FIRE Vacuum Vessel Design and Analysis

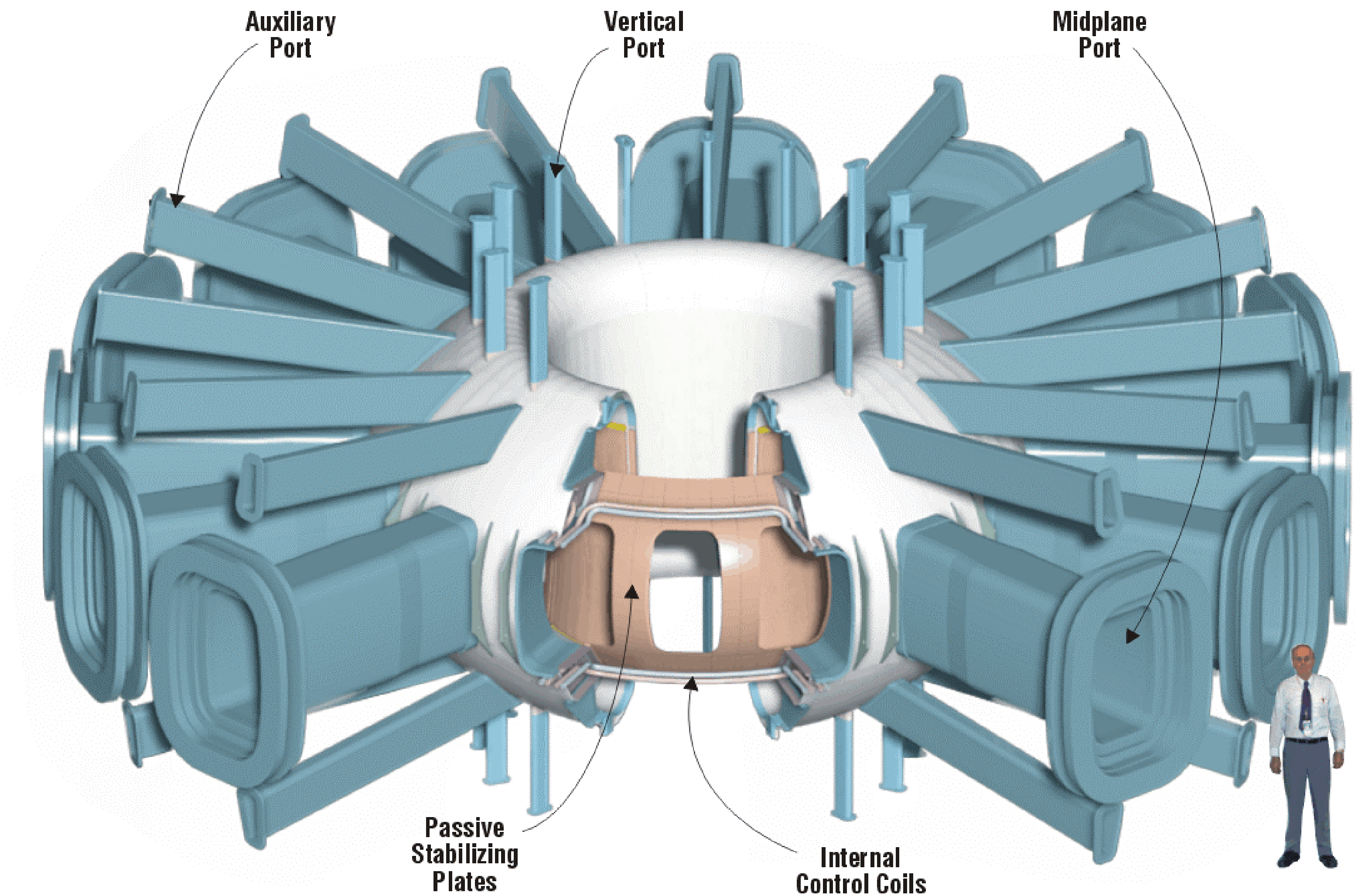
B. Nelson, T. Brown, H-M Fan, G. Jones, C. Kessel,
D. Driemeyer, M. Ulrickson

FIRE Design Review
June 6, 2001
PPPL

Presentation outline

- **Scope of vacuum vessel task area**
- **Design requirements**
- **Design concept and features**
- **Analysis status**
- **Summary**

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 requirements

- **Provide reliable lifetime component**
  - remotely welded joints are double contained
  - all bellows are double contained
- **High quality vacuum**
  - outgassing and leak rate < 10^{-5} torr-l/s
  - bakeable to 150C
  - all welded construction, including torus field joints
- **Must withstand all possible combinations of normal and fault loads**
  - internal pressure, coolant pressure
  - EM loads on vessel and internals (including VDEs)
  - weight and seismic loads on vessel and internals

Vacuum vessel requirements (2)

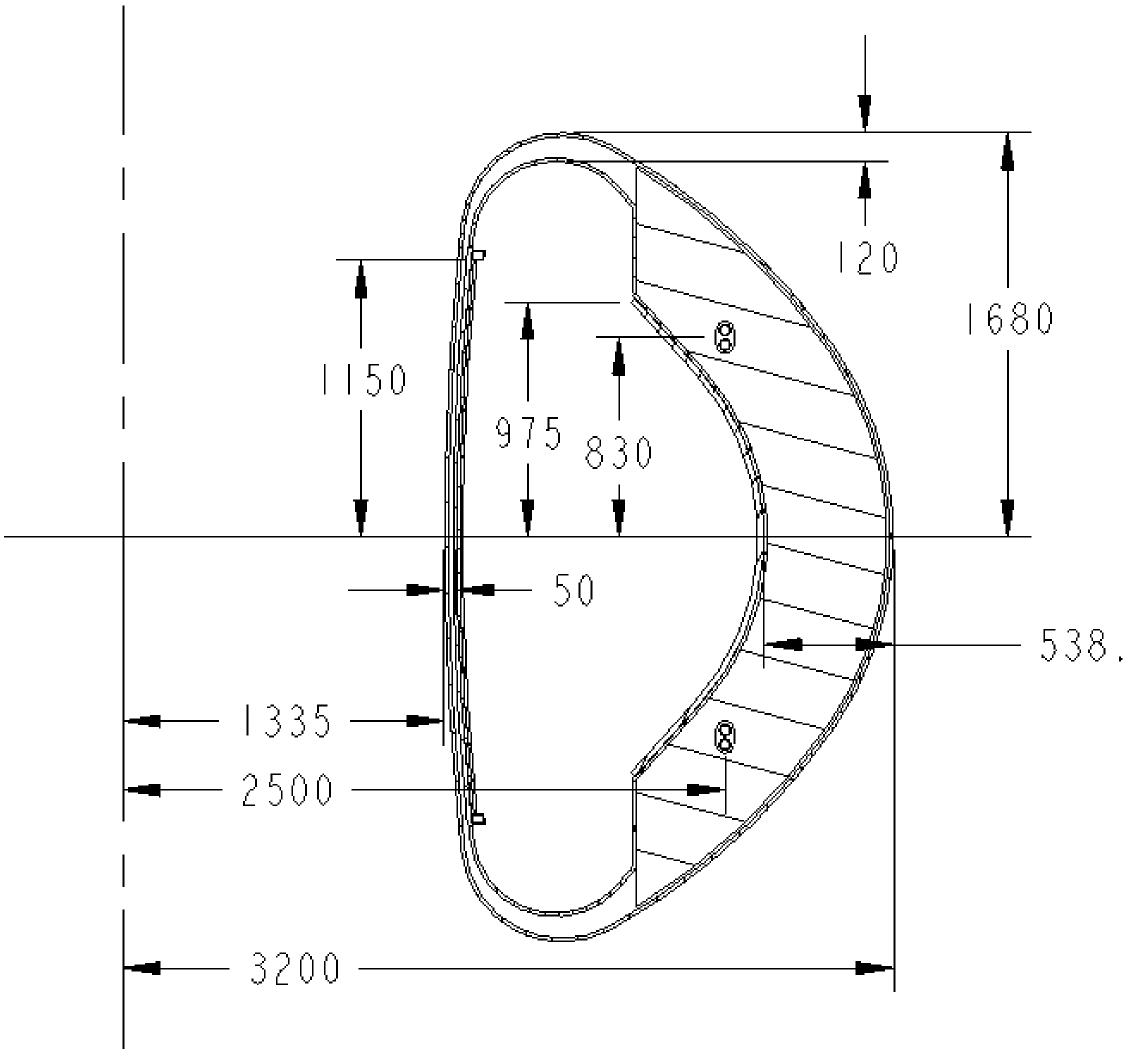
- **Provide system to remove and add heat**
  - Normal oper. - nuclear heating and surface heating from PFCs
  - Off-normal oper. (passive, natural convection during LOCA)
  - Bakeout to 150C

- **Provide for pressure suppression/relief in case of internal leaks**
- **Provide specified electrical properties for passive stabilizing function (no electrical breaks required)**
- **Provide access ports for heating (no NBI), diagnostics and remote maintenance**

Vacuum vessel requirements (3)

- **Provide for remote maintenance**
  - Field joints must be capable of remote leak testing and repair
  - In-vessel re-configuration must be possible
  - Remote TF coil replacement TBD, VV should not be a constraint
- **Design and fabricate vessel shell in accordance with general provisions of accepted (e.g. ASME) code**
- **Fabricate and assemble within acceptable tolerances**
  - Vessel height and width within +/- 20 mm
  - Wall section thickness within +/- 5 mm
  - Location with respect to magnets within TBD
- **Provide for pressure and vacuum testing**
- **Use materials suitable for high vacuum, but there is no requirement for low activation of specific class of waste disposal**

