Fusion Development Facility Machine Design Aspects

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GENERAL ATOMICS

Abstract

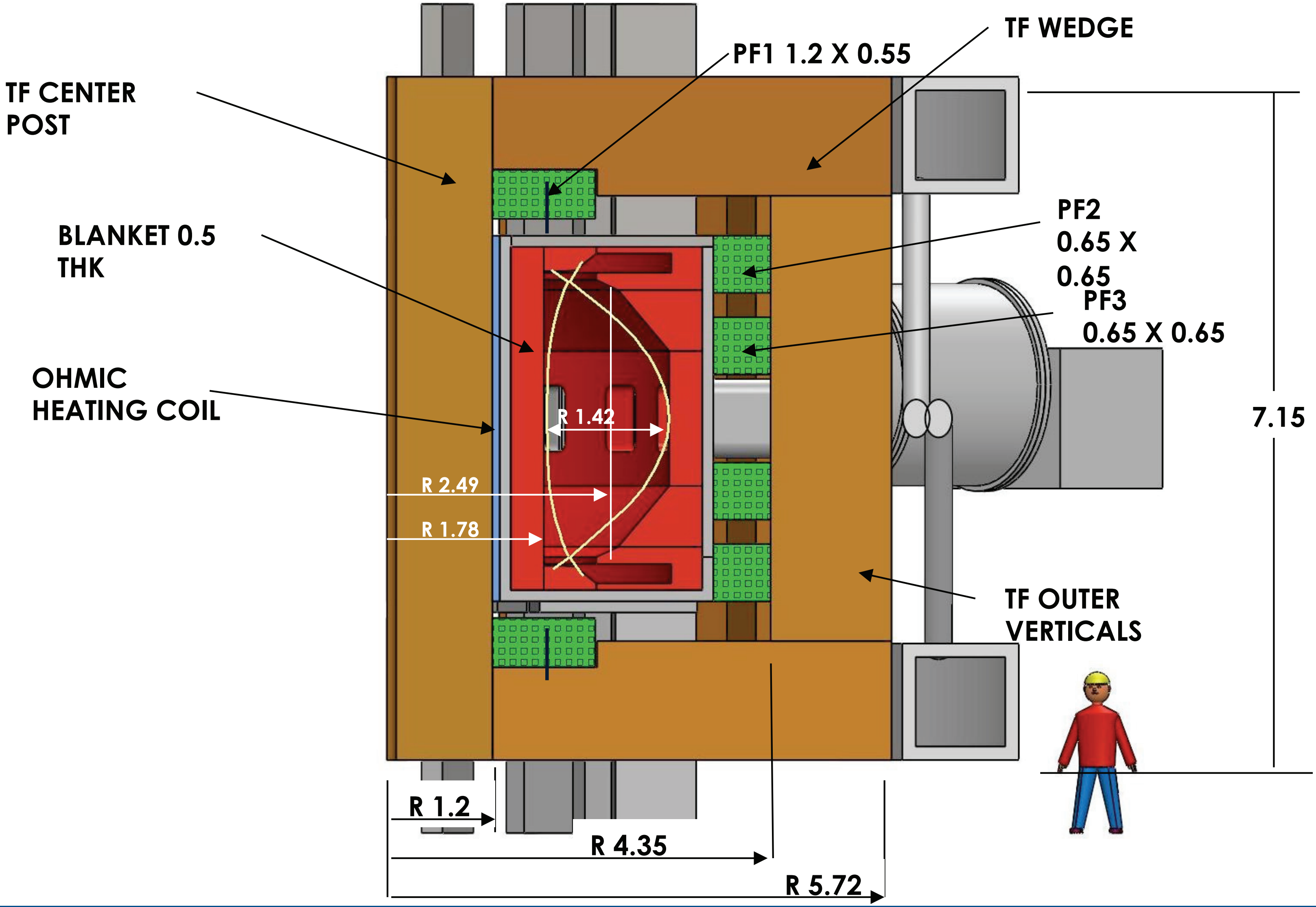
To fill the gap prior to building a fusion demonstration power plant (DEMO), a Fusion Development Facility (FDF) is proposed. As currently configured, FDF is a copper, water cooled coil machine capable of running continuously for several months with the goal to test several blanket configurations in its lifetime. To accommodate multiple changes in blankets, a machine configuration must be chosen that allows for the efficient remote exchange. The TF coil configuration drives the primary maintenance approach decision. A TF coil with joints similar to DIII-D and Alcator CMOD, allow for one maintenance approach while a continuously wound TF coil drives a different approach. The base machine design parameters are described. The different machine configuration options are presented which consider the design aspects for the machine including alignment of the first wall and divertor, coolant access, and exchange of the blanket.

