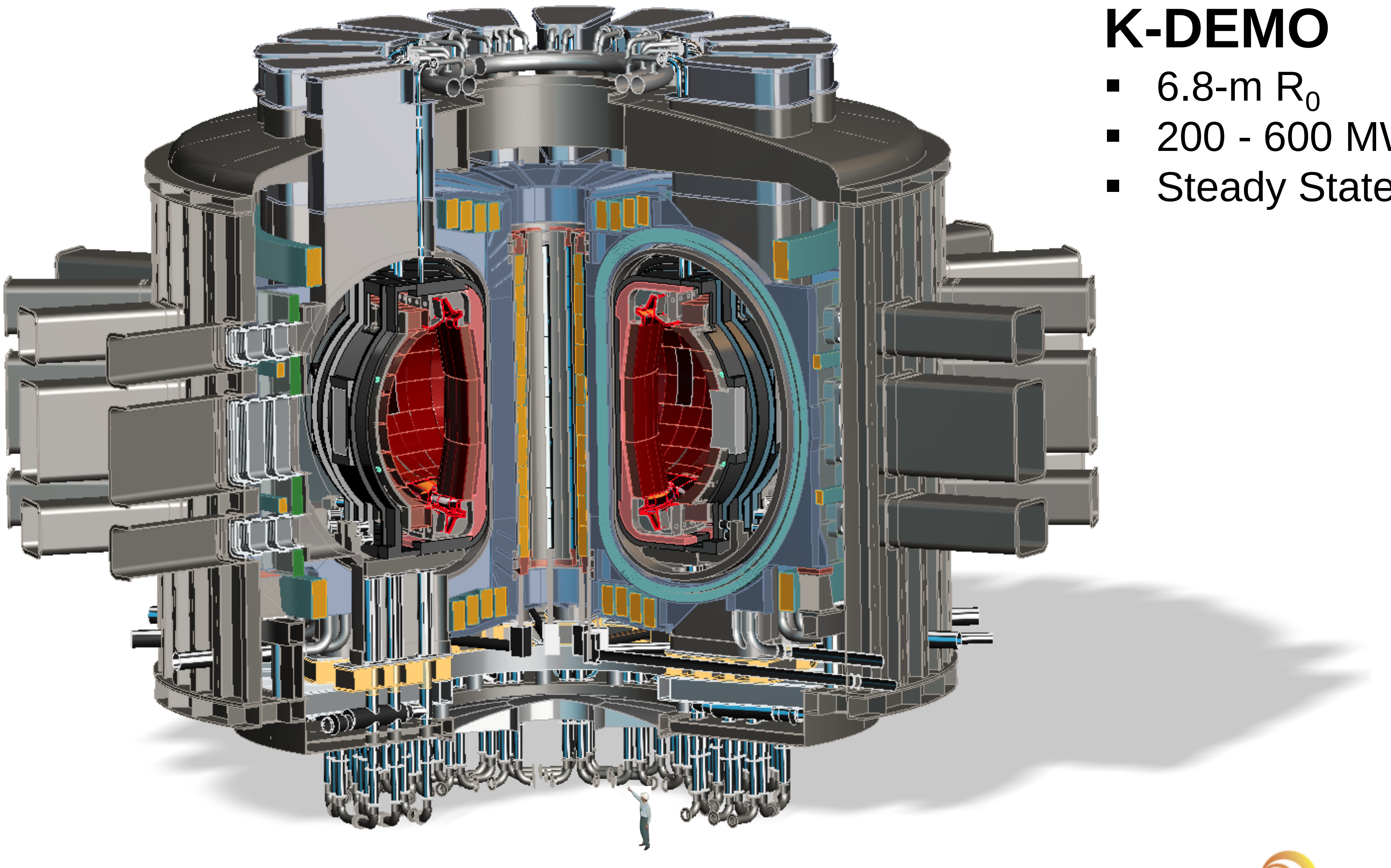


Three blanket and four divertor segments per TF coil



Semi-permanent inboard shield used for alignment, disruption load support and shielding for gaps between modules

