Structural Analysis of the Advanced Divertor eXperiment's Proposed Vacuum Vessel

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Abstract: COMSOL Multiphysics has been used to predict loads and stresses on the vacuum vessel in the initial design for the Advanced Divertor eXperiment (ADX). ADX is a compact high field, high power density tokamak (a device used to study magnetic confinement of plasma for nuclear fusion) proposed by Plasma Science and Fusion Center (PSFC) and collaborators to test divertor configurations at the power densities of next step fusion devices.

The ADX vacuum vessel is designed as 5 Inconel shells and a central cylinder that can be bolted together. This unique design provides flexibility to change the coil configuration if needed to produce new divertor shapes. COMSOL has been used to simulate a disruption, where the plasma loses both its position and current in a few milliseconds, that results in eddy currents, Lorenz forces and stresses in the conductive vessel. These are all predicted by the model and reinforcements must be introduced to ensure the design can withstand these stresses.

Keywords: Lorenz force, tokamak,

1. Introduction

A tokamak is a device that uses magnetic confinement to study plasma. The ultimate goal of a tokamak is to use high magnetic fields to confine the intense plasma and produce nuclear fusion that can be used for power generation. Fig. 1 shows the proposed ADX tokamak. Current is input to the magnetic field coils to produce a “magnetic bottle” that will confine the hot plasma. Fusion power is dependent on the performance of the core plasma which is strongly tied to the strength of this magnetic field. Recent advances in high temperature superconductors could allow us to design a tokamak at higher magnetic fields, and running at these higher fields would increase the performance of the plasma to reactor levels [1]. The focus of research would then switch from improving plasma performance to the support systems in the tokamak

New physics and technology solutions for power exhaust and plasma material interaction are needed for next step fusion devices. Any proposed solution should be tested at the same performance and conditions that would be expected in a reactor. To this end, reactor level heat fluxes and magnetic fields can be attained in a compact high field tokamak that can be used as a test bed for testing this new technology without building a full scale reactor. The Plasma Science and Fusion Center at MIT and collaborators are proposing such a machine, the Advanced Divertor eXperiment (ADX) [2].

ADX is a new high field (>6.5 tesla) high power density tokamak specifically designed to accommodate testing of new technologies for fusion.

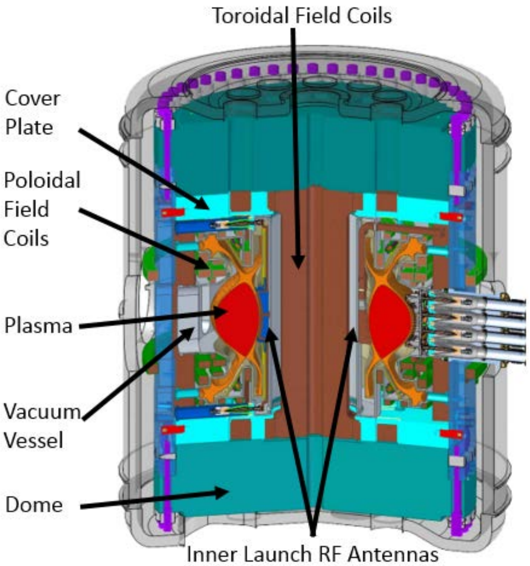


Figure 1: Cutaway of ADX Geometry with plasma shown in vessel

One focus of the ADX is exploring new concepts for the divertor. The divertor functions to accept heat and particle fluxes that escape the magnetic bottle holding the core plasma and guide them to be pumped out of the vessel. The ‘vertical target plate’ divertor, used on the PSFC’s Alcator C-Mod and included in the design for ITER, has demonstrated the ability to handle high power densities, but it is still not good enough for a fusion reactor. The exhaust power densities of a reactor will greatly exceed those of present experiments, so new and more advanced divertor concepts need to be developed and tested. [2] The ADX vacuum vessel is designed to accommodate a coil set capable of testing different divertor configurations (Fig. 2).

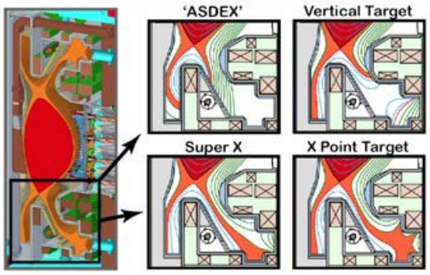


Figure 2: Four proposed divertor configurations possible with ADX coil set

In addition, a key innovation of the vacuum vessel design is that instead of being a single solid cylinder, it is comprised of five separate axisymmetric shells and an inner cylinder that are bolted together to form the vacuum vessel [3].

