Simulating the Design for a Tokamak Fusion Reactor

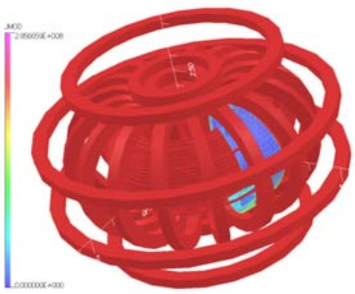
One of the most challenging problems with potential fusion reactors is how the plasma is confined. Electromagnetic simulation is playing a major role in the design of a Tokamak fusion reactor. **By Dennis Youchison**

Electromagnetic simulation is playing a major role in the conceptual design of a Tokamak fusion reactor by calculating eddy currents in the divertor, a device that controls plasma particle exhaust and power removal in the machine.

A preconceptual design study for the Fusion Ignition Research Experiment (FIRE) is underway to assess near term opportunities for advancing the scientific understanding of self-heated fusion plasmas. One of the key issues is to design plasma facing components (pfcs) that are capable of withstanding what is known as a disruption where plasma pressure and toroidal current are quenched on a fast time scale. The eddy currents produced during these transients are sufficiently high that the resulting stresses are capable of damaging plasma facing components. Engineers at Sandia National Laboratories, Albuquerque, New Mexico, used PC-based magnetic simulation software to predict the eddy currents and resulting Lorentz forces caused by disruptions. These calculated forces were then input to stress analysis programs used to optimize the mechanical design of divertor components.

Fusion Challenges

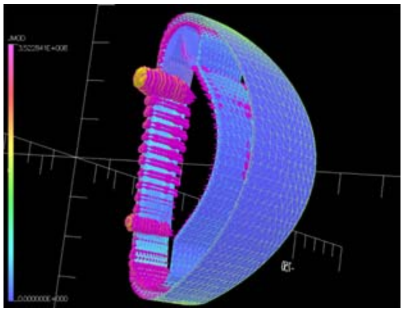
One of the most challenging problems with potential fusion reactors is how the plasma is confined. The hot nuclei in the plasma have to be held together at high densities long enough to allow enough of them to fuse to produce more energy than was used in heating the plasma. Material containers cannot confine such hot particles because of energy loss to the walls. Instead, scientists use a magnetic field to confine the hot particles. Magnetic fields exert force only on charged or magnetized objects. Room temperature gas atoms have as many electrons as protons, and thus are neutral. When the gas is heated to a very high temperature, the electrons have so much energy that they are no longer bound to the nuclei. The resulting gas is called a plasma because the energetic electrons and nuclei move freely. Magnetic fields can bend the path of hot, fast-moving nuclei and electrons into loops. Instead of hitting the wall, the particles in a plasma can be confined to travel in circles within a chamber. If the particles in the plasma never collided with each other, then they would be trapped in loops indefinitely by the magnetic field. However, collisions between the plasma particles do occur, causing the plasma to leak out of the confining magnetic fields.



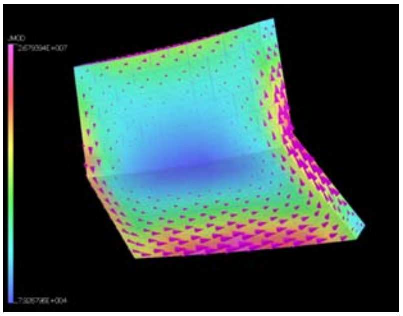
710 coils are used in the FIRE OPERA-3d model.

Over many years, fusion scientists have been perfecting the magnetic containers that hold the hot plasma while they apply the energy needed to sustain the fusion reaction. The most successful design, the tokamak, uses a toroidal or donut-shaped chamber surrounded by strong electromagnets. The main components in a tokamak are the magnet system, external heating and drive system and the divertor system. The magnet system is used to generate the magnetic field used to confine the plasma. The external heating system, which can consist of ohmic, RF, and neutral beam heating, raises the plasma temperature to a level needed to initiate fusion reactions. The divertor is used to control the plasma edge properties and remove ionized impurities and "helium ash" that has already given up its energy to the plasma.

The divertor, the first solid surface that makes contact with the plasma, must be designed to withstand not only normal operations but also events known as disruptions. These disruptions generate hundreds of thousands of amps of eddy currents within milliseconds that in turn create



Current density vector plots at the peak of the transient reveal that most of the eddy currents are carried by the toroidally continuous passive plates and inner vacuum vessel.



The current density vector plot shows the eddy current path in the outer divertor.

high Lorentz forces. Such forces determine the size and strength of the support plates, the connections and the actively cooled, tungsten-brush plasma-facing armor.

