FIRE
Vacuum Vessel
and
Remote Handling
Overview

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Snowmass
July 13, 2002

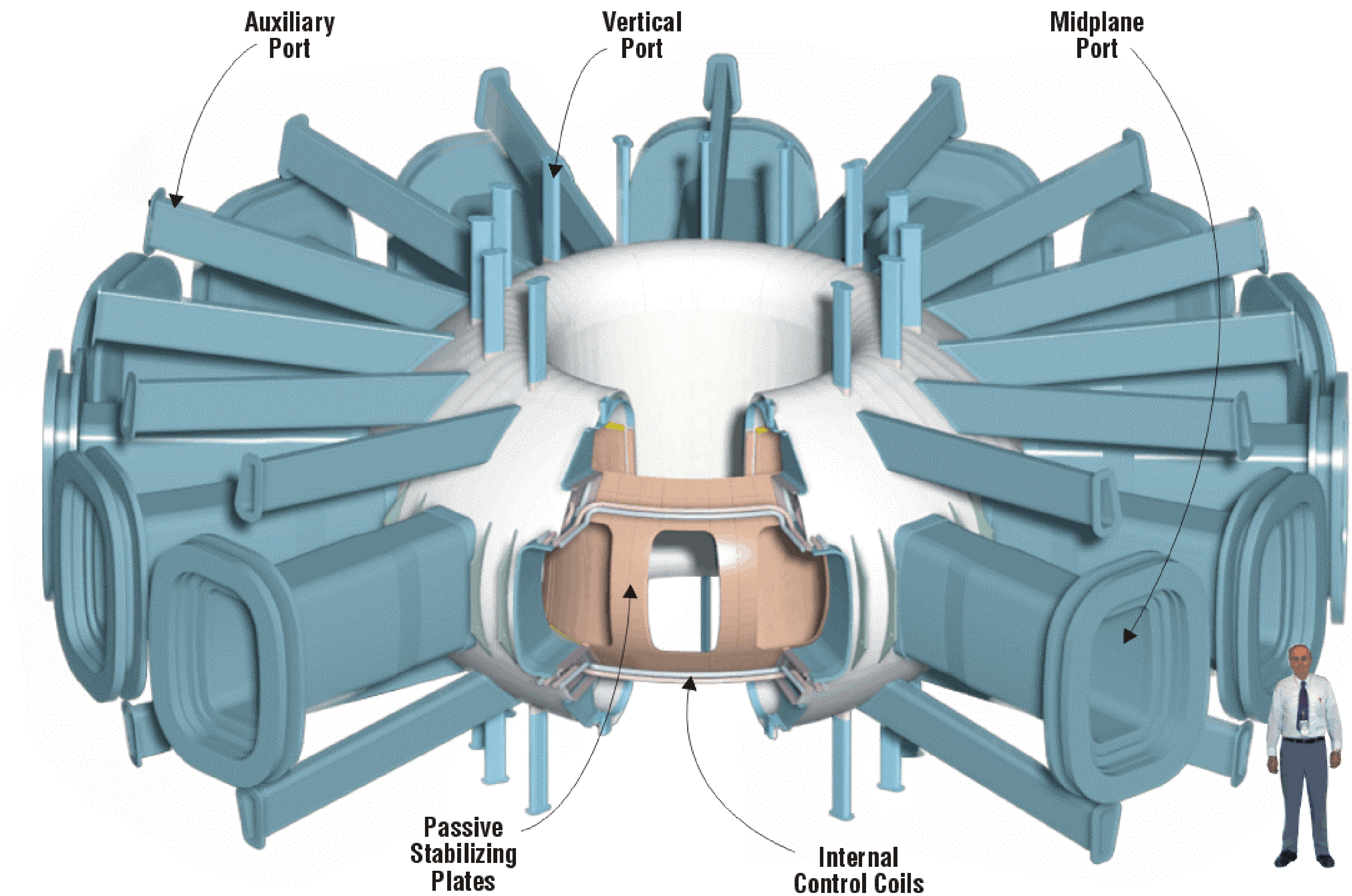
Presentation Outline

- **Vacuum Vessel**
  - Design requirements
  - Design concept and features
  - Analysis to date
  - Status and summary

- **Remote Handling**
  - Maintenance Approach & Component Classification
  - In-Vessel Transporter
  - Component Replacement Time Estimates
  - Balance of RH Equipment

- ***Design and analysis are consistent with pre-conceptual phase, but demonstrate basic feasibility of concepts***

FIRE vacuum vessel



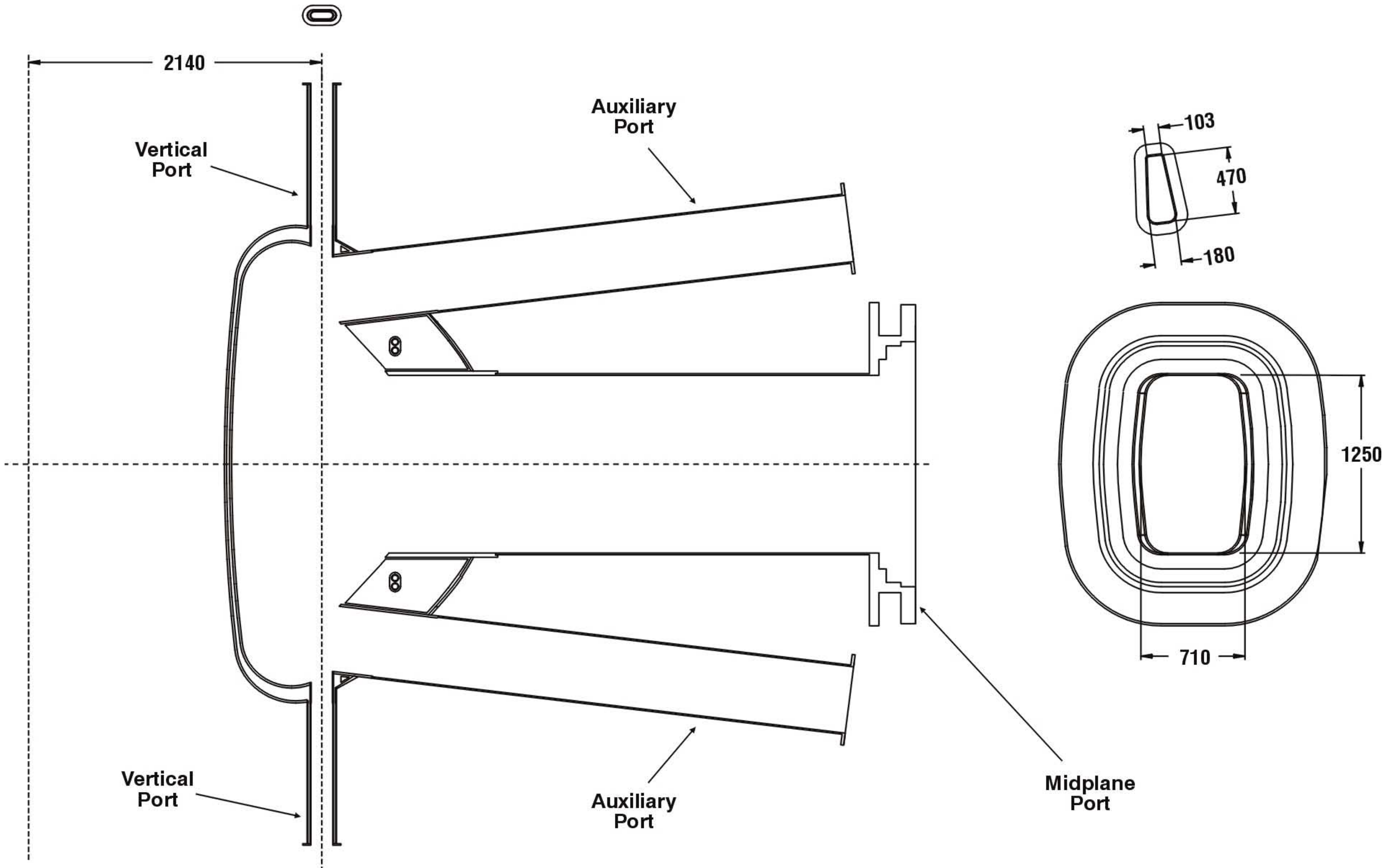
Vacuum vessel functions

- **Plasma vacuum environment**
- **Primary tritium confinement boundary**
- **Support for in-vessel components**
- **Radiation shielding**
- **Aid in plasma stabilization**
  - conducting shell
  - internal control coils
- **Maximum access for heating/diagnostics**

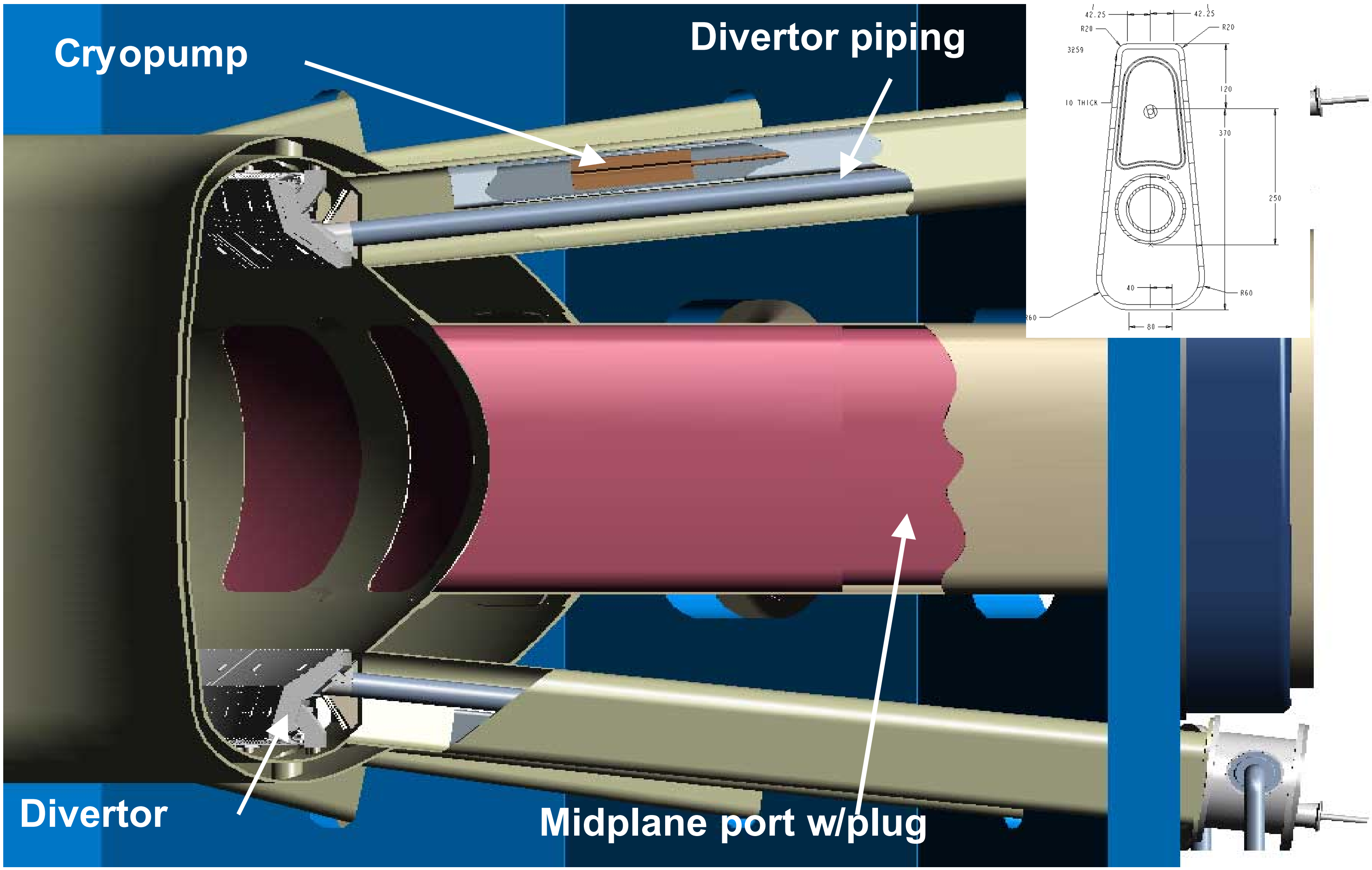
Vacuum vessel parameters

• **Configuration:**	Double wall torus
– Shielding	water + steel with 60% packing factor
– Volume of torus interior	53 m^3
– Surface Area of torus interior	112 m^2
– Facesheet thickness	15 mm
– Rib thickness	15 - 30 mm
– Weight of structure, incl ports	65 tonnes
– Weight of torus shielding	100 tonnes
• **Coolant**	
– Normal Operation	Water, < 100C, < 1 Mpa
– Bake-out	Water ~150C, < 1 Mpa
• **Materials**	
– Torus, ports and structure	316LN ss
– Shielding	304L ss (tentative)