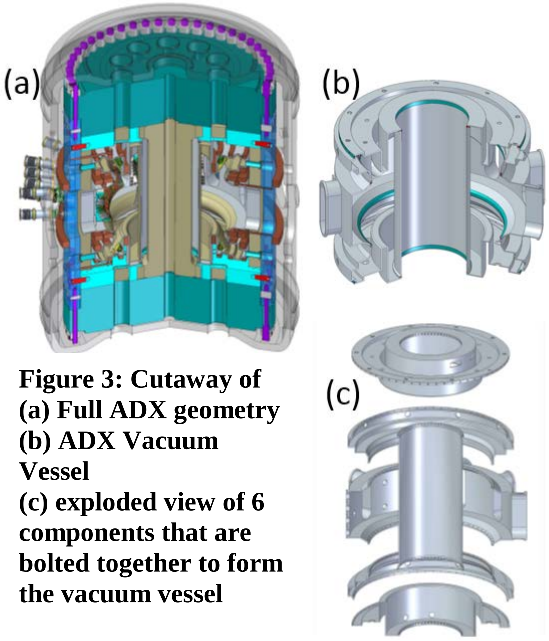


Figure 3: Cutaway of (a) Full ADX geometry (b) ADX Vacuum Vessel (c) exploded view of 6 components that are bolted together to form the vacuum vessel

This approach provides the flexibility to change the coil set to create different divertor shapes should it be deemed necessary. It also provides the advantage of being able to install the in-vessel components to each of the shells before the vessel is assembled increasing safety and reducing assembly time [3].

One structural requirement of the new vacuum vessel is that it can survive a plasma disruption. A disruption occurs when control of the plasma is lost, the plasma current and position evolve very quickly and the plasma is lost in a few milliseconds. This rapid change of position and current in the plasma results in rapidly changing magnetic fields around the plasma. These changing fields cause eddy currents in the surrounding conductive structures, like the vacuum vessel, which create Lorenz forces in the structures due to these currents crossing the magnetic fields. The Inconel© 625 vessel must be able to withstand these loads with an allowable limit of 2/3 yield for membrane stresses. Inconel© 625 is a high strength material with a high electrical resistivity that will reduce the magnitude of the induced eddy currents.

Inconel 625 Properties			
Young's Modulus	Yield Strength	2/3 Yield	Electrical Resistivity
207 GPa	460 MPa	306 MPa	1.29E-6 Ωm

Table 1: Inconel 625 Properties

Additionally, the bolted joints must stay closed, and so we must ensure that the load the bolts will carry due to a disruption will not exceed the preload.

2. COMSOL Modeling

The COMSOL model is broken up into two physics interfaces. First, the magnetic fields, eddy currents and Lorenz forces are predicted with a cyclic symmetry model of the ADX vessel and coils using the magnetic field (mf) physics interface. Then the loads are applied to a model of the vessel using the 'solid mechanics' physics interface to predict stresses and displacements.

2.1 Magnetic Fields Model

The magnetic fields model is a 36^{o} cyclic symmetry model of ADX including the vessel, poloidal field coils and plasma. Similar models were successfully used to predict loading on the inner wall RF antennas designed for ADX [4]

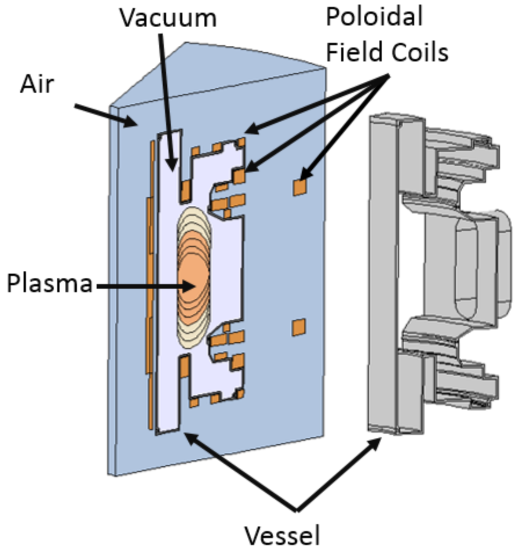


Figure 4: Geometry for cyclic symmetry model used in COMSOL

A plasma disruption is simulated with this model to predict the fields, currents and loads that will result. A vertical displacement event (VDE) disruption where the plasma drifts upward from the midplane before losing all its current during the current quench is chosen as the design scenario. The vessel should see larger eddy currents and loads in this scenario due to the plasma moving closer to the vessel so that it sees higher fields and a higher rate of change of field due to the disrupting plasma.

