Disruption Load Calculations Using ANSYS Transient Electromagnetic Simulations for the ALCATOR C-MOD Antennas

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Abstract-- **ANSYS has been used to compute eddy current loads in C-Mod antenna components due to a disruption. The antennas are on the outbuard mid-plane, away from the direct involvement with halo currents, which characterize loading in the inner divertor and wall. Only inductively driven currents are computed. A rather complex but manageable electromagnetic model is used. Three of the antennas used in C-Mod were analyzed, Lower Hybrid, ICRH, and MHD antennas. The goal of these simulations was principally to quantify upper bound disruption loads.**

I. INTRODUCTION

ANSYS has been used to compute transient electromagnetic behavior of the current diffusion behavior of Bitter plate copper coils. [1], [2] These are coupled thermal-electromagnetic solutions. A similar analysis procedure, exclusive of the thermal component was applied to calculate eddy current loads in C-Mod antenna components due to a disruption. Disruption load calculations for ARIES RS have been performed at the U. of Wisconsin using a similar analysis procedure [4]

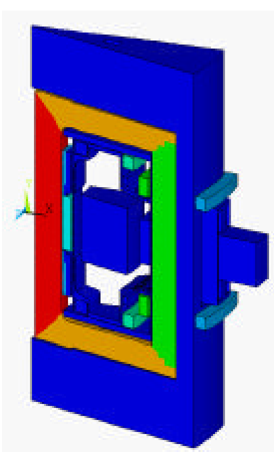

Fig. 1 Model with air removed. The Antenna "block" is the rectilinear "block" passing through the vessel duct. It is moded with orthotropic resistivities." Coil segments have imposed current densities..

The antennas are on the outboard mid-plane, away from the direct involvement with halo currents, which characterize loading in the inner divertor and wall. Only inductively driven currents are computed. This analysis method has been used for components of three different antennas used in C-Mod. "Smeared" orthotropic resistivities were used to model the whole lower hybrid antenna. A model of the ICRH antenna was intended to quantify the loading in the lead straps behind the back plate. An analysis of the active MHD antenna was also performed to help quantify loads on the antenna and frame. These analysis are used in conjunction with simpler and usually more conservative calculations using B-dot's and equivalent circuits. The method has yielded additional understanding of the shielding effects from neighboring structures, and highlighted the need to postulate all possible closed current loops within the vessel internals.

II. ANSYS MODELING AND SOLUTION PROCEDURE

An ANSYS transient analysis is used with a rather complex but manageable electromagnetic model is used. It is based on a vector potential solution. Cyclic symmetry is employed to reduce model size. This introduces the error/uncertainty of effectively modeling multiple antennas and, at present, restricts the analysis to axisymmetric plasma behavior. Antennas are modeled as "smeared" regions or discretely. The plasma is slowly ramped up to establish an electromagnetic steady state. This can be substituted by an ANSYS static solution [4]. During this time toroidal and poloidal field coil currents are established to produce a field distribution that the code uses along with the eddy currents to calculate Lorentz Forces. The plasma is modeled using two regions, allowing a shift in current center by simultaneously increasing the current in the lower half and decreasing the current in the upper half. This models the downward translation of the plasma. The two currents are then quickly ramped down to simulate the current quench. ANSYS solid 97 elements are used throughout. The first element KEYOPT option is used to define the solution degrees of freedom. The vector potential degrees are

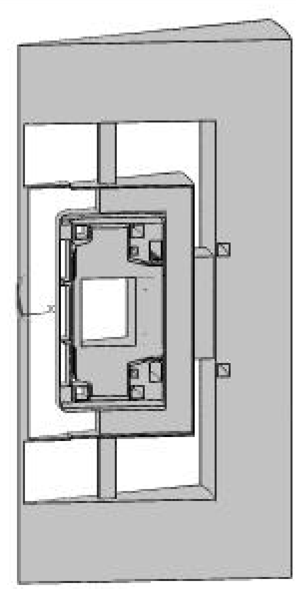

Fig. 2 Air elements surrounding the conducting elements. In this model, the plasma is approximated as a rectangular cross section.

specified for all the elements, and the volt degree of freedom is added for those elements that model the conducting regions such as vessel, and divertor components. Only toroidal plasma currents are simulated, However the method could be used with poloidal currents in the plasma, and it might be possible to force some representation of halo currents in this way.