Vessel port configuration

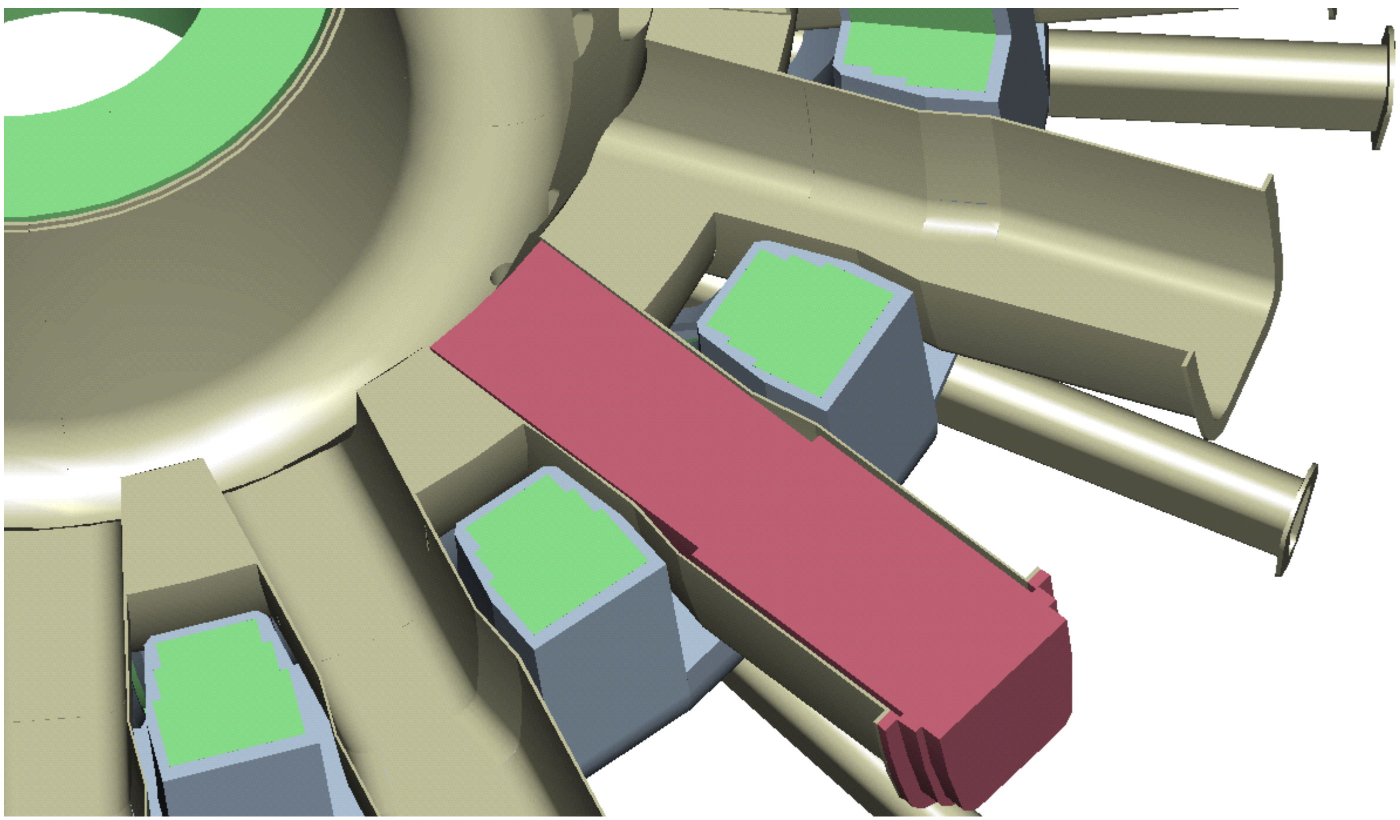


Vessel ports and major components



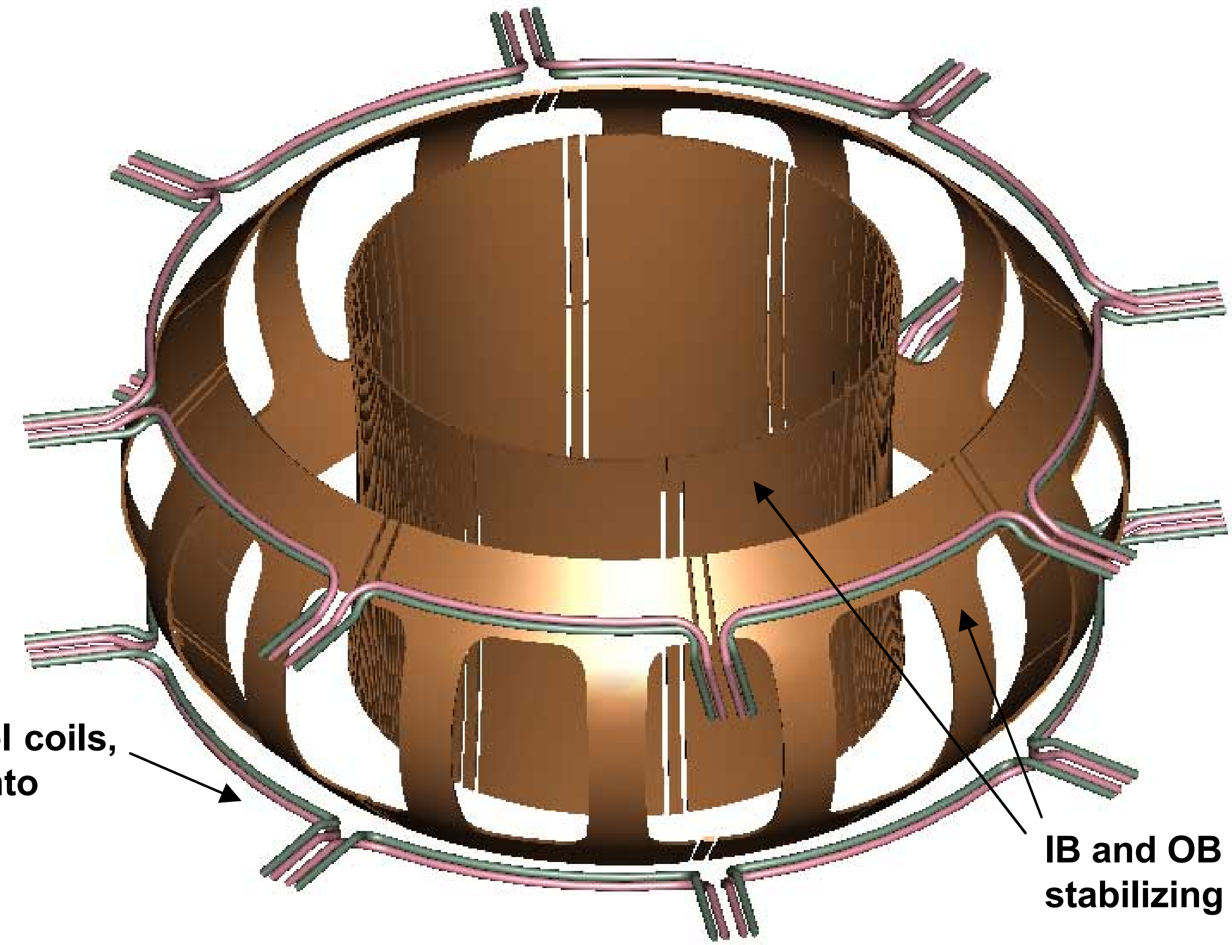
Nuclear shielding concept

- Vessel shielding, port plugs and TF coils provide hands-on access to port flanges
- Port plugs weigh ~7 tonnes each as shown, assuming 60% steel out to TF boundary



Active and passive stabilizing sys.

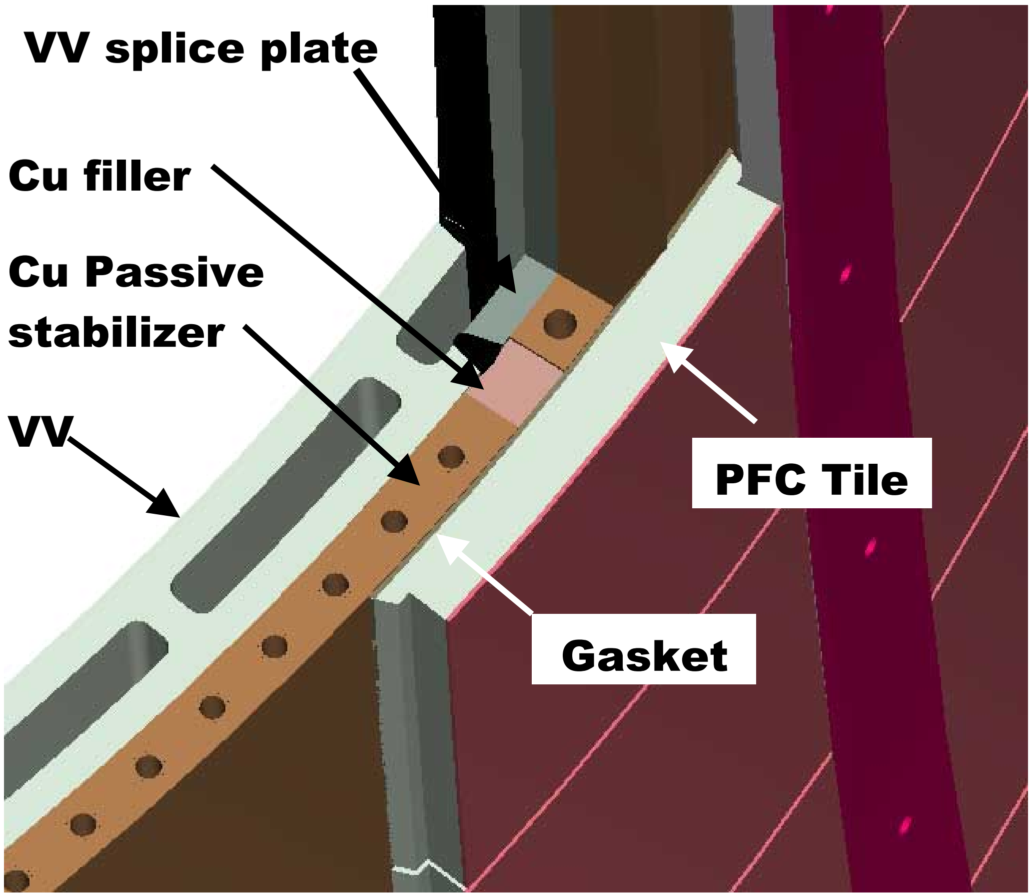
- **passive plates ~25 mm thick copper with integral cooling**



Active control coils, segmented into octants

IB and OB passive stabilizing conductor

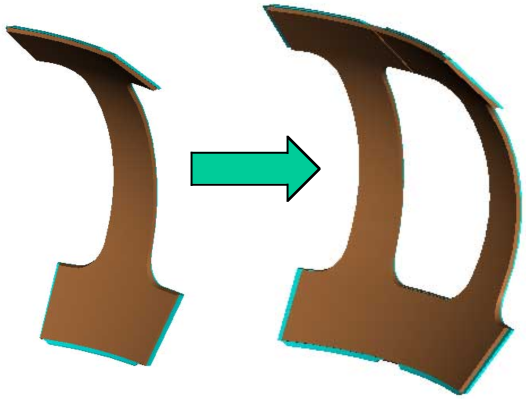
Passive conductor is also heat sink

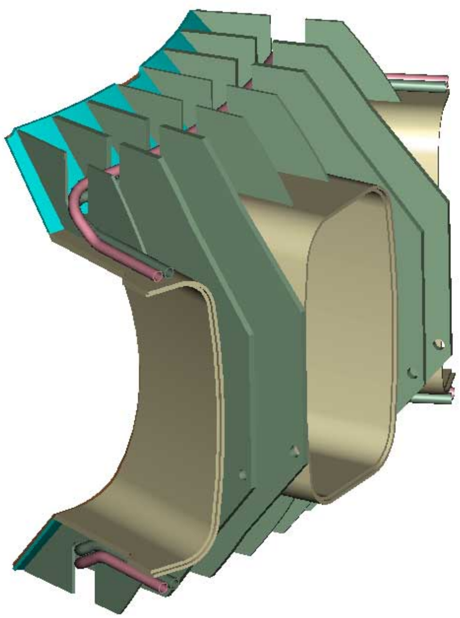


- **Copper layer required to prevent large temperature gradients in VV due to nuclear heating, PFCs**
- **Passive plates are required in most locations anyway**
- **PFCs are conduction cooled to copper layer**
  - Reduces gradient in stainless skin
  - Extends pulse length

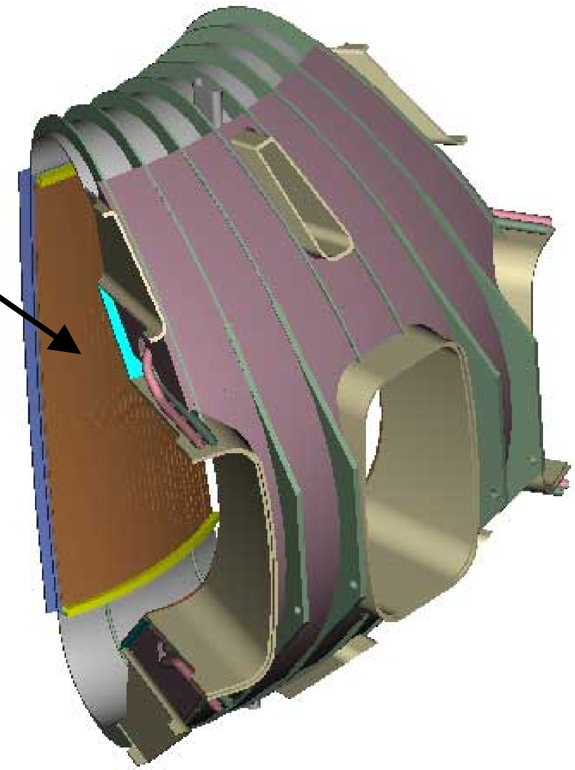
VV octant subassy w/passive structure

Outboard passive conductor





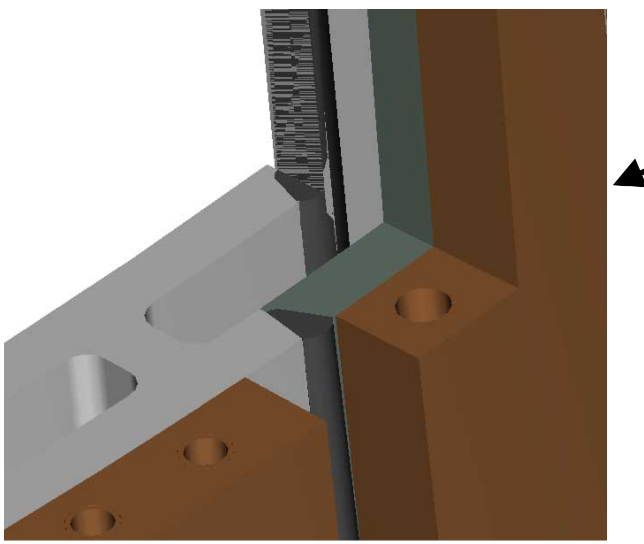
Inboard passive cond.