The plasma current is 1.5MA in the design scenario for ADX, and the poloidal field coil currents that will produce a magnetic equilibrium are provided from an ACCOME solution [1], [5]. Both the plasma current and coil currents are input to COMSOL as external current densities.

The VDE can be divided into two parts, the plasma movement and then the current quench. The plasma movement, when the plasma centroid moves away from the equilibrium position, is modeled by building a stack of plasmas vertically, seen in Fig. 4, and then changing the current density in each volume to simulate the plasma moving upwards. The dark orange section shows the plasma in equilibrium, and the lighter orange sections show volumes that the plasma can move into. This is done by creating a different interpolation table for each plasma volume with a different time history of current so that the plasma current shifts upwards, as seen in Fig 5.

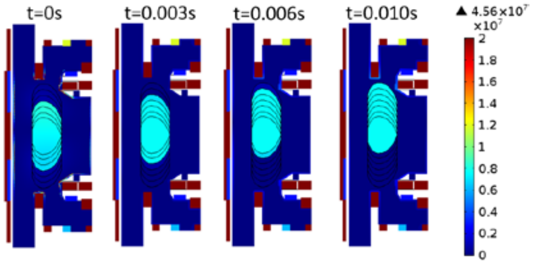


Figure 5: Plot of Current Density (A/m^2) in ADX during the VDE. Changing which volumes are carrying current simulates the plasma moving upwards.

After the plasma rises (or falls) it then rapidly loses all of its current. The plasma current drops from 1.5MA to 0MA in 1 ms as seen in Fig 6.

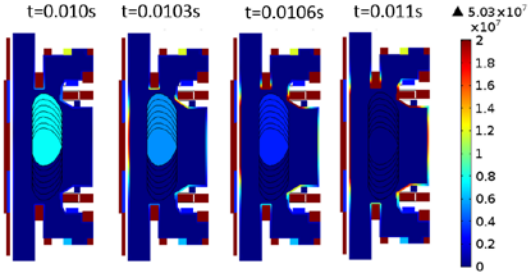


Figure 6: Current Density (A/m^2) during the current quench. Plasma current drops from 1.5 MA to 0 MA in 1 millisecond

This rapid change in current causes a rapid change in magnetic field in the surrounding area. Fig. 7 shows a contour plot of the poloidal flux at equilibrium (t=0) at the end of the plasma rise (t=0.010s) and at the end of the current quench (t=0.011s).

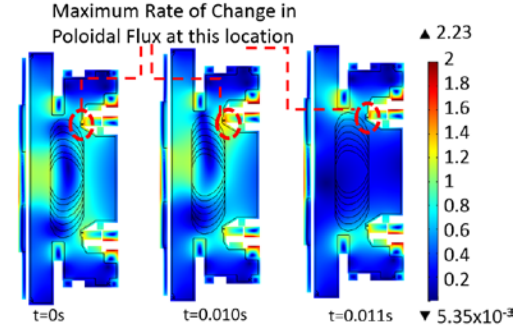


Figure 7: Contour plot of Poloidal Flux Density (T) during VDE.

Fig. 8 plots a time history of flux at the location of most rapid change. Note the flux rising as the plasma moves up towards this location followed by the sharp drop in field when the plasma loses its current.

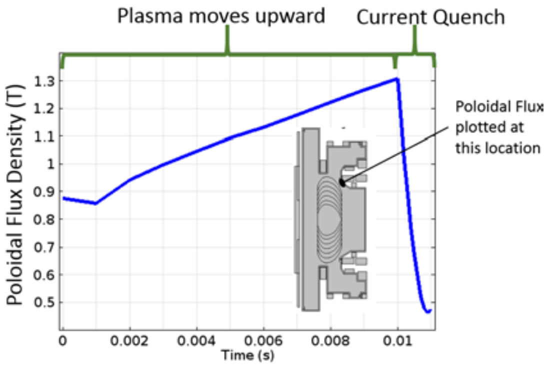


Figure 8: Time history of Poloidal Flux at location of largest change

This rapid change in magnetic fields causes eddy currents in the surrounding conductive structures due to the voltages induced by the changing fields.