S. Korea Fusion DEMO



K-DEMO

- 6.8-m R_0
- 200 - 600 MW P_{net}
- Steady State

NFRI 국가핵융합연구소 National Fusion Research Institute

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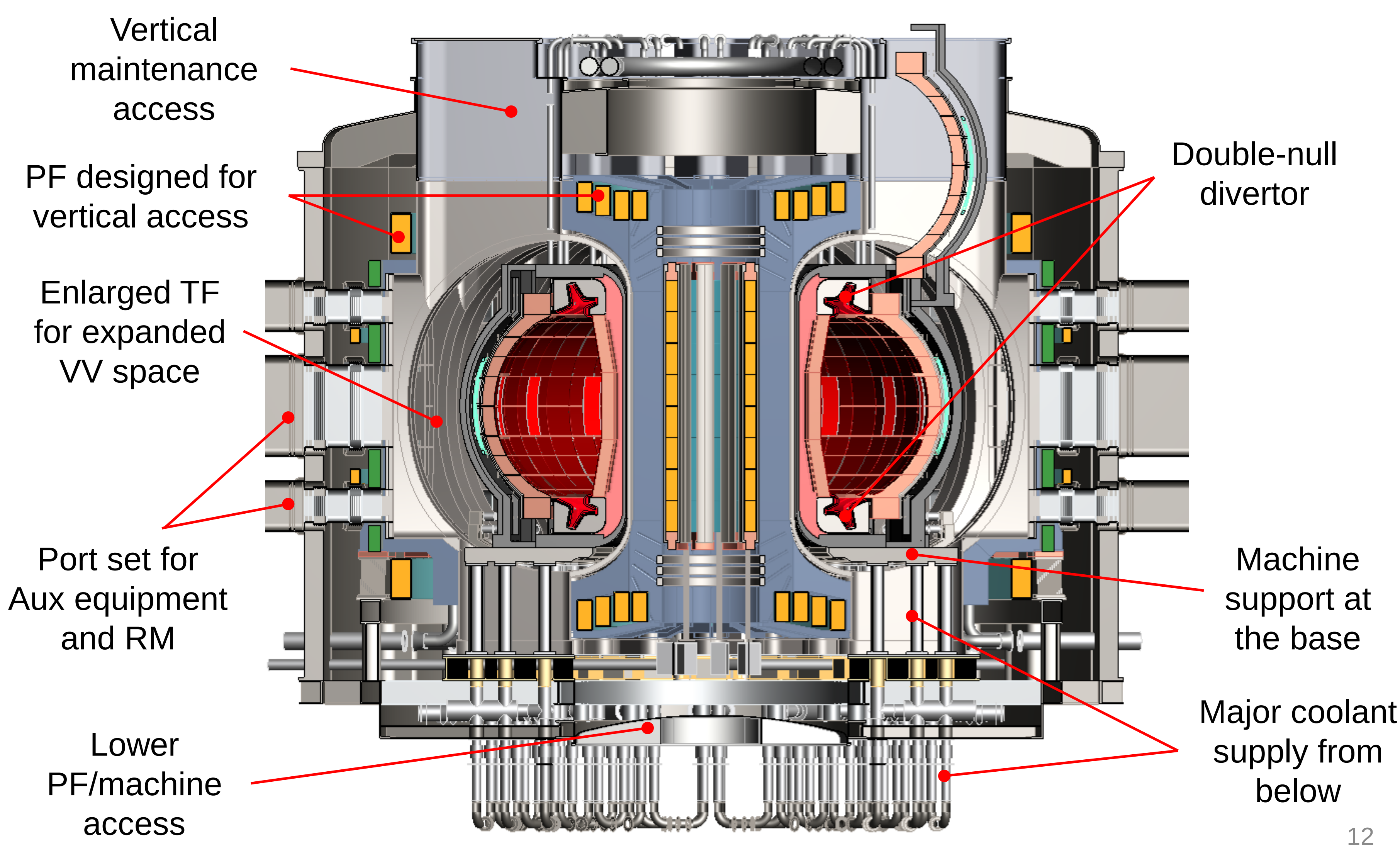
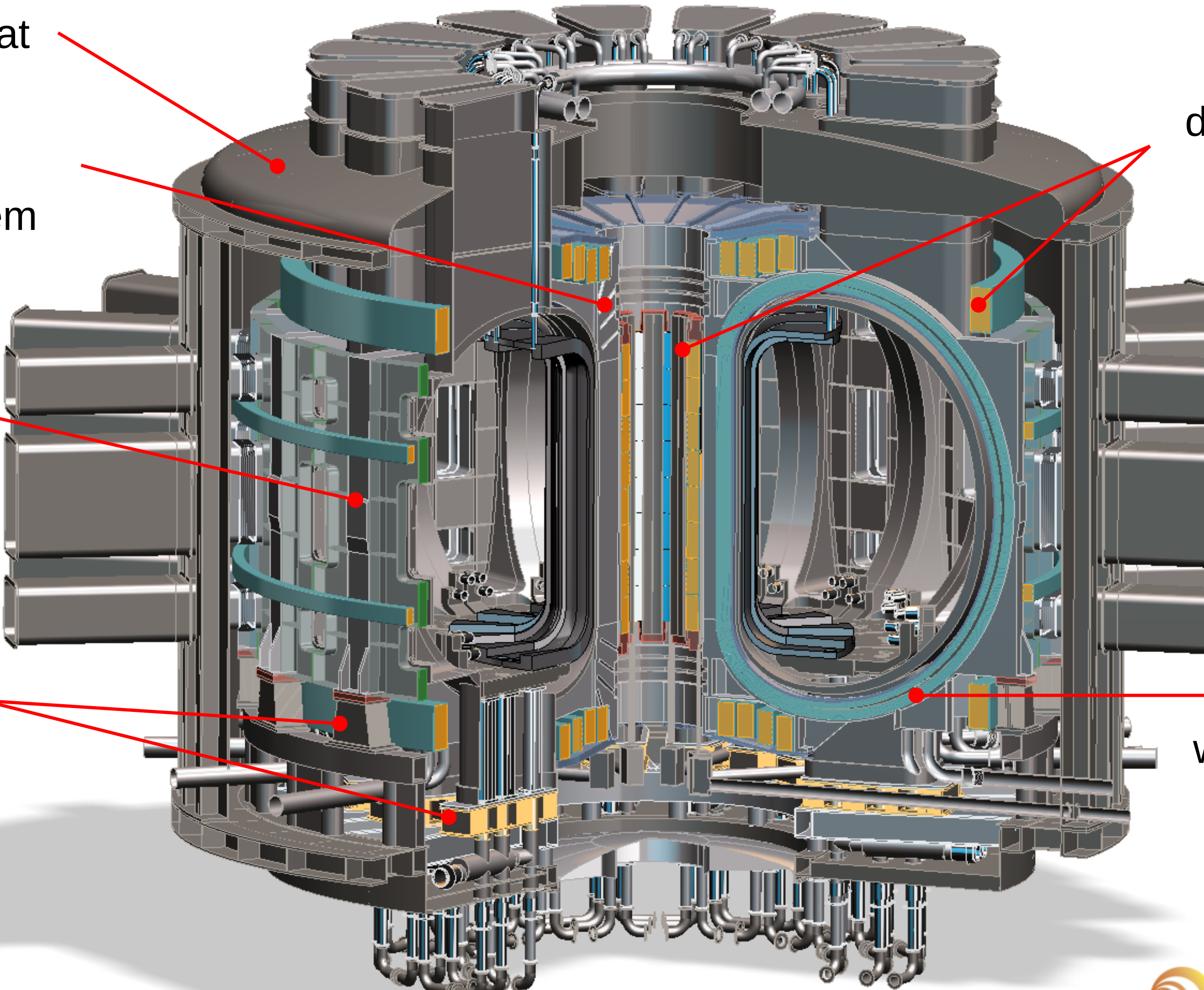
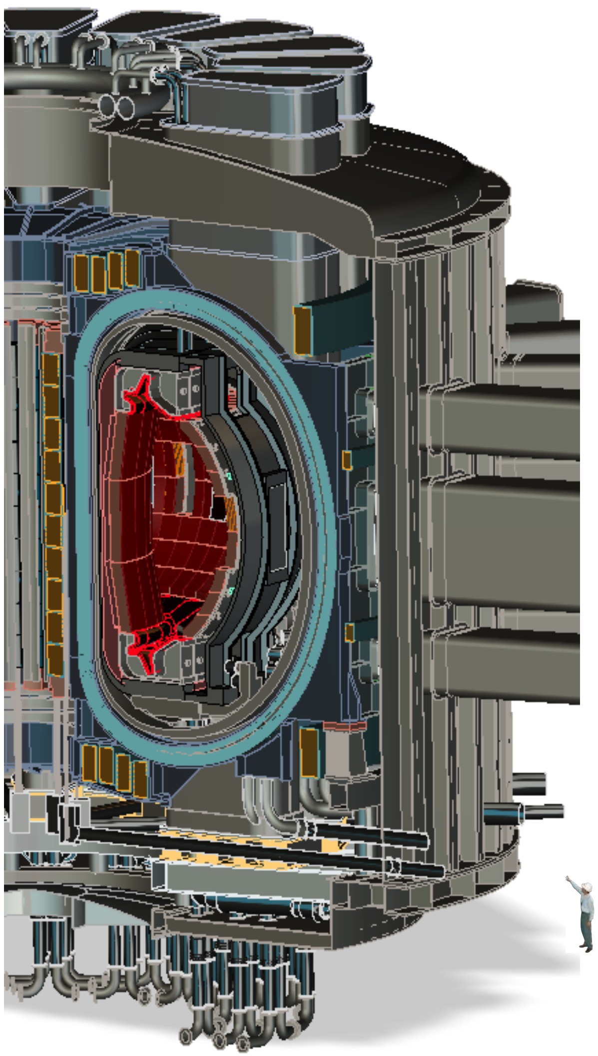
K-DEMO incorporates high-availability design features