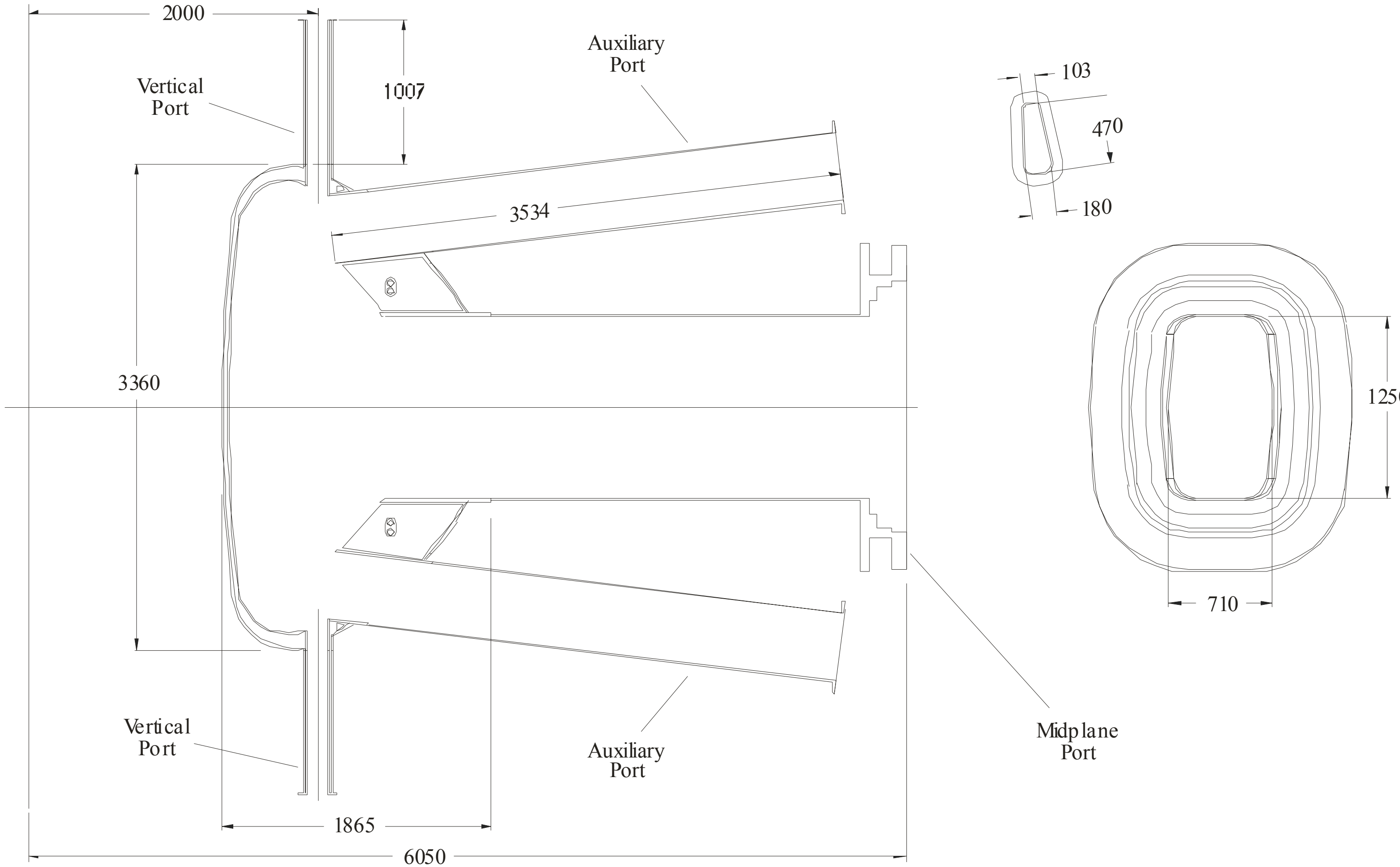
Vessel shell dimensions



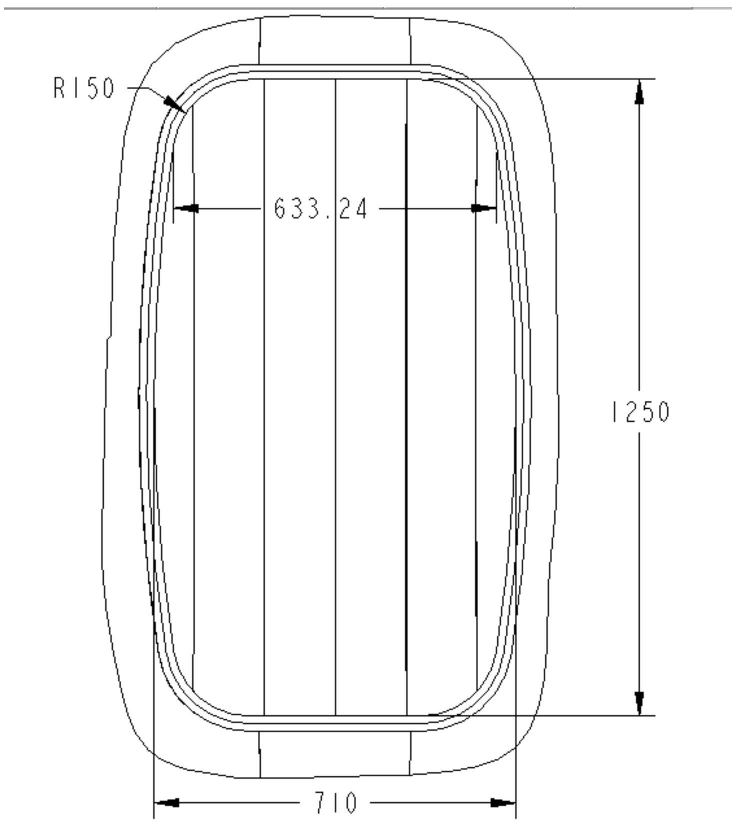
Vacuum vessel parameters

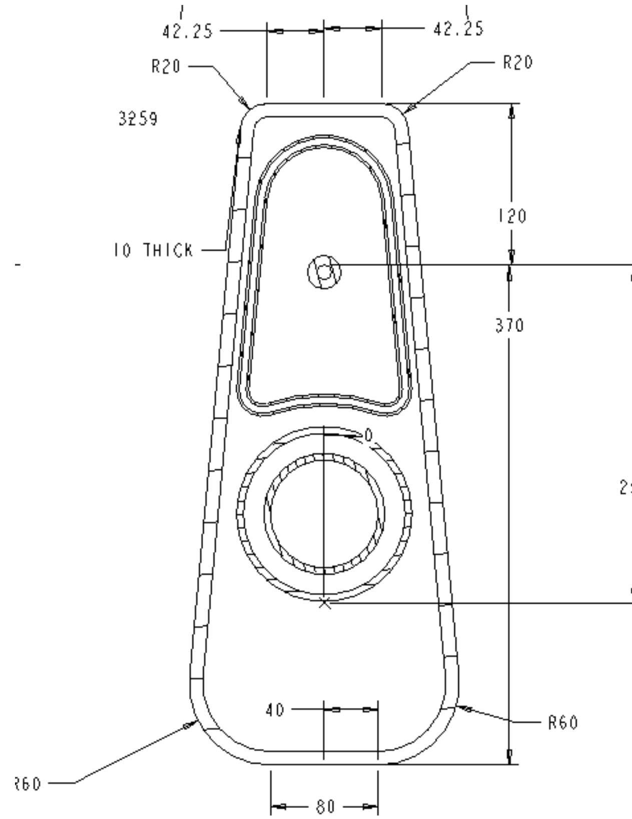
• **Configuration:**	Double wall torus
– Shielding	water + steel with 60% packing factor
– Volume of torus interior	35 m^3
– Surface Area of torus interior	89 m^2
– Facesheet thickness	15 mm
– Rib thickness	15 - 30 mm
– Weight of structure, incl ports	50 tonnes
– Weight of torus shielding	80 tonnes
• **Coolant**	
– Normal Operation	Water, < 100C, < 1 Mpa
– Bake-out	Water ~150C, < 1 Mpa
• **Materials**	
– Torus, ports and structure	316L ss
– Shielding	304L ss (tentative)

Vessel port configuration



Vessel port details





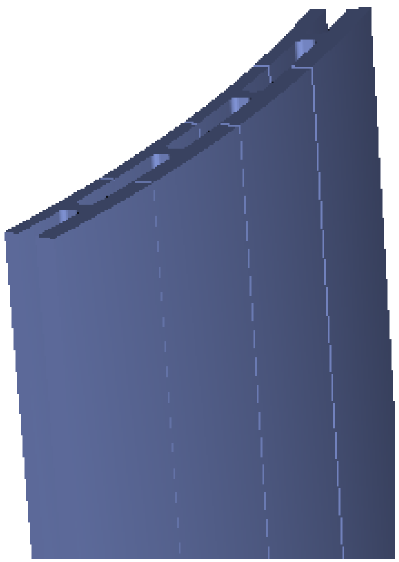
Midplane port
Port dimensions = 0.71 x 0.63 x 1.25 m
Cross sectional area of port ~ .8 m^2

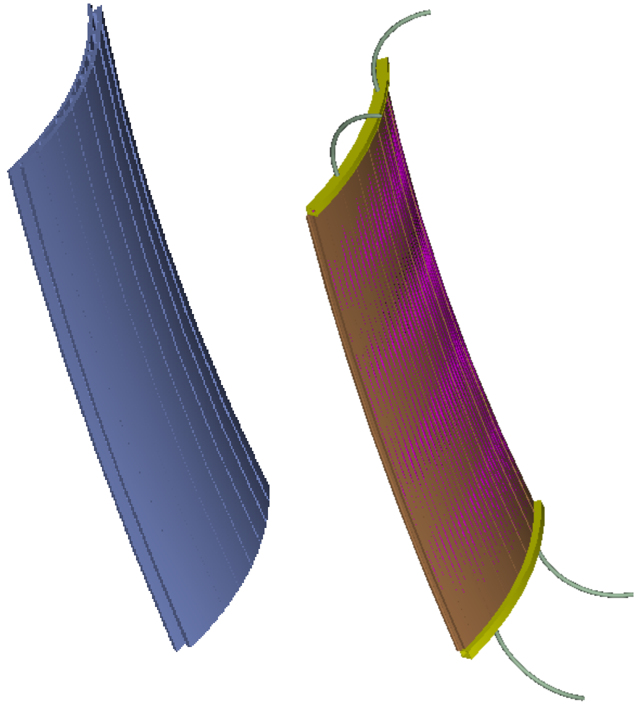
Auxiliary port
Port dimensions = 0.47 x .104 x .180 m
Cross sectional area of port ~ .067 m^2

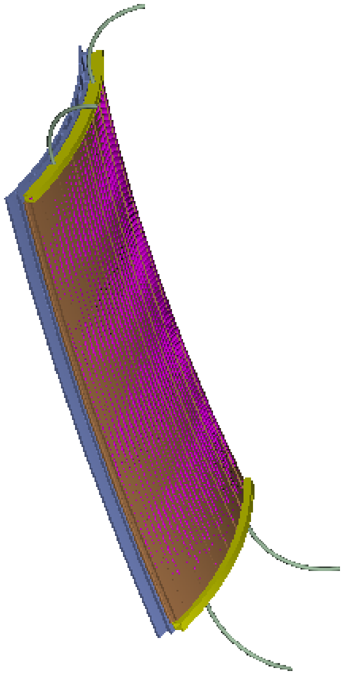
Vessel fabrication concept

- **Vessel manufactured in octants**
- **Each octant made from 4 major subassemblies,**
  - Inboard, with integral passive plates
  - Outboard, with integral passive plates, active coils, and midplane port openings
  - Upper and lower sections with integral port assemblies, divertor brackets
- **Ports are added after octant is assembled in TF coil pair**
- **Octants are joined with inboard splice plates**

Vessel inboard shell fabrication





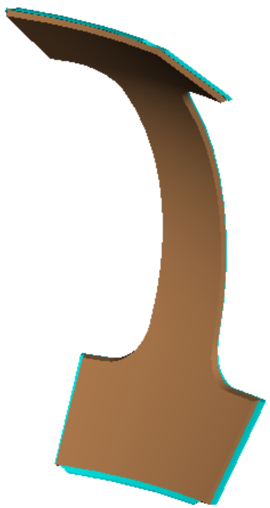


Weld the formed extrusions together

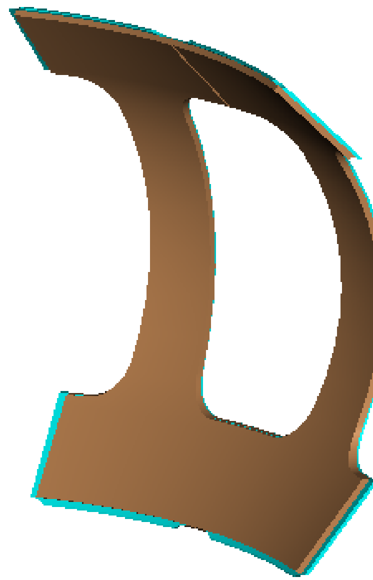
•Machine surfaces of steel weldment,
•Fab copper by gun drilling/machining or use a sandwich structure
•Attach manifolds to copper

Diffusion bond the formed copper assembly to the steel assembly

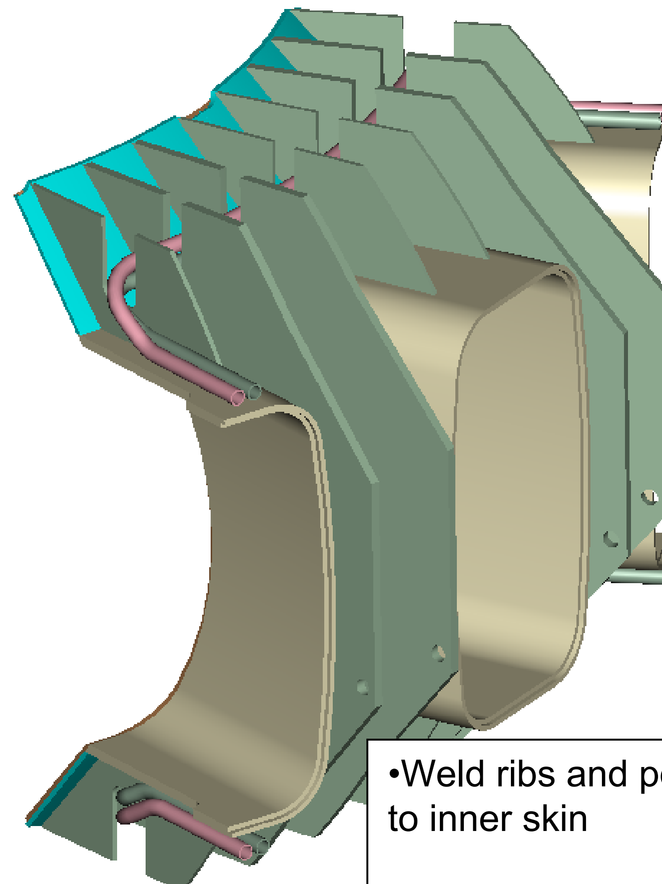
Vessel outboard shell fabrication



Diffusion bond copper to inner face sheet

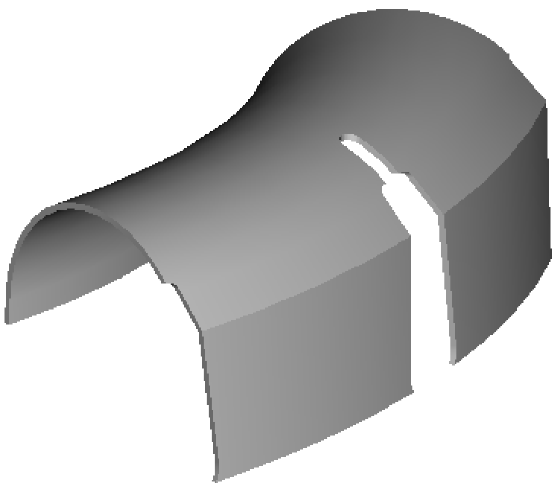


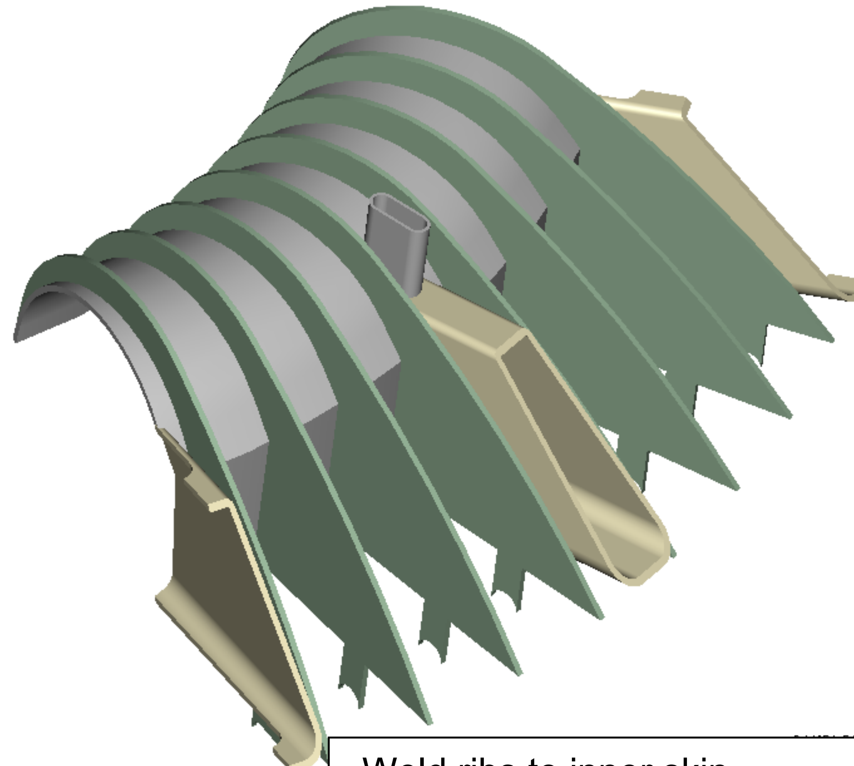
Join two ½ sections to form one octant



- Weld ribs and port stubs to inner skin
- Add conduit for active control coils

Vessel upper and lower shell fab.

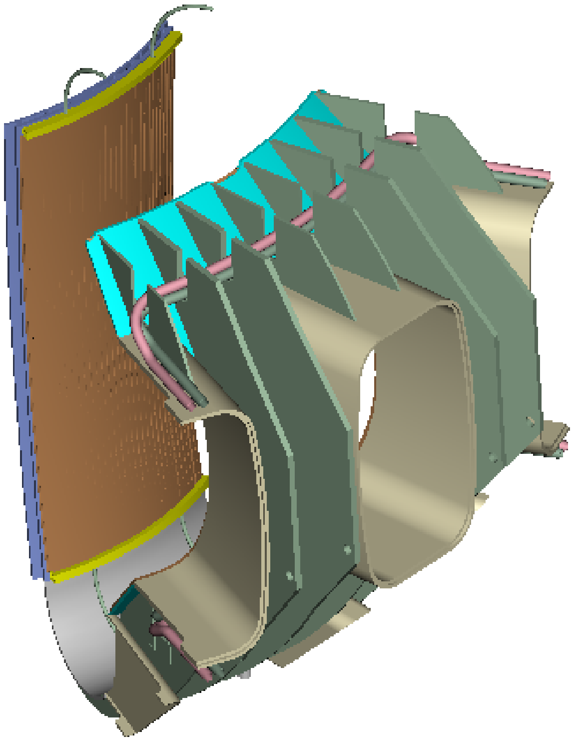




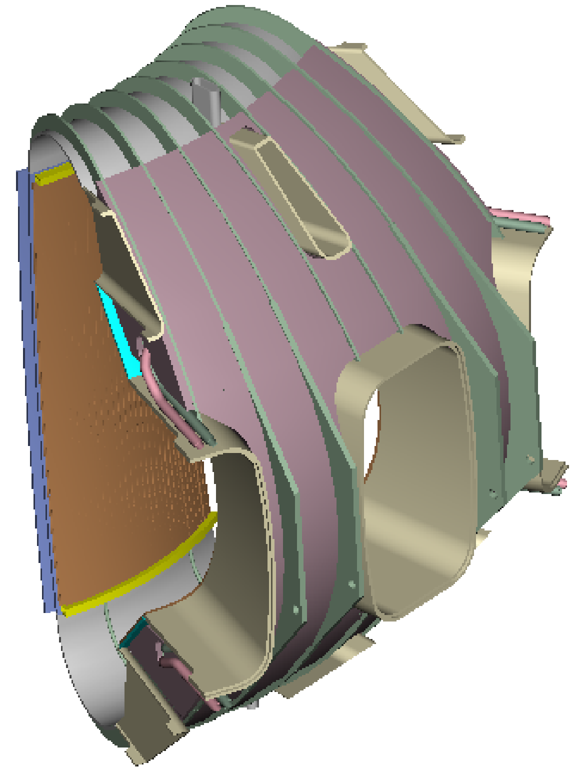
Form and trim inner skin

- Weld ribs to inner skin
- Add port reinforcing stubs

Vessel octant subassembly fab.