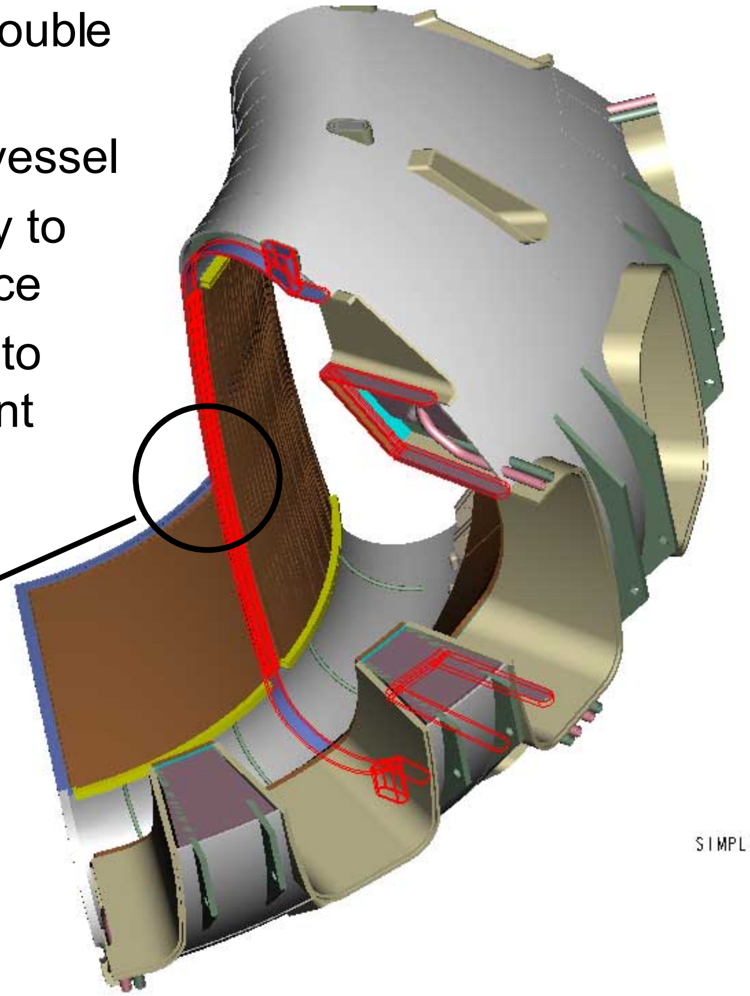


Vessel octant prior to welding outer skin between ribs

Vessel octant subassembly fab. (3)

- Octant-to-octant splice joint requires double wall weld
- All welding done from plasma side of vessel
- Splice plates used on plasma side only to take up tolerance and provide clearance
- Plasma side splice plate wide enough to accommodate welding the coil side joint





Vessel analysis

- **Vessel subjected to numerous loading conditions**
  - Normal operation (gravity, coolant pressure, thermal loads, etc.)
  - Disruption (including induced and conductive (halo) loads
  - Other loads (TF current ramp, seismic, etc.)
- **Preliminary FEA analysis performed**
  - Linear, static stress analysis
  - Linear, transient and static thermal analyses
- **Main issues are disruption loads, thermal stresses**

Vacuum vessel mechanical loads

Load	Value	Comment
Gravity load	~3.5 MN	VV ~130 tons, FW,div. ~35 tons, port plugs ~ 185 tons
Vertical displacement event (VDE) load		
Vertical	16 - 32 MN	Based on J. Wesley guidance [1]
Lateral, net	6 - 11 MN	
Seismic load (assumed)		
Vertical acceleration	0.2 g	
Lateral acceleration	0.2 g	
Maximum total vertical load	~22-42 MN	Gravity + VDE * 1.2 (dyn load factor)
Maximum total lateral load	~8-14 MN	VDE * 1.2 (dyn load factor)
Maximum local EM load		Rough estimate from halo currents
Local pressure on vacuum vessel from internal components	~4-7 MPa	with peaking factor up to 0.75 Ip
EM load from TF ramp	~0.75 MPa	Poloidal conductivity of vessel increased due to Cu stabilizers
Coolant pressure		
Normal operation	<10 atm	
Bakeout	<10 atm	

[1] Disruption loads per Wesley, based on 10T, 50% halo current or 12 T, 40% halo current

Disruption effects on VV

- **Disruptions will cause high loads on the VV due to induced currents and conducting (halo) currents flowing in structures**
  - Direct loads on vessel shell and ribs
  - Direct loads on passive plates
  - Reaction loads at supports for internal components
  - Divertor assemblies and piping
  - FW tiles
  - Port plugs / in-port components (e.g. RF antennas)

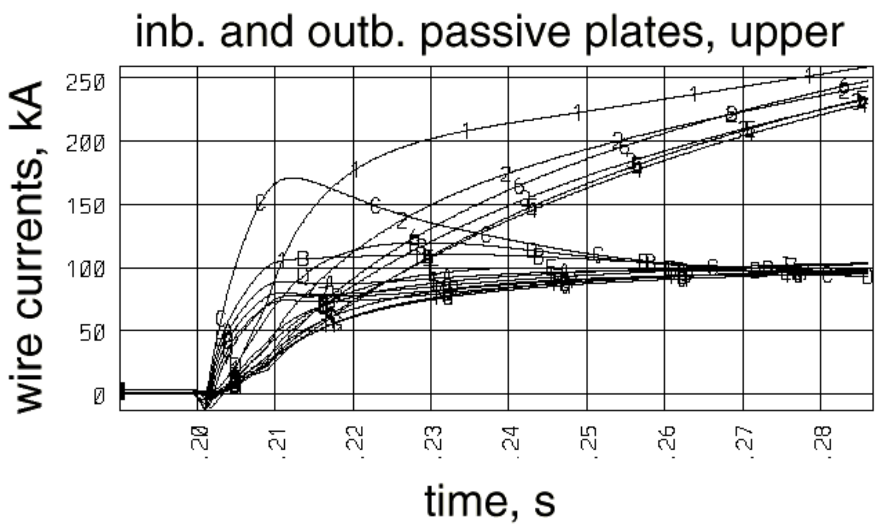
- **Dynamic effects should be considered, including:**
  - Transient load application
  - Shock loads due to gaps in load paths (gaps must be avoided)

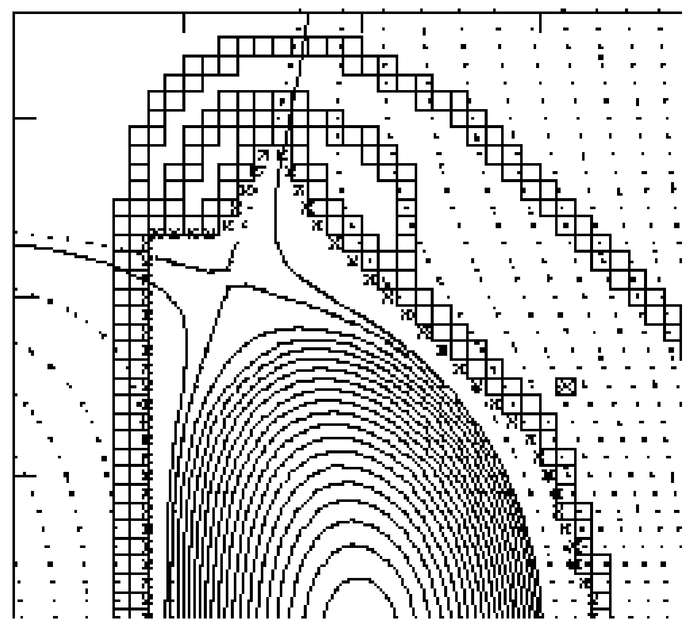
- **All loads should be considered in appropriate combinations**

  e.g. Gravity + coolant pressure + VDE + nuclear / PFC heating + Seismic + …

TSC runs confirm induced currents will concentrate in passive structures

- **Several TSC disruption simulations prepared by C. Kessel**
- **Centered disruption induces 5 MA in passive plates (out of 6.5)**

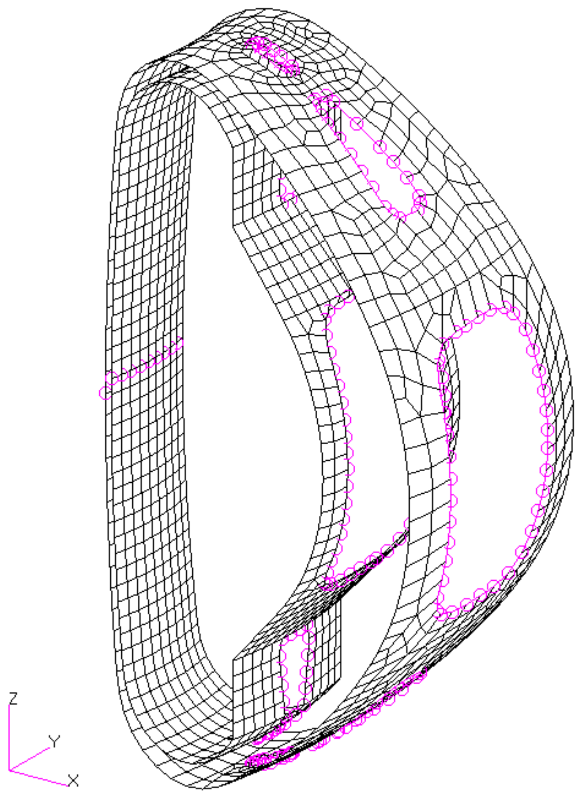




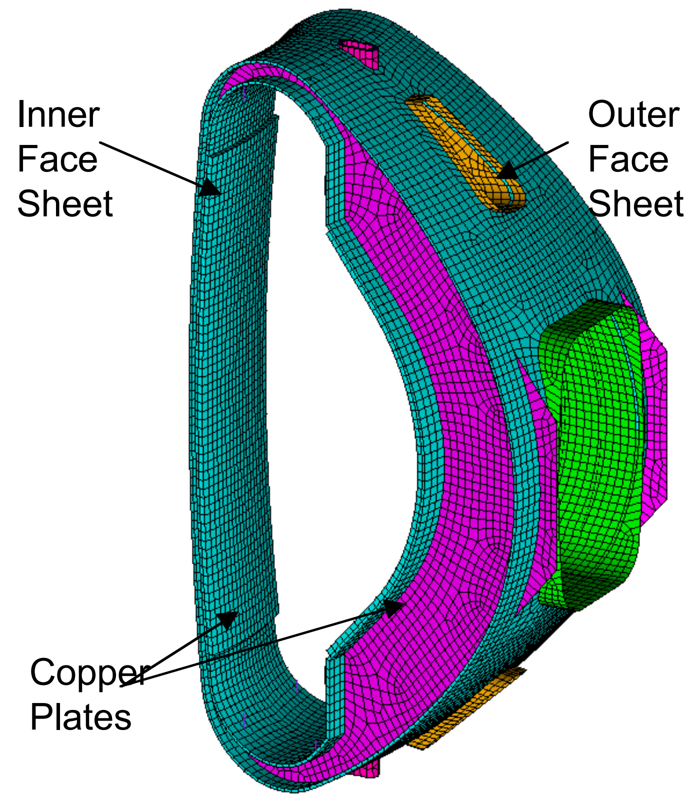
- **VDE simulation used as basis for further analysis**

VDE analysis based on TSC runs

- **TSC output used to create drivers for Eddycuff model of VV**
- **Peak loads applied to ANSYS model of VV**
- **Halo loads from TSC mapped directly onto VV model**

