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PPPL- 4550

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# NSTX Disruption simulations of Detailed Divertor and Passive Plate Modelss by Vector Potential Transfer from OPERA Global Analysis Results

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September, 2010

Prepared for the U.S. Department of Energy under Contract DE-AC02-09CH11466.

# NSTX Disruption Simulations of Detailed Divertor and Passive Plate Models by Vector Potential Transfer from OPERA Global Analysis Results

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The National Spherical Torus Experiment (NSTX) project is planning upgrades to the toroidal field, plasma current and pulse length. This involves the replacement of the center-stack, including the inner legs of the TF, OH, and inner PF coils. A second neutral beam will also be added. The increased performance of the upgrade requires qualification of the remaining components including the vessel, passive plates, and divertor for higher disruption loads. The hardware needing qualification is more complex than is typically accessible by large scale electromagnetic (EM) simulations of the plasma disruptions. The usual method is to include simplified representations of components in the large EM models and attempt to extract forces to apply to more detailed models. This paper describes a more efficient approach of combining comprehensive modeling of the plasma and tokamak conducting structures, using the 2D OPERA code, with much more detailed treatment of individual components using ANSYS electromagnetic (EM) and mechanical analysis. This capture local eddy currents and resulting loads in complex details, and allows efficient non-linear, and dynamic structural analyses.

## 1. Introduction

Upgrades to the National Spherical Torus (NSTX) include upgrades to the toroidal field, plasma current and pulse length. These involve the replacement of the center-stack, including the inner legs of the TF, OH, and inner PF coils. A second neutral beam will also be added. The increased performance of the upgrade requires qualification of the all components including the vessel, passive plates, and divertor for higher disruption loads. The vessel, passive plates, and divertor components are complex mechanical and electromagnetic structures. Global disruption simulations are of necessity, coarse in the regions of these complex structures in order to adequately model plasma motions and current changes in all of the passive conducting structures. The General Requirements Document (GRD) [1] specifies five quench positions and many translations and quench rates that must be addressed. For NSTX, a relatively simple OPERA transient electromagnetic axisymmetric model of the plasma, vessel and internals is used to obtain currents and loads. This analysis provides only toroidal currents. However the vessel, divertor and passive plate structures are complicated non-axisymmetric designs that result in eddy currents that cross toroidal field lines and develop significant loads not captured in the axisymmetric analysis. A procedure has been developed which maps the vector potential (VP) solution from the axisymmetric simulation to the detailed vessel/passive plate/divertor models. These are derived from the 3D Pro Engineer CAD models and include details of copper plate cuts, support brackets and representations of individual bolts. and welds. The detailed models are first analyzed in a transient electromagnetic analysis in ANSYS with the VP from the axisymmetric analysis imposed as a boundary condition. Imposition of the VP solution eliminates the need to model air around the complex geometries in the ANSYS model, but is only approximate. It is only as good as the correspondence between the OPERA 2D model and the 3D ANSYS model. This limits the accuracy of the approach. For operating tokamaks, it is one step better than the usual practice of applying measured field transients in the absence of a new component to an analysis of the new component.

Halo currents are added in the electromagnetic model as nodal loads at specified entry and exit regions. The entry and exit points have been specified in the NSTX GRD based on operating experience. The vector potential distribution for a 1/r toroidal field is added to obtain the correct background field for Lorentz force calculations. Forces are then applied to structural models in both static and dynamic analyses.

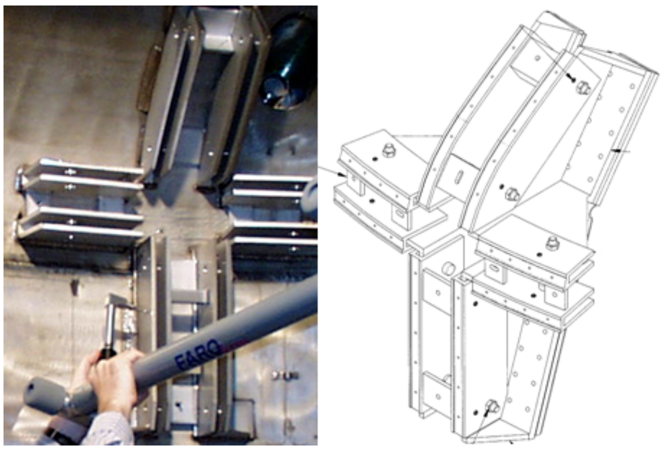


Fig.1 Upper Passive Plate Bracket Detail.