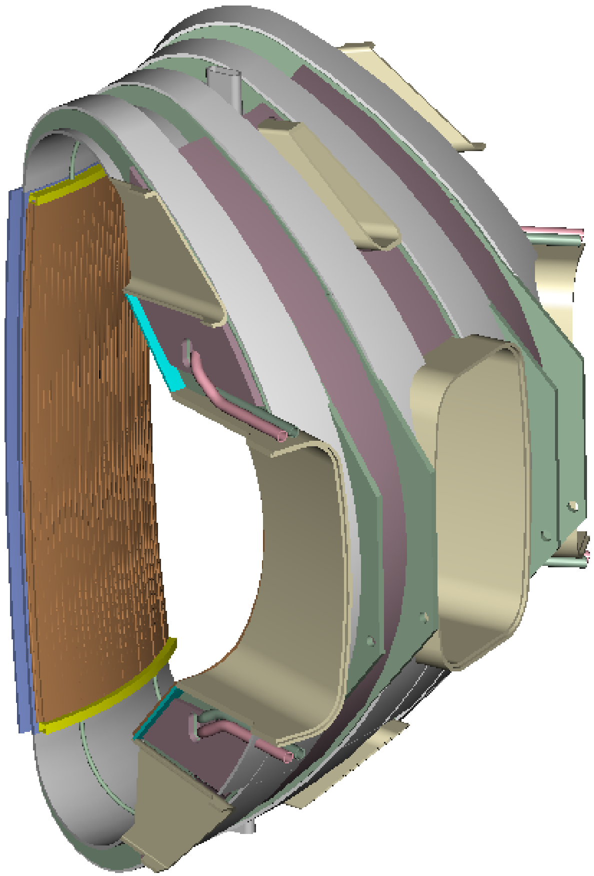


Weld inner skins and ribs of inboard, outboard, top and bottom sections together

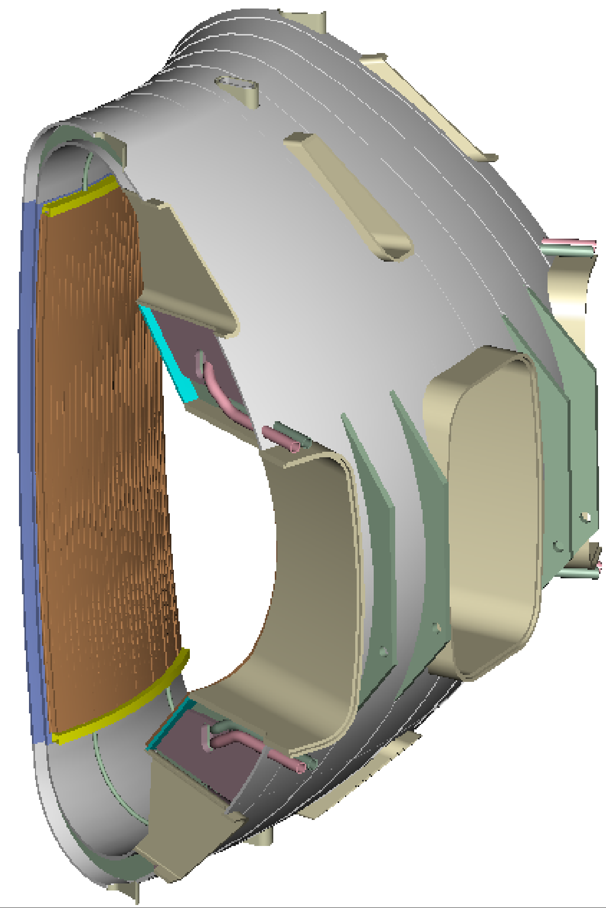


Add shielding subassemblies between ribs

Vessel octant subassembly fab. (2)



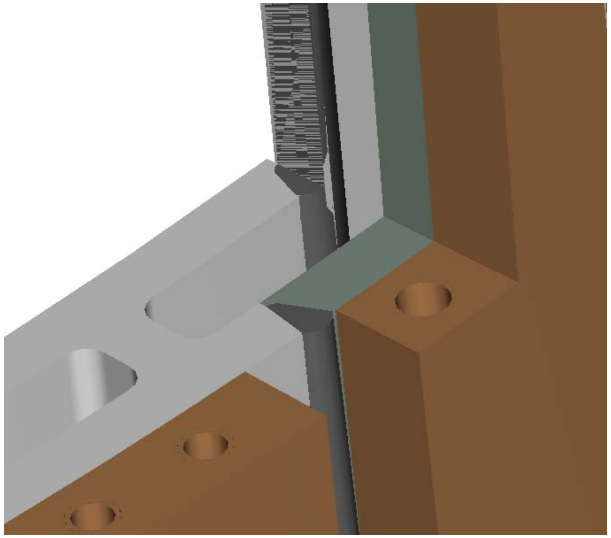
Add outer skin on / between ribs

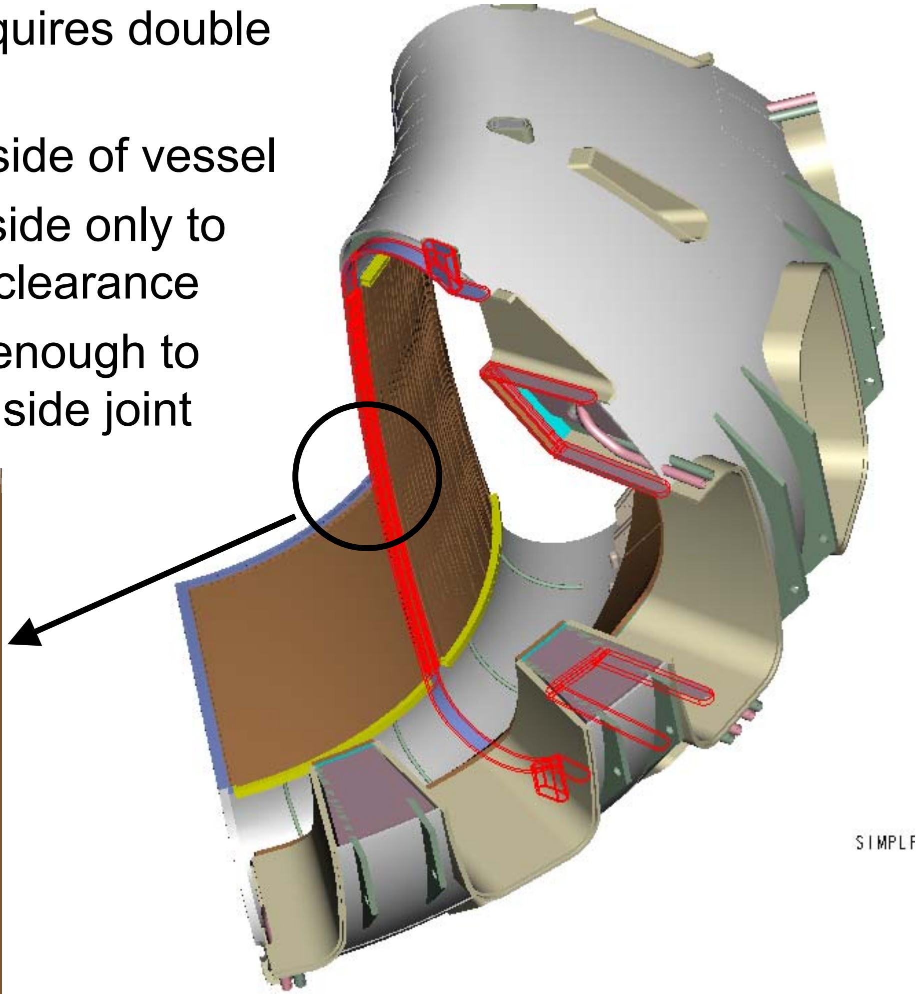


Completed octant ready for assembly

Vessel octant subassembly fab. (3)

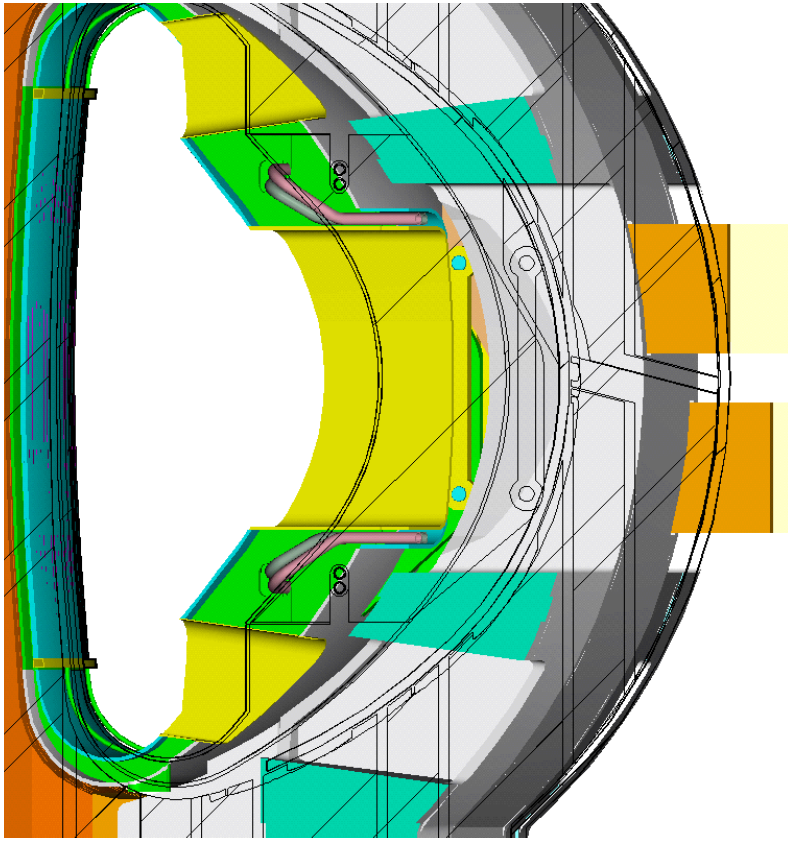
- Octant-to-octant splice joint requires double wall weld
- All welding done from plasma side of vessel
- Splice plates used on plasma side only to take up tolerance and provide clearance
- Plasma side splice plate wide enough to accommodate welding the coil side joint

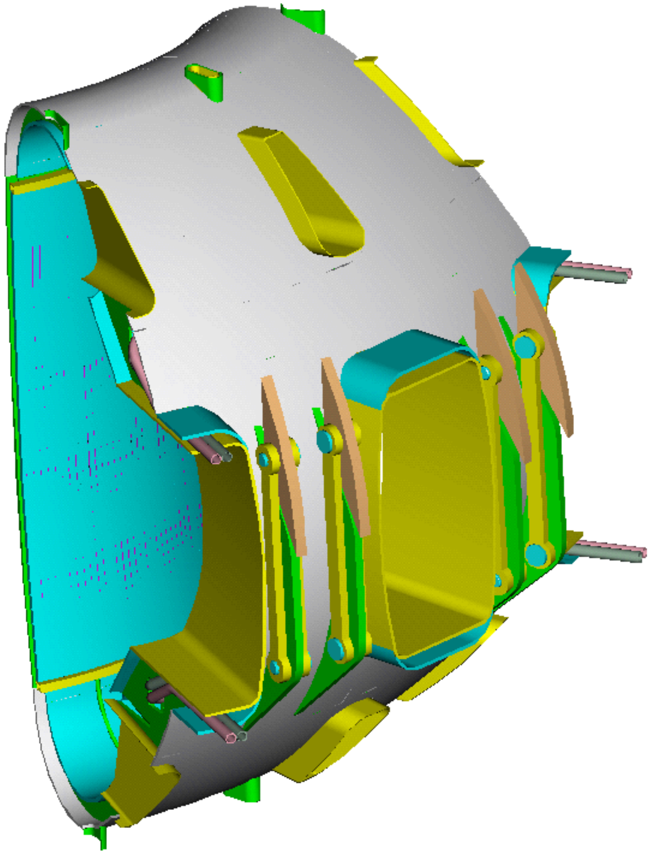




Vessel support concept

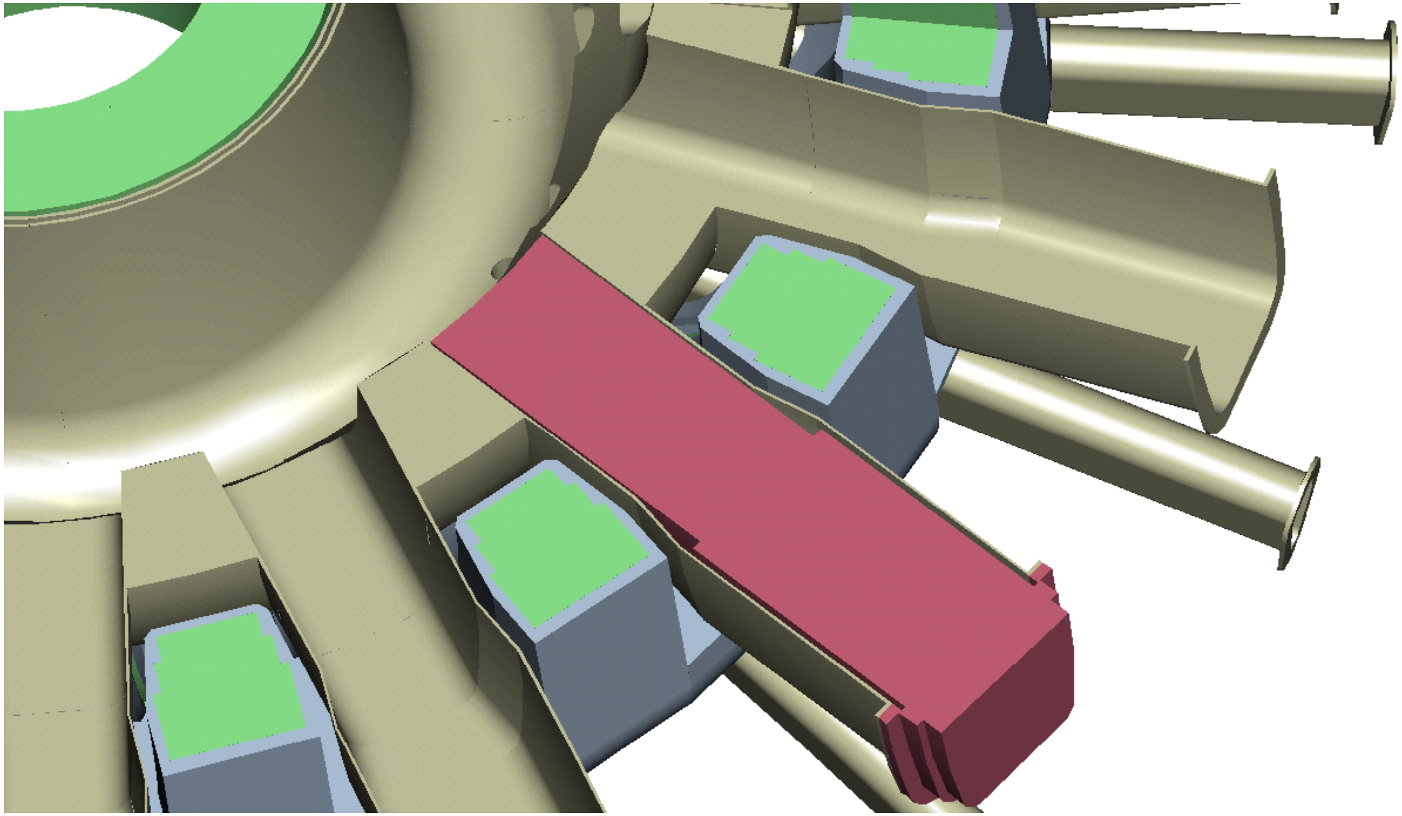
- **Links and ribs provide vertical and lateral support between vessel and TF coil structure**