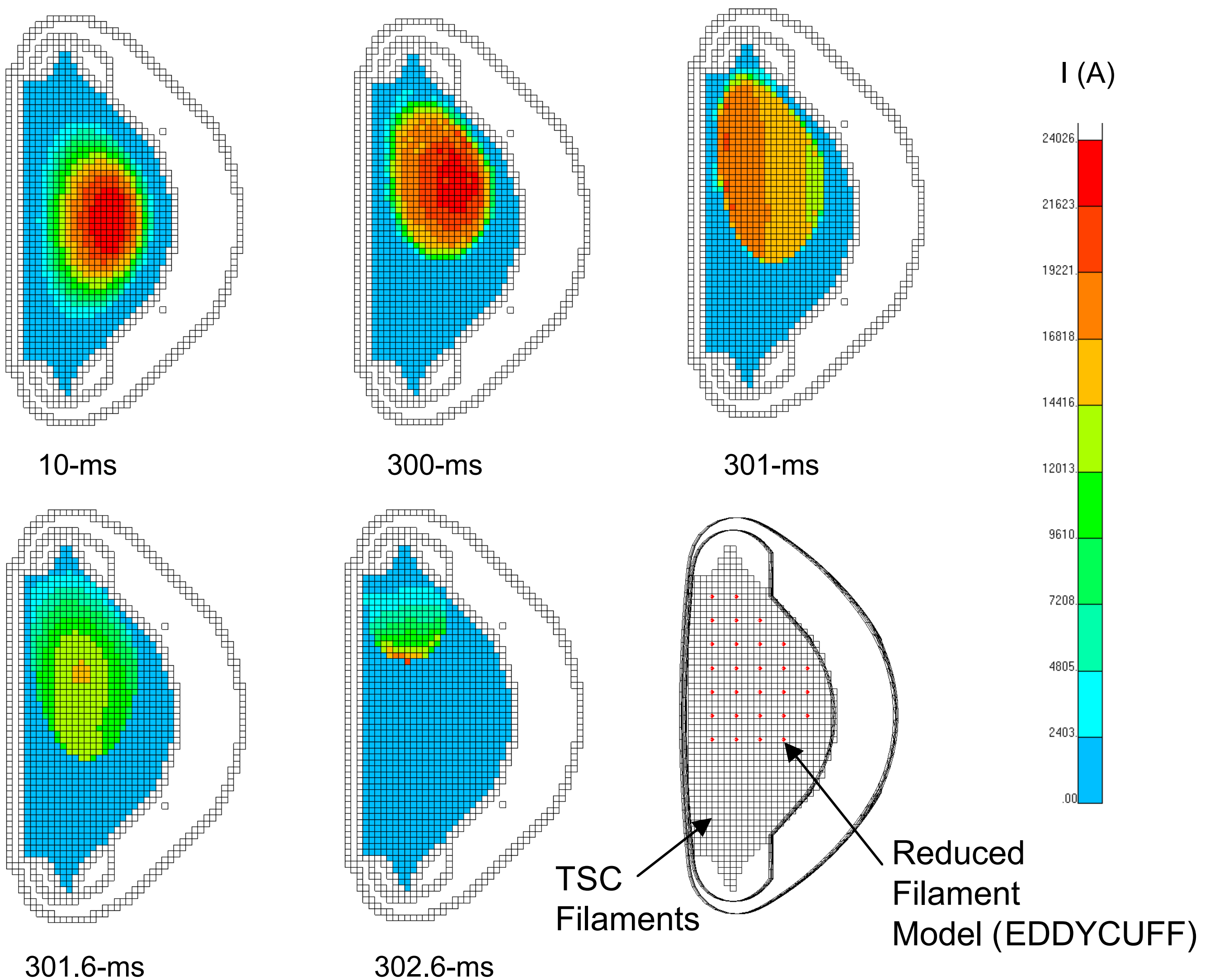


EDDYCUFF EM Model

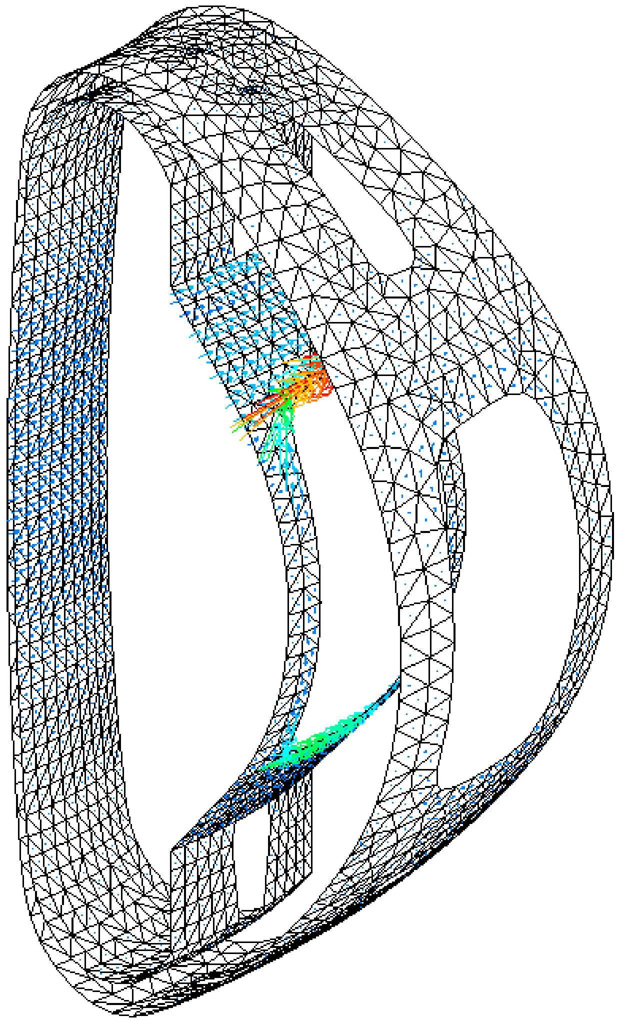


ANSYS Structural Model

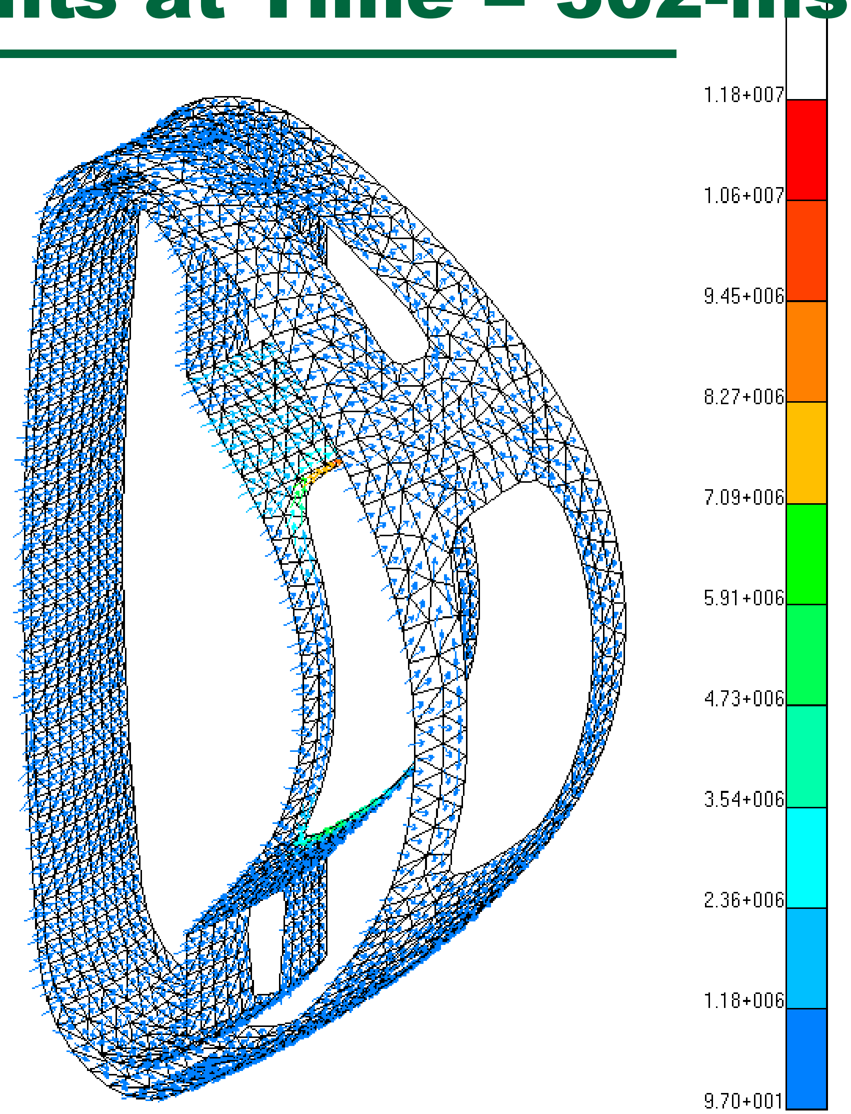
Plasma Evolution (TSC)