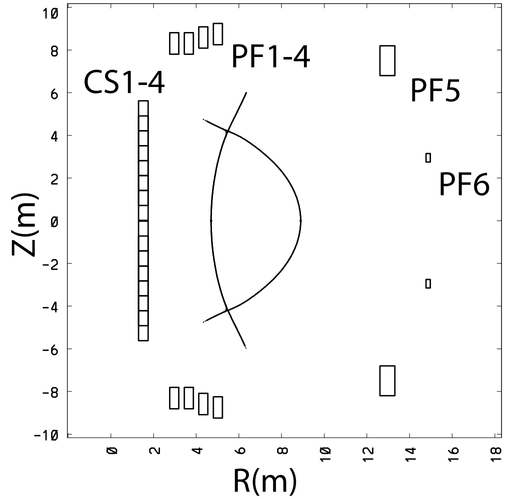


Magnetic system components evolved from ITER experience



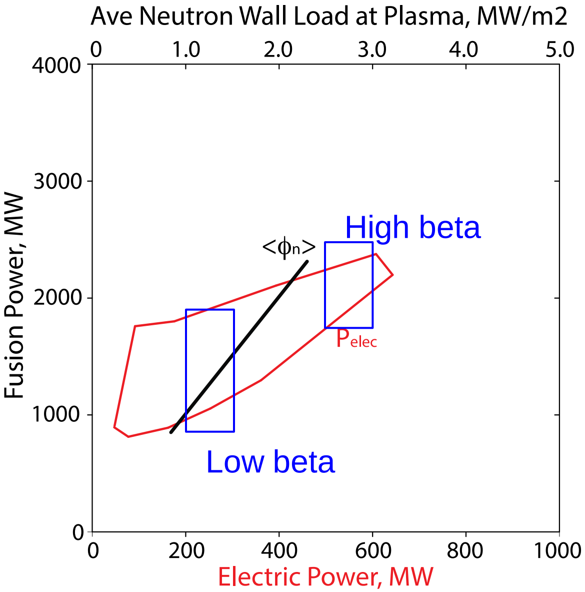
K-DEMO Poloidal Field coil arrangement satisfies performance goals with large vertical openings