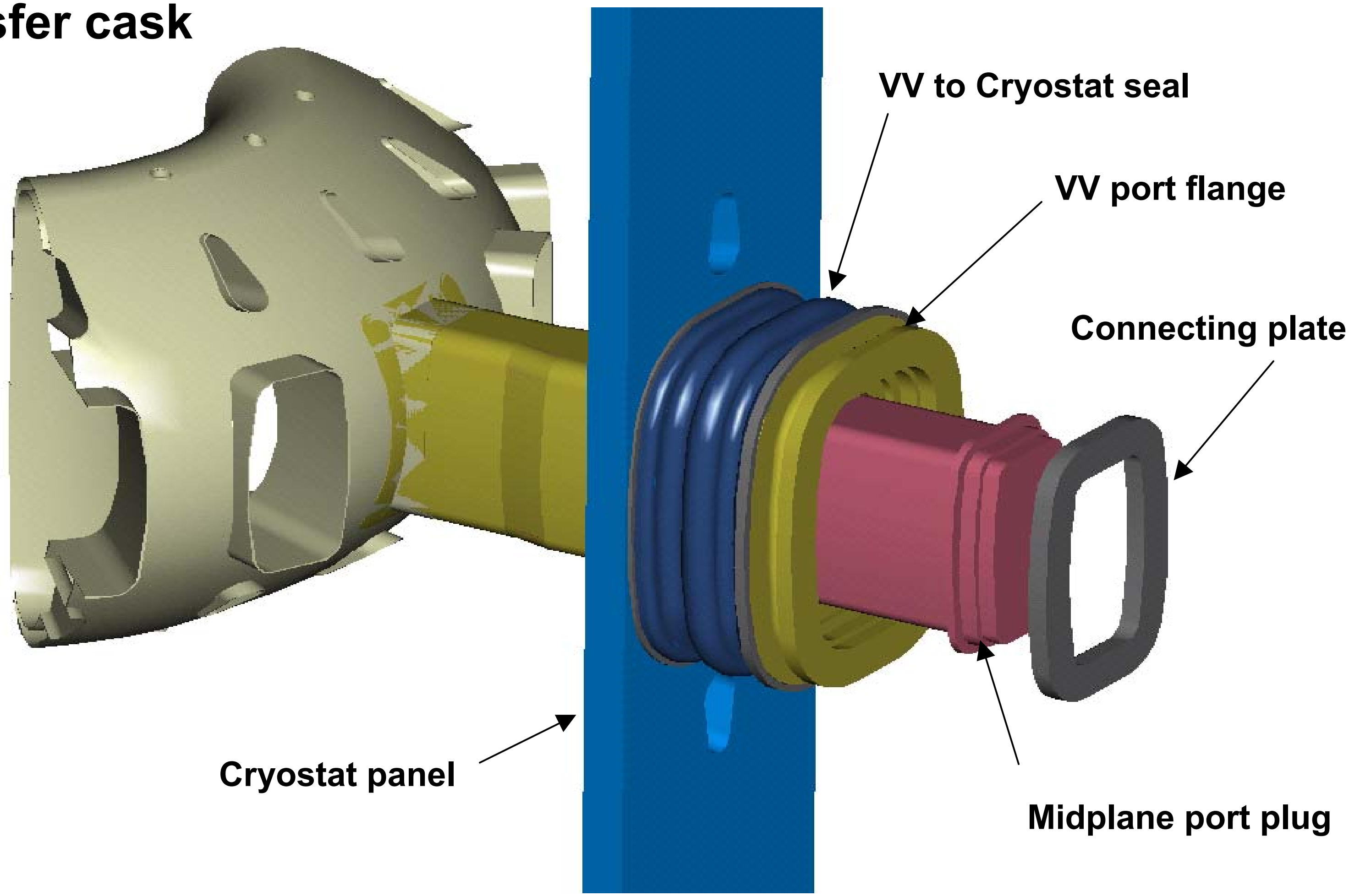
Nuclear shielding concept

- 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



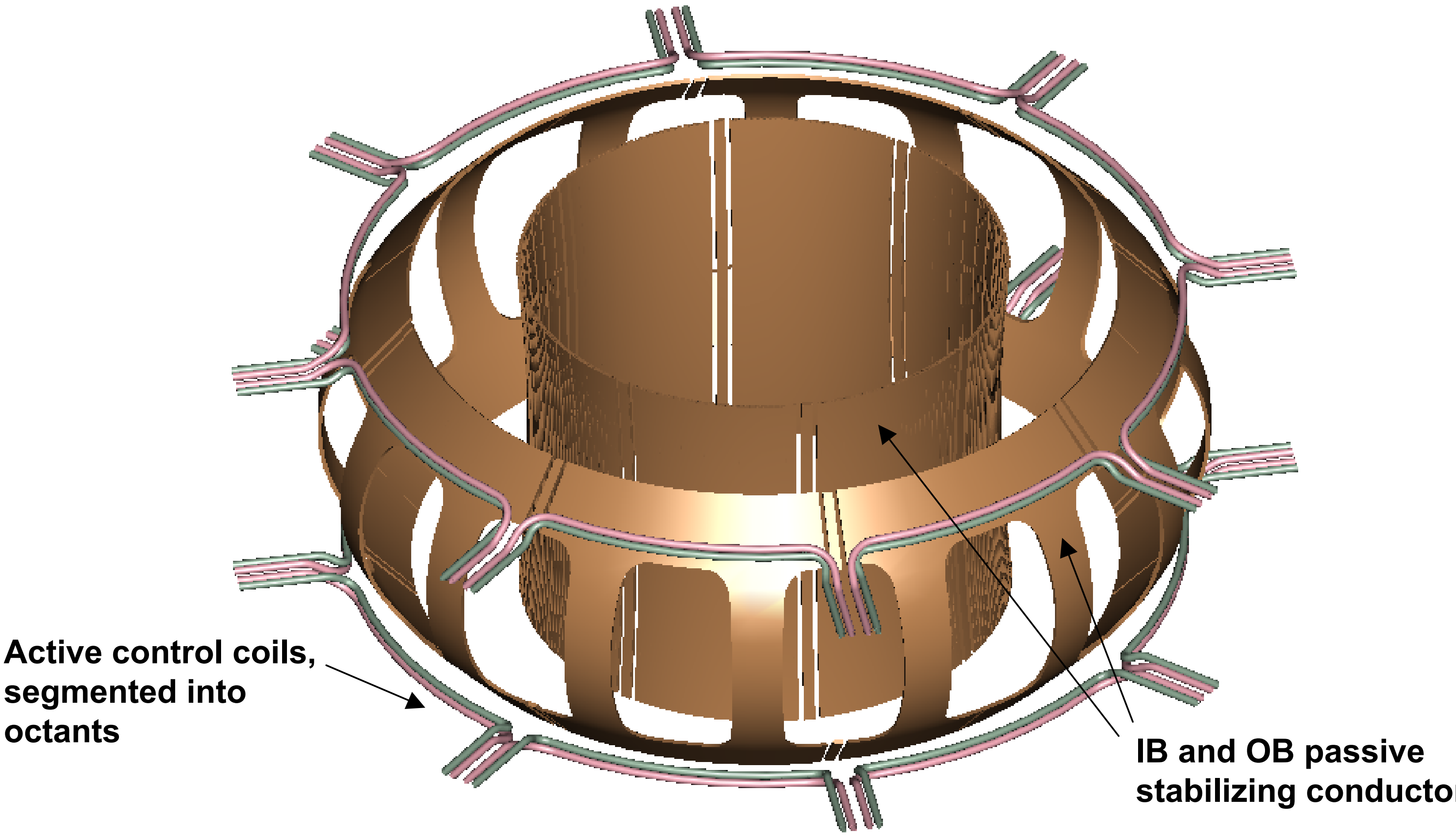
Port plug designed for RH

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

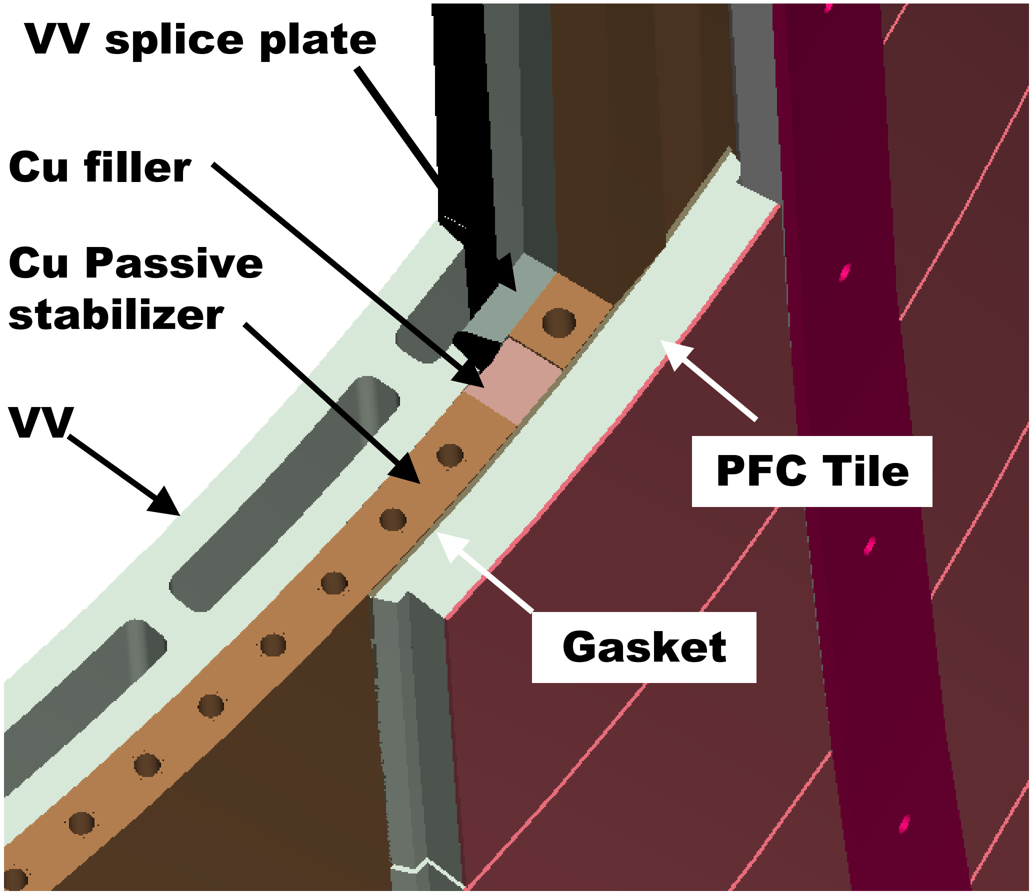


Active and passive stabilizing sys.

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



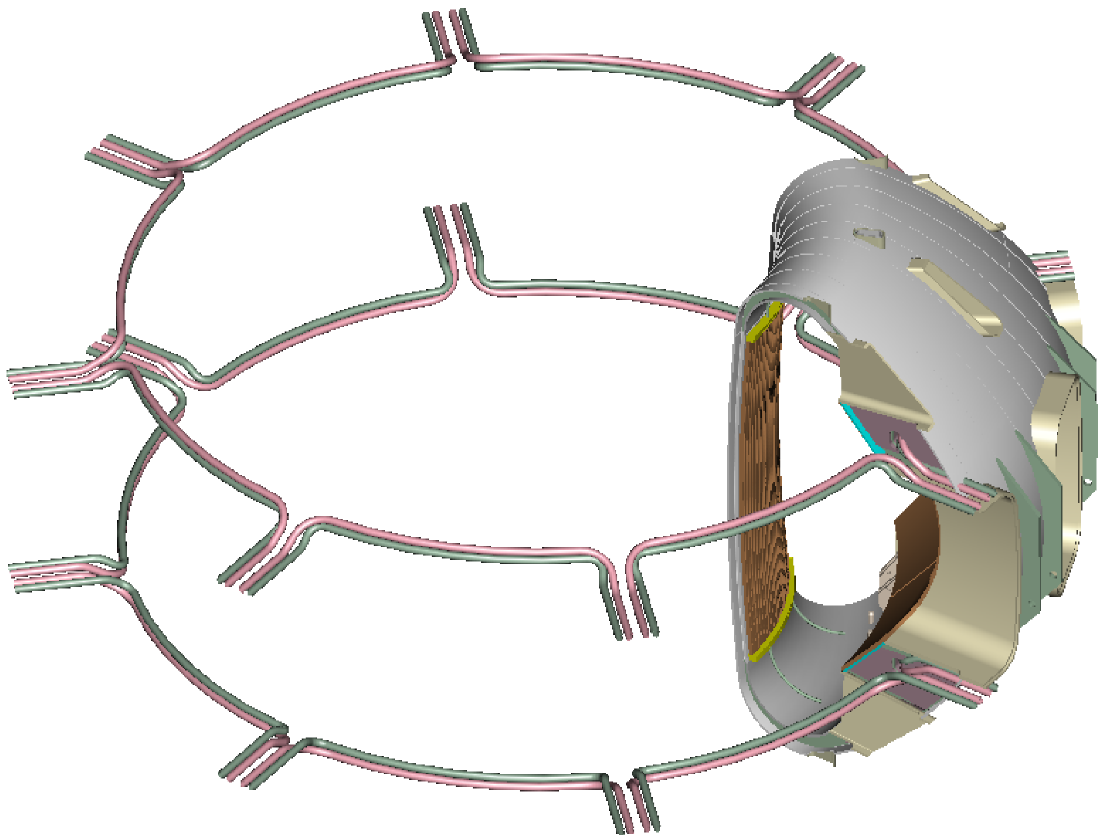
Passive conductor is also heat sink



- 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

Active coils integrated with vessel

- **2 pairs of 40 mm ID conduits located between double walls of vessel**
- **MgO insulated cables inside conduit, with redundant cables**
- **Leads and jumpers bypass around the octant assembly joints**