Induced Eddy Currents at Time = 302-ms

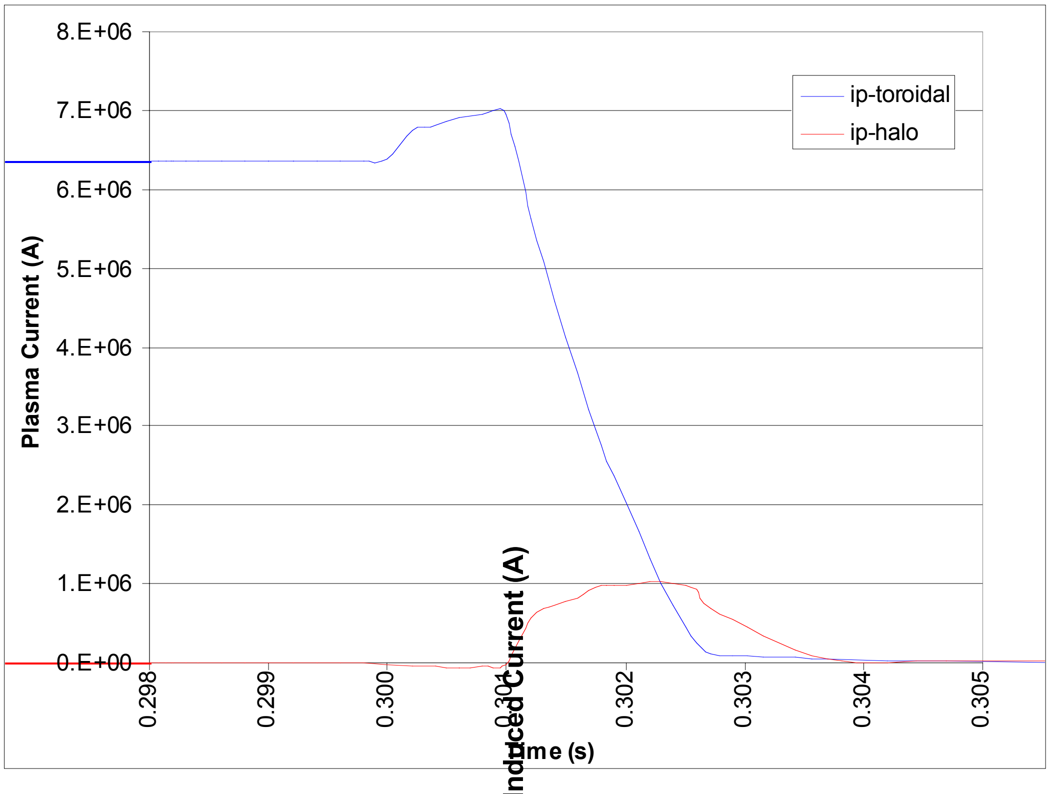


Proportional Current Vectors

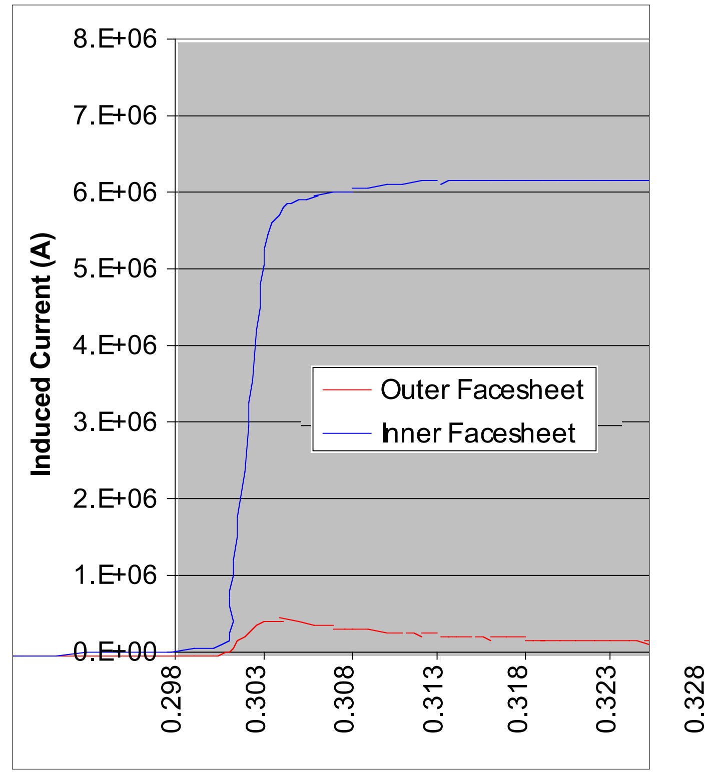


Constant Current Vectors

Current vs Time



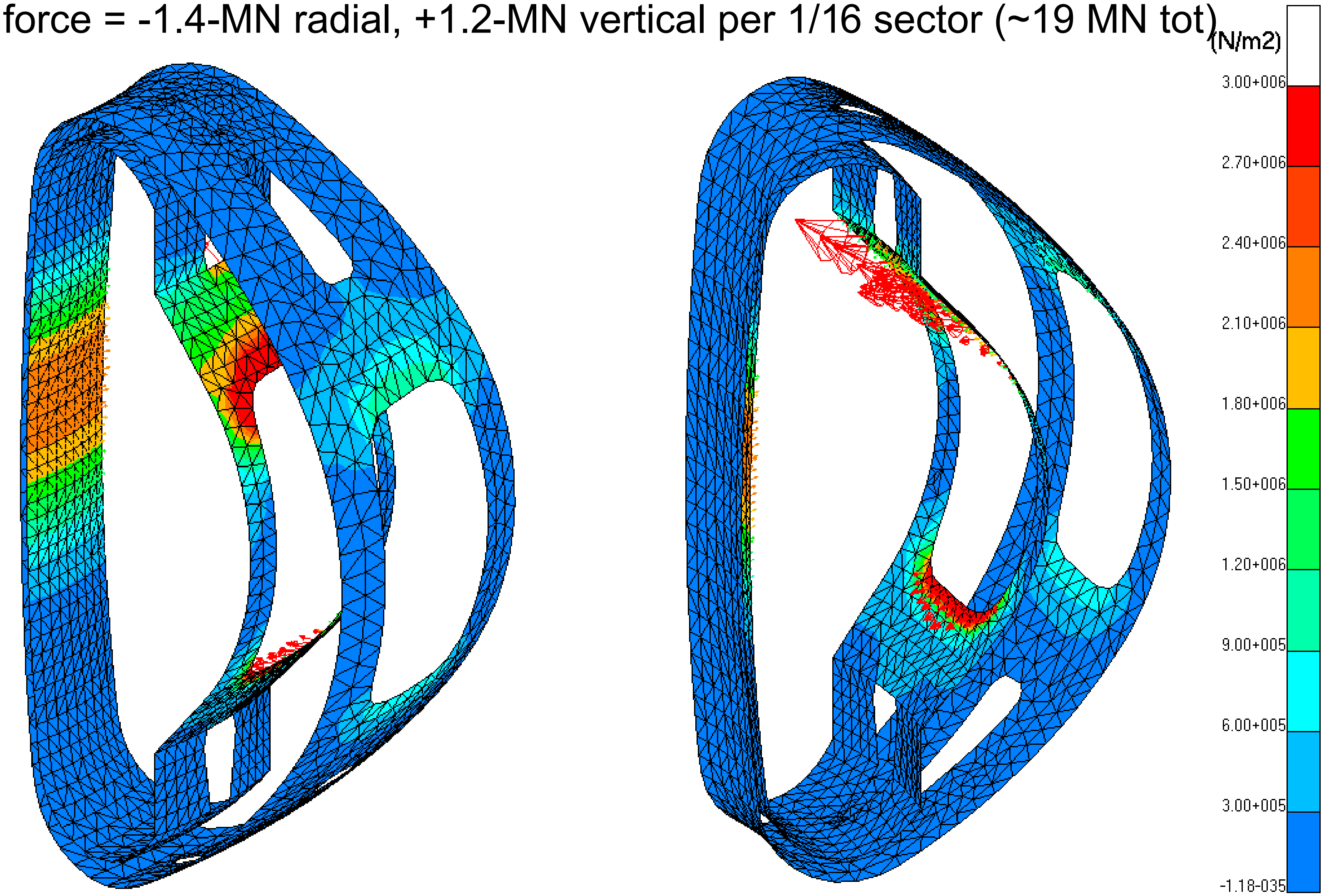
Plasma Current



Induced Vessel Current

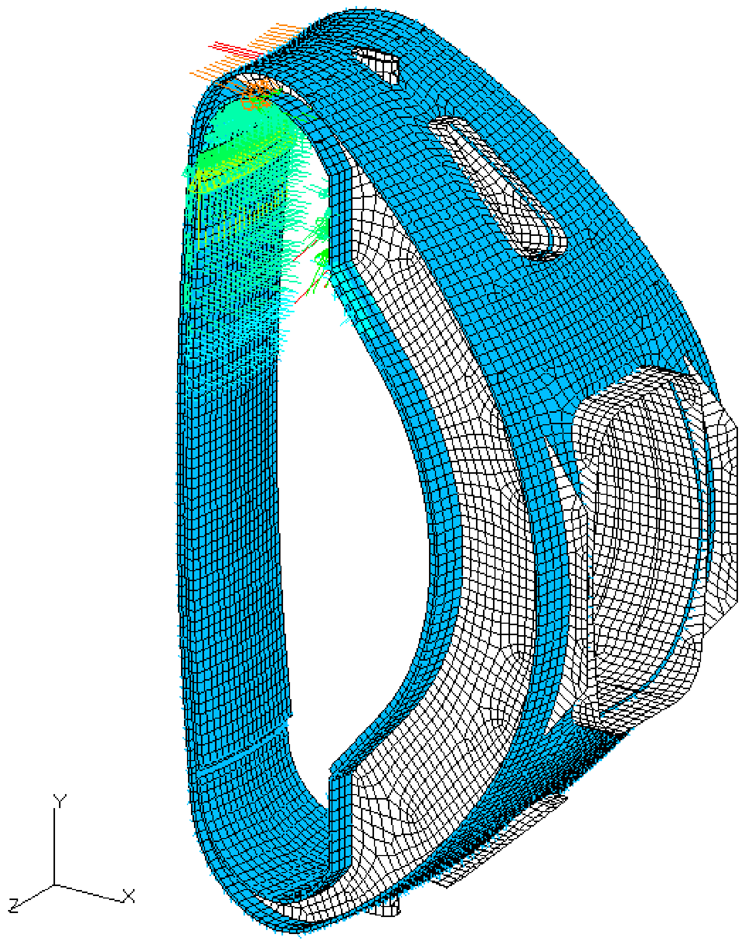
EM Pressure due to Induced Tor. Current

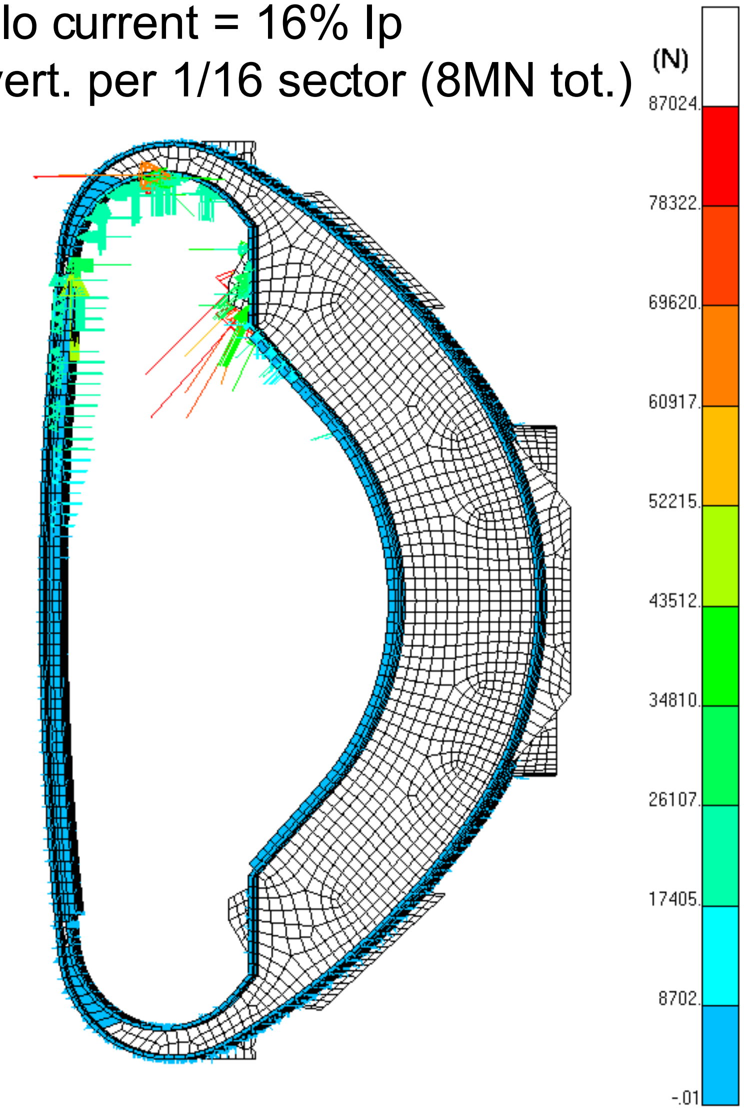
- Max force = -1.4-MN radial, +1.2-MN vertical per 1/16 sector (~19 MN tot)



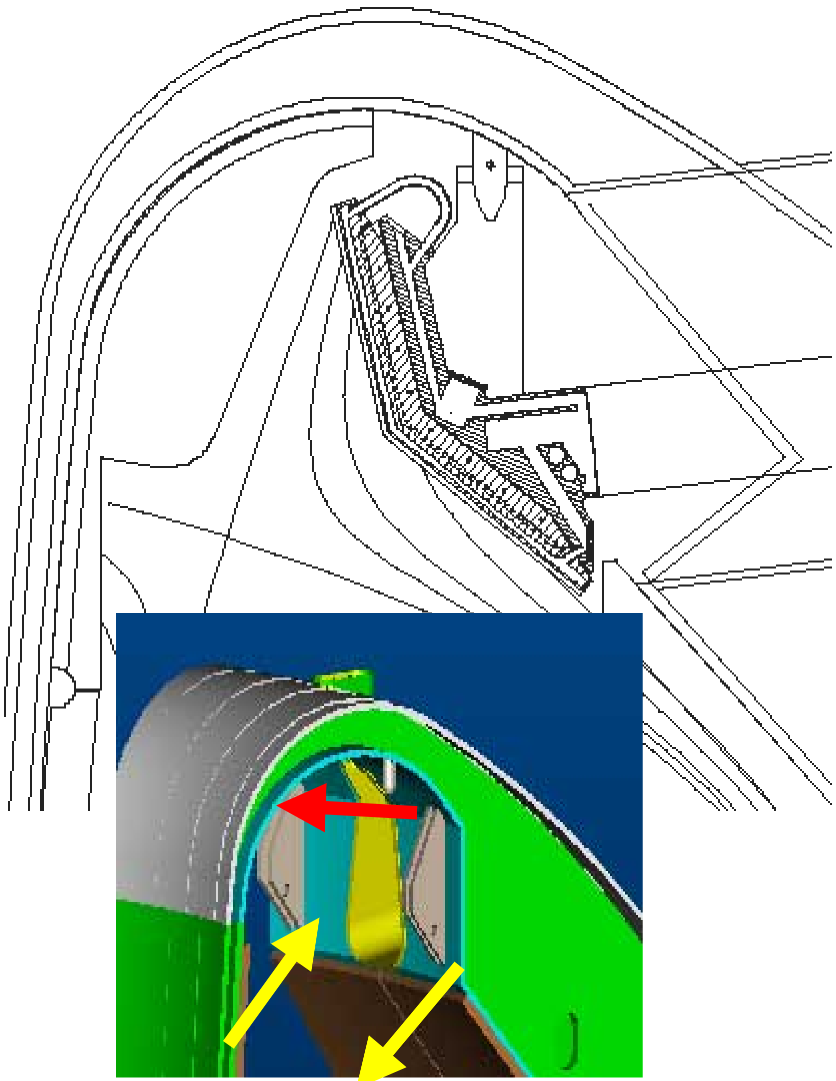
EM Forces due to Halo Current

- Mapped directly from TSC to ANSYS, Halo current = 16% Ip
- Max force = -0.24-MN radial, +0.48-MN vert. per 1/16 sector (8MN tot.)

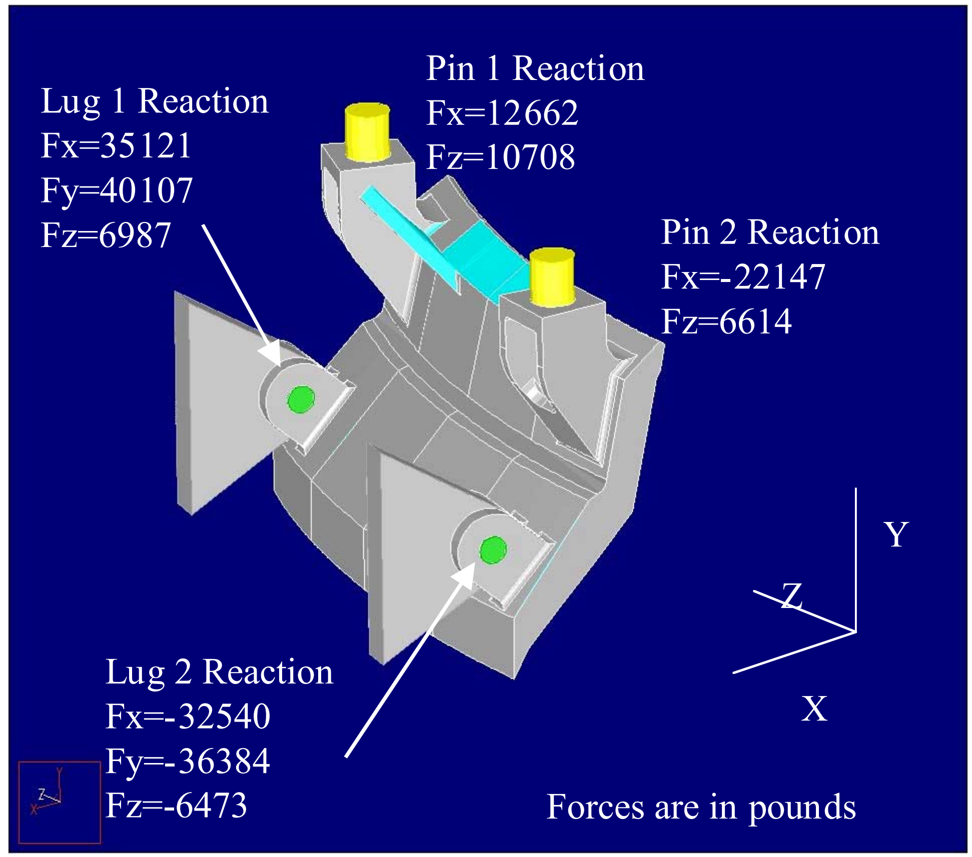




Divertor loads from current loop



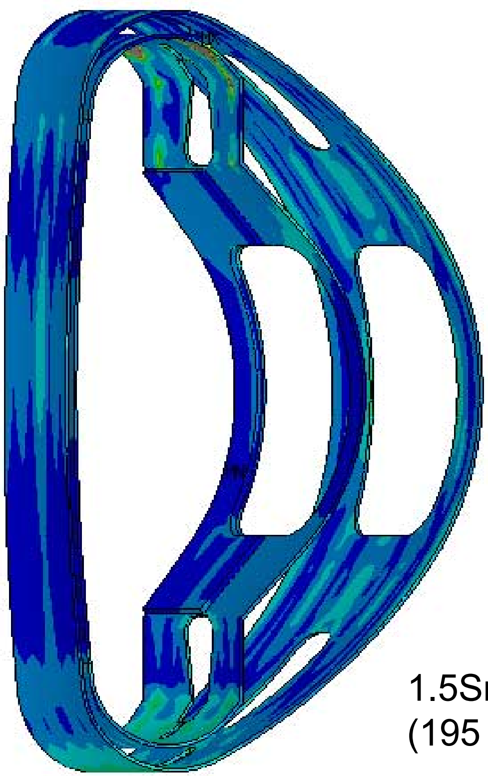
- **Loads based on PC-Opera analysis** **ref Driemeyer, Ulrickson*

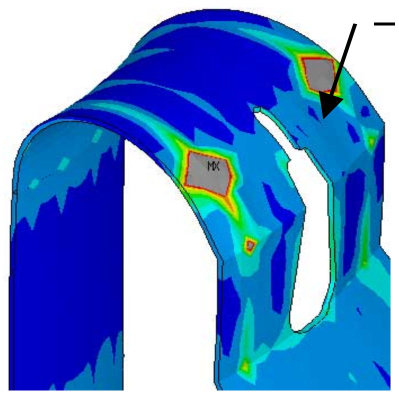


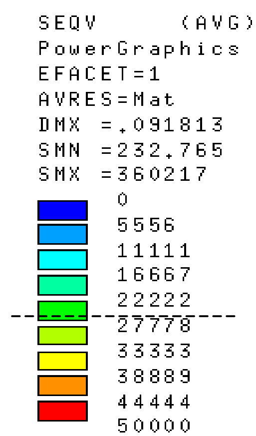
Combined stress, with VDE

- **Stresses due to gravity, coolant pressure, vacuum, VDE**
- **VDE load includes direct EM loads on vessel (induced current and halo) and non-halo divertor loads**

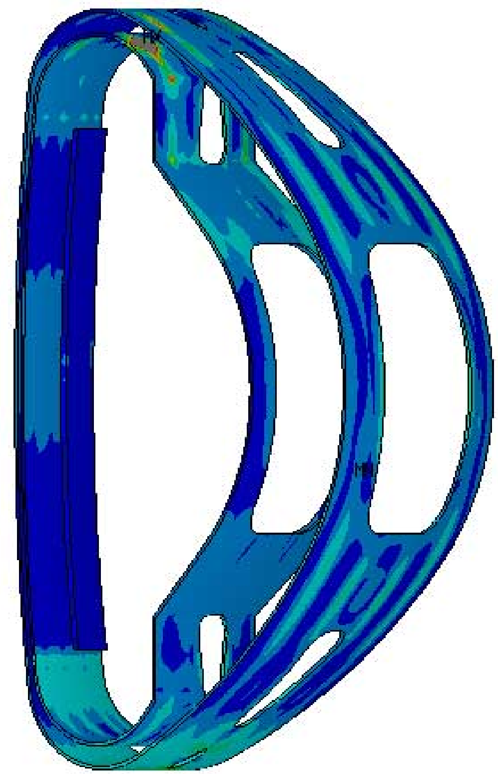
Stress concentrations around div suport pins – (need reinforcement and finer FEA model)







1.5Sm = 26 ksi (195 Mpa)



Stress is in psi

Stress > 50 ksi is in gray color

Nuclear heating and thermal effects

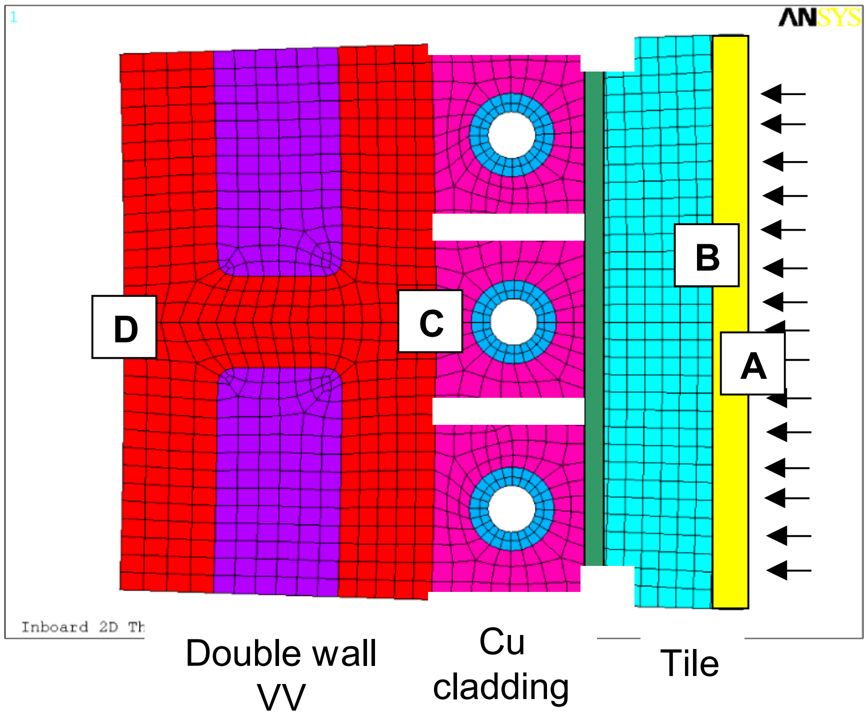
- **Vacuum vessel is subject to two basic heat loads:**
  - Direct nuclear heating from neutrons and gammas
  - Heating by conduction from first wall tiles (which in turn are heated by direct nuclear heating and surface heat flux)

- **A range of operating scenarios is possible, but the baseline case for analysis assumes:**
  - 200 MW fusion power
  - 100 W/cm^2 surface heat load on first wall
  - pulse length of 20 seconds