Developing The Calculations

Initially, a simple L/R analysis was performed in order to estimate the eddy currents induced in the FIRE divertor structures for the case of a plasma disruption.

An analytical approximation of the inductance of a rectangular plate was used to estimate induced eddy currents for the outer and inner divertor. The force on the divertor modules would then be 1.9 MN for the outer divertor and 2.8 MN for the inner divertor. These 'back of the envelope' calculations were useful for determining the rough magnitude of the forces that were involved, but because of the assumptions that were involved in producing them and particularly the fact that they did not take the geometry of the divertor into account, it was realized that more accurate predictions were required.

Fusion researchers have developed electromagnetic simulation codes but those codes evolved over many years with less-than-intuitive user interfaces, making it very difficult to model complex geometries such as the divertor and quickly obtain results needed for the design analysis. Another problem with these codes is that they run on expensive, high-end mainframes with restricted access.

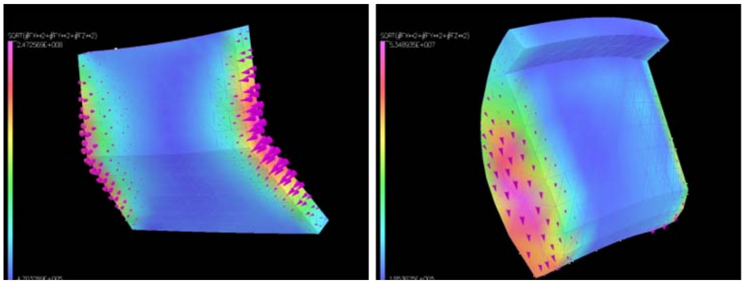
As a result, Sandia decided to run the simulation on OPERA, a PC-based electromagnetic simulation program from Vector Fields.

Because of the symmetrical design of the Tokamak, it was possible to model a one-sixteenth section of the torus, including the structure of the reactor and the electromagnetic coils. The plasma was modeled as a compilation of 668 different current filaments. The currents in each filament change over time to simulate how the plasma responds during a disruption event. Output from a plasma simulation code, TSC developed at Princeton Plasma Physics Laboratory, was used to generate the time response functions used to drive the filaments. The finite element mesh contains 92,000 elements and solves the time response equations for each of the filaments. It took 46 hours to complete a 300 ms simulation on a 1.7GHz PC. About 90 percent of the total processing time was required to compute the superimposed fields from the 710 coils including the plasma filaments.

Accurate Load Estimates

The analysis provided graphical outputs consisting of vector and contour plots that showed the magnetic fields, current densities and force densities superimposed on the surfaces of the model.

Several disruption scenarios were analyzed. The most severe case, a vertical disruption event, resulted in a maximum total force to an outer divertor plate of 86.7kN produced by 121kA of current intercepting a 12T magnetic field. This is much reduced from the initial scooping calculations, because the toroidally continuous divertor was segmented into 16 insulated plates. It was obvious from the initial OPERA runs that this reduced the size of the eddy current loops and hence the resultant Lorentz force on any one plate. The baffle and inner divertor were likewise segmented. Each inner divertor segment experiences a maximum total force of 14.3 kN and each baffle segment endures a 22.4 kN force. However, the sum of forces on each segment over the entire outer divertor is 1.4 MN. Insulation that isolated the divertor from the passive plates and the inner vacuum vessel also forced the eddy currents to flow along less deleterious paths. The toroidally continuous passive plates carry most of the eddy currents produced during the disruption, about 3.1 MA, but since these currents are parallel to the toroidal magnetic field they only see the contribution of the much lower poloidal field to the Lorentz forces. In contrast, due to their location, the divertor pfcs must contend with a large toroidal field component and higher forces.



Vector plots of Lorentz force densities reveal that the outer divertor (left) and the baffle (right) experience moments around different axes based on their position in the magnetic field.

OPERA was used to calculate the Lorentz force densities and exported these values in tabular format into Mathcad, where a four-point Gauss-Legendre Quadrature analysis was performed to determine the total forces. The total forces were then exported to a mechanical finite element analysis software package used by the Boeing engineers performing the mechanical design of the divertor.

The ability to accurately estimate eddy currents made it possible to design the divertor based on accurate load conditions, This is just one of many design tasks that must be completed in order to carry out the design of any burning plasma experiment such as FIRE that may eventually explore the many issues that are critical to the development of commercial fusion reactors.

Dennis Youchison, Sandia National Laboratory, Kirtland Air Force Base, Albuquerque, New Mexico, USA

For More Information Contact:

HIMARC Simulations
501 N. Huntley Drive
West Hollywood, CA 90048
Telephone: (310) 657-7992
Fax: (443) 583-0340
Email: jmgery@aol.com
Web: www.vectorfields.com