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**

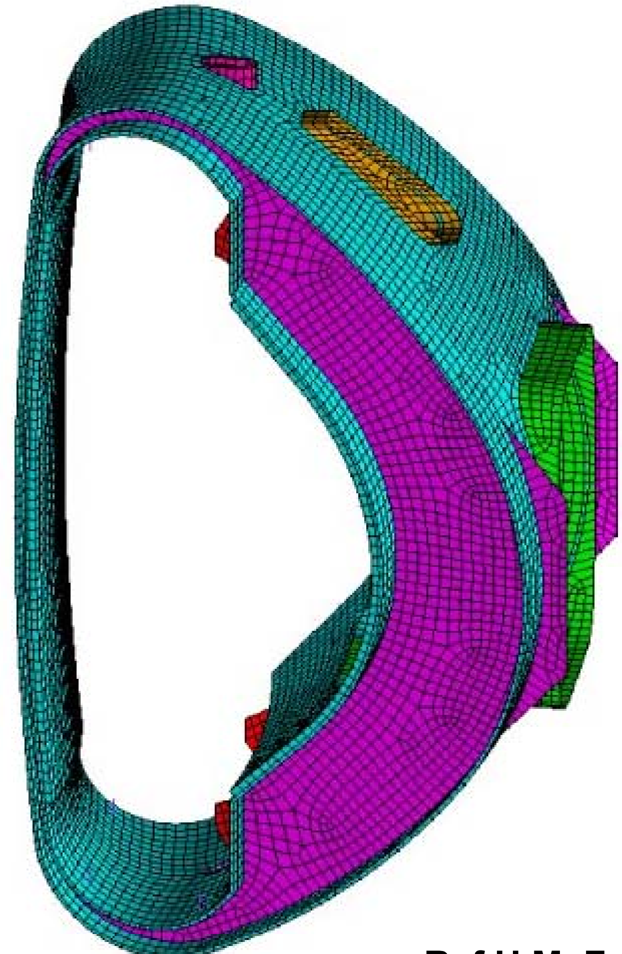
Vacuum vessel mechanical loads

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

VV analysis, ANSYS FEA model*

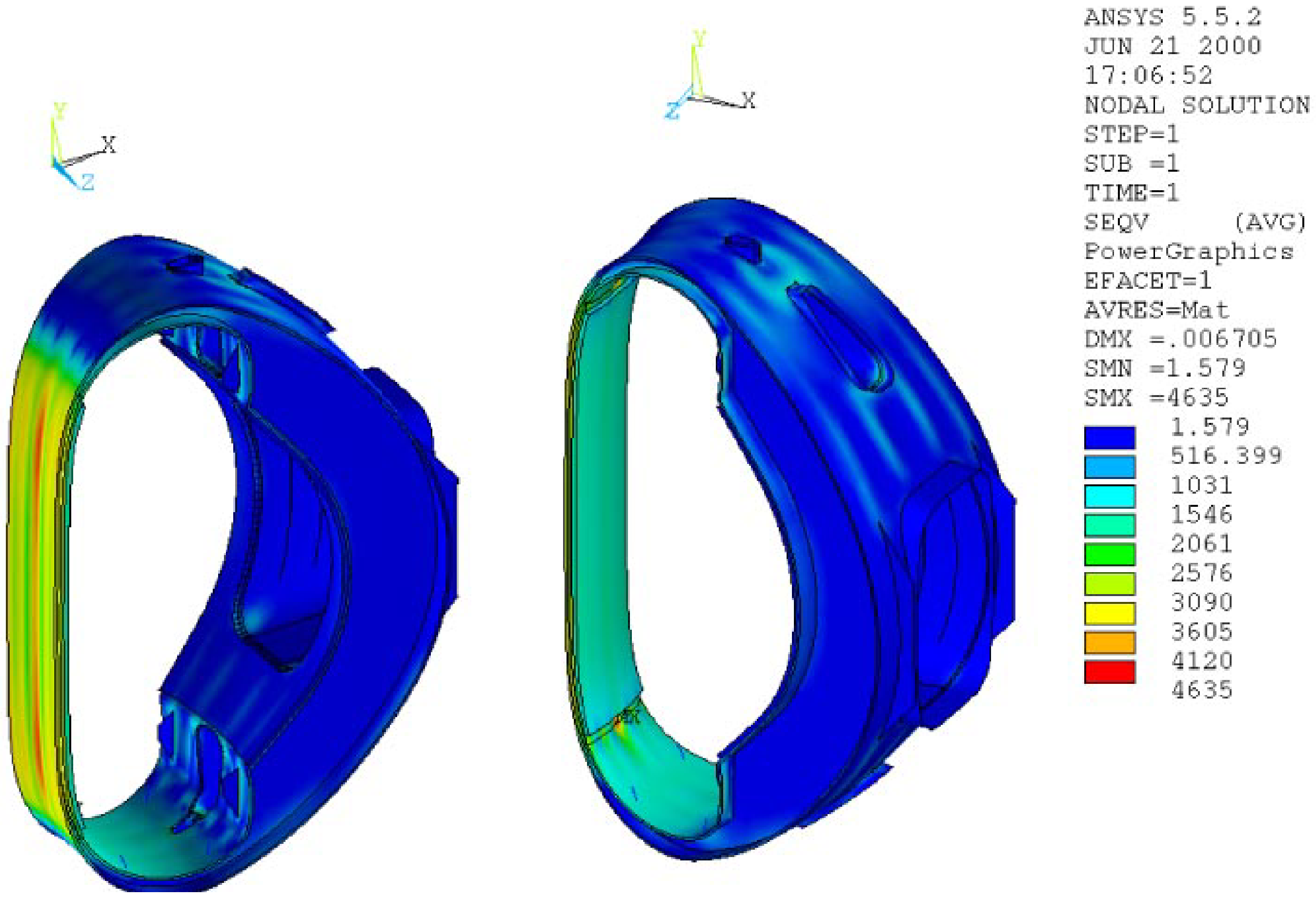
- **Model prepared by HM Fan**
- **64 poloidal ribs inboard, 64 poloidal ribs outboard**
- **thickness of elements assumed**
  - 15 mm for vessel facesheets,
  - 30 mm for port at midplane,
    5 mm for port above/below
    plane,
    idal ribs,
  - 30 mm for OB ribs at supports



*** Ref H.M. Fan**

VV stress from TF ramp

- **TF ramp to full current in 20 seconds**



Disruption effects on VV

- **Disruptions will cause high loads on the VV due to induced currents and conducting (halo) currents flowing in structures (No thermal effects are expected for VV)**
  - 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)

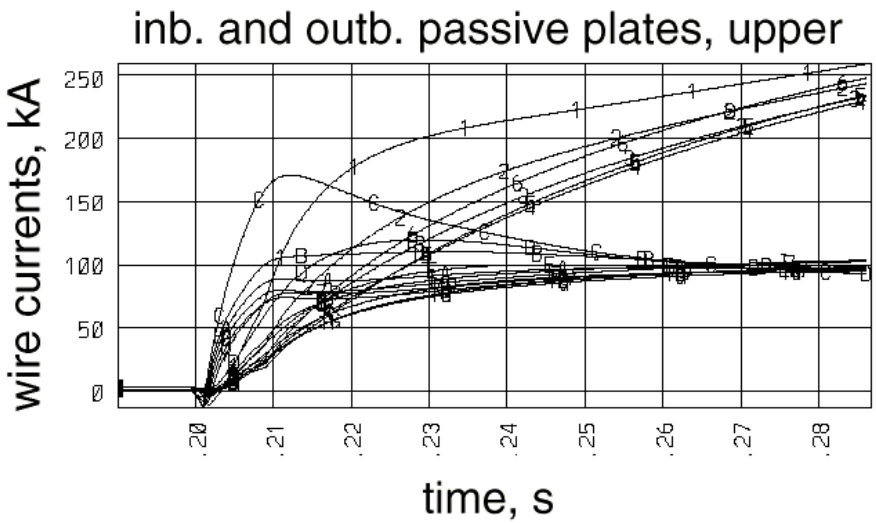
- **Dynamic effects should be considered, including:**
  - Load reversal during the event
  - Shock loads due to gaps in load paths

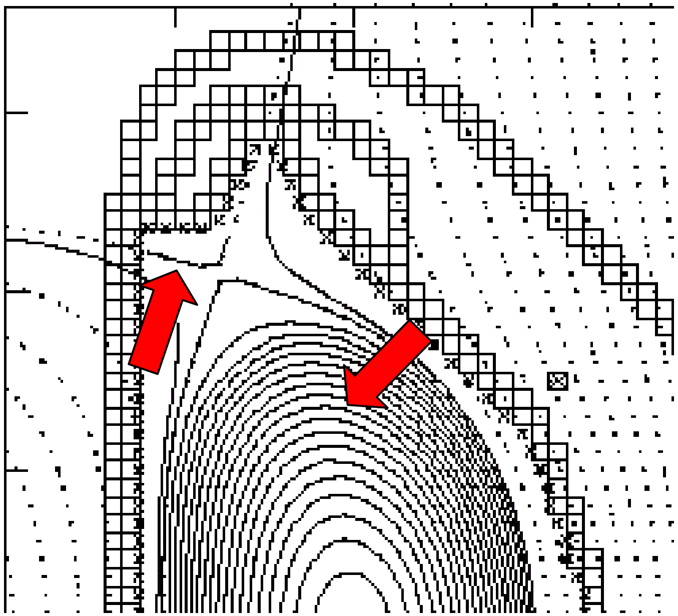
- **All loads should be considered in appropriate combinations**

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

Induced currents / loads will concentrate in passive structures

- **Centered disruption simulation (C. Kessel) shows current and field direction**





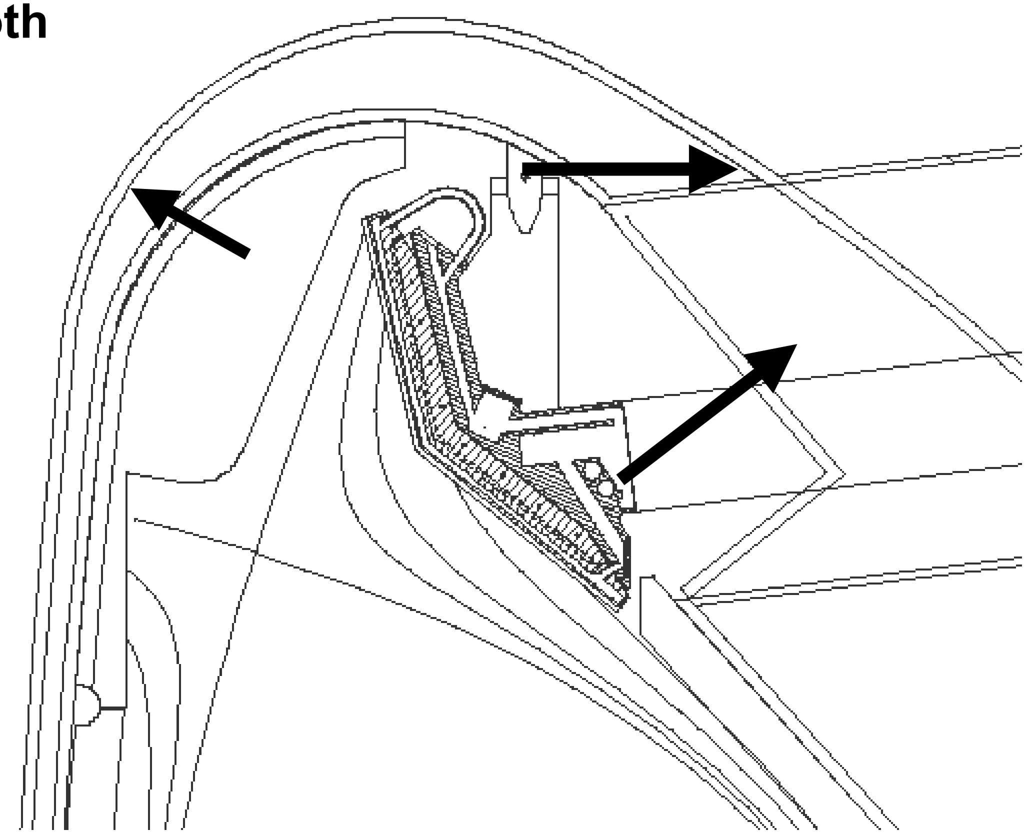
Parameter		IB passive plate	OB passive plate
Est. induced current	(kA)	1500	800
Bpoloidal (assumed)	(Tesla)	1	1
Pressure	(Mpa)	3	1.6
Direction		“shear”	“normal to surface”