III. DISRUPTION EDDY CURRENT LOADS ON THE LOWER HYBRID ANTENNA

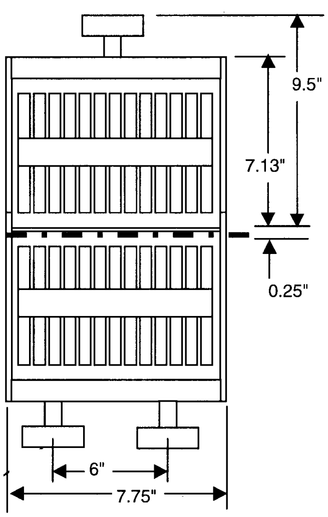

Fig. 3 Simplified resistivity model from Douglas Loesser[3]
24% Nominal Vertical Area
35% Nominal Horizontal Area. There are two discrete waveguides - CS shown

The lower hybrid antenna is modeled as a large block with adjustments in resistivity to model the complexity of the individual plates and structures. This is shown in Fig. 4

Two cases with a .125m vertical translation of the plasma prior to plasma decay were run at two rates of decay. The peak rate of change of the plasma current for a 1MA plasma is 1 MA per millisec (twice the average), and for a 2 MA plasma disruption the rate is twice that for a 1 MA plasma. The forces and currents internal to this "block" are substantial, but they net to small forces and moments.

Table 1. Load summary on Antenna "block", Orthotropic Resistivity) 2MA VDE current decay after vertical motion 2MA /millisec) Steel resistivity

FX (N)	FY (N)	FZ (N)	MX	MY	MZ)
(rad)	(vert)	(tor)	(N-m)	(N-m)	(N-m
-1437	-195	2345	-9717	-1487	-238

Table 2. Load summary on Antenna "block" (4.5 degree wedge model)

Event	FX (N)	FY (N)	FZ (N)	MX	MY	MZ)
	(rad)	(vert)	(tor)	(N-m)	(N-m)	(N-m
1	2141	0	0	6621	0	0
2	150	-82	1458	-4	-998	-105
3	1490	-102	-664	-5301	432	-47
4	181	-117	1734	-6.5	-1172	-146
5)	913	-174	1062	-5656	-745	-206

1) 1MA centered disruption/decay in .001sec
2) 2MA VDE, Constant Ip vertical displacement in .5millisec
3) 2MA VDE current decay after vertical motion 1MA/millisec
4) 2MA VDE, Constant Ip vertical displacement in .25millisec
5)2MA VDE current decay after vertical motion 2MA/millisec

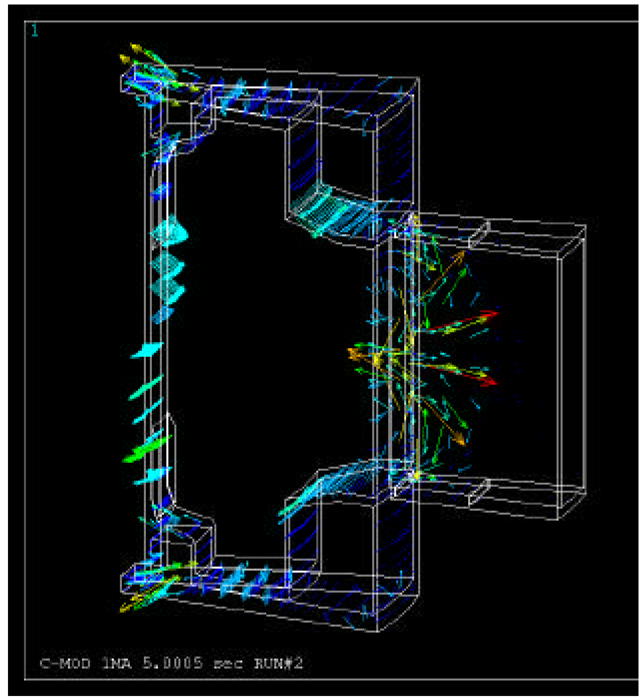

Fig. 4 Eddy Currents in the vessel at the end of load step #5 .

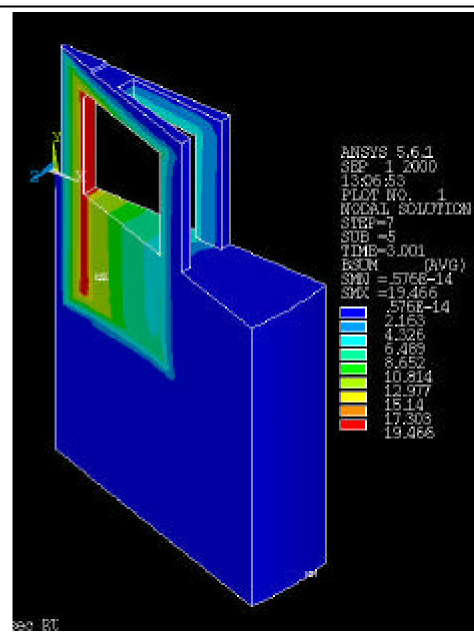

Fig. 5 TF Field . All but the TF coil elements in the upper half have been removed to show the TF coil modeling.