System Parameters

R = 6.8 m, DN
a = 2.1 m
κ_x = 2.0
δ_x = 0.625
B_T = 7.4 T

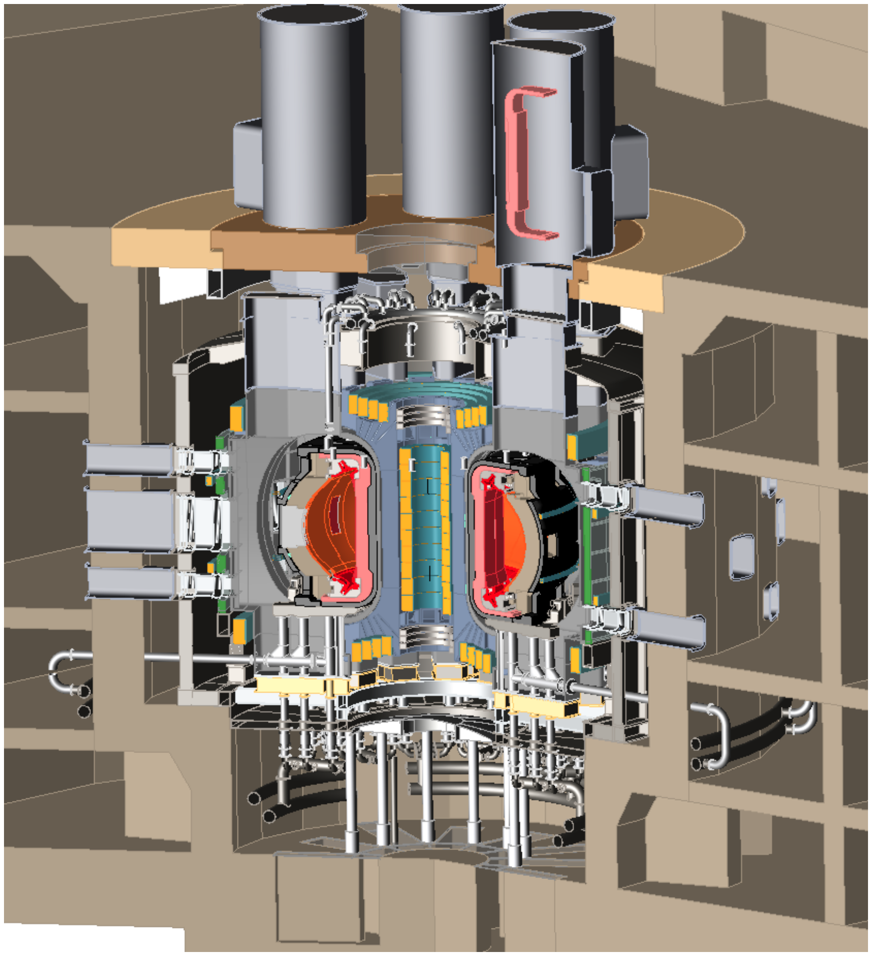


Operating Space

Low P_{elec} ~ 200-300 MW
$\beta_N^{total} \leq 3.0$
Ip = 11-12 MA

High P_{elec} ~ 500-600 MW
$\beta_N^{total} \leq 4.15$
Ip = 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.

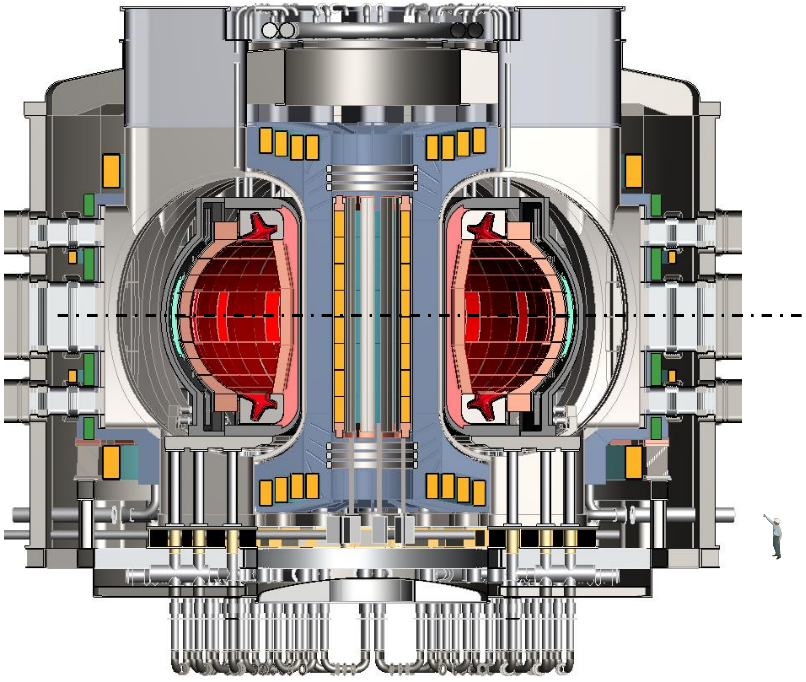
Further developed integrated designs of all options is needed to ensure that high availability can be achieved, compatible with component requirements and cost objectives.

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

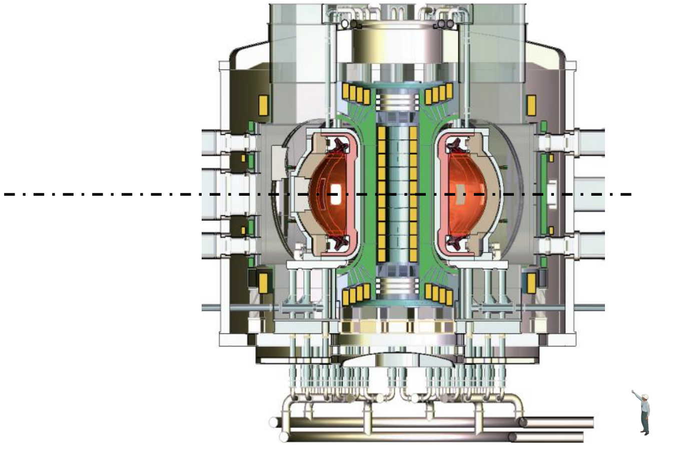
K-DEMO 6.8-m device

P_{elec} ~ 200-600 MW, TBR > 1
P_{fus} = **2181** MW, < W_n > 2.09 MW/m^2



PPPL 4.0-m AT Pilot Plant

$Q_{engr} \geq 1$, TBR > 1
P_{fus} = **674** MW, < W_n > 2.2 MW/m^2



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Summary

- **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.**