- **Vessel is cooled by water**
  - Flowing in copper first wall cladding
  - Flowing between walls of double wall structure

Heat loads on vessel, at IB midplane

- **Fusion power of 200 MW**
- **Surface heat flux is variable, but 100 W/cm² is assumed**

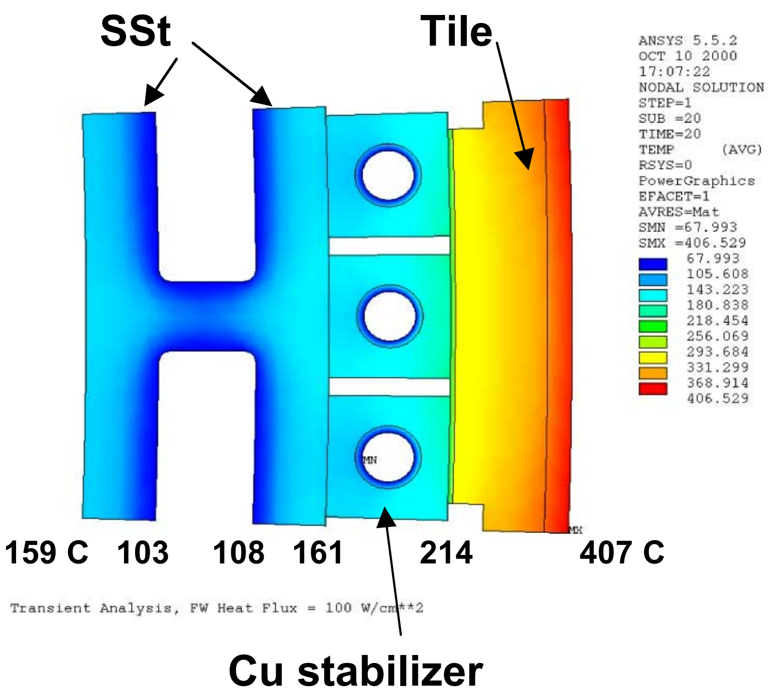


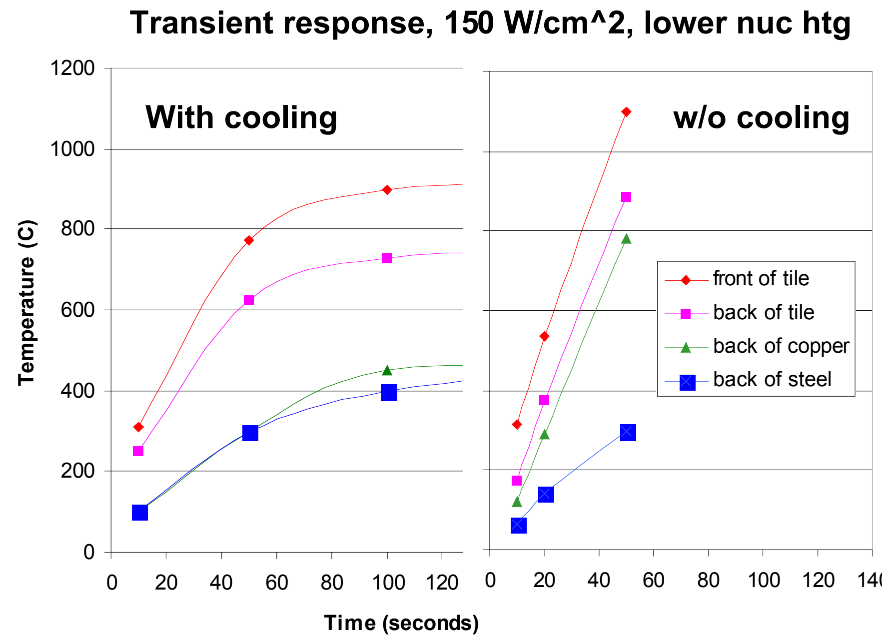
Volumetric Nuclear Heating, IB midplane*

Location	(W/cm^3)
A - Be FW	33.3
B - Cu FW	46.9
C – VV	33.8
D – VV	30.3

* ref M. Sawan

2-D temp distr after 20 sec pulse

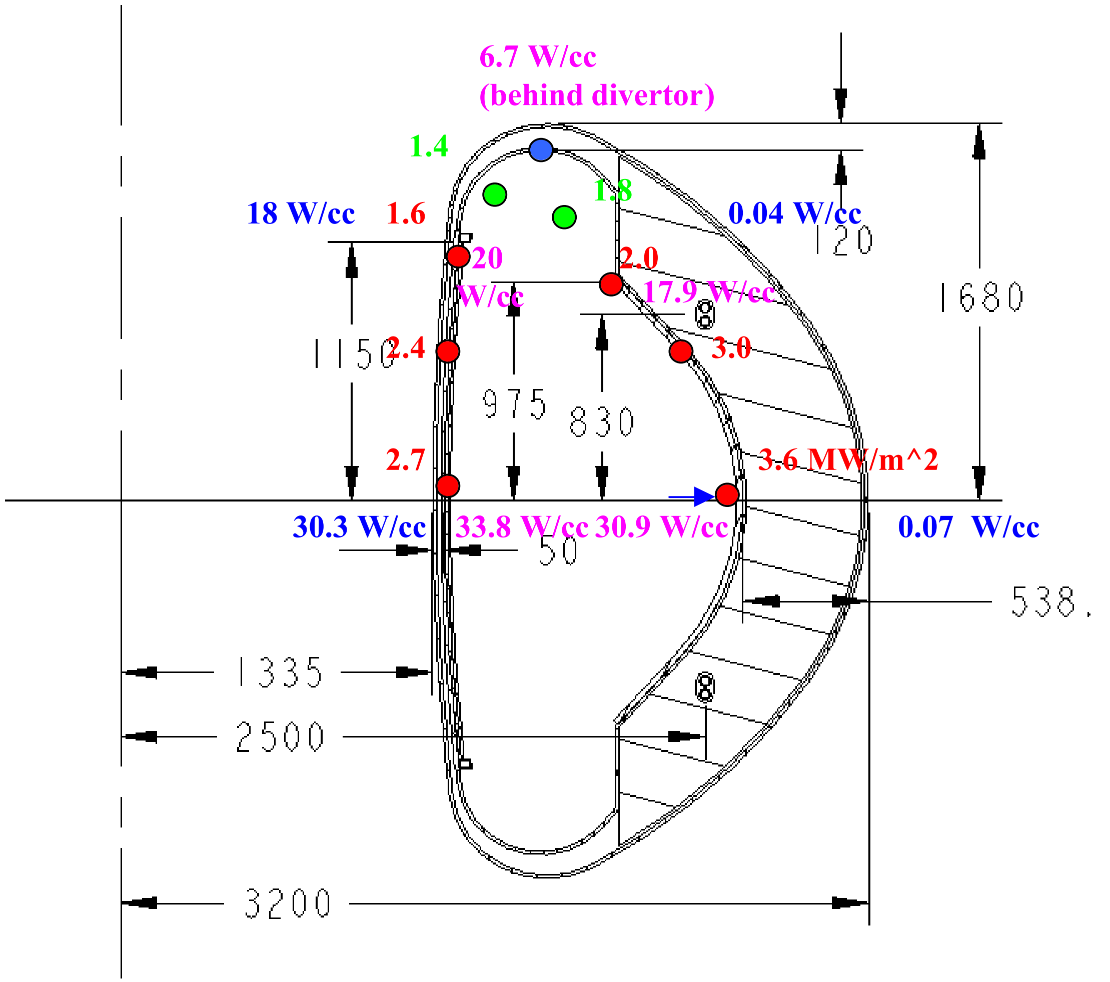




Inboard midplane

Outboard midplane

Nuclear heating distribution*



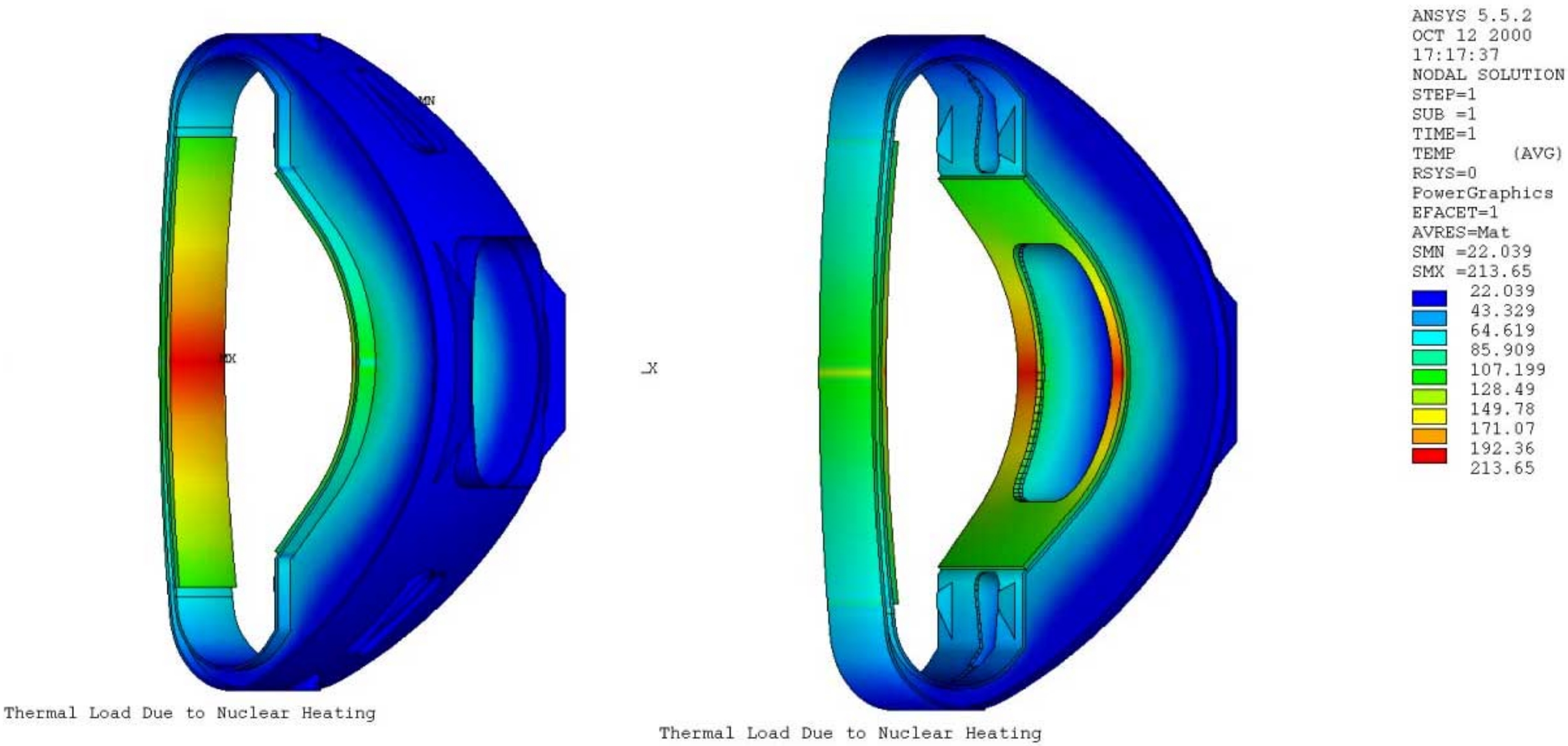
Neutron wall loading

Volumetric heating:

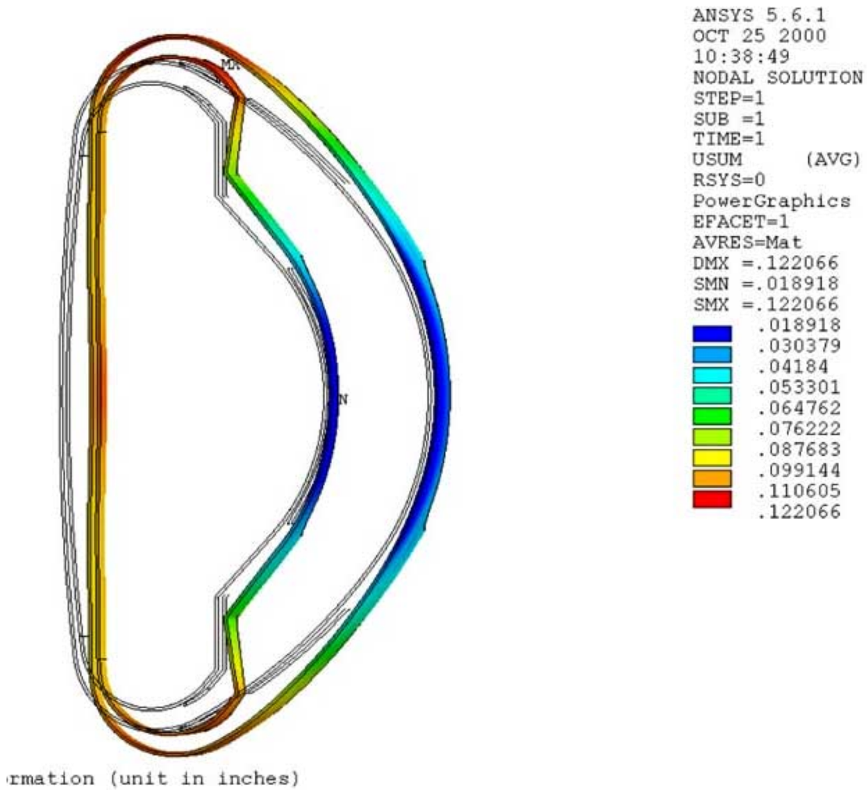
plasma side, ss
coil side, ss
divertor

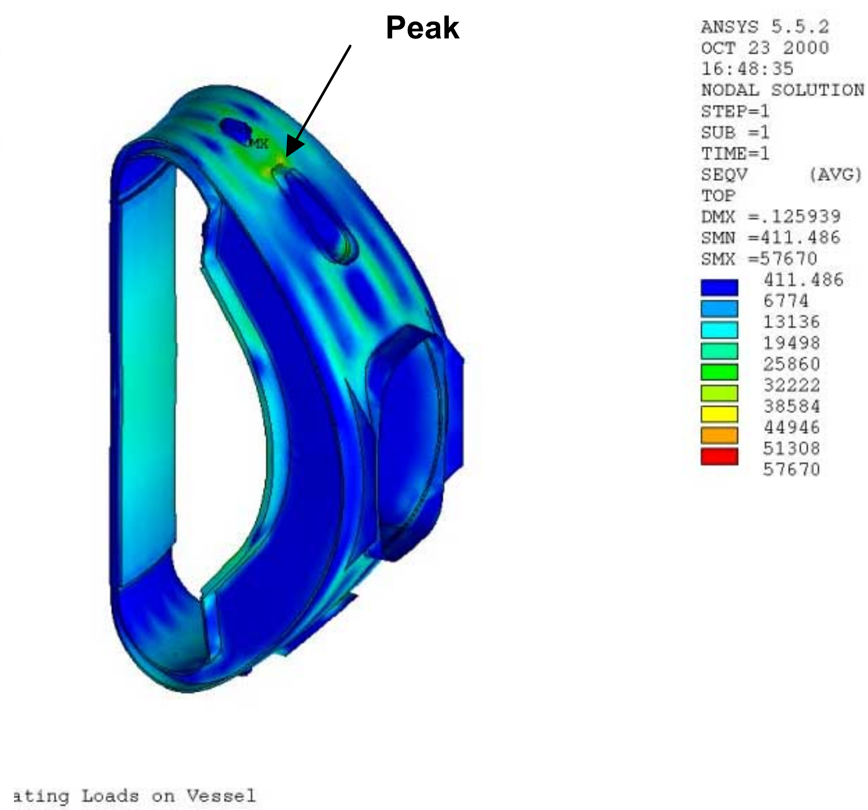
* Ref M. Sawan

3-D temp distr in VV after 20 s



VV thermal deformation and stress





Deformation

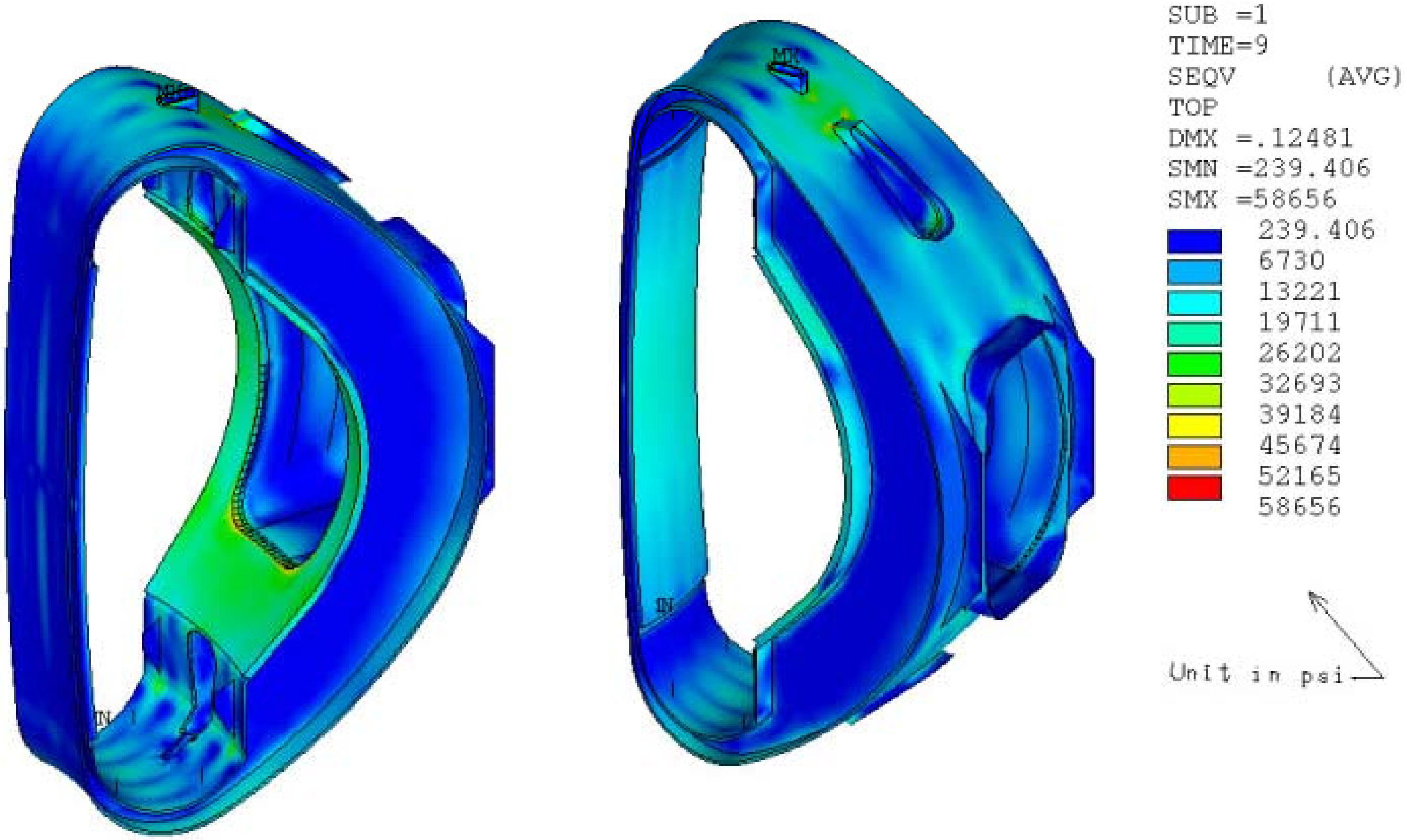
(Max ~ 3 mm)

Stress

(High stress region very localized)

Combined stresses, 20 s pulse

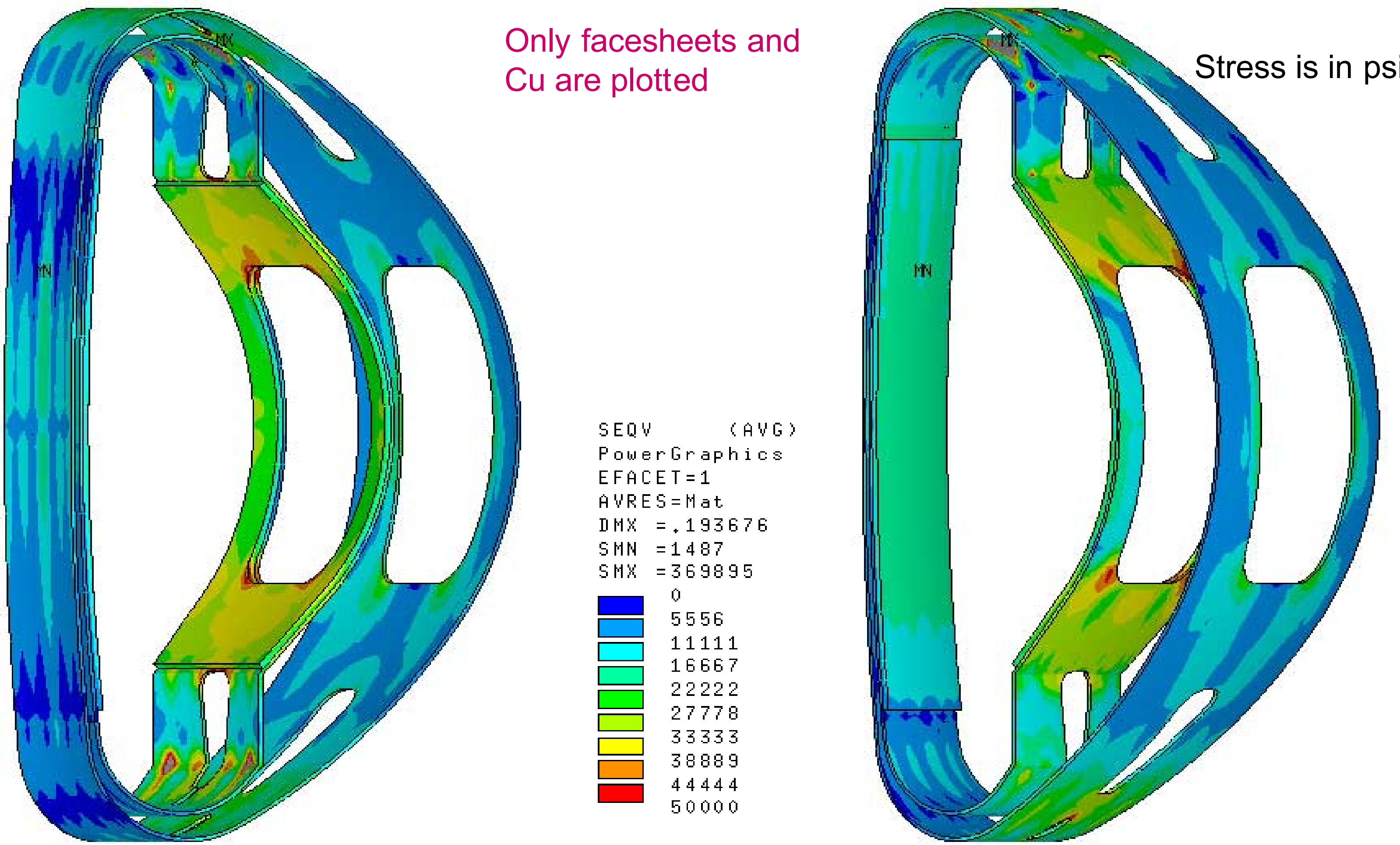
- **Nuclear heating, gravity, coolant pressure, vacuum**



Only very local regions exceed 3*Sm (390 Mpa or 52 ksi)

Combined stresses, 20 s pulse, *with VDE*

- **Nuclear heating, gravity, coolant pressure, vacuum, VDE**



Conclusions of vessel analysis

- **Can vessel take disruption loads?   YES**
  - but additional load cases must be run using updated geometry
- **Can vessel achieve pulse length? ITS CLOSE**
  - 20 second pulse should be achieveable
  - Thicker tiles, external heaters are options to be explored for more margin
- **What next?**
  - Optimized geometry and refined FEA models
  - Revised load cases, including lower fusion power, lower surface heat flux, higher plasma current
  - Dynamic analysis
  - Fatigue analysis, including plastic effects

Remote Handling*

- **Maintenance Approach & Component Classification**
- **In-Vessel Transporter**
- **Component Replacement Time Estimates**
- **Balance of RH Equipment**

*ref T. Burgess

Remote Maintenance Approach

- Hands-on maintenance employed to the fullest extent possible. Activation levels outside vacuum vessel are low enough to permit hands-on maintenance.
- In-vessel components removed as integral assemblies and transferred to the hot cell for repair or processing as waste.
- In-vessel contamination contained by sealed transfer casks that dock to the VV ports.
- Midplane ports provide access to divertor, FW and limiter modules. Port mounted systems (heating and diagnostics) are housed in a shielded assembly that is removed at the port interface.

Remote Maintenance Approach (2)

- **Upper and lower auxiliary ports house diagnostic and cryopump assemblies that are also removable at the port interface.**
- **Remote operations begin with disassembly of port assembly closure plate.**
- **During extended in-vessel operations (e.g., divertor changeout), a shielded enclosure is installed at the open midplane port to allow human access to the ex-vessel region.**
- **Remote maintenance drives in-vessel component design and interfaces. Components are given a classification and preliminary requirements are being accommodated in the layout of facilities and the site.**

Remote Handling, Classification of Components

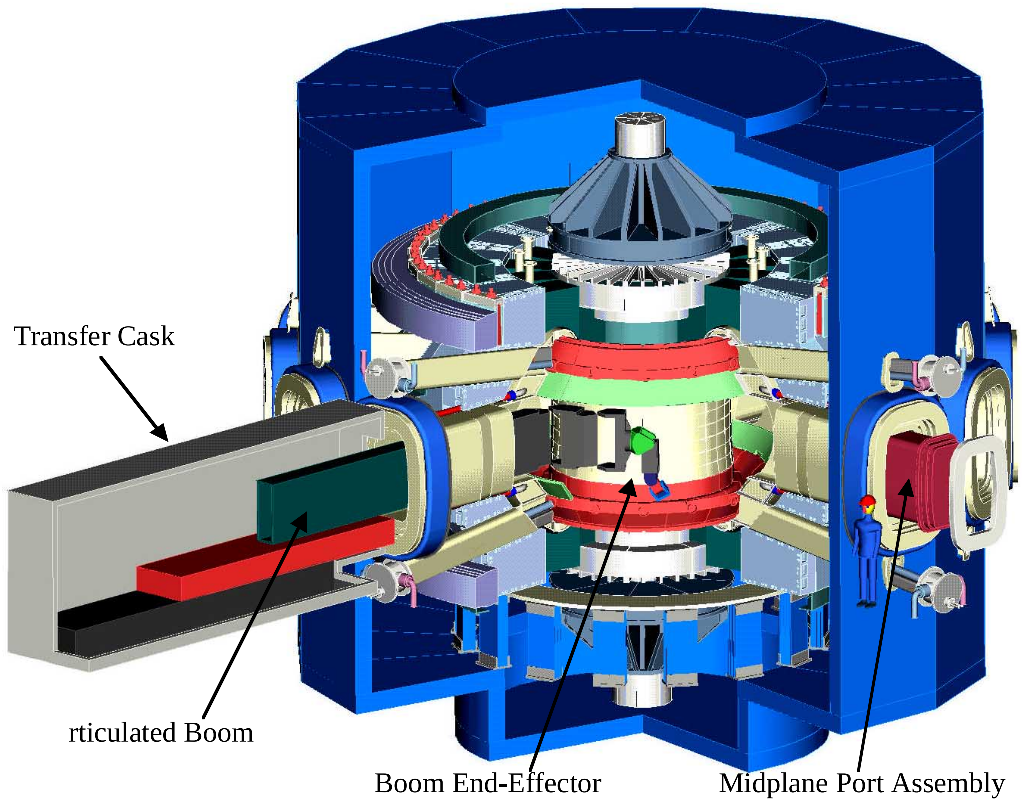
Class 1	Class 2	Class 3	Class 4*
Divertor Modules Limiter Modules Midplane Port Assemblies - RF heating - diagnostics	First Wall Modules Upper and Lower Horiz. Auxiliary Port Assemblies - cryopumps - diagnostics	Vacuum Vessel Sector with TF Coil Passive Plates In-Vessel Cooling Pipes - divertor pipes - limiter pipes	Toroidal Field Coil Poloidal Field Coil Central Solenoid Magnet Structure

