Structural Analysis of High-field-Side RF antennas during a disruption on the Advanced Divertor eXperiment (ADX)

Plasma Science and Fusion Center
Massachusetts Institute of Technology
Cambridge, MA, USA
doody@psfc.mit.edu

Abstract— The Advanced Divertor and RF tokamak eXperiment (ADX) is a compact, high-field device proposed by the MIT Plasma Science and Fusion Center and collaborators [1], which will address critical gaps in world fusion research on the pathway to fusion energy. In addition to developing and testing new divertor concepts at reactor level magnetic field strengths and power densities, ADX will test new antenna concepts for Lower Hybrid Current Drive (LHCD) and Ion Cyclotron Range of Frequency (ICRF) heating systems. In particular, ADX will be purpose-built to allow antennas to be positioned on the high magnetic field side of the torus, i.e., on the inner wall. With antennas placed at this location, plasma-wall interactions are greatly reduced and favorable RF wave physics projects to dramatic improvements in current drive efficiency and current profile control as well as very effective scenarios for RF heating and flow drive [2][3][4].

Initial designs for a high field side LHCD and ICRF antennas have been completed and are analyzed to determine the loads induced during a full-current plasma disruption. While locating antennas at the inner wall is beneficial from an RF standpoint, it exposes them to a higher toroidal field which, when combined with the eddy currents caused by a disrupting plasma, will lead to higher loads. Using COMSOL Multiphysics [5], a model of the ADX vessel and coils is created to predict the magnetic fields, eddy currents and loads acting on the antennas during a disruption. Structural models are then run to predict the stresses and to provide guidance for design improvement, such as determining where structural reinforcements may be necessary.

Keywords—ADX; Lower Hybrid; ICRF; High field side launch;

I. INTRODUCTION

The MIT Plasma Science and Fusion Center and collaborators are proposing a high performance Advanced Divertor and RF tokamak eXperiment (ADX) [1] that is specifically designed to test innovative divertor ideas and advanced concepts for lower hybrid current drive and ion cyclotron range of frequency actuators. In particular, this device will be purpose-built to incorporate launch structures on both the low-magnetic-field side and high-magnetic-field side of the torus, as shown in Fig. 1.

Compared to launchers located on the low-field-side (LFS), high-field-side (HFS) launchers provide access to favorable RF wave physics, leading to substantial improvements in current drive and heating efficiencies:

*Accessibility to lower $n_i$ LHCD for improved current drive efficiency (30% to 50% improvement)
*Better LH wave penetration, allowing current drive well inside the pedestal region in a reactor
*100% mode conversion and absorption of ICRF fast waves, leading to direct electron heating and access to flow-drive regimes

In addition, the HFS scrape off layer (SOL) has extremely favorable attributes for reducing levels of plasma-material interactions with the antennas/launchers, particularly in double-null discharges [6]:

![Fig. 1 Proposed geometry for ADX](image-url)
*Lower heat and particle exhaust fluxes
*Fewer unconfined fast ion orbits
*Strong intrinsic impurity screening

Moreover, the impact of antenna structures on blanket neutronics and tritium breeding is minimized at the HFS location.

The advantages of HFS launchers do come with new challenges, however. First is the question of space, or more specifically, the reduction of space as we move from the LFS to the HFS in a tokamak. Since the size of the antenna is determined by wavelength and not machine size, previous studies have shown that an antenna can be placed on the HFS\[7\][8]. Preliminary designs for an inner launch lower hybrid current drive antenna (LHCD) and ion cyclotron range of frequency antenna (ICRF) created for ADX, shown in Fig. 2 and 3, are used for this paper.

A second challenge, and one that is the focus of this paper, is the expected increase in mechanical loads that the antenna structure will need to carry during a disruption. ADX is being designed with a 1.5 MA plasma current and 6.5 T toroidal field at the plasma center, with future upgrade to 8T. This toroidal field will be even higher on the HFS where the launchers will be placed. Eddy currents generated during a disruption will cross this toroidal field and generate large structural loads in the launch structures.

Models have been built to predict the fields, eddy currents, loads, stresses and displacements of the current designs for the inner launch lower hybrid antenna and the inner ICRF antenna for ADX during a disruption using the finite element program COMSOL. The predicted stress levels will be used to inform the antenna designs going forward as to material choices and what restraints are required. For this analysis, 2/3 yield was chosen as the maximum allowable membrane stress.

