HELICON ANTENNA SUPPORTS NUCLEAR FUSION

Engineers and scientists at General Atomics share how they use multiphysics simulation to achieve magnetically confined fusion in the DIII-D tokamak.

By **GEMMA CHURCH**

FUSION IS AN ENERGY PRODUCTION process where two deuterium atoms are accelerated to the point where they overcome the Coulomb force and fuse into one helium atom and a neutron, releasing a tremendous amount of energy as a result. It is the Holy Grail of energy production since it is carbon-free, low waste, and has almost a limitless source of fuel. Nuclear fusion powers the Sun and could unleash a clean energy revolution, if only we could harness its power here on Earth.

»» *KEEPING THE DIII-D TOKAMAK IN TOP SHAPE*

THE TOKAMAK IS a promising design that relies on magnetic fields to confine hot plasma. Plasma is an ionized gas. It is made up of both positive ions and free electrons that have no charge. Usually, plasma is created at low pressures.

Tokamak fusion devices use a series of magnetic coils to create, shape, and stabilize the plasma within a doughnut-shaped (or toroidal) chamber (Figure 1). External heating systems are then used to heat the plasma to extremely high temperatures of the order of 150 million °C to achieve nuclear fusion.

In San Diego, USA, General Atomics (GA) operates the DIII-D National Fusion Facility on behalf of the U.S. Department of Energy as part of an ongoing effort to achieve magnetically confined fusion. As a user facility (Figure 2), the DIII-D tokamak hosts over 650 researchers from around the world to carry out cutting-edge fusion research.

The DIII-D tokamak operations group has performed multiphysics simulation to help optimize and validate the operations and diagnostics equipment to keep the facility running optimally. GA's Humberto Torreblanca, DIII-D tokamak chief operator, said: "We do not need to use simplified models for engineering analysis anymore thanks to COMSOL Multiphysics®, nor do we have to assume we are working with perfect scenarios. We can look at the complicated geometry of the tokamak and work out a range of complex multiphysics models."

"As a result, we can design and push our ideas without damaging our machine. It gives us very accurate results instead of having to make simplifying assumptions to do the calculations," Torreblanca added.

For example, while the internal magnetic fields in the DIII-D tokamak had already been mapped, the operations team had to rely on simplified magnetic field maps for the external fields (Figure 2). Torreblanca explained: "The tokamak is surrounded by many components and systems and the magnetic field can generate forces and currents that can affect and damage these systems. Analysis and simulation helps avoid potentially costly damage and delays in the research program."

Torreblanca imported the tokamak geometry using LiveLink™ *for* SOLIDWORKS® to study the external magnetic field at certain locations and to see how it would affect specific systems.

"This saved me a lot of time because the model was easy to set up and it also replaced our previous methods, which were more time

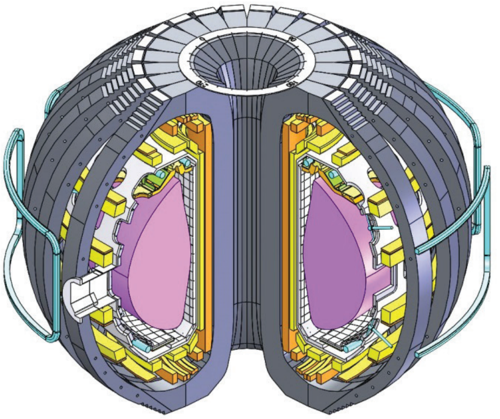

Figure 1. The interior of the DIII-D tokamak nuclear fusion device.

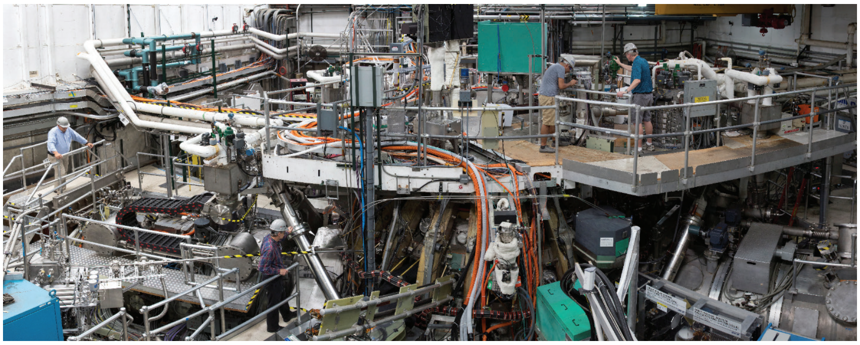

Figure 2. The DIII-D tokamak is surrounded by complex systems and components, which are exposed to strong magnetic fields.