• Supported by GA IR&D funding.

FDF Design Features

- **Steady State Operation**
  - Up to 2 weeks continuous operation
  - Neutron fluence 1-2 MW/m^2
  - Duty factor on yearly basis = 0.3
  - 3-6 $MW\text{-}yr/m^2$ in 10 years
- **Magnets – Water Cooled Copper**
  - Central Solenoid designed for removal and replacement; not a lifetime component
  - TF has copper plate construction with joints
  - PF Coil set has low flat top current requirements to minimize power consumption
- **Tritium Breeding Blankets**
  - Designed for exchange 2-3 times in machine lifetime to test different concepts
  - Tritium breeding ratio >1
  - Provide sufficient shielding to TF and PF coils from material damage (~50 cm)
- **Auxiliary Heating**
  - ECCD
  - Lower Hybrid
  - Neutral Beam

FDF Machine Configuration



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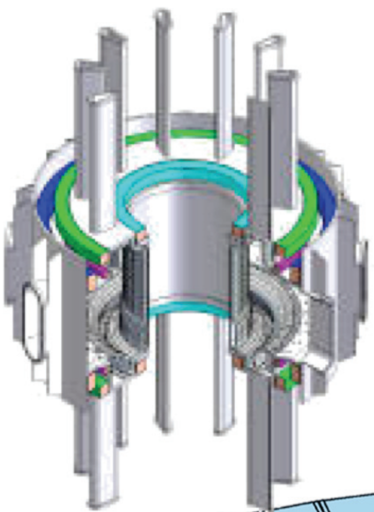
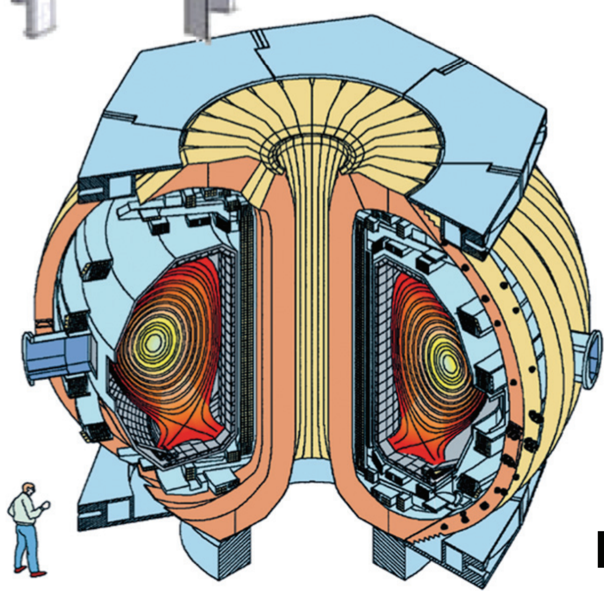
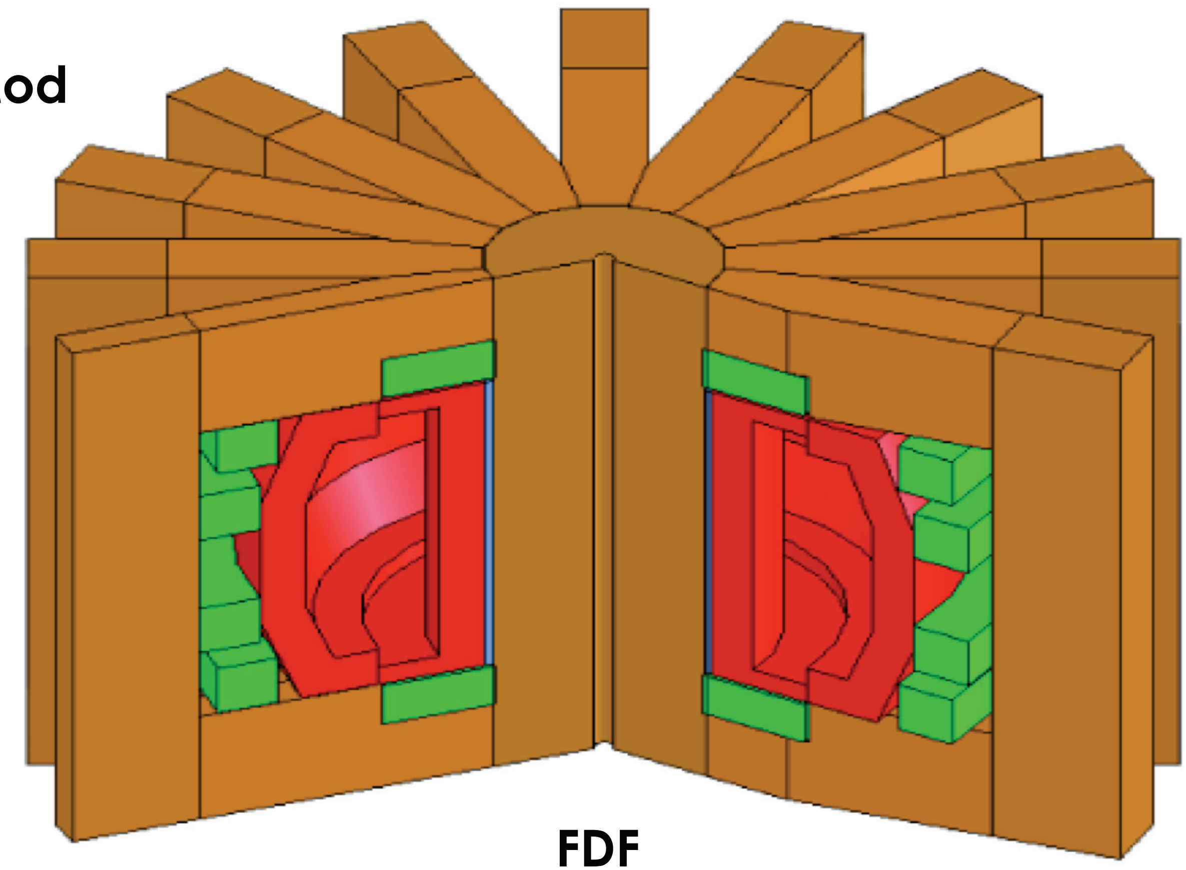
FDF is approximately 50% bigger than DIII-D