To partially address the rigor of the procedure, toroidal current inventories in the ANSYS detailed transient EM analysis have been compared with the toroidal currents in the OPERA axisymmetric analysis.

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Current inventories in passive plates also compare well with measured operating currents.

## 2. Procedure Details

### 2.1 Opera Analyses

OPERA axisymmetric analyses utilize a specialized formulation of the VP degree of freedom. Computations are done with r*A theta as the solution degree of freedom. The resulting VP solution must be divided by the radius of the coordinate point before passing this to the 3D ANSYS EM analysis.

### 2.2 Preparation and Use of the Table Data

Vector potentials obtained from OPERA are arranged in 81x81 tabular form so that they can be mapped into ANSYS as table data. Data transfer is done in a cylindrical coordinate system with only r-z coordinate results from the 2D analysis mapped to the 3D model.

*dim,vect%inum%,table,81,81,1,x,z,,5 ! Specifies a 81X 81 parameter table

*tread,vect%inum%,'VecPot_case_%inum%','txt' ! Reads the table text file into the table

A typical number of time points extracted from the OPERA analysis produced 44 tables The time points represented by the tables are input with a parameter set. . Macros are developed that read these table values into ANSYS. The meshes in OPERA and ANSYS are dissimilar, but since ANSYS interpolates the tables between two adjacent indices, proper indexing of the coordinates yields a reasonable approximation of the VP. The ANSYS EM element type used was SOLID 97 which is converted to SOLID 45 for the structural analyses. The lower order elements are needed to support the EM ANSYS analysis. Material properties used are that of Stainless Steel except for the passive plates which are made up of a high strength copper.

### 2.3 Application of the Background Fields.

The poloidal background fields are extracted from separate analyses of the scenarios, or operating experience. Figure 3 shows maps of enveloped poloidal fields from all (96) design equilibria for the planned upgrade of NSTX. The poloidal and toroidal background fields are converted to VP gradients. The resulting VP values are superimposed on the VP values from the OPERA analysis.

$$\mathbf{B} = \nabla \times \mathbf{A} = \frac{1}{r}\begin{vmatrix} u_r & u_\theta & u_z \\ \frac{\partial}{\partial r} & \frac{\partial}{\partial \theta} & \frac{\partial}{\partial z} \\ A_r & rA_\theta & A_z \end{vmatrix}$$

The above equation can be solved for the VP for a constant field in any one of the directions. An expression of the total field in terms of VP is obtained by superposition. While the expressions are linear in A and B, they are coupled in the coordinate directions, so that the presence of a radial field induces a non uniform vertical field. The specified field can be obtained only over a limited range from the field point chosen.

! ANSYS Commands

!d,i,ay,vect%inum%(x,z) ! Interpolates and applies the Vector Potential on the node

d,i,ay,BackBz*x/2-BackBr*(z-z0)+vect%inum%(x,z) ! Intrepolates and applies the Vector Potential on the node

! Applying the Toroidal Field

d,i,az,-0.5*BR*log(x*x) ! applies vector potential for toroidal magnetic field

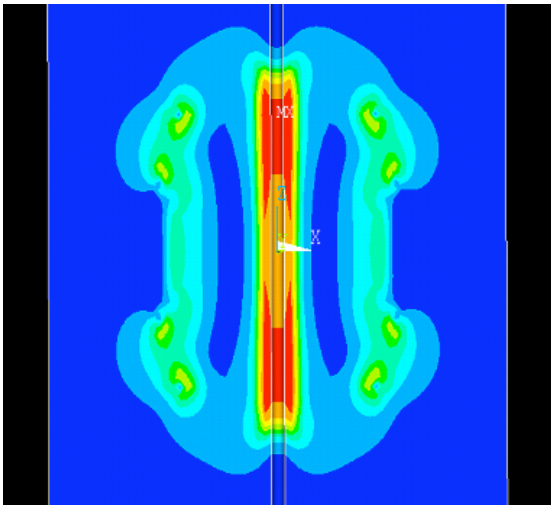

Fig.2 Re-Construction of the OPERA Poloidal Field in ANSYS using a wedge of elements after reading in an OPERA VP Result