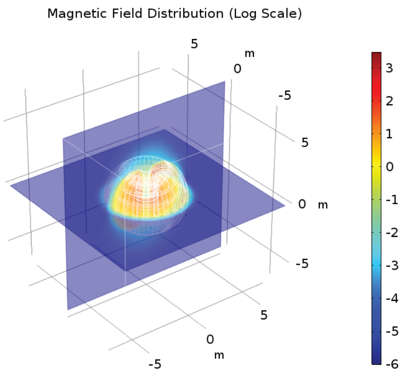

Figure 3. Simulation results of the magnetic field distribution inside and outside the tokamak vessel.

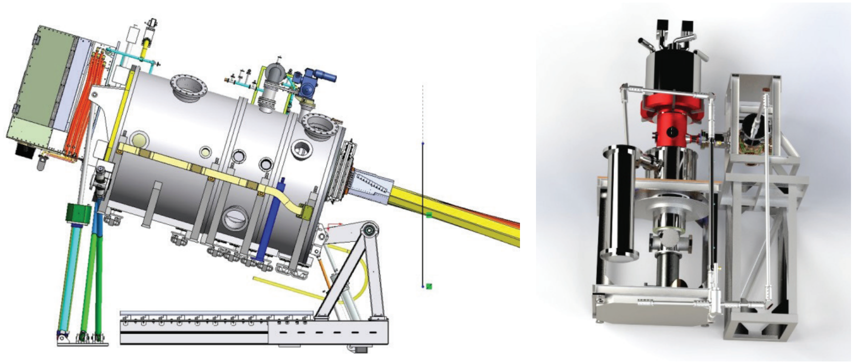

Figure 4. Current DIII-D external heating systems: neutral beam (left) and gyrotron (right).

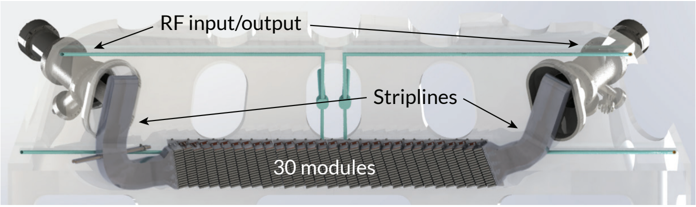

Figure 5. The helicon antenna featured on the DIII-D tokamak.

intensive,” Torreblanca said.

For example, static, slow, or fast varying magnetic fields have damaged some of the tokamak’s vacuum turbo pumps, which are vital for both main and subsystems on the tokamak. The team used multiphysics simulation to significantly improve analysis of the time-varying magnetic field distribution outside the tokamak vessel to find the best location to fit these pumps to improve reliability (Figure 3).

» A HELICON ANTENNA TO HARNESS THE SUN’S POWER

THE DIII-D TOKAMAK needs to achieve temperatures that are ten times hotter than the core of the Sun to achieve nuclear fusion. Currently, two systems (Figure 4) are used to achieve this: a neutral beam system (which injects 20 MW of power in the form of high-energy deuterium atoms) and the electron-cyclotron heating (ECH) system (where gyrotrons are used to inject up to 4 MW of microwave power to heat electrons). A novel heating system using a helicon antenna (Figure 5) that can inject 1 MW of radio frequency (RF) power is being designed and built.

Multiphysics simulation has been fundamental to optimizing the design of the helicon antenna. DIII-D will be the first tokamak to use such an antenna at MW power levels to couple RF power to the plasma to drive current and heat the plasma as predicted by specialized physics codes.

The helicon antenna consists of a 1.7 m array of 2 end modules and 28 center modules. Power can be injected from either end of the antenna through two striplines connected directly to the end modules, which then couple power inductively to each of the passive center modules in succession. DIII-D plasmas are on for up to 10 seconds with 10 to 15 minutes between pulses to allow the support systems to cool down to room temperature. The antenna is being designed to follow the same operation cycle.

Torreblanca explained: “Multiphysics gave us the ability to try new materials and allowed us to work out which material gives the best results. The antenna needs to survive the strong electromagnetic forces due to plasma disruption events that induce large currents on its structure. In order to reduce this current, a material with low electric conductivity is required. However, at the same time, a material with high thermal conductivity is needed to dissipate the high temperature that the antenna is exposed to from the plasma. A hybrid design made of CuCrZr and Inconel gave us the best of two worlds. Simulation made our work easier because we could look at many different materials with a few clicks.”

Torreblanca said: “It was easy to compute the antenna’s electromagnetic fields and visualize them. We coupled the electromagnetic analysis with heat transfer to model the RF loss distribution and get a map of the hot spots, which helped us refine the antenna design.”