Alcator C-Mod



DIII-D



FDF

Device Engineering Optimization

- **Engineering Inputs**
  - Current density in TF central turns (16.7 MA/m^2)
  - Radial build of CS (.085 m)
  - Radial build of TF (1.2m)
  - Resistivity of copper for coils (0.02 μohm-m)
  - Shield thickness = 50 cm
  - Water velocity = 10 m/s
  - TF water temp rise < 50C
  - TF Von Mises stress < 275 MPa
  - OH Stress < 275 MPa
- **Design code optimizes the machine parameters to meet physics requirements to minimize machine size and operating power**

FDF Machine Parameters

Major Radius	2.49 m
Minor Radius	0.71 m
Plasma Elongation	2.31
Aspect Ratio	3.5
Plasma Current	6.7 MA
Triangularity	0.71
Normalized Beta	3.69
Bootstrap Fraction	0.6
Stored Energy	70 MJ
Fusion Power	246 MW
Wall Loading	2MW / m^2
Field on Axis	6 T
Power to Run Plant	507 MW

TF Coil Parameters

Field on axis	6 T
Field at conductor	12.5 T
Power in TF Coils	265 MW
Weight of TF Coils	3917 Tons
Central Column	
Current Density	1.67 kA / cm^2
Avg Axial Stress	119 MPa
Peak Axial Stress	132 MPa
Avg Hoop Stress	-83 MPa
Peak Hoop Stress	-185 MPa
Von Mises Stress	276 MPa *
Delta T (Design)	50 C
No. of Return Legs	12
TF Ripple	2%

* Limiting parameter for device size

PF Coil Parameters

Number of PF Coils	6
Total Power for PF Coils	90 MW
Total Mass of Coils	550 Tons
Current Density	0.8 kA / cm^2
Initial Magnetization Coil Currents	
PF1a*, PF6a*	1.82 MA-turns
PF1b*, PF6b*	1.38 MA-turns
PF2, PF5	0.32 MA-turns
PF3, PF4	0.14 MA-turns
Start of Flat Top Coil Currents	
PF1a*, PF6a*	2.13 MA-turns
PF1b*, PF6b*	1.99 MA-turns
PF2, PF5	-2.81 MA-turns
PF3, PF4	-1.09 MA-turns