*** Activation levels acceptable for hands-on maintenance**

In-Vessel Remote Handling Transporter

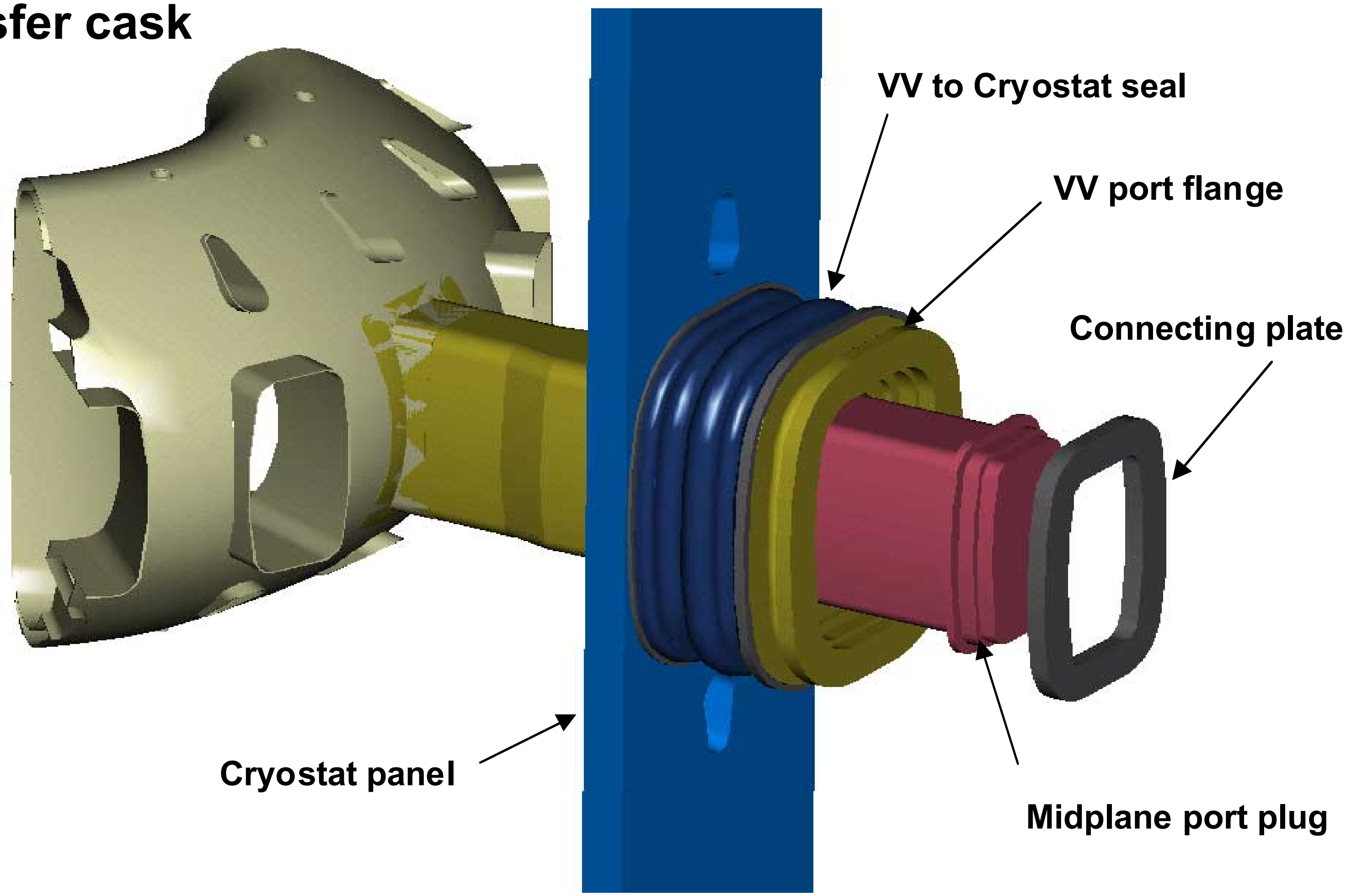
Cantilevered Articulated Boom (± 45° coverage)

- **Complete in-vessel coverage from 4 midplane ports.**
- **Local repair from any midplane port.**
- **Handles divertor, FW modules, limiter (with component specific end-effector).**
- **Transfer cask docks and seals to VV port and hot cell interfaces to prevent spread of contamination.**

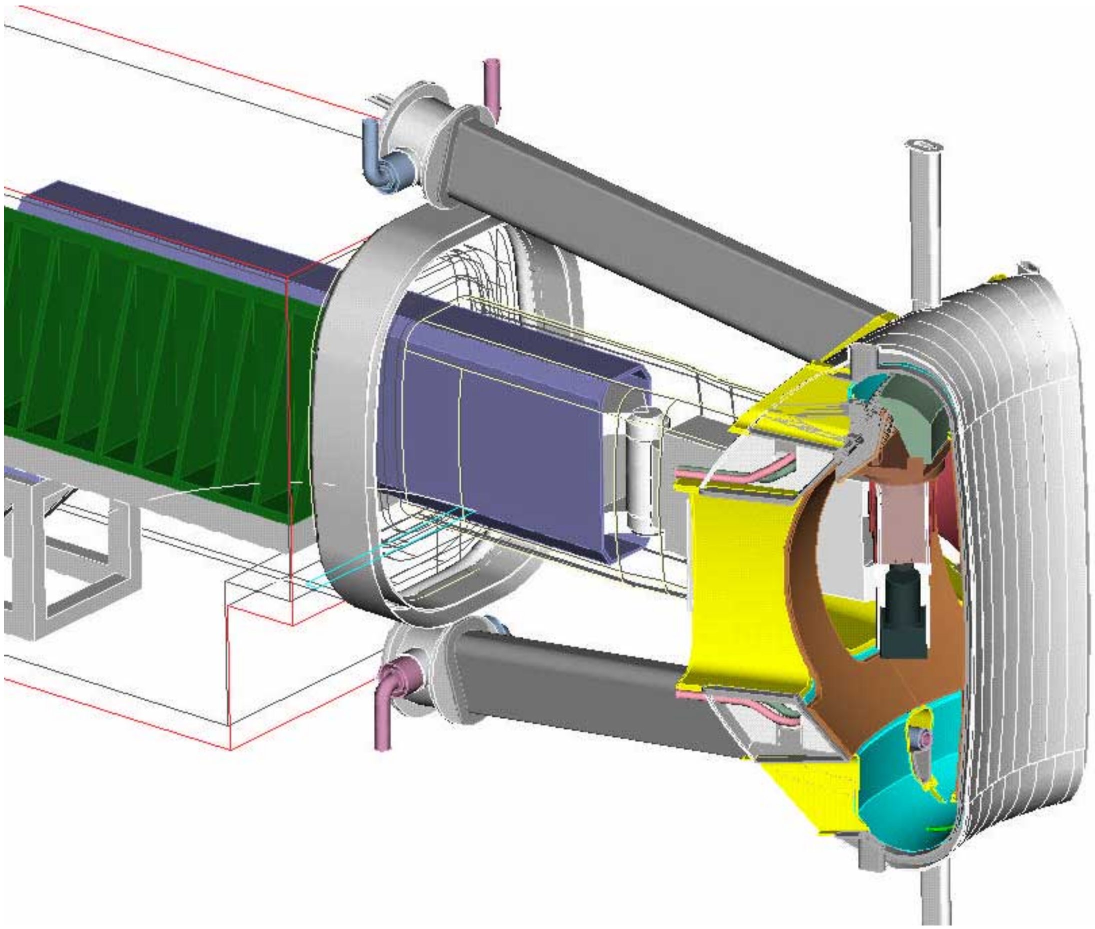


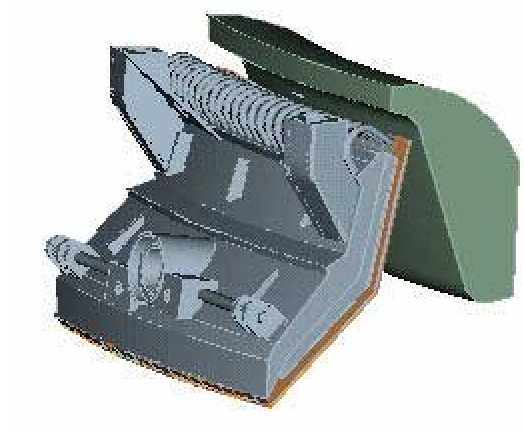
Port plug designed for RH

- **Plug uses ITER-style connection to vessel, accommodates transfer cask**



In-Vessel Remote Handling (2)

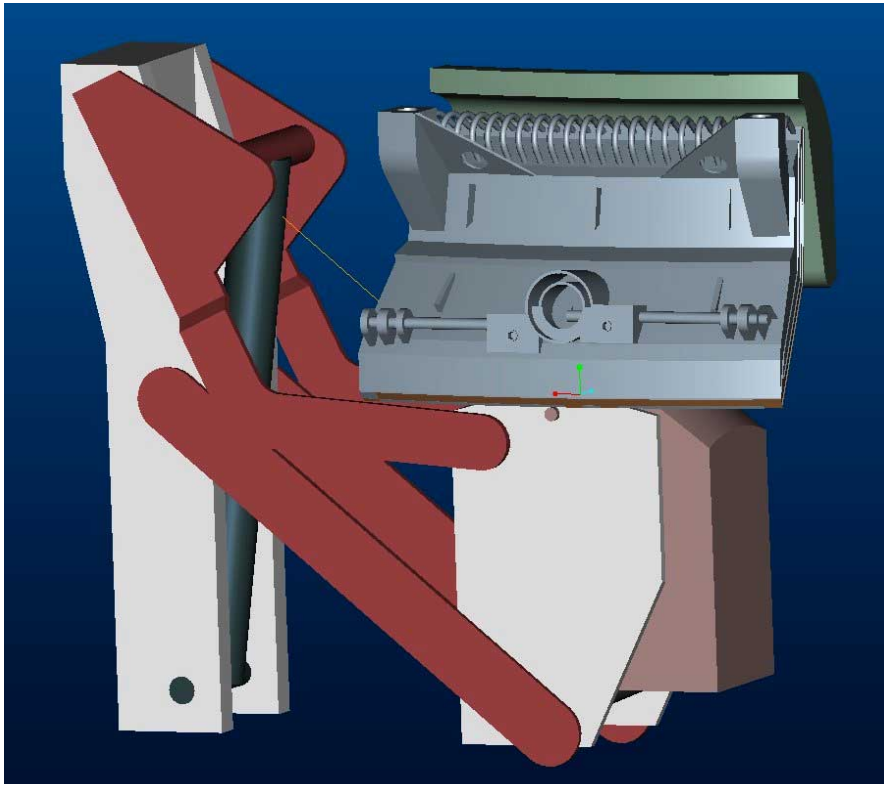




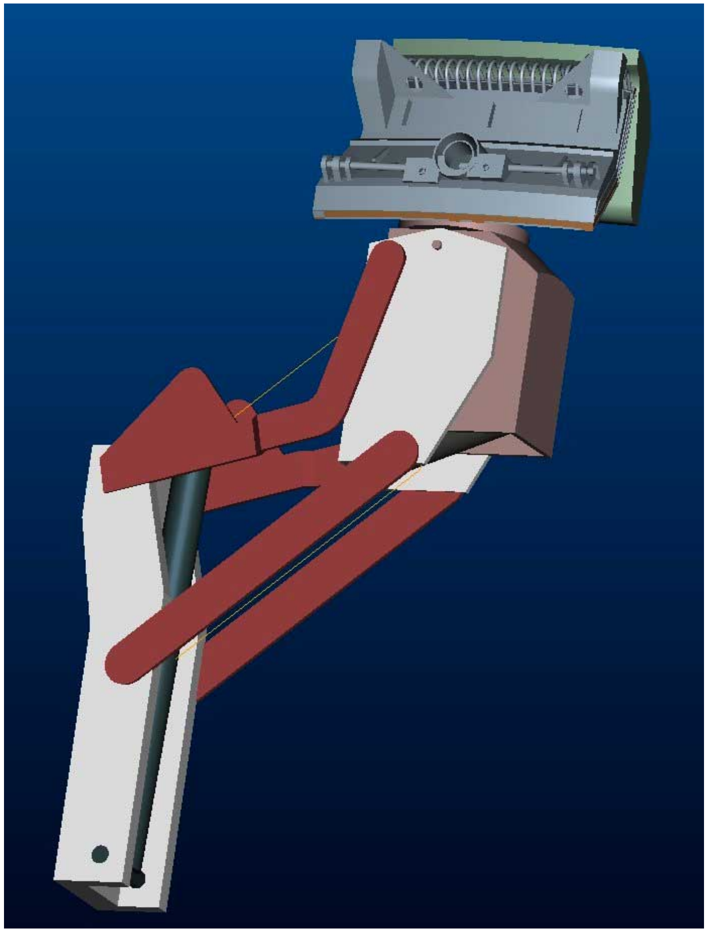
Divertor and baffle handled as one unit

Divertor Handling End-Effector

- **Six (6) positioning degrees of freedom provided by boom (2 DOF) and end-effector (4 DOF)**
- **Module weight = 800 kgs**



Transport position



Installation position

Component Maintenance Frequency and Time Estimates

Component or Operation	RH Class	Expected Frequency	Maintenance Time Estimate*
Divertor Modules	1	TBD replacements > 2	One module: 3.3 weeks
Limiter Modules			All (32) modules: 5.9 months
Midplane Port Assemblies			One module: 3.3 weeks
In-vessel Inspection		Frequent deployment	Bank (5?) modules: 3.5 weeks
FW Modules	2	TBD replacements ≤ 2	One module: 3.3 weeks**
Combined FW and Divertor Modules			All (#TBD) modules: TBD
Auxiliary Port Assemblies †			12 month time target
Vacuum Vessel Sector with TF Coil	3	Replacement not expected	TBD, replacement must be possible and would require extended shutdown
Passive Plates			
In-Vessel Cooling Pipes			

* Includes active remote maintenance time only. Actual machine shutdown period will be longer by ~ > 1 month.

** Based on single divertor module replacement time estimate.

† Based on midplane port replacement time estimate.

Remote Handling Equipment Summary

- **In-Vessel Component Handling System**
  - In-vessel transporter (boom), viewing system and end-effectors (3) for: divertor module, first wall / limiter module and general purpose manipulator

- **In-Vessel Inspection System**
  - Vacuum compatible metrology and viewing system probes for inspecting PFC alignment, and erosion or general viewing of condition
  - One of each probe type (metrology and viewing) initially procured
-
- **Port-Mounted Component Handling Systems**
  - Port assembly transporters (2) with viewing system and dexterous manipulator for handling port attachment and vacuum lip-seal tools
  - Includes midplane and auxiliary port handling systems

Remote Handling Equipment Summary (2)

- **Component & Equipment Containment and Transfer Devices**
  - Cask containment enclosures (3) for IVT, midplane and auxiliary port
  - Double seal doors in casks with docking interfaces at ports and hot cell interfaces
  - Cask transport (overhead crane or air cushion vehicles TBD) and support systems
  - Portable shielded enclosure (1) for midplane port extended opening

- **Remote Tooling**
  - Laser based cutting, welding and inspection (leak detection) tools for:
    - **vacuum lip-seal at vessel port assemblies (2 sets)**
    - **divertor coolant pipes (1 set)**
  - **limiter coolant pipes (1 set)**
  - Fastener torquing and runner tools (2 sets)

- **Fire Site Mock-Up**
  - Prototype remote handling systems used for developing designs are ultimately used at FIRE site to test equipment modifications, procedures and train operators
  - Consists of prototypes of all major remote handling systems and component mock-ups (provided by component design WBS)