Table 1:

<table>
<thead>
<tr>
<th>Allowable Stresses</th>
<th>Yield Strength (MPa)[9]</th>
<th>2/3 Yield (MPa)</th>
</tr>
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<tbody>
<tr>
<td>304L Stainless Steel</td>
<td>210</td>
<td>140</td>
</tr>
<tr>
<td>Inconel 625</td>
<td>460</td>
<td>307</td>
</tr>
<tr>
<td>Copper (C110)</td>
<td>65</td>
<td>43</td>
</tr>
</tbody>
</table>

II. FINITE ELEMENT ANALYSIS MODELING

A. ADX Vessel and Magnetic Field Model

A cyclic symmetry model of ADX is built in COMSOL to predict the magnetic fields. A 36° section of ADX is constructed including the vessel, coils and plasma. The plasma current is set as 1.5 MA, and the associated coil currents are provided using an ACCOME solution [10] for a representative plasma equilibrium shown in Fig. 4. These currents are then input to the model for each respective coil and plasma, and COMSOL calculates the magnetic field that will be generated.

Fig. 4: (a) Poloidal flux plot and coil currents for a design point equilibrium from an ACCOME solution. (b) Geometry used for cyclic symmetry model of ADX
From this equilibrium, the plasma current is decreased to zero in 1 ms to simulate a midplane plasma disruption, as shown in Fig. 5.

The changing fields due to the loss of plasma current create eddy currents in the surrounding structures, including the inboard lower hybrid launcher and ICRF antenna. These eddy currents cross the toroidal field creating Lorentz forces in the antennas.

To predict the toroidal field, a separate model is built of the 20 leg TF coil for ADX. The ADX TF coils use the same design as Alcator C-Mod, simply extending the height of the inner and outer legs to accommodate ADX’s greater height. From this model it can be seen that to attain the toroidal field of 6.5 T at a radial position of 0.73m specified in the design point, the inner wall antennas would see a toroidal field of approximately 10 T.

**B. Inner Wall ICRF Antenna**

With the ICRF placed at the inner wall of the model, we can predict the eddy currents and loads induced in the antenna structure. The ICRF two-strap antennas are made from Inconel 625 which is copper plated. The strap is protected by a steel frame, which also holds a set of TZM Faraday rods, at the height of the plasma, and steel shielding as the strip follows the inner wall up and down towards the connections to coaxial radial feeders (not shown). The low electrical conductivity of the Inconel strap results in reduced eddy currents which will be beneficial structurally. At the 1.5MA/6.5T design point, the strap sees a maximum deflection of less than 1 mm and membrane stresses remain below the allowable limit for Inconel 625 (Fig. 7).

**C. Inner Wall Lower Hybrid Launcher**

With the Lower Hybrid antenna placed at the inner wall of the model, we can predict the eddy currents and loads induced in this antenna structure. The lower hybrid launcher can be broken down into a number of components, shown in Fig. 8.
The four, eight-way splitters that couple with the plasma are all made of 304L stainless steel with the internal surfaces copper plated to reduce RF losses. The couplers are stacked together and held in place by the two outer Inconel plates which are bolted to the inner wall of the vessel and add strength to the structure. Each splitter is connected to a series of WR187 waveguides that brings power to the splitters. Since the WR187 waveguides and eight-way splitters have different dimensions, a transformer piece is designed to join the two.

Initially, both the WR187 waveguides and transformer were modeled to be constructed of copper. Analysis of the HFS lower hybrid for ADX show that waveguides and transformers that were made of copper would see excessive stress (limits shown in Table 1), as shown in Fig. 10, due to the eddy currents crossing the high toroidal field.