The antenna is excited at its resonant frequency (476 MHz), and the GA team needed to know how the temperature would affect this frequency. Torreblanca said: “We need to understand if there is a drift in the antenna resonant frequency due to temperature so we can compensate for it in the antenna design or its operation parameters so it can operate reliably for 10 seconds.”

“Multiphysics simulation helped us to model the temperature distribution across a range of physical scenarios. This means we can work out whether it is possible to use the antenna for 10 seconds without damaging it, or we can calculate whether the antenna could operate for a few seconds and still be able to drive current and heat the plasma,” Torreblanca added.

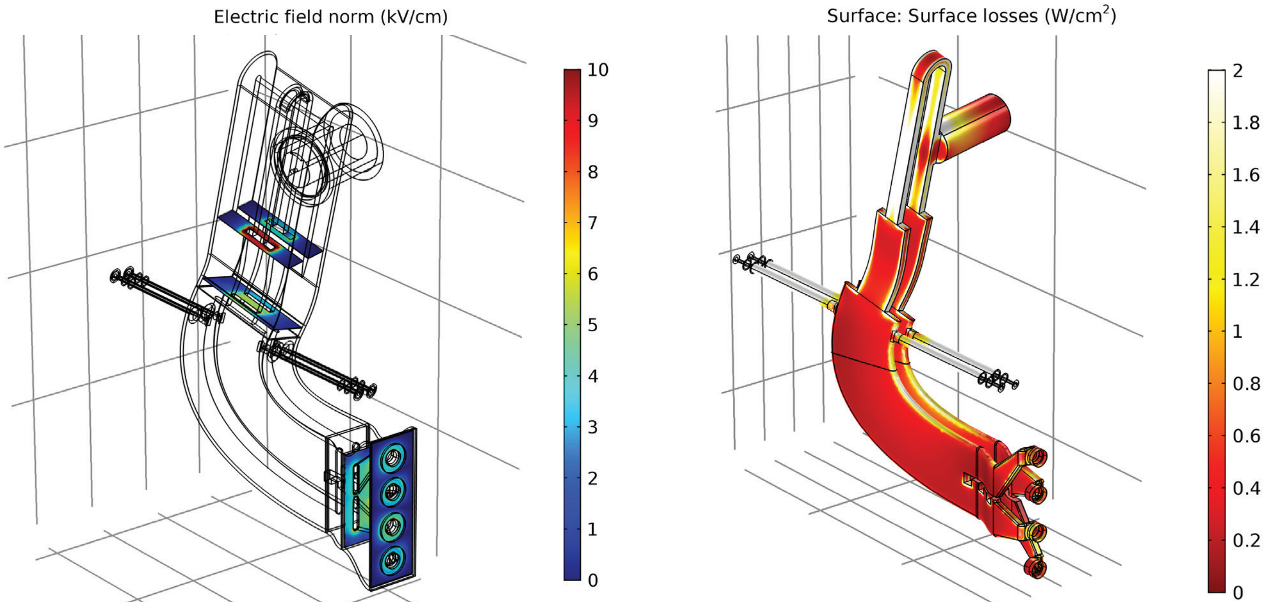

Figure 6. The antenna's stripline, showing the electric field distribution (left) and the RF losses (right).

SMALL-SCALE TESTS FOR BIG INSIGHTS

THE DIII-D GROUP built scaled-down test versions of key antenna components, allowing the team — in combination with multiphysics simulation — to test the parameters and conditions of these components of the full-scale antenna before they are built. Their tests included a one-quarter scale model and an RF resonator enclosure designed to replicate the electric field values of a full-scale antenna module and its stripline to find out whether arcing or multipacting phenomena will adversely affect the system (Figure 6). "We are validating these scaled versions of the antenna components, and simulation is providing a good match with the experimental results. This gives us even more confidence with the parameters and geometry of the antenna," according to Torreblanca.

"The insights from the simulation are always illuminating. We think that we know how the field will work and then we look at the visualization and we understand the design or performance better. As a result, we can be confident that the system will work the way we want," Torreblanca added.

The DIII-D research program is a key part of the worldwide effort to develop a viable nuclear fusion device in large part due to its highly collaborative approach among institutions and the integration of simulation and modeling to optimize its work.

Torreblanca concluded: "We are working on a global energy problem. If we can get good results in a timely fashion using COMSOL software, then that's a step forward to achieving nuclear fusion." ◎

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> —**HUMBERTO TORREBLANCA, DIII-D TOKAMAK CHIEF OPERATOR, GENERAL ATOMICS**

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