* PF1 and PF6 divided into two coils for divertor control

Central Solenoid Coil Parameters

Number of Independent Coils	6
Volt Seconds in Solenoid	25 V-s
Flat Top Power in CS	90 MW
Power at full current	108 MW
Current Density	1.6 kA/cm^2
Initial Magnetization Coil Currents	
CS1, CS6	2.81 MA-turns
CS2, CS5	2.93 MA-turns
CS3, CS4	3.36 MA-turns
Start of Flat Top Coil Currents	
CS1, CS6	-1.11 MA-turns
CS2, CS5	0.58 MA-turns
CS3, CS4	0.31 MA-turns

Flux swing optimized to minimize flat top currents to reduce steady state cooling requirements on central solenoid

TF Coil Design Considerations

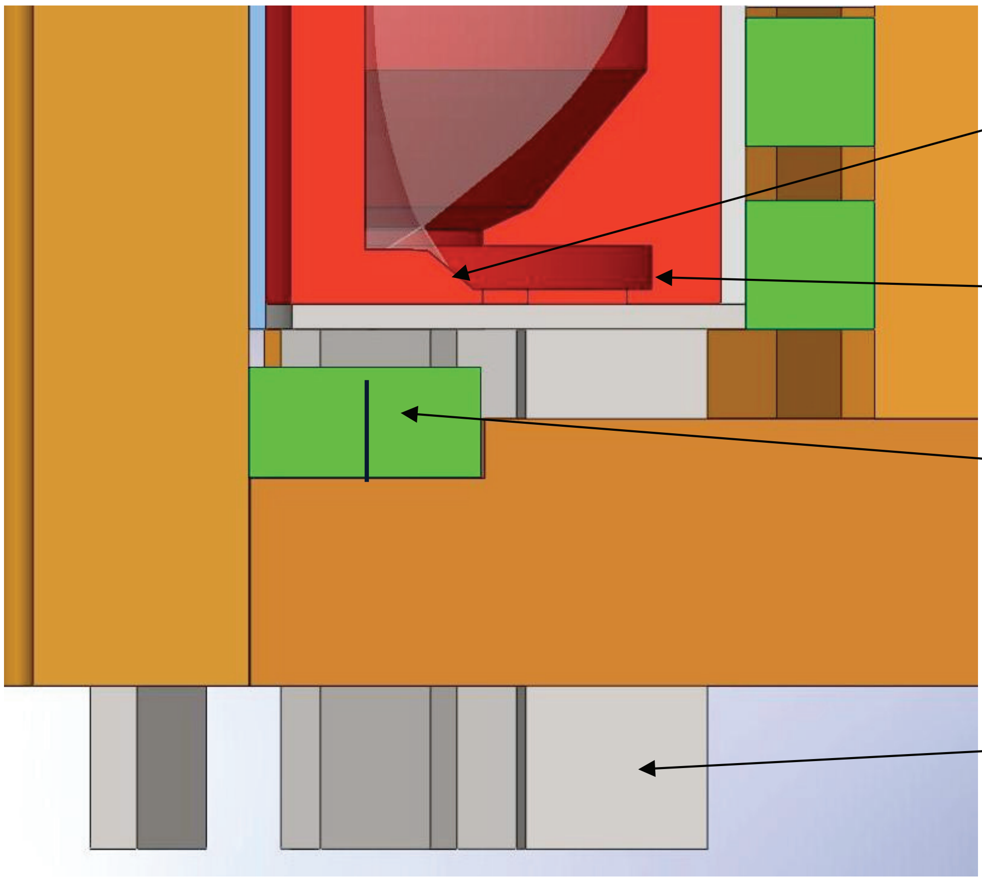
Joints

- **Fixed or Bolted (DIII-D)**
  - Coil connections made through rigid bolted joints that carry much of the loads
  - Large amount of copper required for steady state operation could carry loads
  - Separation or prying open of joints needs to be evaluated
- **Sliding (C-Mod)**
  - No loads transmitted through joints
  - Copper or external structure must carry loads

Insulators

- **Radiation resistance resins required as a minimum**
- **Inorganic insulators might be necessary depending on shield thickness**