Eddy Currents in the vessel at the end of load step #5 are shown in figure 4. During load step #4 the 2 MA plasma is translated downward ..0625m in one one half a millisec. During loads step 5 the plasma decays from 2MA to 1.5 MA and translates downward another .0625m.This occurs over .5 millisec. Load step 6, the plasma decays to 1 MA after another .5 millisecond with no translation. Note the mid-plane inner wall current reversal. When the current decays, a coherent vessel current develops in the same direction as the plasma current

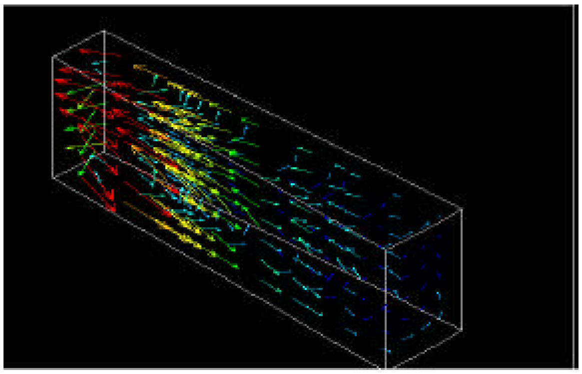

Fig. 6 Eddy Currents in the "block" that models the lower Hybrid Antenna.

In Figure 7 the eddy current vectors in the lower hybrid “block” are shown. The main eddy current component is a loop around a vertical axis. The largest loads from this current pattern result from currents crossing with the toroidal field and producing a moment about a radial axis

IV. THE MHD ANTENNA

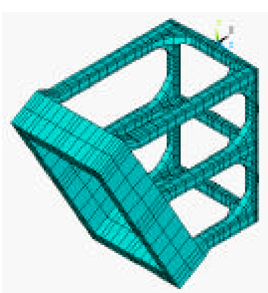

Fig. 7 Structural Model to which loads were later applied

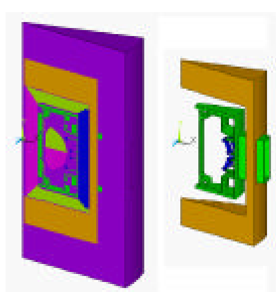

Fig. 8 Model with Air at Left and Conducting Structures at rght

This analysis is based on an MHD antenna design that has recently been improved. Loads on the earlier MHD antenna were small as long as it was to be exposed only to the inductively driven currents calculated here. Insulation details have been improved to reduce the likelihood of shorts or insulator breakage. It was suggested that it would be wise to insulate the frame from the vacuum vessel. In one run where the antenna was connected electrically to the frame, loads were much higher. The analysis exaggerates the tendency of the vessel toroidal currents passing through the antenna because the cyclic symmetry assumption represents the equivalent of 10 antennas. The flux linked by a single frame was judged small and currents for this change in flux were estimated to be small as well. This analysis assumes that disruptions tend to translate the plasma current inward and down (or up) and away from the antenna. Halo currents are ignored. The antenna was conservatively modeled as a closed loop. the