$$\varepsilon = -\frac{\partial \phi}{\partial t}$$

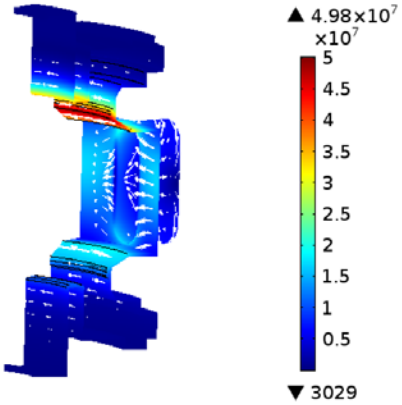


Figure 9: Eddy Currents (A/m^2) generated in ADX vessel. Currents are largest at the top of the vessel where the plasma is located during the current quench and travel in the toroidal direction while flowing around the port

These eddy currents will cross the remaining magnetic fields causing Lorenz forces in the vessel.

This cyclic symmetry model predicts the poloidal fields in ADX, but the highest magnitude field is the toroidal field that is generated by the toroidal field (TF) coils. The toroidal field is highest at the ID of the vessel, decays as 1/r as it moves radially outward, and remains constant throughout the disruption. A separate model is built of the entire 120 turn TF coil to predict the field and field distribution.

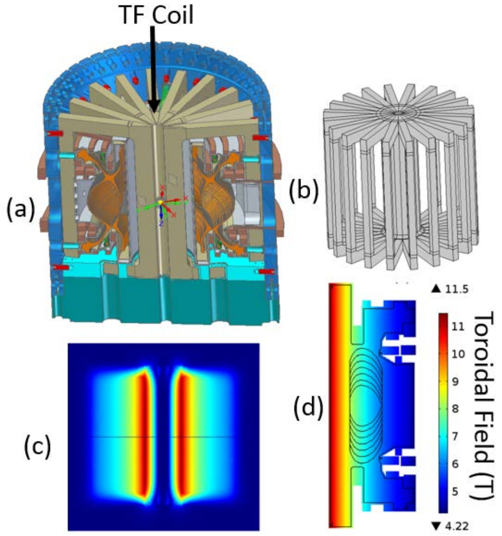


Figure 10: (a) TF Coil shown in ADX Vessel (b) Full TF Coil Model used in COMSOL (c) B Field distribution predicted in TF Model (d) TF Field mapped to ADX Vessel model

The design criteria is that the toroidal field have a value of 6.5T at the center of the plasma (r=0.73m), so the coil current is set to match that criteria. The TF in the vessel varies as a function of radius, so once the field distribution is computed in COMSOL, a table is created with the TF as a function of radius which is then read into the structural model to compute Lorenz forces.

2.2 Solid Mechanics Model

The poloidal fields and eddy currents are read from the solution of the magnetic fields model. These fields and eddy currents, along with the toroidal field table can be used to calculate the Lorenz forces acting on the vessel.

$$\boldsymbol{F = J \times B}$$

$$\begin{bmatrix} F_x \\ F_y \\ F_z \end{bmatrix} = \begin{bmatrix} mf.Jx \\ mf.Jy \\ mf.Jz \end{bmatrix} \times \begin{bmatrix} mf.Bx \\ mf.By + B_{ToroidalTable}(r) \cdot \cos(\theta) \\ mf.Bz + B_{ToroidalTable}(r) \cdot \sin(\theta) \end{bmatrix}$$

Only the vacuum vessel is included in the solid mechanics model. The sides of the vessel are allowed to move only in the radial and vertical direction to simulate cyclic symmetry. The vessel is held fixed at the top and bottom surfaces where it is in contact with the cover plate.

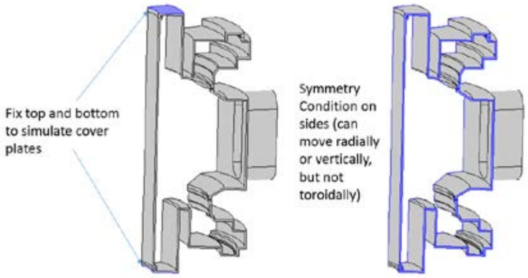


Figure 11: Boundary conditions for structural model

The results of the structural model of the vessel with loads corresponding to the 1.5MA plasma/6.5T toroidal field design point reveal that some modifications will be necessary to reinforce the vessel. As designed, the upper and lower pockets of the vessel that contain many of the poloidal field coils has very little support and little stiffness. During a VDE, the plasma moves closer to this area and when it disrupts, large eddy currents and loads are induced here. These large forces lead to large stresses approaching yield and a maximum deflection of more than 1 cm.