Halo loads on divertor

- **Force towards the VV on both inboard and outboard sides**

- **total force = 0.8 MN OB***
  = 0.3 MN IB*

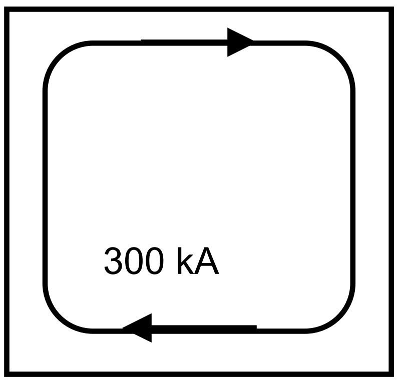
**ref M.. Ulrickson*

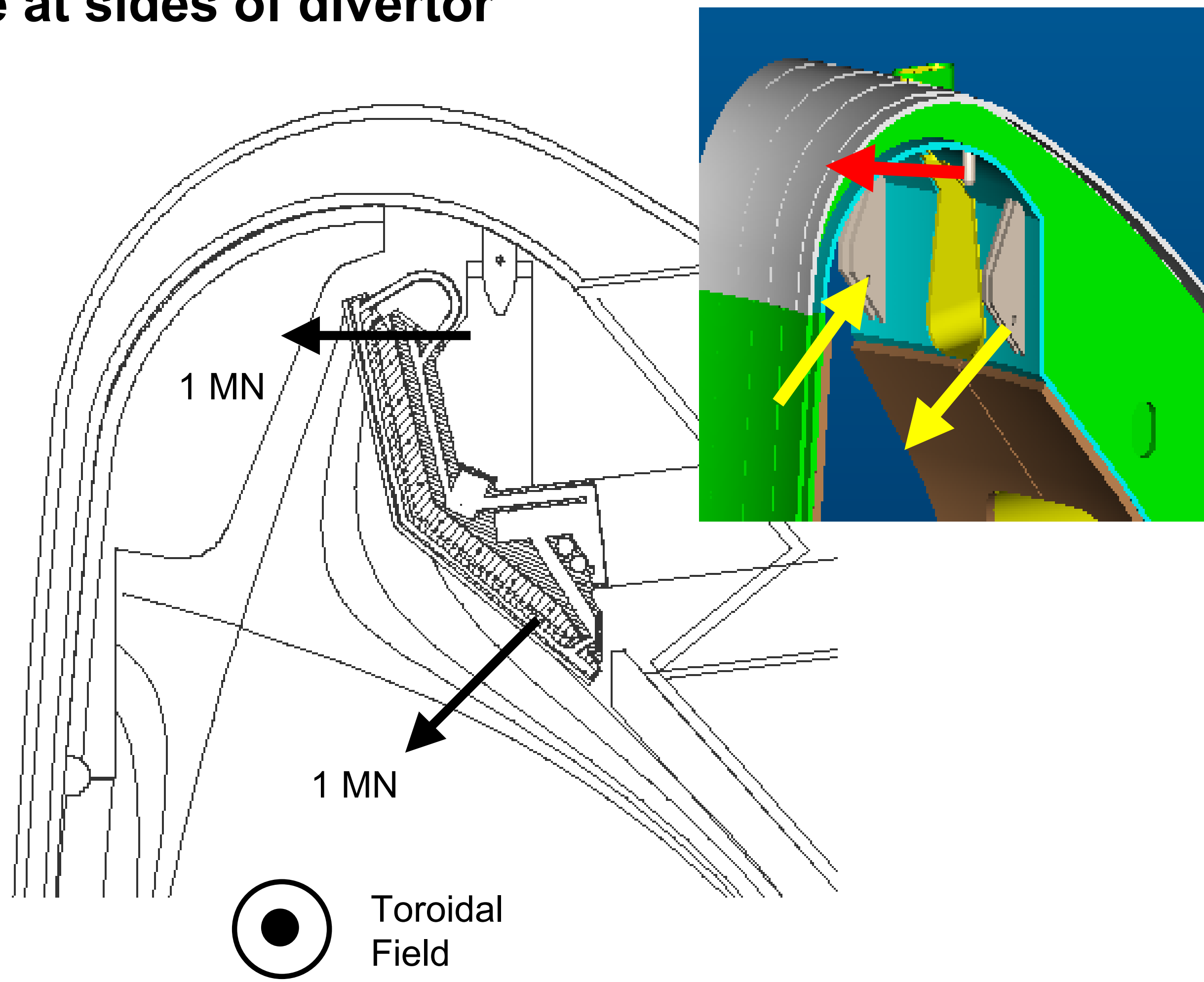


Divertor loads from current loop

- **Loads reverse at sides of divertor**

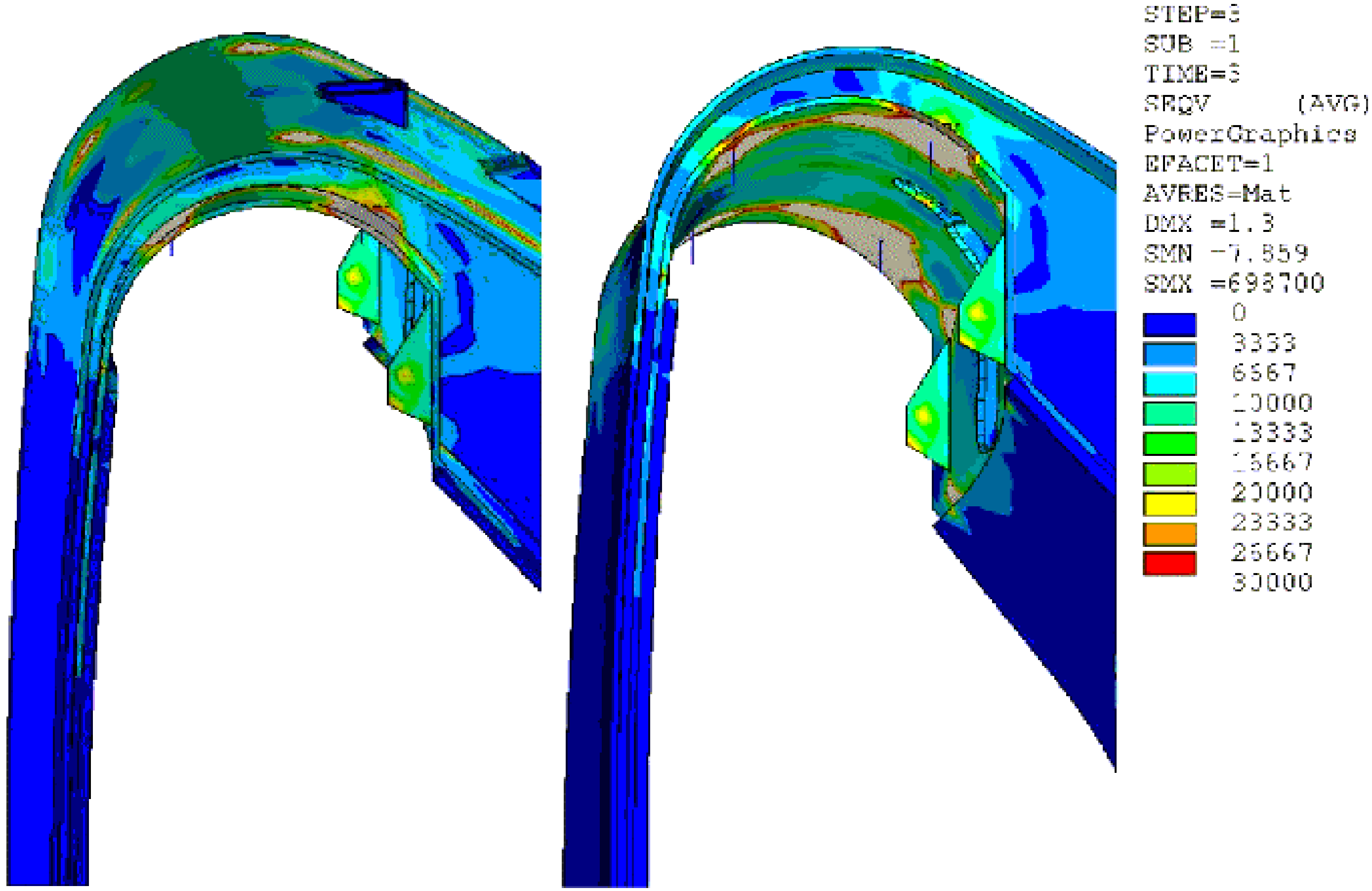
**ref M.. Ulrickson*





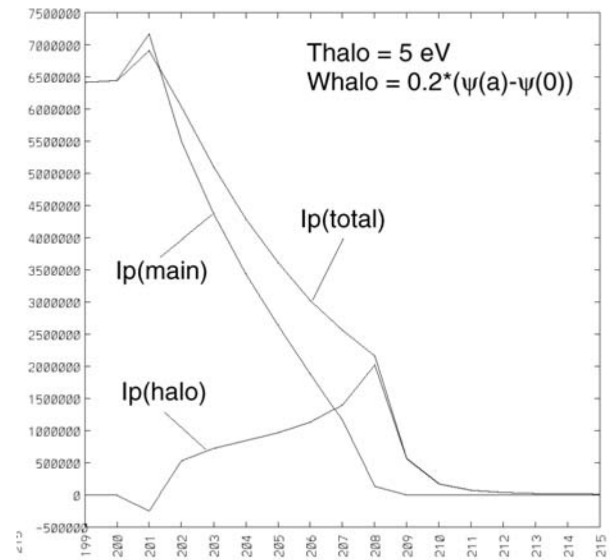
Stresses from divertor halo loads

- **High stress around pins, > 30 ksi**



Halo currents in vessel

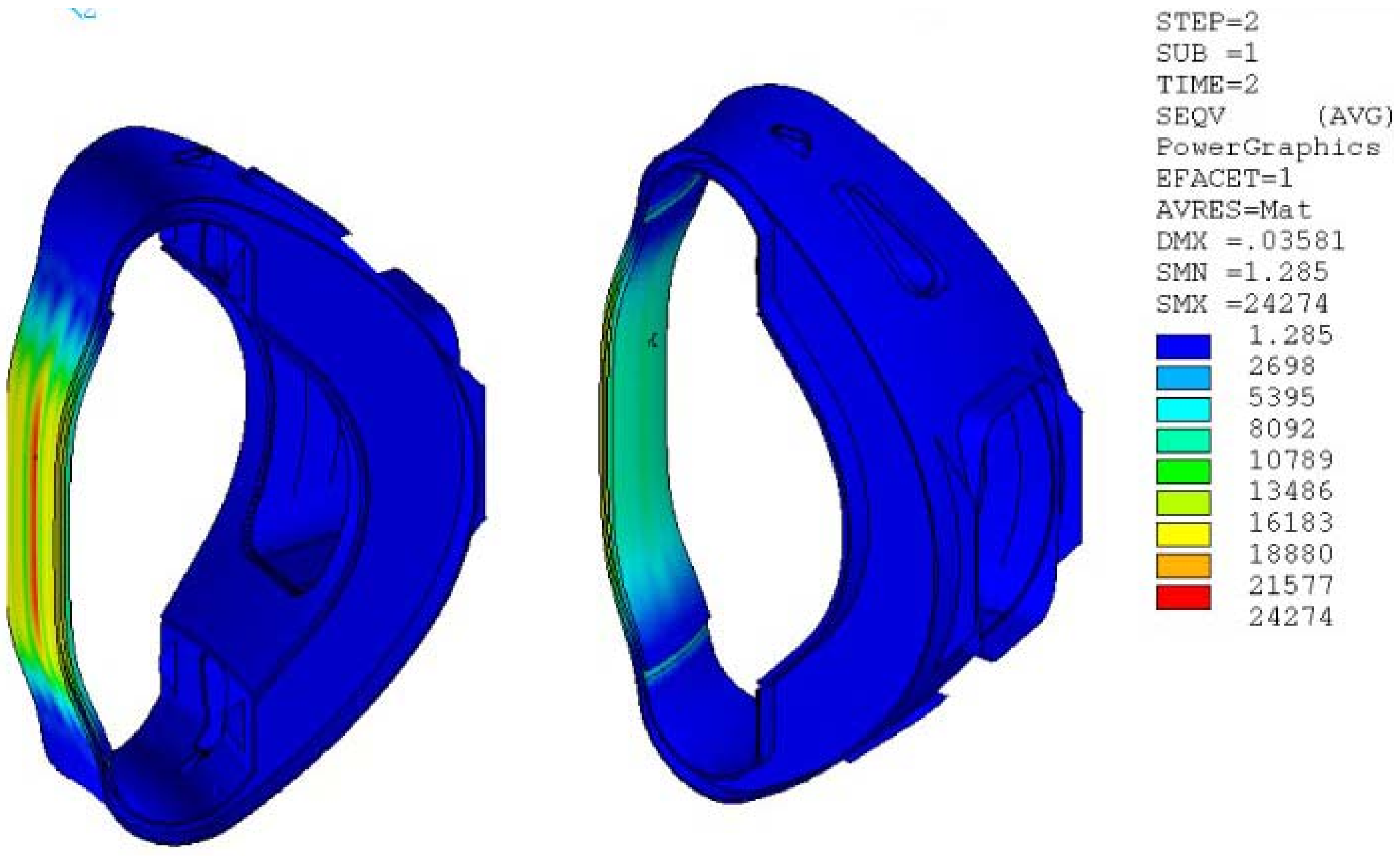
- **Ip assumed to be 6.55 MA**
- **From C. Kessel, I halo = 2 MA**
- **From Wesley, I halo < 0.4 x Ip = 2.6 MA**
- **Max toroidal peaking factor = 2**
- **Max I halo < 0.75 Ip**



Parameter		**Inboard**	**Outboard**
Avg radius of wall	(m)	1.3	2.6
Current density, J = Ih/(2*pi*R) w/o TPF	(MA/m^2)	0.25	0.125
Jmax = 2 x Javg	(MA/m^2)	0.5	0.25
Btoroidal	(Tesla)	16	8
Pressure on wall	(Mpa)	~ 8	2