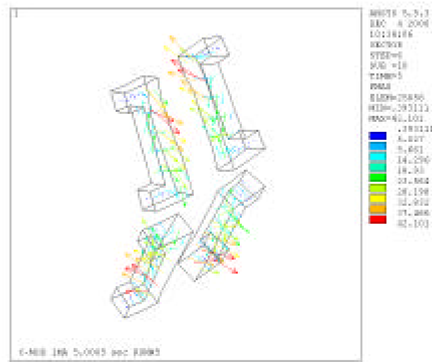

Fig. 9 Nodal Force Vectors

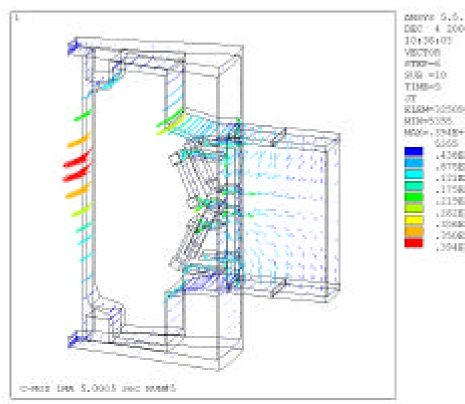

Fig 10 Currents Induced in the Vessel

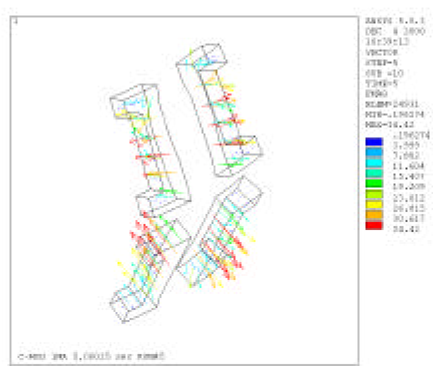

Fig 11 Nodal Force Vectors

cross section of the rectangular section modeling the MHD antenna is 2.273e-3. This is intended to model the 5 turns of 1/8 inch SST wire which is .098 sq in , or 6.3338e-5 sq m. The resistivity multiplier is: 2.273e-3/6.3338e-5 =35.88 which is applied to the "smeared" representation of the bundle of wires. The largest nodal Lorentz Force is 42 Newtons. For an upper bound on the force assume 12 nodes are loaded this way per leg. This works out to about 100 lbs on one of the vertical legs of the antenna, and -100lbs on the other, as a force couple. The net is zero. The structural model at left was loaded with 900 lbs on each leg ., The five turns of wire are split up into six spans in each vertical leg. The spans between the ceramic insulators scale to about 2 inches. Each of these single wire spans would see 100/30 lbs. Or 3.3 lbs. This is judged to be acceptable.

V. ICRH ANALYSES

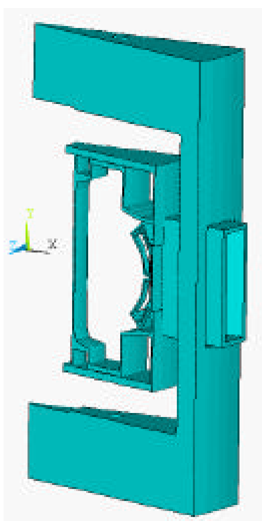

Fig. 12 Conducting components of the model (in which currents are not specified.)

Lead/Strap modifications have been made to the ICRH antenna to improve arcing behavior.. In the first modeling, the loads on the modified strap were very small. This was thought to be due to a continuous modeling of the backplate. The Disruption analysis was re-run removing all the antenna components between the strap/lead and the plasma i.e. converting them to air in the same model. The resulting moments on one strap are Mrad=11.0N-m, and Mvert=88.0 N-M. This is higher than first previously reported, but still an order of magnitude lower than quoted in the design review (8000 in-lb?). A static poloidal field analysis was run with only a 2MA plasma (no PF coil currents), and only .2T at the strap was obtained - This is the field only due to the plasma. In previous studies of poloidal field changes at the TF fingers coil current data indicates that the PF coil currents do not change in the time frame of the disruption. So at most the Bdot is the poloidal field that relates to the loss in the plasma.

VI. CONCLUSION

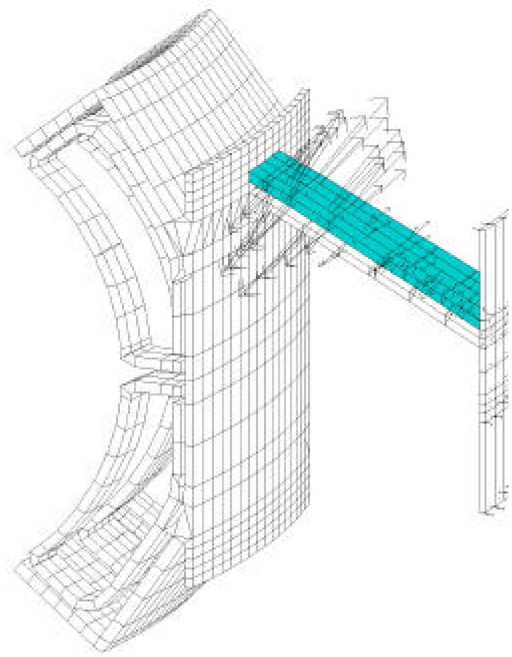

Fig. 13 Forces in the lead strap

Transient electromagnetic simulations done in ANSYS can be used to simulate disruption effects on tokamak components. The problem is largely model building, and the bookkeeping needed to apply currents in appropriate regions of the model. Plasma disruptions, including moving plasmas can be simulated with transient current time histories in designated plasma regions. ANSYS computes Lorentz forces that result from the eddy currents, but a full set of toroidal and poloidal coil currents need to be input to obtain the proper fields.

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[3] FIRE/NSO Toroidal Field Coil Structural/Thermal Analyses” P. Titus 18th IEEE SOFE, October 25-29 1999, Albuquerque NM.

[3] email with Lower Hybrid Antenna area percentages for orthotropic resistivities, Douglas Loesser Sept 2000

[4] “Electromagnetic Disruption effects in the ARIES RS Tokamak Design” Crowell and Blanchard, 14 Topical on the Technology of Fusion Energy, October 15-19 2000, Park City Utah.UWFDM-1148