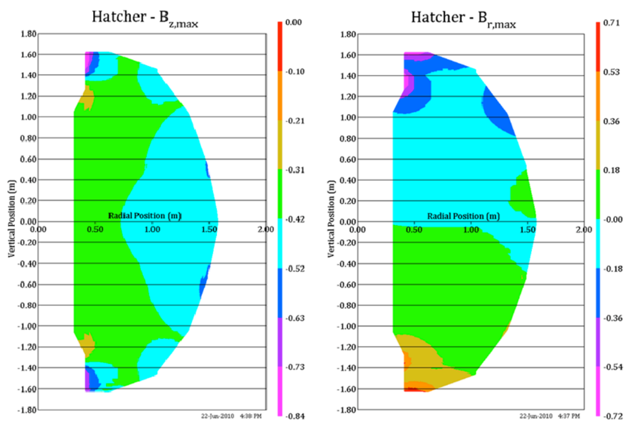


Fig.3 Maximum Poloidal Field Magnitudes for All NSTX Upgrade Planned Scenarios (R. Hatcher Data, J Boales Plot).

### 3.0 ANSYS 3D Model

The ANSYS EM analysis is transient analysis that must track the time points and VP from the OPERA transient analysis

In order to obtain tractable models of the components, yet still capture the effect of shared currents with the vessel, symmetry and cyclic symmetry can be used. On poloidal cuts of the system, the volt degree of freedom is coupled across cyclic symmetry faces using the ANSYS CPCYL command. Where current transfer is small for example across the equatorial plane of the vessel, volt degrees of freedom are allowed to "float"..

Concurrently with the addition of halo currents, the EM model is solved for eddy currents and Lorentz forces, which are saved in the results file for input to the structural analysis.

### 4.0 Addition of Halo Loads

Halo currents are applied at the appropriate entry and exit points specified in the GRD by a nodal amp "force" ANSYS command. Entry is modeled with positive nodal currents and exit is modeled as negative nodal currents. Halo current flow needs to be considered in choosing the symmetry boundary conditions In the passive plate model presented here, the symmetry sector is 60 degrees/lower half, and the halo current specified in the GRD is multiplied by the peaking factor, then divided by 6. The symmetry conditions imposed in the passive plate model actually model identical halo currents in the top and bottom of the vessel, and a toroidal distribution of currents uniformly multiplied by the peaking factor.

Halo currents are added in the transient ANSYS analysis. The halo current distribution between the entry and exit points will have resistive and inductive components. The inductive vs. resistive distribution of Halo currents by A. Brooks for the NSTX center stack casing[4]. Halo currents were modeled initially as poloidal. currents in the plasma Then interrupted with entry and exit points on the casing and peaking factors in accordance with the GRD. Early analyses of the current distributions in the NSTX centerstack casing claimed a resistive re-distribution that improved the peaking factor. The A.Brooks analysis showed that an initial inductive distribution that maintained the peaking factor throughout the height of the centerstack and then produced a resistive re-distribution. The decision is to retain the peaking factor in the halo current distribution, but with an appropriate time duration. In the procedure outlined here, the distribution of entry and exit nodes are chosen to retain the peaking factor.

There is also the question of timing of the inductive currents from the plasma quench and the halo current peak. Some guidance in the time phasing of these current peaks is provided in [2] and figure 4. Time duration of the loading is important in properly simulating the dynamic response.

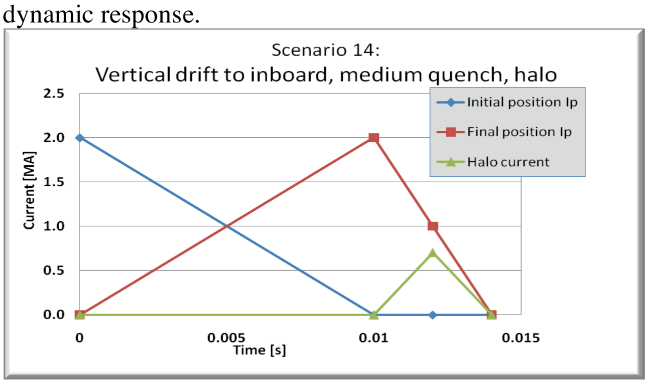


Fig.4 Quench and Halo Current Timing from ref [3]

### 5.0 Effects of a Slow VDE and a Subsequent Fast Quench

A downward Vertical Displacement Event (VDE) produces currents that run counter to the plasma current. These are then canceled by the quench currents. If the VDE is slow enough to allow the counter currents to decay, while preserving the magnitude of the plasma current, a more severe loading on the lower in-vessel components results.