Divertor Design



Target plate at 10 degree angle to field line to spread SOL power

Pumping ducts for outboard leg pumping

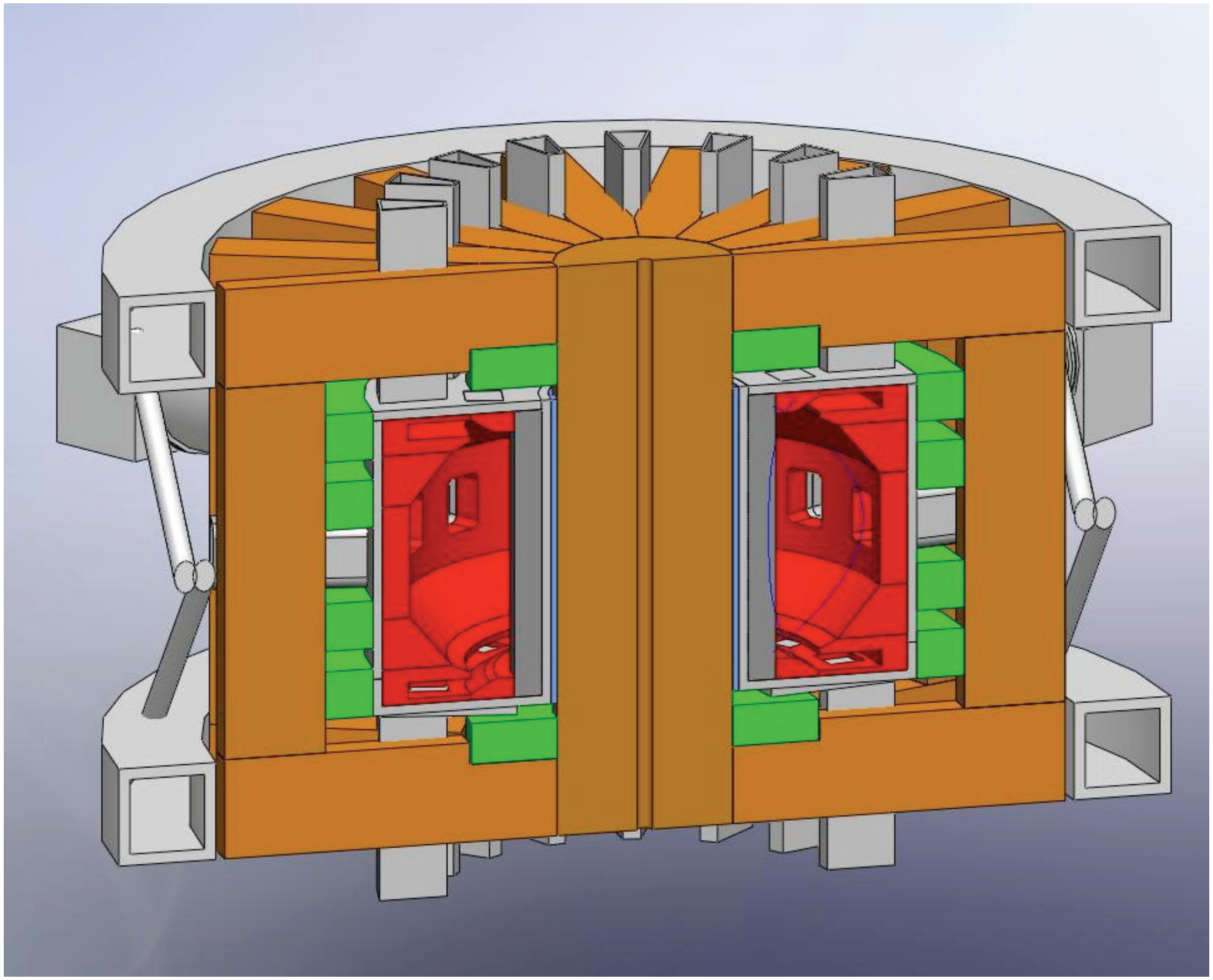
Divertor shaping coil with two independently controlled modules

Pumping ports to provide steady state particle control

Machine Maintenance Goal to Exchange Blanket 2-3 Times in Lifetime

- To achieve the maintenance goal of replacing the blanket approaches to maintenance focus on handling large components
- Vertical lifts are simplest method to move heavy components
- Tritium containment is critical design factor requiring either casks to transport components or exposing tokamak hall to tritium
- The disconnection and reconnection of fluid and electrical connections required for maintenance is a significant fraction of machine disassembly/assembly regardless of concept. Methods of simplifying these connections are critical to minimizing maintenance downtime.
- Access for plumbing to various components to be considered in design of machine