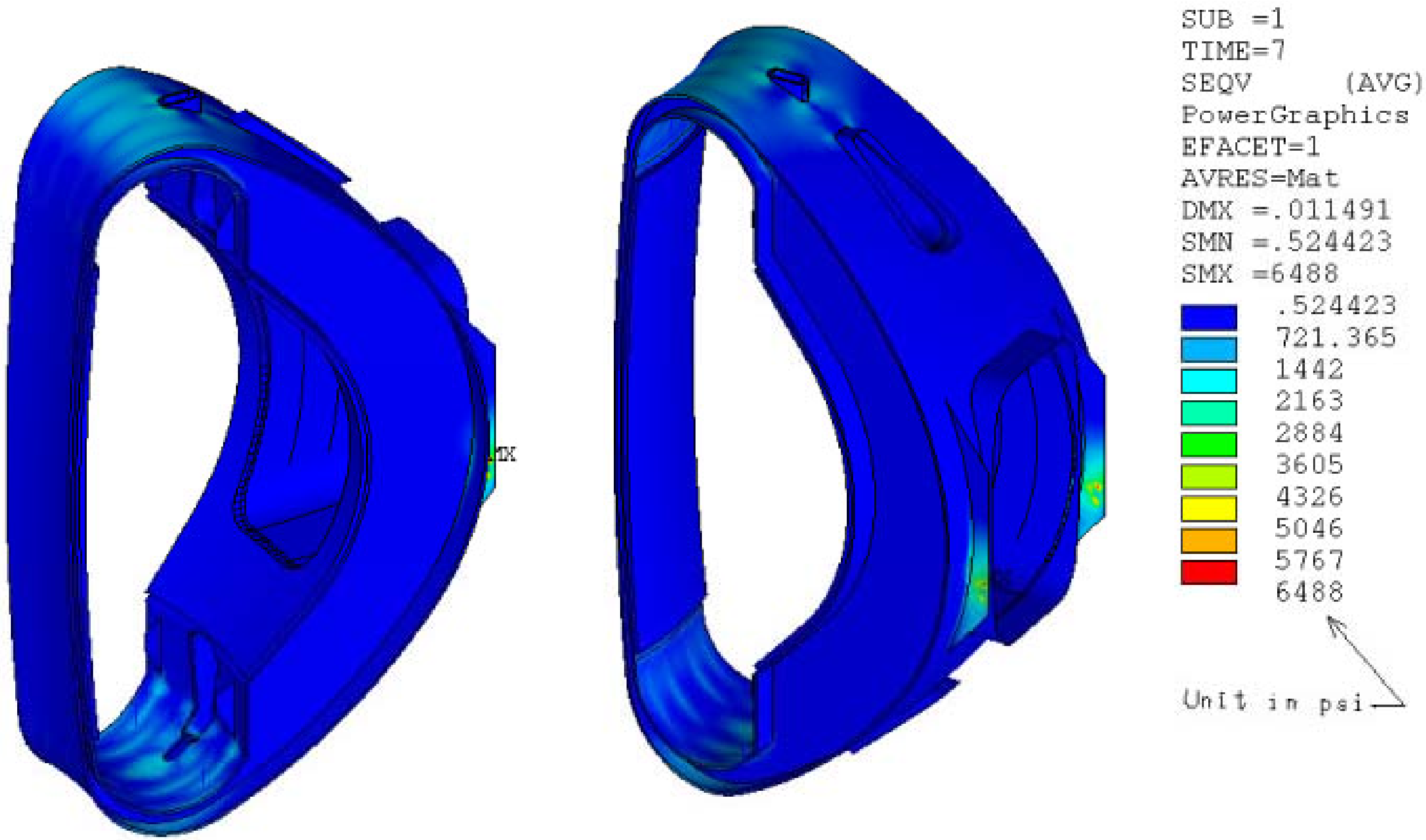
Stress on IB wall from halo

- **Symmetric loading assumed, 4 MPa applied pressure over central region**



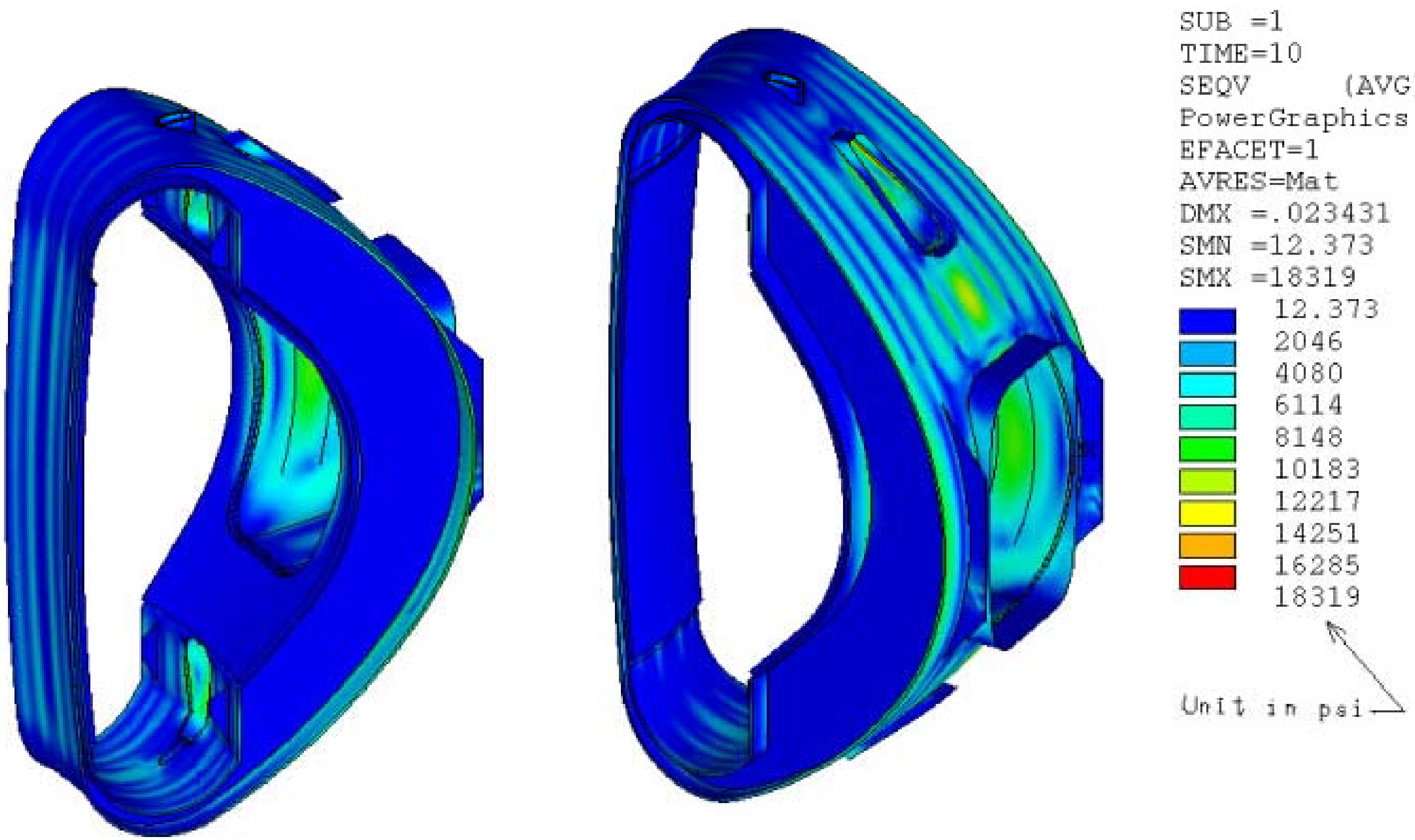
Gravity loads / VDE est.

- **Vertical load = 3.5 MN incl. internals, nominal stress ~ 4ksi, peak = 6.5 ksi**
- **VDE loads = 38 MN vertical, 13 MN lateral incl. dyn amp factor of 1.2**



Combined stress, start of pulse

- **Stresses due to TF ramp, gravity, coolant pressure, vacuum**



Nuclear htg and thermal effects

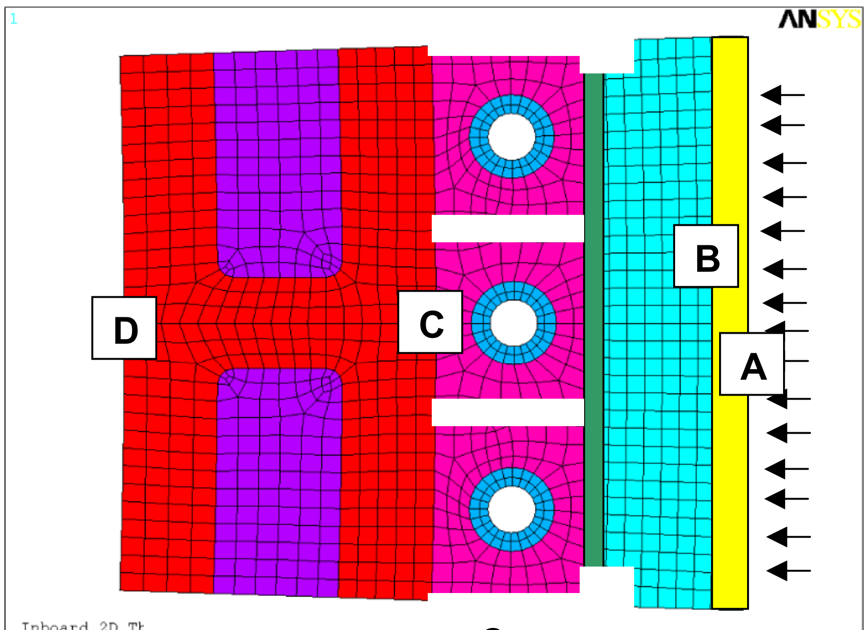
- **Vacuum vessel is subject to two basic heat loads:**
  - Direct nuclear heating from neutrons and gammas
  - Heating by conduction from first wall tiles (which in turn are heated by direct nuclear heating and surface heat flux)

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

- **Fusion power of 200 MW**
- **Surface heat flux is variable, but 100 W/cm^2 is assumed**



