

# Protecting Fusion Reactors from Extreme Heat

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< 30 to 60 MHz ion-heating antenna installed into the CEA WEST machine



**NUCLEAR FUSION**, the process that powers the sun, has the potential to generate virtually unlimited amounts of greenhouse-gas-free and safe energy on earth. Although fusion power has long been pursued, the benefits of developing a reliable system to generate this energy is well worth the effort. French Atomic Energy Commission engineers are using ANSYS software

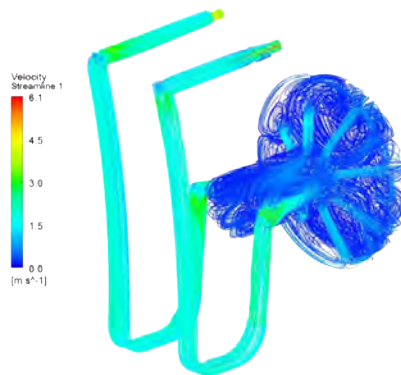
to overcome the difficult challenges involved in designing and protecting fusion reactor components, which must face plasma temperatures that reach 150 million degrees C. ANSYS electromagnetic and structural simulations are leveraged to design components to withstand enormous thermal loads; ANSYS fluid dynamics software is applied to cooling system design; and optical simulation is used to calibrate infrared temperature measurement systems so that engineers can accurately distinguish bright spots caused by direct heat flux from heat flux merely caused by reflections.

***“With a single antenna prototype costing millions of euros, accurate simulation is critical to the development of nuclear fusion as a potential energy source.”***

Generating electricity from fusion reactions requires that hot plasmas be maintained at enormous temperatures. To achieve these temperatures, CEA's tungsten (W) experimental superconducting tokamak (EST) reactor injects several megawatts of high-energy radio-frequency (RF) radiation into the plasma using antennas that are a few meters long and half a meter wide, and weigh several tons. Because these antennas are extremely close to the hot plasma, CEA uses ANSYS multiphysics software to design the antennas to resist thermal stresses generated by the plasma's heat flux, ohmic heating and RF reflections. ANSYS software can simulate infrared measurements of the plasma-facing components to ensure their accuracy. Simulation helps CEA increase the RF performance of these antennas and reduce their cost and the number of prototypes required, resulting in a savings of millions of euros.

#### **ANTENNA DESIGN CHALLENGES**

Plasma is a state of matter in which the electrons have been torn from their parent atoms, so the electrons and ions move independently. Plasma is conductive, so running an electric current through it heats it as if

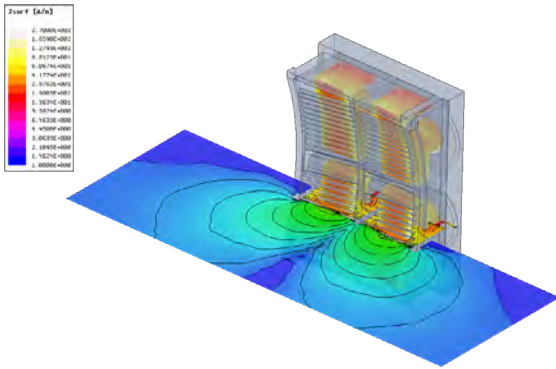


**ANSYS Fluent simulation shows pressure distribution in water-cooling circuit of antenna.**

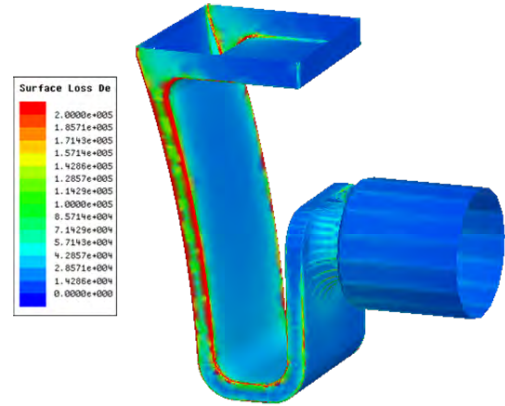
it were a radiant space heater. Because plasma resistivity decreases as its temperature rises, this method can achieve temperatures of a few tens of millions of degrees, but still higher temperatures are needed. To raise the temperature beyond this level, the CEA research machine WEST (tungsten [W] environment in steady-state tokamak) injects powerful RF waves in the plasma. As the plasma radiates an intense heat load on the antennas — a few tens of kilowatts per square meter (kW/m<sup>2</sup>) on average and megawatts per square meter (MW/m<sup>2</sup>) in the hottest areas — the antennas must be cooled by internal circulating-water channels to limit the temperature to a maximum of a few hundreds of degrees. In addition, the megawatts of RF power generate additional heat fluxes from ohmic losses in the antenna, and some of the RF power is reflected from the plasma back to the antenna. The antenna must also withstand mechanical