Toroidally Continuous Ring Blanket Machine Concept



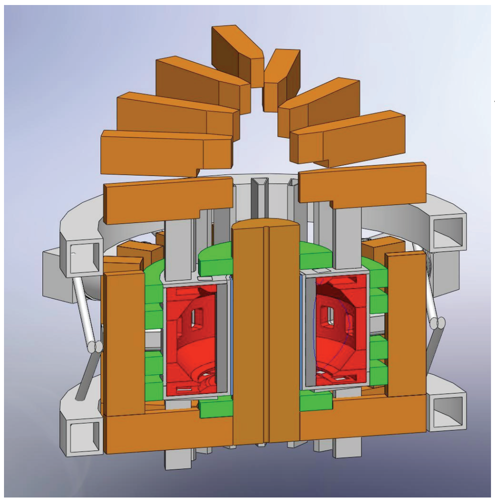
Toroidally Continuous Ring Blanket Machine Concept

- **Features**
  - Blanket removal achieved with vertical motions
  - Tritium containment achieved through use of casks
  - Maximum lift required ~ 70 tonnes

- **Advantages**
  - Toroidal alignment of PFCs assured with continuous rings, reducing peak power due to edges
  - Strong internal structures for EM and disruption loads

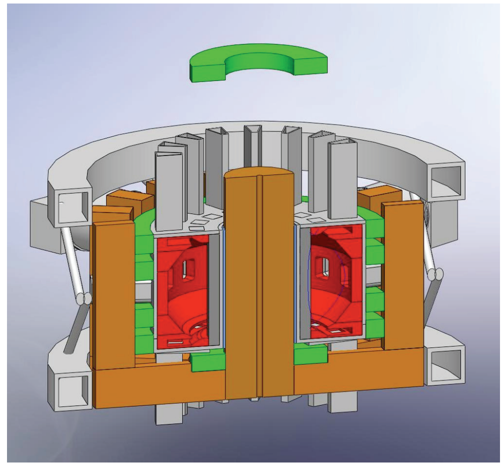
- **Disadvantages**
  - Access for lower module coolants likely through upper modules
  - Local repairs made through inside or disassembling large portions of the machine

Disassembly Steps for Ring Concept

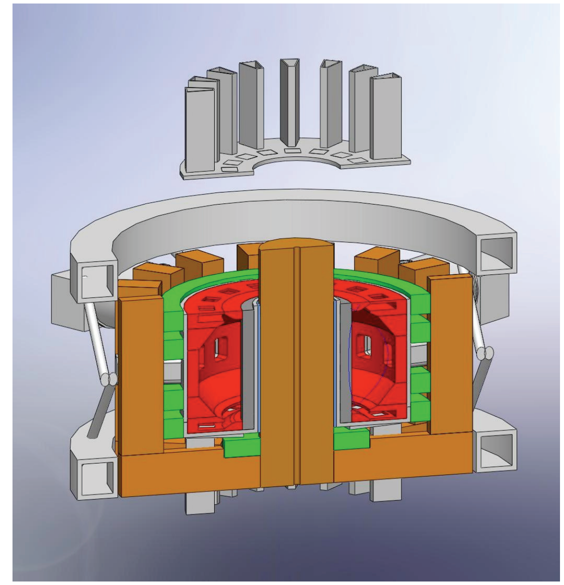


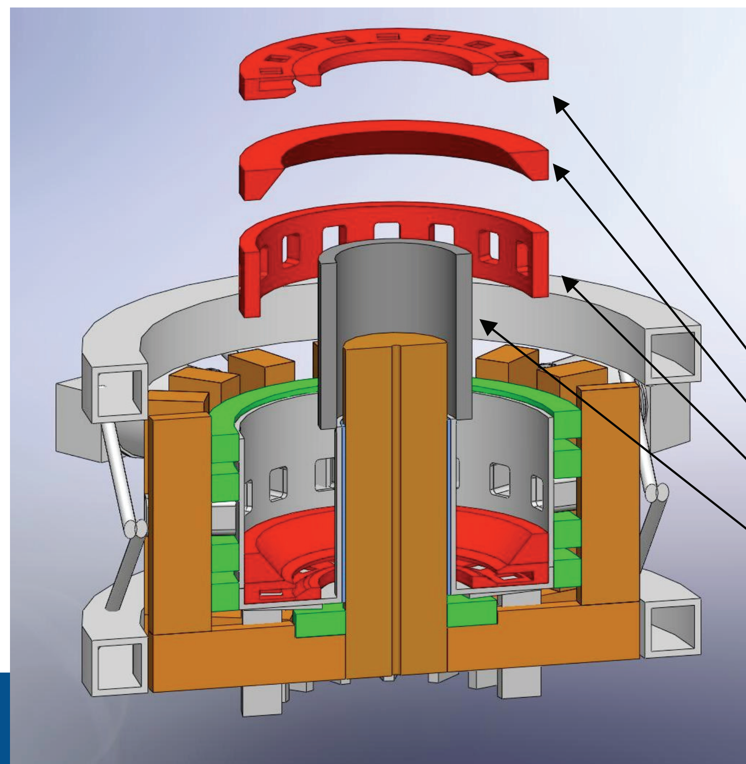
TF Wedges
(44 tonnes each)