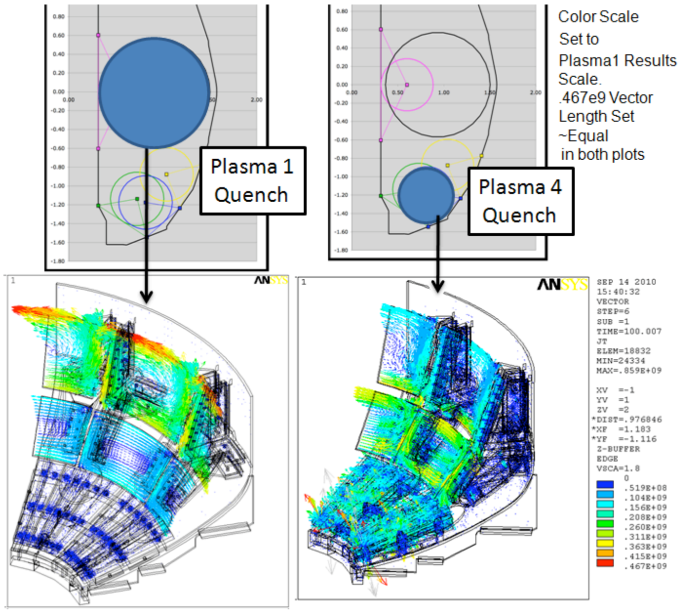


Fig.5 Current Density Vectors for Two Fast Quench Positions

Figure 5 shows results for simulations of fast quenches at the GRD specified plasma positions 1 and 4. for the full 2MAmp NSTX Upgrade plasma. The plasma 4 quench produced higher stresses in the secondary passive plates.

### 6.0 Structural Response, Static and Dynamic

The ANSYS EM pass on the model produces Lorentz forces in a results file that can be read into the structural pass using the SNSYS LDREAD command. In this example of the passive plates, the mesh and element inventory is the same between the ANSYS EM and structural analyses. More elements could be added, for example gaps, as long as the node numbering correspondence between the EM and

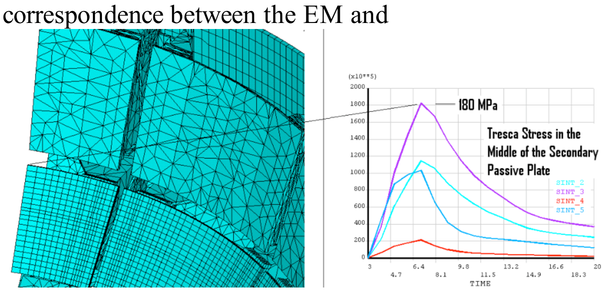


Fig.6Tresca Stress at the Middle of the Passive Plates (at the Cyclic Symmetry Plane from the Static Analysis

structural model is not lost. Solid 97 elements used in the EM analysis are converted to solid 45 elements in the structural analysis. Both element types are eight

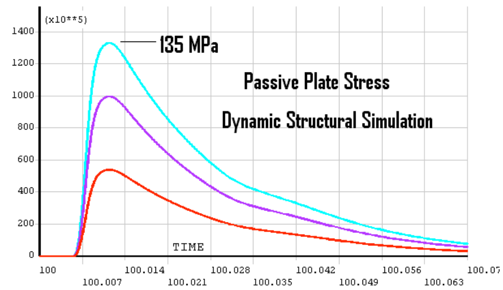

Fig.7 Tresca Stress at the Middle of the Passive Plates from the Dynamic Analysis (Same Location as Fig 6)

node bricks, and one of the limitations of this procedure is that poor element formulations are required, dictated by the solid 97 element which is required for vector potential and volt degrees of freedom. Results of the static and dynamic analyses are shown in figure 6, and 7. The dynamic load factor for this location is a bit less than 1.0. Figure 8 shows the increase in stress in the secondary passive plate when the plasma quenches at the lower region of the vessel.