ANSYS HFSS model of the magnetic field generated by 50 MHz antenna



HFSS simulation shows ohmic losses on 50 MHz antenna.

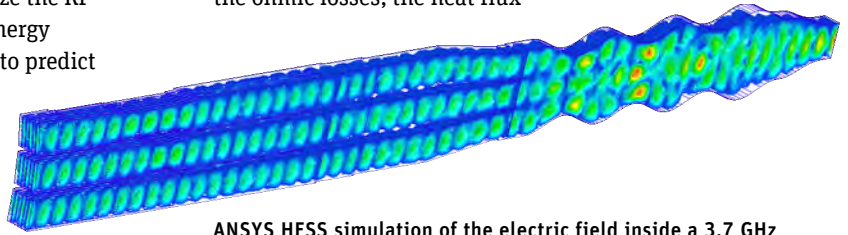
loading during the sudden loss of plasma confinement, a phenomenon — called disruption — that occurs when plasma becomes unstable. During this event, the electrical current circulating in the plasma falls from a few million amperes to zero in 10 milliseconds or less. This generates substantial mechanical torque on the plasma-facing components such as the antenna.

**SIMULATING THERMAL LOADS**

CEA engineers use ANSYS HFSS to optimize the RF design of the antenna to maximize the energy transferred from antenna to plasma and to predict ohmic loads for subsequent thermal stress analysis. Modeling the radiating medium is complicated by the fact that the magnetic plasma is inhomogeneous — its density and temperature increases from its edge to its center — and nonlinear in both the frequency and the spatial domains. At the plasma edge near the antenna, the plasma can be approximated

with a gyrotropic medium, which has been altered by the presence of a quasi-static magnetic field. At the request of CEA and the International Thermonuclear Experimental Reactor (ITER), a multinational experimental fusion reactor under construction, ANSYS added the ability to support complex gyrotropic mediums to HFSS so it can be used to model the plasma edge facing the antenna.

The thermal loads on the antenna include the ohmic losses, the heat flux

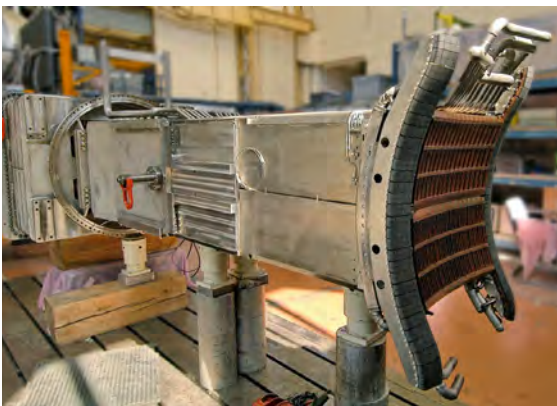


ANSYS HFSS simulation of the electric field inside a 3.7 GHz antenna. The RF power is injected from the right side of the picture and flows toward the left side. The power is divided in three (in the vertical direction) then in six (in the horizontal direction) and is phase-shifted before being launched to the plasma.

**FUSION POWER**

Fusion power could be an ideal energy source. It runs on hydrogen isotopes (such as deuterium, which can be found in sea water, and tritium, which can be generated inside the reactor), does not generate greenhouse gas and creates no radioactive waste except the reactor vessel itself. It requires much less land mass than wind or solar power installations for similar power and could produce power 24/7. But producing a self-sustaining fusion reaction requires that isotopes of hydrogen — deuterium and tritium — be heated to over 150 million C, a temperature at which they become plasma: an electrically charged gas that is common in space but rare on earth. At these temperatures, deuterium and tritium fuse to form helium, a neutron and large amounts of energy. Sustaining such a high temperature requires that the plasma be contained by magnetic fields generated by superconducting electromagnets.