Divertor Coil (65 tonnes)



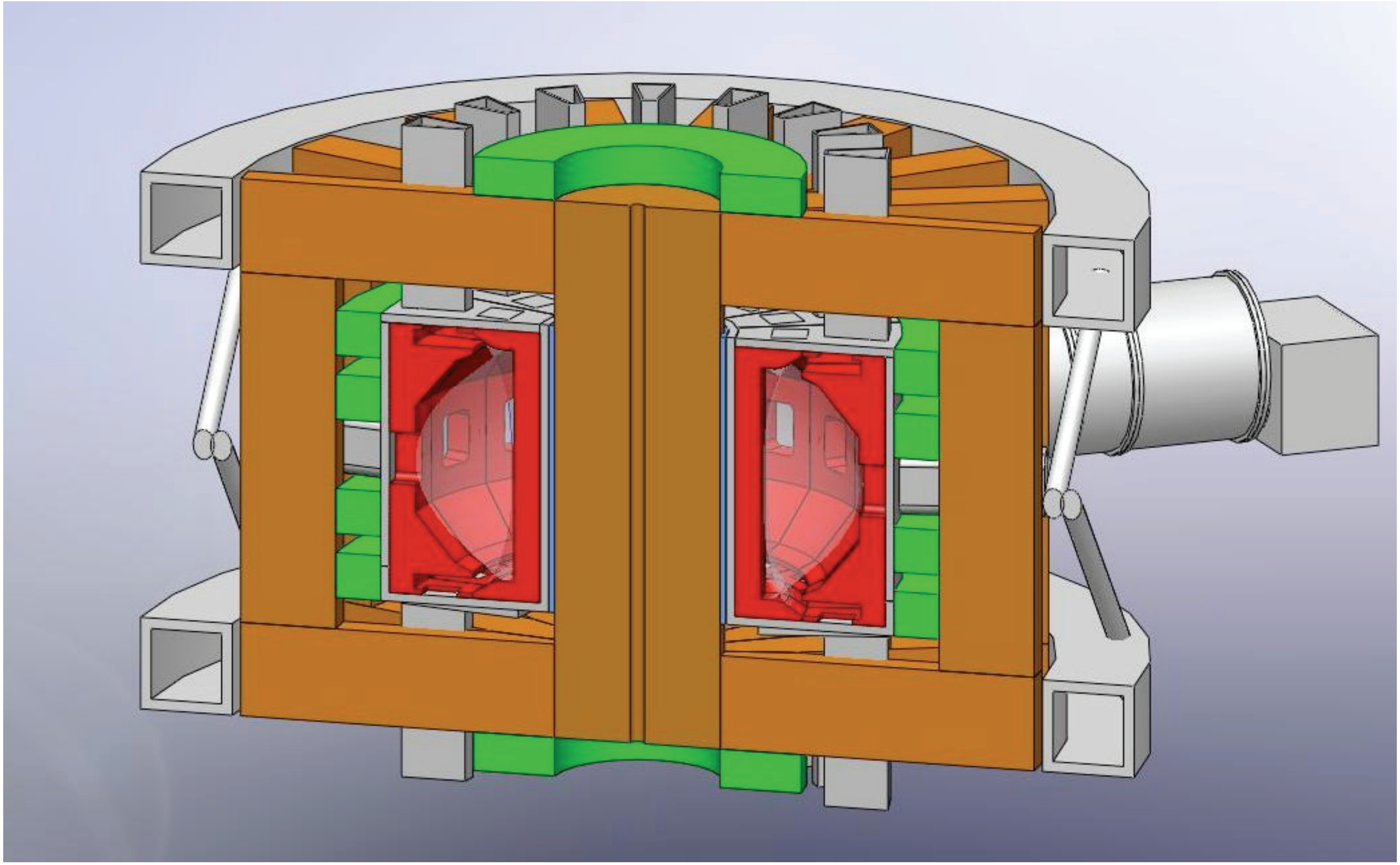
Vacuum Vessel Top (66 tonnes)





Divertor Module (35 tonnes)
Outer Module (37 tonnes)
Equitorial Module (38 Tonnes)
Inner Wall Module (60 tonnes)