While it may be possible to support the waveguides and transformer to reduce the stresses, at this stage of the design, it is preferred to explore ways to reduce the load and eliminate the higher stresses. As a result, the waveguides and transformers are now designed as being similar to the splitters, with a stainless steel body and copper plating on the inner surfaces. This benefit is that, like the splitters, the waveguides’ bodies will be more electrically resistive – and so experience smaller eddy currents and loads – while the copper coating on the surface will still allow for low RF losses. Additionally, while we are reducing the magnitude of the loads on the waveguides, we are also increasing their strength and therefore improving our design margin of safety. This greater margin opens the possibility of running at higher plasma currents and/or toroidal fields than the current design point. For the current design, we treat all the WR187’s as being copper-plated steel. It is possible that the waveguides that are above the vessel and see lower magnitude of changing fields during a disruption could remain copper; future work as the design progresses will determine if that is a viable option.

With the steel waveguides, stresses in the lower hybrid assembly will remain within allowable limits for a midplane disruption where the plasma loses all its current while still at the centerline of the vessel. For the splitters, this is likely the worst case since the splitters are located in such close proximity to the plasma at equilibrium. However, in an upward moving vertical displacement event (VDE) the plasma would rise upward towards the top of the vessel before losing its current. This case would be worse for the waveguides. The changing fields due to the moving plasma would generate eddy currents in the waveguides, and then when the plasma did lose all of its current, it would be closer to the waveguides leading to the waveguides seeing a larger change in field, larger eddy currents and larger loads.

Data from a VDE on Alcator C-Mod was used to simulate a VDE on ADX. The C-Mod reference VDE was used to define the fall rate, or in this case the rise rate, of the plasma and the distance traveled before the current quench. In COMSOL, the VDE is modelled by physically moving the electrical current of the plasma up inside the vessel before having its current fall from 1.5 MA to 0 in 1 ms. While the plasma is rising, the fields around the waveguides do change, but not as quickly or in as great a magnitude as they change during the current quench, so the loads induced during the plasma’s motion are of lesser concern.
During the current quench following the VDE, the eddy currents and loads generated on the waveguides are at a higher level than during a midplane disruption.

We can see from Fig. 11 that, even during the VDE, the waveguides above the vessel do not see the changing fields of the current quench and hence do not experience large eddy loads (Fig. 12) or forces. This indicates that we may be able to use copper waveguides in this location, but further work must be done.

Fig. 11: Results from COMSOL model of VDE in ADX.
(a) The plasma rises in the vessel over 0.010 s and then loses its current in 0.001 s.
(b) Vertical Fields created during the disruption
(c) Radial Fields created during the disruption

Fig. 12: Current Density (A/m$^2$) of Eddy Currents generated during VDE Disruption. Note that the eddy currents in the waveguides are an order of magnitude greater for the VDE than for the midplane disruption.
As seen in Fig. 13, the stresses in both the steel waveguides and the coupler remain within the allowable limits of 2/3 yield.

![Stress Diagram](image)

**Fig. 13: Stresses and displacements for inner launch lower hybrid. Stresses are below 2/3 yield for Inconel625**

III. CONCLUSIONS

The proposed ADX tokamak is being designed to test advanced divertor concepts at high magnetic fields and power densities. It will also be built to employ RF launchers placed on the HFS of the plasma to take advantage of the better wave penetration and absorption for improved current drive and heating, as well as lower levels of plasma-material interactions at this location as compared to the LFS. The advantages of HFS launch do come with tradeoffs, particularly the higher toroidal field on the HFS, which will lead to higher structural loads during a disruption when eddy currents are generated in the antennas.

The finite element program COMSOL has been used to predict fields, eddy currents, loads and stresses during a midplane disruption and a VDE for ADX with 1.5 MA of plasma current and a 6.5 T toroidal field at the plasma center. This analysis shows that the membrane stresses and displacements all stay within the allowable limits for both the inner launch lower hybrid and ICRF antenna.

IV. FUTURE WORK

This preliminary analysis has demonstrated that installing launchers on the inner wall of the ADX tokamak is feasible for a 1.5MA/6.5T design point. With an upgrade to the power supply, a 2MA/8T design point has been proposed, and will be analyzed to determine structural loads and stresses. As the design is refined, additional and more detailed disruption scenarios, for example, a VDE where the plasma also moves inward, will be provided and analyzed. The present analysis has only dealt with eddy currents caused by the disruption, but in the future, halo currents must be accounted for and studied. The design intent is that all halo current will be taken by limiters protecting the antennas, but this must be confirmed and then the limiters must be analyzed to confirm they are able to take the halo current and resulting loads.

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