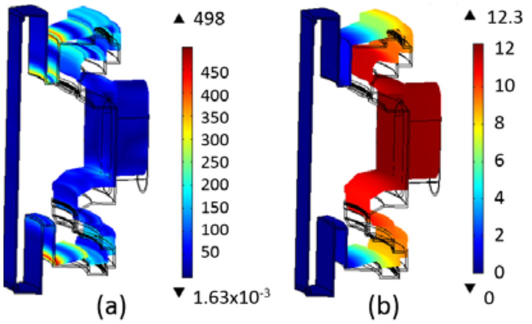


Figure 12: (a) Von Mises Stress (MPa)
(b) Deflection (mm)
Deformation plotted 10x

Both of these results are unacceptable, so COMSOL has been used to analyze the effect additional restraints would have on the design.

The natural place to add a restraint is in the gap between the vessel and the cover plate above the poloidal field coil pocket. The gap between the vessel and the cover plate can be filled by an Inconel spacer block so that the rear pocket receives the same support as the ID of the vessel, as shown in Fig. 13.

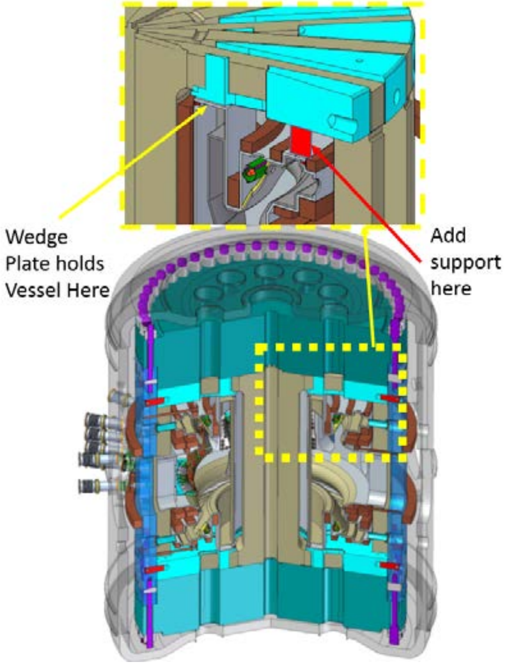


Figure 13: Add support block to reinforce the OD section of the top of the vessel

This block will need to accommodate waveguide runs and leads for RF launchers located on the high-field, ID side of the vessel, but this can be done with cutouts and openings in the block. The block is simulated in COMSOL by adding a fixed boundary condition to the top surface of the coil pocket. As seen in Fig. 14

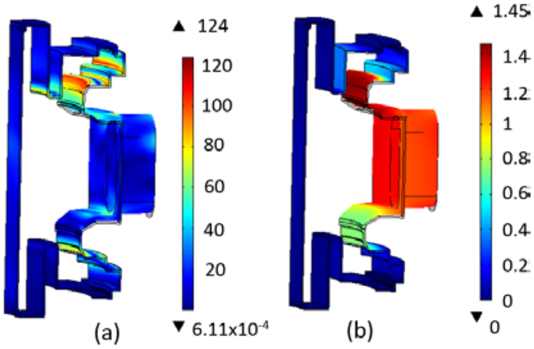


Figure 14: (a) Von Mises Stress (MPa)
(b) Deflection (mm)
Deformation plotted 10x

the addition of this block reduces the stress and deflection in the vessel to within allowable limits.

The design point for ADX is a 1.5 MA plasma with a 6.5 T toroidal field at the plasma center, which was determined based on the existing power supply infrastructure at the PSFC. However, with a power supply upgrade, the ADX could run with a 2MA plasma and an 8 T toroidal field at the plasma center. Fig. 15 shows the results of a structural analysis of the vessel at this high performance point.

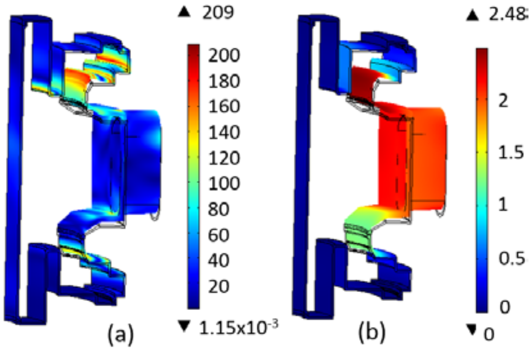


Figure 15: (a) Von Mises Stress (MPa)
(b) Deflection (mm)
Deformation plotted 10x

The stresses and displacements do rise as one would expect, but both remain within allowable limits.