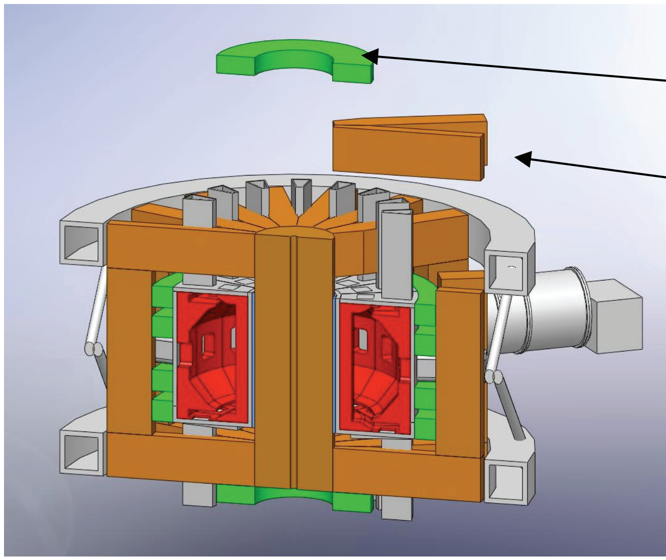
Wedge Blanket Maintenance Machine Concept



Wedge Blanket Maintenance Machine Concept

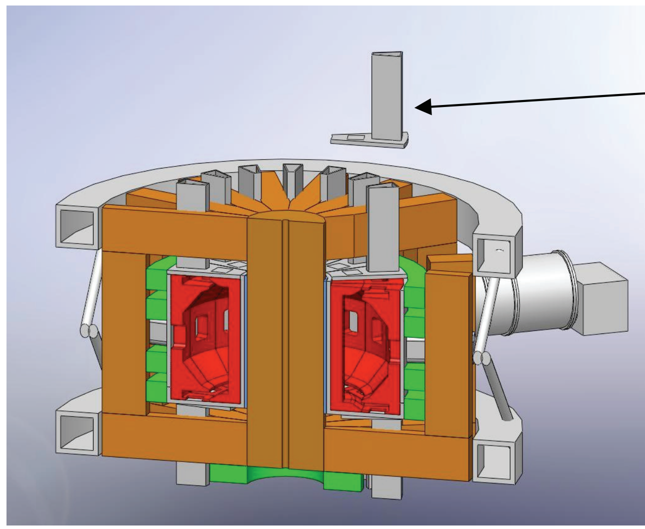
- **Features**
  - Divertor control coil mounted outside TF reducing its effectiveness
  - "orange slice" segments of blanket removed for repair or replacement
  - Tritium containment achieved through use of casks
  - Maximum lift required ~ 70 tonnes
- **Advantages**
  - Less disassembly required for replacement of single module failure
  - Coolant for each module is achieved with top coolant connection
  - Different blanket types could be tested for same poloidal flux at a different toroidal location to compare performance
- **Disadvantages**
  - Alignment of different modules is not guaranteed

Disassembly Steps for Wedge Maintenance Concept

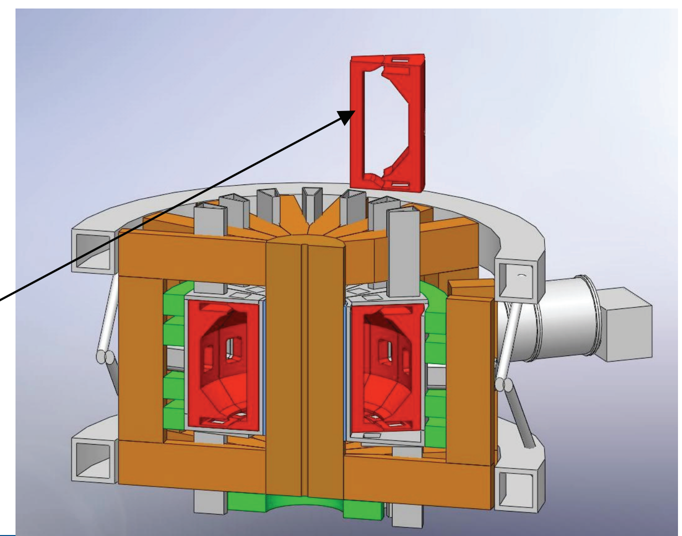


Divertor coil (65 tonnes)

TF upper sections (2wedges x44 tonnes each)



Wedge section of vacuum vessel top (4 tonnes)



Remove blanket section (15 tonnes)