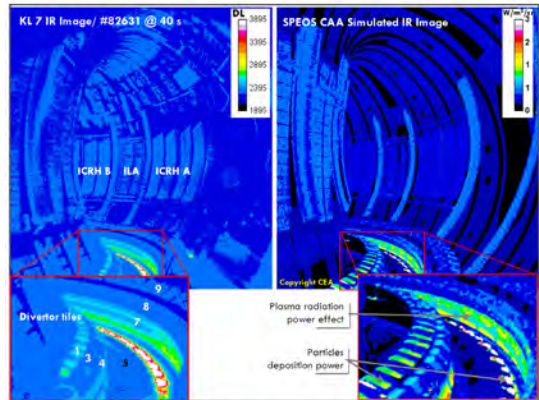
generated by the plasma, and the RF power reflected by the plasma back to the antenna. The plasma heat flux and the reflected RF power are determined by previous physical experiments and physics models. The ohmic losses, as mentioned earlier, are calculated by HFSS. ANSYS Fluent computational fluid dynamics (CFD) software is used to optimize the fluid flow and heat transfer through the cooling channels. ANSYS Mechanical finite element analysis (FEA) software takes all these thermal loads into account and calculates the temperatures at every point in the antenna. ANSYS Mechanical then converts these temperatures into thermal stresses, adds them to the mechanical stresses, especially the torques generated by disruption events, and determines the stresses and deflections throughout the antenna. Fatigue analysis using ANSYS Mechanical is performed to determine the lifetime of proposed designs, especially the number of disruption events they can handle.



Plasma current drive antenna in isolation  
*Courtesy: C. Roux, R. Volpe, CEA*

### SIMULATING INFRARED MEASUREMENTS

The heat load on the antenna and other plasma-facing components depends upon many factors that cannot be fully simulated in advance. In particular, infrared (IR) cameras are used to monitor the antenna's surface temperatures so that the plasma can be safely shut down before these expensive components are damaged. Verifying the accuracy of these temperature measurements is critical. For example, the IR system needs to be able to detect very small hot spots and temperature gradients. Because the metallic environment of the tokamak is highly reflective, multiple reflections from hot regions will interfere with the thermal signals used to evaluate surface temperatures, leading to inaccuracies. Inaccurate temperature measurements could result in unnecessary (and expensive) shutdowns of the reactor if the temperature is overestimated. In the inverse case, if the temperature is underestimated, there is a risk of damage to the in-vessel components.



ANSYS SPEOS simulation (right) correlates well with IR image of fusion reactor (left).

To address these challenges, CEA uses ANSYS SPEOS software to simulate the ability of the IR system to measure the temperature of the antennas and other components in the vessel such as the lower divertor (a region of the tokamak that receives the largest part of the heat load from the plasma). SPEOS models the complex physical phenomena involved in the interactions of photons with matter and their propagation inside the IR system. This software predicts the radiometric images that will be generated by different types of materials in order to anticipate how the aging of materials will affect future IR imaging. SPEOS is used to predict the global response of the complete IR system by considering all the infrared sources, the 3D geometry of the tokamak, and material properties as determined by the surface bidirectional scattering distribution function (BSDF). SPEOS is also used to model the IR camera, including its geometrical optical properties such as its dimensions, wavelength range, spectral transmittance and pixel count. The simulations determine the actual IR images that will result from different surface temperatures, enabling the IR system to be calibrated to deliver accurate measurements (for example, to correct false hot spots due to reflection).

With a single antenna prototype costing millions of euros, accurate simulation of the electromagnetic interactions between magnetized plasmas and RF antennas, the thermal stresses on the antenna, and IR temperature measurements on the antennas are critical to the development of nuclear fusion as a potential energy source. ANSYS multiphysics software helps CEA engineers address all these challenges as they move toward producing fusion power on the scale of modern electric power plants. The result is that the number of full antenna prototypes has been substantially reduced, and the time to design antennas has been reduced from five years to one year. Simulation has also helped CEA engineers increase the performance and reduce the manufacturing cost of these antennas. ⚠