COMSOL is used to examine additional restraints that could further reduce the vessel deflection. With the addition of the blocks between the vessel and cover plate, the maximum deflection is seen in the poloidal field coil pocket. The large ‘C’ shape in the design built to accommodate the coils provides little resistance to vertical forces. Connecting the back side of this opening from top to bottom would add more strength to the vessel and reduce deflection. An ‘Attachment’ boundary condition is added in COMSOL between the tops and bottoms of these openings to simulate a mechanical connection. This additional restraint reduces the max deflection in the vessel to less than 1 mm.

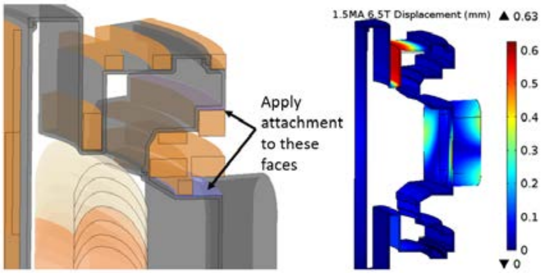
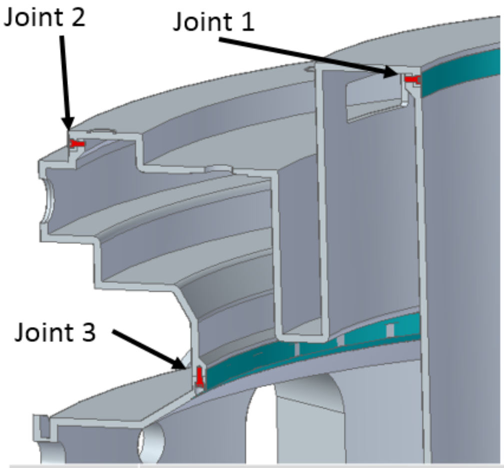


Figure 16: Deflection of the vessel with a proposed connection between the top and bottom of the coil pocket. Note that this is a preliminary analysis and this piece has not been designed.

Note that this mechanical connection has not been designed, and may need to run through the coils to connect the two parts of the cavity. If this is deemed necessary, models will be run to determine the loading on the coils and if they will be safe.

Now that we have established that, with additional restrains, the vessel can withstand the loads from a VDE disruption, we must do the same for the bolted joints. The segmented vessel and bolted joints that hold them together is a new innovation, so care must be taken to ensure the bolts will hold during a disruption. As designed, each flange between segments will be held together by 60 3/8” Grade 8 bolts. The bolts will be preloaded to 90% of yield, which for a grade 8 bolt is 35 kN. Integrating the stress on each joint in the COMSOL model of the vessel gives the load that the bolts will have to carry at that joint. The maximum tensile load seen by any joint is 110 MN. Dividing this maximum load by the bolt preload shows that the maximum load can be safely carried by 32 bolts without exceeding the preload, as shown in Fig. 17. Since ADX is designed to have 60 bolts per joint, the maximum load is below the bolt preload and so the bolted joints will be safe through a disruption.



Joint	Number of Bolts Required to Carry max Load During VDE
Joint 1	3
Joint 2	32
Joint 3	18

Figure 17: Bolted Joints at the top of the vessel will experience higher loads during the VDE disruption. 32 bolts are required to keep the load carried by the bolts below the preload for the maximum load seen during the VDE disruption. ADX is designed to have 60 bolts per joint.

This preliminary analysis does not include the effect of halo currents, which will likely increase the loading and need to be included in future models.

3. Conclusions

COMSOL Multiphysics has been used to predict the loads, stresses and displacements on the current design for the vacuum vessel for the proposed Advanced Divertor eXperiment (ADX) tokamak. The 'mf' physics interface was used to build a cyclic symmetry model of the tokamak, including magnetic field coils and the plasma, and simulate a VDE disruption including plasma movement and current quench. This model predicts the fields, eddy currents and Lorenz forces resulting in the vessel due to a disruption. These loads are then used in a structural model of the vessel to evaluate the stresses. As originally designed, the stresses in the ADX vessel were above allowable limits, but the addition of a few restraints suggested by the results from the COMSOL model were able to bring both the stresses and deflections down to within allowable limits. Additionally, the ADX vessel uses the novel approach of constructing its vacuum vessel of a solid inner cylinder and 5 axisymmetric shells bolted together. The COMSOL model confirms that the bolting will be strong enough to survive the loads induced during a disruption and hold the vacuum vessel shells together.

4. References

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