Double wall VV

Cu cladding

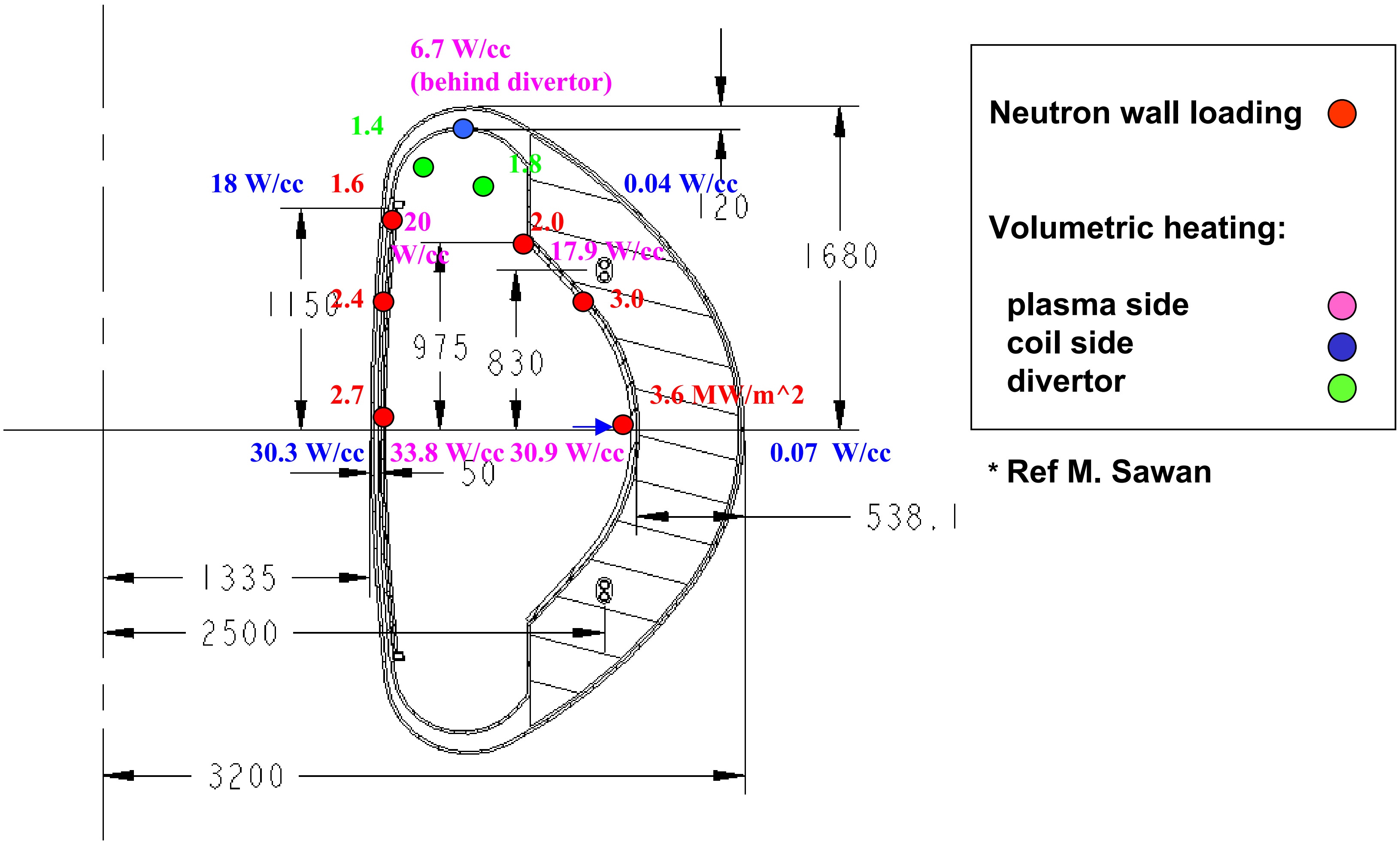
Tile

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

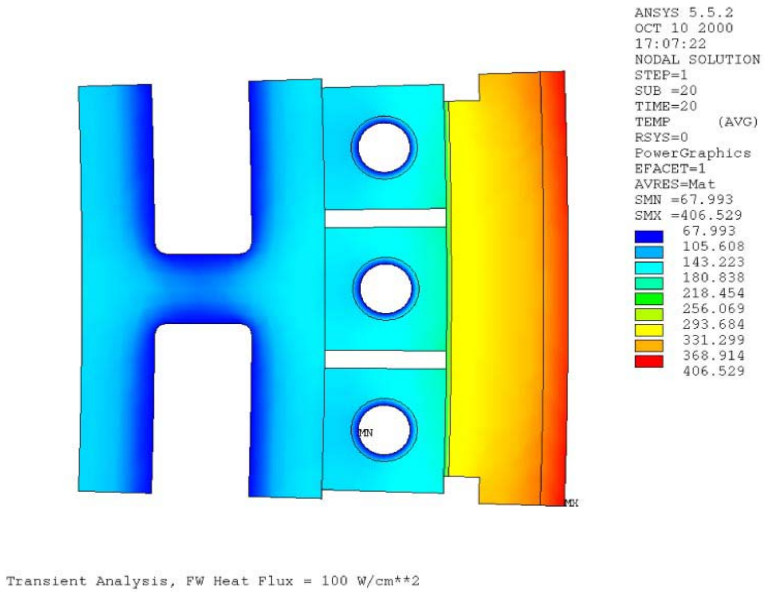
* ref M. Sawan

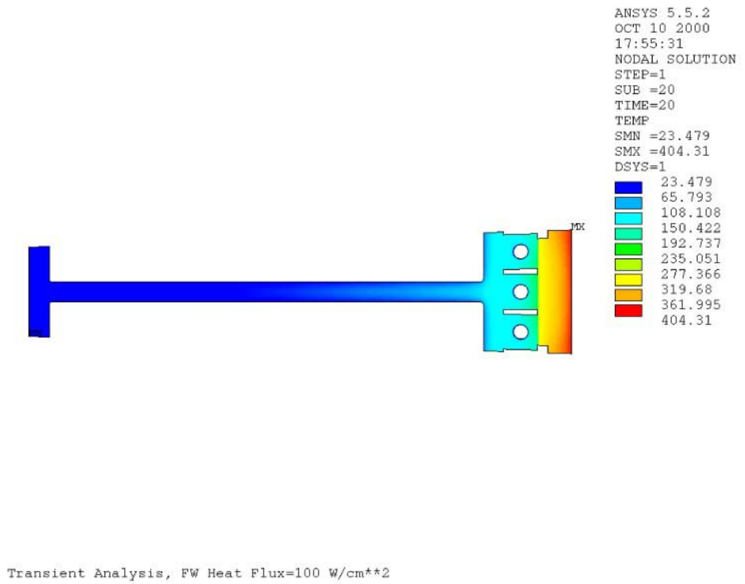
Nuclear heating distribution*



* Ref M. Sawan

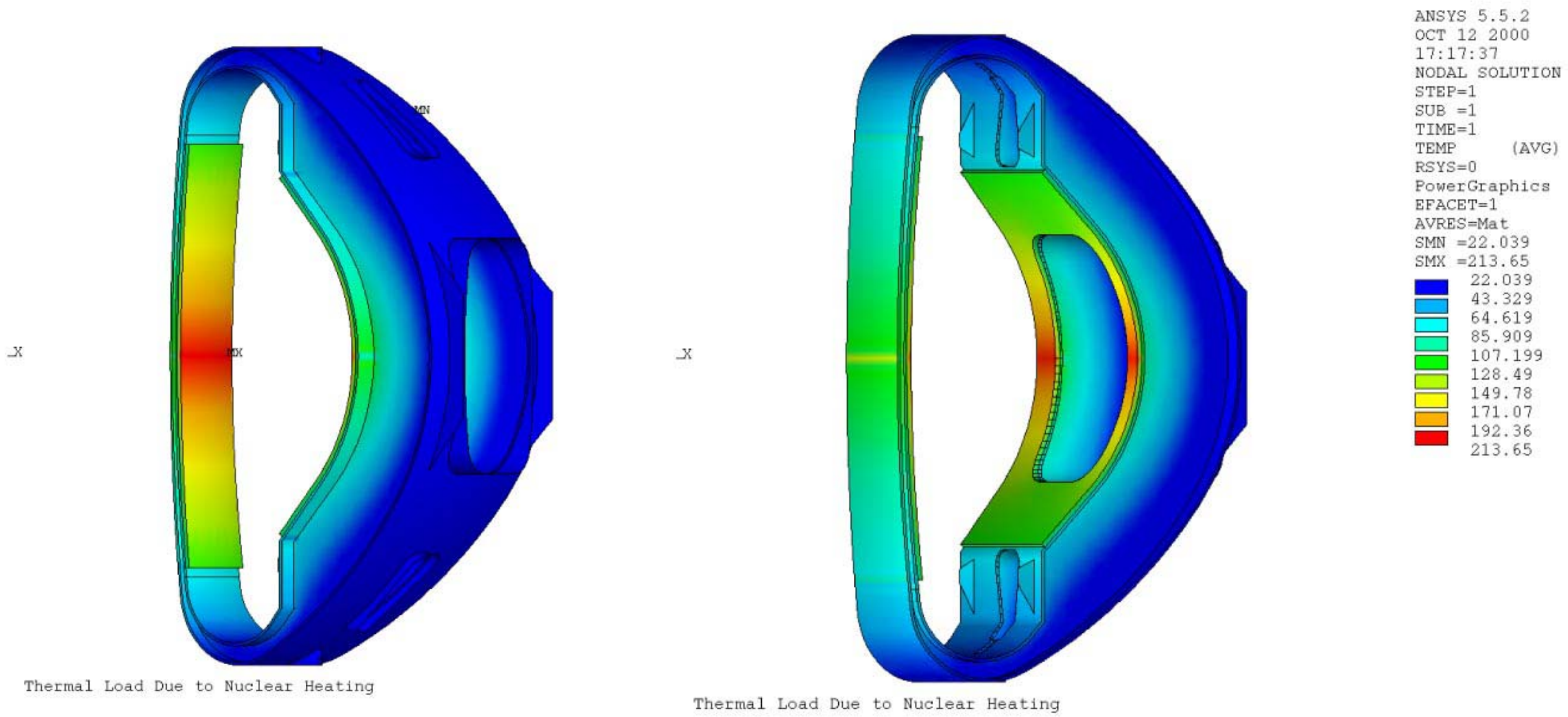
2-D temp distr after 20 sec pulse



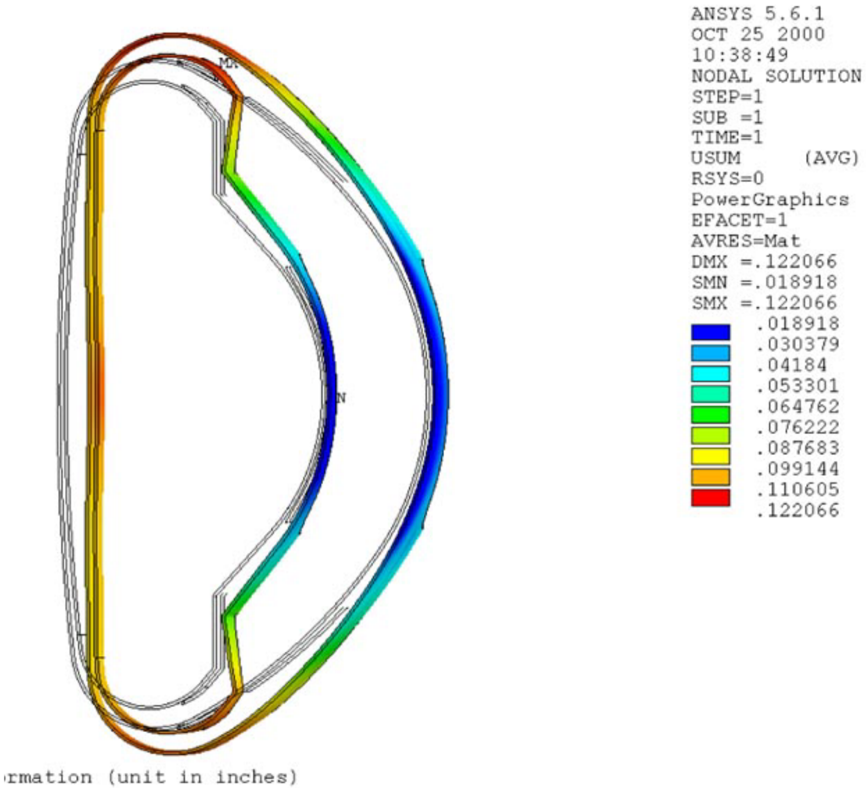


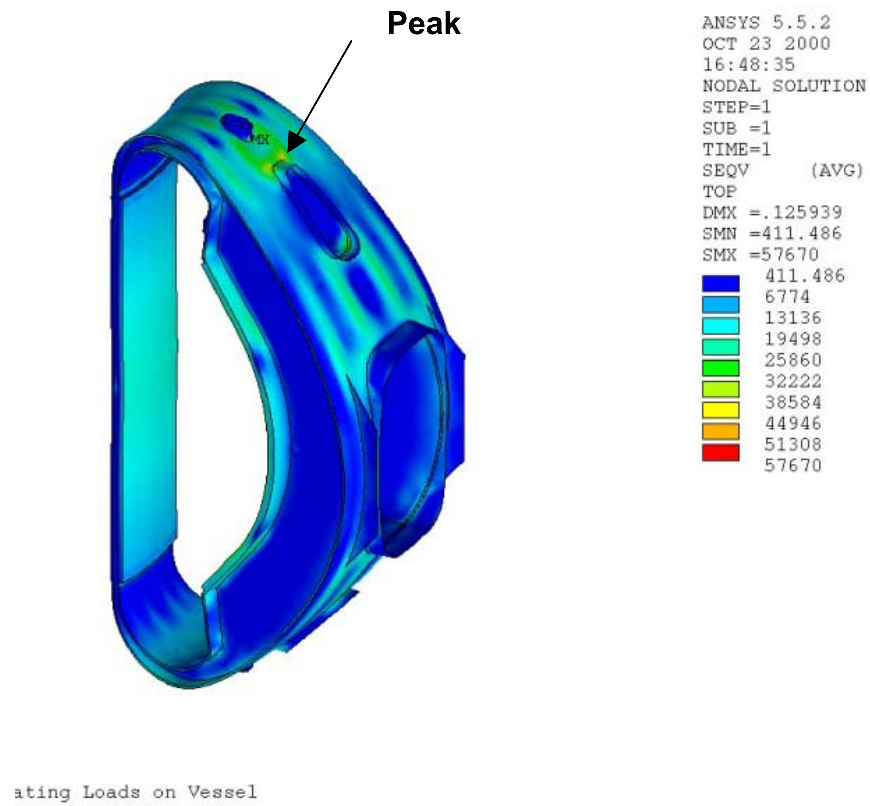
Inboard midplane **Outboard midplane**

3-D temp distr in VV after 20 s



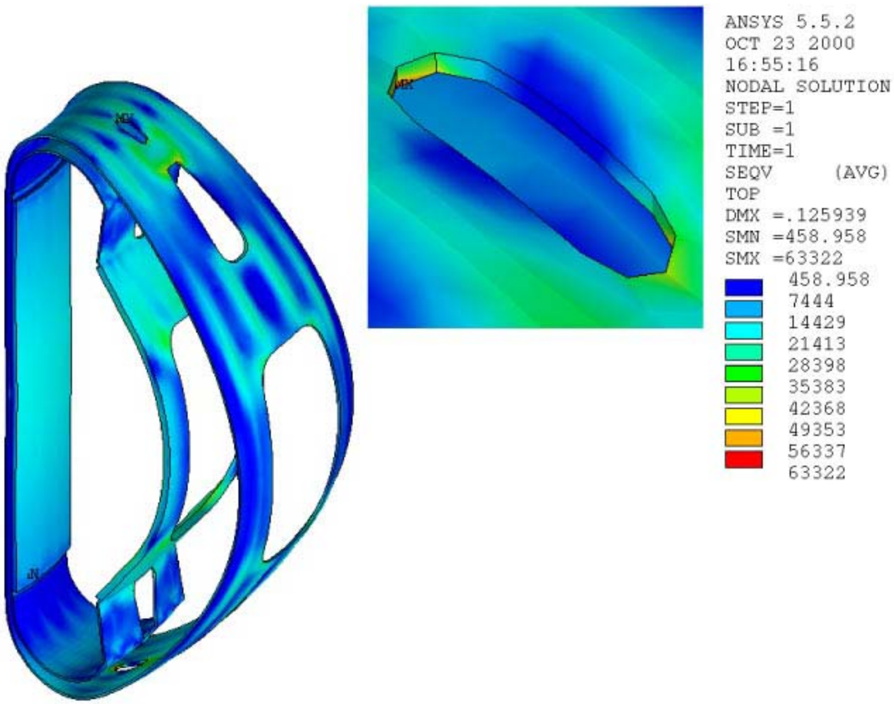
VV thermal deformation and stress



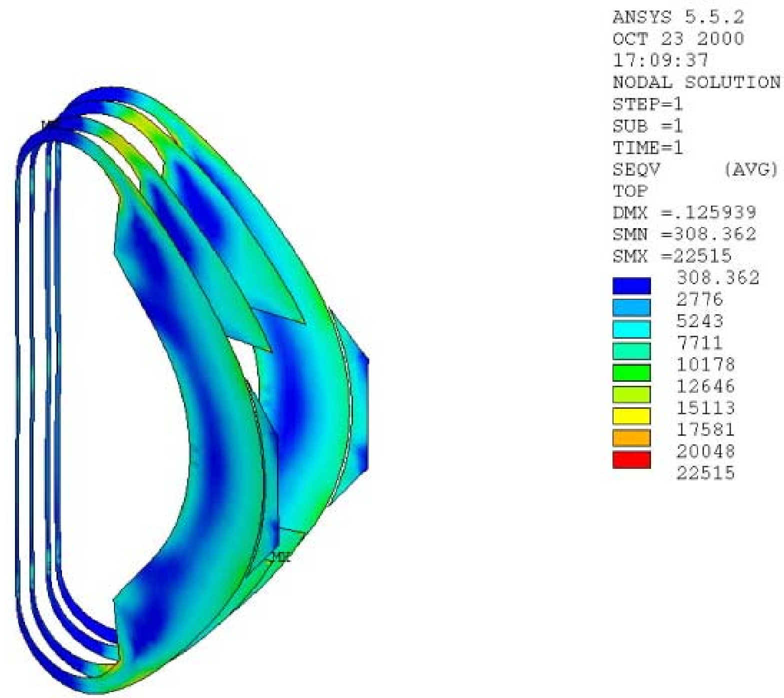


deformation **stress**

VV thermal stress in skin and ribs



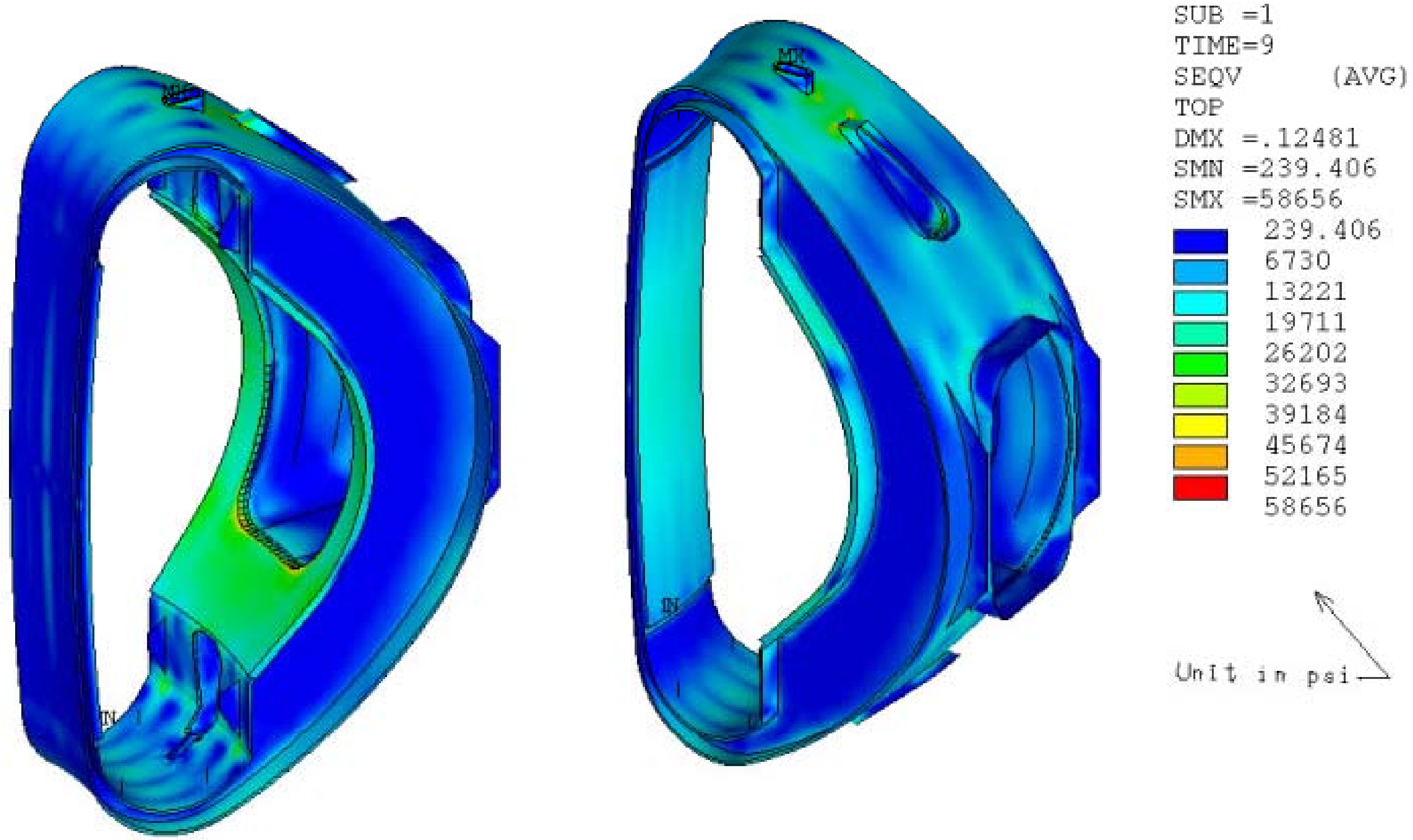
skin



ribs

Combined stresses, 20 s pulse

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



Preliminary VV stress summary

Load condition	Torus and support points: General stress[a] (allowable stress = 195 MPa)	Torus and support points: Peak local stress[a] (allowable stress = 390 MPa)	Ports and (Support points): General stress (allowable stress = 195 MPa)	Ports and (Support points): Peak local stress[a] (allowable stress = 390 MPa)
1. Gravity (w/internals)	15	23	(24)	(45)
2. Vacuum load	~10	~25	TBD	TBD
3. Coolant pressure[b] (1 MPa)	~100	~130	TBD	TBD
4. Simulated VDE[c]	<100	~240	(~ 300)	(~400)
5. Halo Loads on divertor	120	170	(~150)	(>400)
6. Thermal stress from nuclear heating[d]	170	300	<200	~330
7. TF ramp-up[e]	~ 25	~ 32	TBD	TBD
Combined, 1,2,3,7	83	124		
Combined, 1,2,3,6		240		400

[a]Estimated demarcation between general and peak local stress, peak primary + secondary = 3 × Sm.

[b]Stress values estimated from previous analysis

[c]VDE loads applied in simplified manner as body force, supports on outside.

[d]Temperature gradient of ~90°C based on 20-s full-power pulse, simulated temperature distribution.

[e]Stress estimate based on 20 s current ramp in TF coils

Vacuum vessel design issues

- **Thermal stresses vs pulse length**
- **Disruptions**
  - Load definition
  - Divertor supports
  - Vessel supports
- **Passive stabilizing conductor integration / fab**
- **Concepts are being developed for:**
  - Divertor interface
  - Vertical and lateral supports

Summary

- **Double wall vessel is appropriate for requirements**

- **Mechanical design and analysis indicate**
  - 15 mm facesheets ok with 1 Mpa limit for coolant pressure (with port reinforcement)
  - 64 inboard and 64 outboard ribs
  - large midplane ports have limited tangential access
  - trapezoidal ports used for both divertor cooling and pumping
  - active coils buried in VV walls looks feasible
  - passive plates bonded to VV surface also provide FW heat sink

- **Issues being addressed include:**
  - Disruptions / stresses / in-vessel component attachments / VV supports
  - Thermal stress vs pulse length