Electromagnetic Wave Simulation in Fusion Plasmas

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Introduction

Fusion is a form of nuclear energy which has impressive advantages from the point of view of fuel reserves, environmental impact and safety. If successful, fusion energy would ensure a safe, resource conserving, environmentally friendly power supply for future generations. In a world wide cooperation to achieve this goal, seven parties including Europe, Japan, Russia, USA, China, South-Korea and India are building ITER, a 4.6 billion Euro international experiment which, after 10 years of construction, will put fusion research on the way to demonstrating an energy-yielding plasma on earth.

In an operating tokamak fusion reactor[1], part of the energy generated by fusion itself will serve to maintain the plasma temperature as fuel is introduced. However, to achieve the desired levels of fusion power output, in the startup of a reactor the plasma has to be heated to its operating temperature of greater than 10 keV (over 100 million degrees Celsius) and additional current induction must be applied.

Heating and current drive can be achieved by radio frequency waves. If electromagnetic waves have the correct frequency and polarization, their energy can be transferred from the source to the charged particles in the plasma. In this work we focus on the propagation of electromagnetic waves in a tokamak plasma in the Lower Hybrid [2,3] and Ion Cyclotron [2] frequency ranges. The wave propagation and heating process in these two frequency ranges are different, and as a result also the radiating antennas at the plasma boundaries have different features. IC antennas are composed of metal loops (called straps), and fed by coaxial power lines, while LH antennas are arrays of open-ended waveguides (called grill).

Antennas for typical fusion applications have complex shapes, and are charged with the difficult mission of delivering high powers (MW) while at the same time operating in prohibitive conditions of thermal and mechanical stresses. Antennas are often the component which determines the success or failure of the heating system, and for the difficulties in testing real life structures, the availability of a predictive simulation tool is very important for this class of antennas. Hence, the challenge of simulating the actual antenna geometry in presence of a realistic plasma model, without inserting it into the experiment for which it is being designed. Moreover, computer simulations are indispensable for evaluating experimental results and plays a mayor role in the understanding of the physical processes involved.

The difficulty of simulating RF waves of fusion plasmas comes from the fact that the plasma is a medium which is inhomogeneous, anisotropic and lossy Even worse, hot plasmas are spatially dispersive, meaning that the property of this medium is non-local. Hot plasma effects are therefore commonly treated in the spectral domain, where spacial dispersion effects are treated more easily [4]. However spectral domain solver represent the solution in terms of basis functions which defined over the whole computational domain and are consequently unable to represent the tokamak vessel or of the launching antenna structure and are limited to the description of the core plasma.

Use of COMSOL Multiphysics

We exploited COMSOL unique capability of allowing the definition of the full 3D dielectric tensor of a spatially varying media to model the harmonic propagation of waves in a (cold) magnetized plasma. With COMSOL we were able to take into model the exact shape of the tokamak first wall and of the antenna launching structure. Also, the toroidal helical magnetic field topology and the plasma density were directly input from experimental measurements.

In particular we modeled the propagation of waves in the Alcator C-Mod tokamak experiment [5] for the Lower Hybrid (4.6GHz) and Ion Cyclotron (80 MHz) frequency ranges.

For the LH frequency range, we developed a new approach to do single mode analysis in a 3D FEM solver [6] and we included the effect of electron Landau damping (an hot plasma effect) by means of an innovative iterative routine developed in MATLAB, as described in [7,8]. The non Maxwellian electron velocity distribution arising from the interaction of the LH waves with the plasma, was taken into account by a Fokker Plank code which was included in the iteration loop.

For the IC frequency range, we modeled for the first time in a single self-consistent simulation, the behavior of a realistic antenna geometry when facing a (cold) plasma.

In the case of LH waves, the wavelength arising from the propagation in a plasmas is rather short (~mm) compared to the device size (~m), thus making the electromagnetic problem very large. Consequently the models require a large number of DOF for the waves to propagate. In particular we were able to solve models with more than 20E6 unknowns by the aid of the MUMPS library[9], using the massive parallel computing resources at NERSC [10].