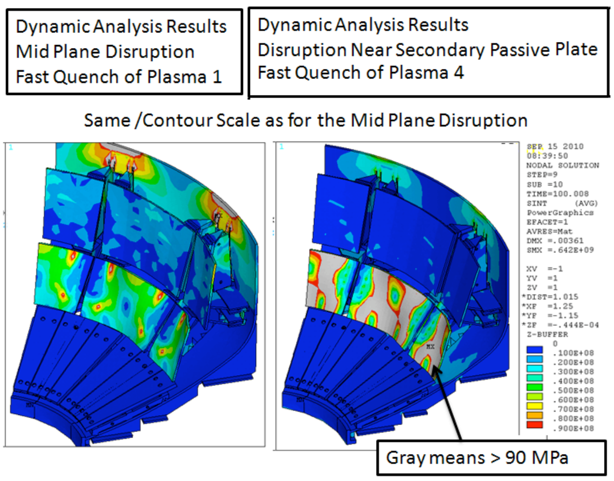

Fig.9 Stress Results for Two Fast Quench Positions

### 6.0 Benchmark of Currents Flowing in the Passive Plates, Mid-Plane Disruption

The OPERA axisymmetric Analysis produces only toroidal currents. The results of the OPERA/ANSYS disruption simulation show eddy currents in the plates. In the ANSYS results there is a clear net toroidal current in the primary passive plates represented by larger current densities at the top of the plate than at the bottom. Based on the top and bottom current densities, at the time in the disruption that produced the largest current densities , the conduction cross section of the primary passive plates and the triangular current density distribution, the fraction of IP flowing in the Primary Passive Plates is: (.467e9-.311e9)*5.4848e-3/4 /2E6 = .107

The upper bound of measured net currents in the primary passive plates is also about 10% of the plasma current[3]. Experimental data from [3] is plotted in figure 7. Currents in the secondary passive plates are not as readily determined from the current vector plot but it is clear that they are lower, consistent with measured data.

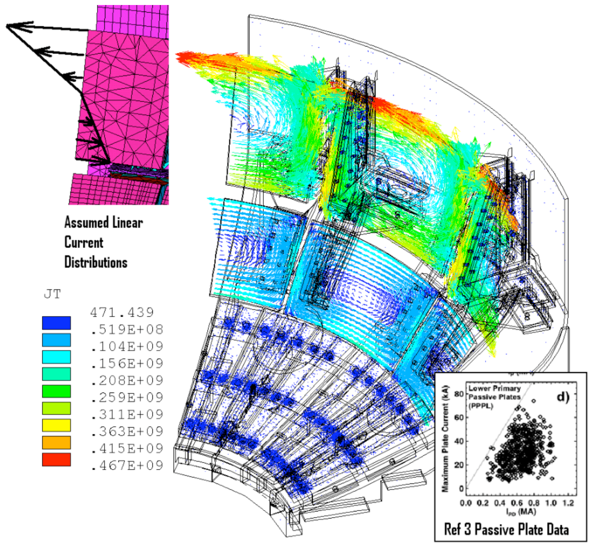

Fig.10 Currents Densities in the Passive Plates and Net Currents Reported in [3] (Analysis results are for a mid-plane 2MA Plasma Disruption)

### 7.0 Applications Other Than The Passive Plates

This procedure has been applied to the neutral beam armor plate backing structure, various diagnostic components, and the centerstack casing, using a common set of OPERA disruption VP files.

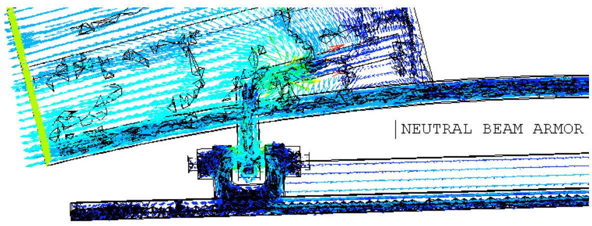

Fig.11 Current Densities in the Neutral Beam Armor Plate Backing Plate,

## Acknowledgments

The author would like to thank Larry Bryant, and Joseph Boales for testing and de-bugging the procedures described in this paper. .

## References

[1] NSTX General Requirements Document

[2] Disruption specification J. Menard spreadsheet: disruption_scenario_currents_v2.xls, July 2010.

[3] "Characterization of the Plasma Current quench during Disruptions in the National Spherical Torus Experiment" S.P. Gerhardt, J.E. Menard and the NSTX Team Princeton Plasma Physics Laboratory, Plainsboro, NJ, USA Nucl. Fusion 49 (2009) 025005 (12pp) doi:10.1088/0029-5515/49/2/025005

[4] Inductive and Resistive Halo Current s in the NSYX Centerstack, A.Brooks, Calc # NSTX-103-05-00

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