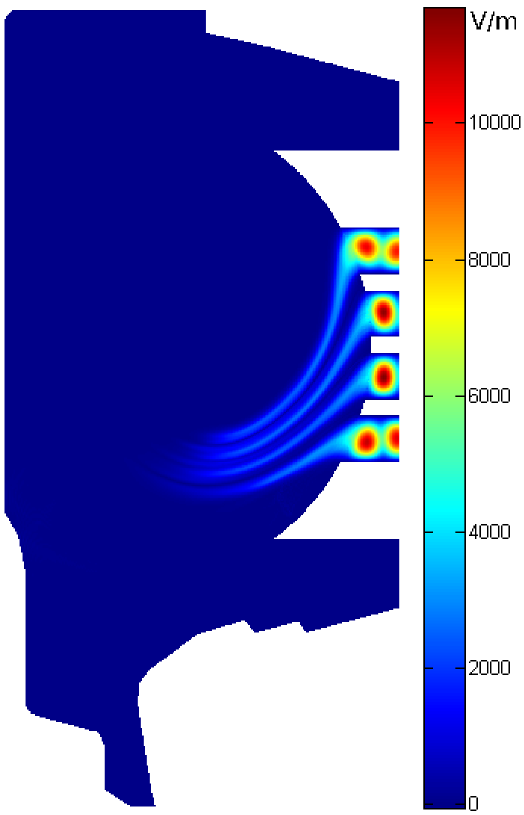

Illustration 1: Magnitude of the electric field of LH waves as they propagate in a poloidal cross section of the Alcator C-Mod tokamak. This result takes into account ELD and the non maxwellian electron distribution arising from the interaction of the LH waves with the plasma.

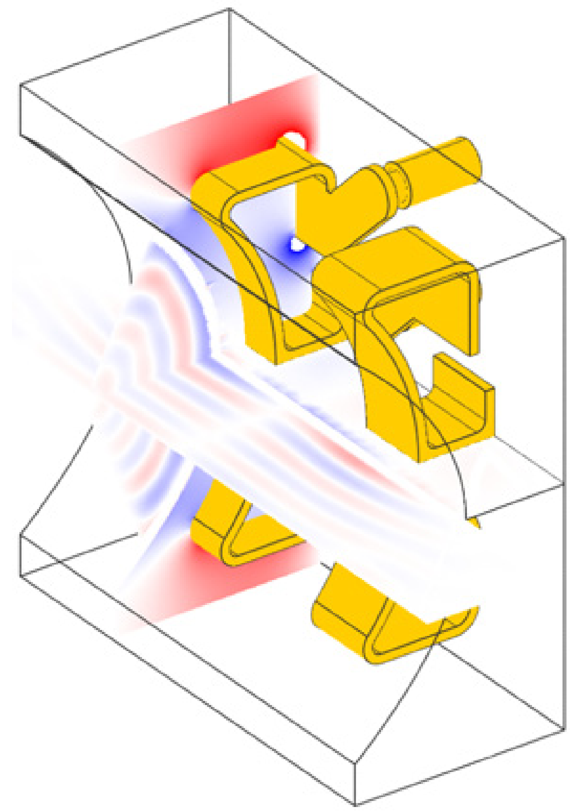

Illustration 2: Snapshot of the ICRF waves as they are radiated from the antenna and they propagate in a section of the Alcator C-Mod tokamak.

Conclusion

In summary, COMSOL has been used to a model the propagation of electromagnetic waves in fusion plasmas. For the first time, a finite element method has been used to solve the wave propagation for realistic fusion plasma parameters in the LH and IC frequency ranges. Moreover, for LH waves, a new efficient iterative algorithm has been developed to take into account the dispersive effects of a hot plasma. The advantages of the FEM approach include a significant reduction of computational requirements compared to full wave spectral methods and an exact description of the antenna geometry, while seamlessly handling the plasma region.

Reference

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