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Computational electromagnetics for nuclear fusion engineering and design

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Abstract

Nuclear fusion is the process that heats the stars by the collision of atomic nuclei which fuse together to form heavier elements and release energy. The generation of energy using this process has several advantages: no carbon emissions, abundant fuel supplies, efficiency, reliability and operationally safe. One way to achieve the necessary conditions for producing fusion energy on earth is by controlling a hot gas of fully ionized hydrogen isotopes (plasma) with strong magnets in a ring-shaped magnetic chamber known as tokamak. The real-time control of this hot plasma requires magnetic diagnostic and actuators which must be designed to be reliable and immune to undesirable interferences. The heating and stabilization of the plasma partly rest on Radio-Frequency (RF) antennas which must be designed and controlled carefully to avoid undesired plasma-wall interactions that can produce excessive heat-loads and endanger the integrity of the machine. Also, the safe installation of the different diagnostics, devices and structures in and around the fusion machine requires the knowledge of the Lorentz forces induced by the time-varying electromagnetic fields present during the operation of the machine.

As can been expected from the above examples, nuclear fusion engineering and design can be greatly benefited from the use of computational electromagnetic software tools. In this work we are going to present how the open-source finite element tool ERMES has been upgraded to tackle nuclear fusion-related problems. The updated version of ERMES can solve problems from the static regime (electrostatic and magnetostatic), to the high-frequency regime (interaction of radio frequency waves with plasma and walls), passing through the quasi-static low frequency regime (induced eddy currents). A novel finite element formulation has been implemented to compute the interaction of the electromagnetic waves with the inhomogeneous anisotropic cold plasma present in the scrape-off layer close to the RF antennas. New numerical models have been developed to estimate the probability of arcing under different failure scenarios (e.g. unmitigated superconducting coil quench). The generality of these new developments allows a straightforward application in engineering problems outside the nuclear fusion environment as in the design of helicon plasma thrusters, high voltage engineering, inductive heating, and bio-electromagnetism.

1. Introduction

Nuclear fusion is the process that heats the stars by the collision of atomic nuclei which fuse together to form heavier elements and release energy. The generation of energy using this process has several advantages: *no carbon emissions* (the only by-products of fusion reactions are small amounts of helium), *abundant fuel supplies* (fuel material can be extracted from water and produced from lithium and so is strategically secure), *efficiency* (one kilogram of fusion fuel can provide the same amount of energy as 10 million kilograms of fossil fuel), *operationally safe* (major accidents impossible, no meltdown, no criticality issues concerning reactivity), *reliable power* (fusion power plants could supply constant amounts of electricity independently of weather conditions).

One way to achieve the necessary conditions for producing fusion energy on earth is by controlling a hot gas of fully ionized hydrogen isotopes (plasma) with strong magnets in a ring-shaped magnetic chamber known as tokamak. The real-time control of this hot plasma requires magnetic diagnostic and actuators which must be designed to be reliable and immune to undesirable interferences. The heating and stabilization of the plasma partly rest on Radio-Frequency (RF) antennas which must be designed and controlled carefully to avoid undesired plasma-wall interactions that can produce excessive heat-loads and endanger the integrity of the machine. Also, the safe installation of the different diagnostics, devices and structures in and around the fusion machine requires the knowledge of the Lorentz forces induced by the time-varying electromagnetic fields present during the operation of the machine.

As can been expected from the above examples, nuclear fusion engineering and design can be greatly benefited from the use of computational electromagnetic software tools. This article shows how an upgraded version the open-source finite element code ERMES (Otin, 2013a) has helped in the solution of fusion engineering problems. The features of the new ERMES are described in the next section. After that, four nuclear fusion application examples are explained in detail.

2. ERMES

ERMES (<u>E</u>lectric <u>R</u>egularized <u>M</u>axwell <u>E</u>quations with <u>S</u>ingularities) is a finite element code in frequency domain which implements in C++ a simplified version of the weighted regularized Maxwell equation method (Otin, 2010). This finite element formulation produces well-conditioned matrices which can be solved efficiently with low-memory consuming iterative methods (Otin et al., 2013b). Also, thanks to the null kernel of its differential operator, it can operate indistinctly in the quasi-static and the high frequency regimens.

Therefore, ERMES is a versatile tool which has been applied to a wide variety of engineering problems. For instance, it has been applied to microwave engineering (Otin, 2010), bio-electromagnetics (Otin, 2011a; Otin and Gromat, 2012; Otin and Salmon, 2017), electromagnetic compatibility (Otin et al., 2011b; Otin et al., 2015a), and electromagnetic forming (Otin, 2013c; Otin et al., 2014a).

ERMES can be downloaded from the Computer Physics Communications Program Library (Otin, 2013a) or from the software section of the developer website (Otin, 2018). ERMES is available for Windows and Linux operative systems and has a user-friendly interface integrated in the pre- and post-processor GiD (GiD, 2019). GiD is used for geometrical modelling, data input, meshing and visualization of results.

A new version of ERMES is under development and testing. Novel finite element formulations had been implemented to compute the interaction of the electromagnetic waves with the inhomogeneous gyrotropic cold plasma present in the scrape-off layer close to the RF antennas. New numerical models have been developed to estimate the probability of arcing under different failure scenarios (e.g. unmitigated superconducting coil quench). Also, ERMES is been upgraded to work on high performance computing platforms, which is useful when we need to solve large problems with high accuracy. Some application examples of these new features are showed in the following.

3. Induced Lorentz forces

The large time-varying magnetic fields used for confining and controlling the plasma induce eddy currents in any metallic structure placed close to the tokamak machine. These induced currents interact with the background magnetic field and can produce forces able to cause undesired vibrations or even endanger the mechanical integrity of the installed structure.

Any new design must be checked against the induced forces to ensure its structural integrity and reliability. To estimate these forces, we must first define a set of worst-case scenarios (i.e. set the variation in time of the plasma and coil currents that generate the maximum fields). We can obtain the worst-case scenarios from measurements or from simulations. These simulations can include the dynamic of the plasma and its coupling with the coils or just consists in an imposed set of currents with the maximum values allowed by a specific tokamak machine. Once the field sources are defined, we can place the new design in the required location and calculate the induced volumetric Lorentz force density. Later, this force density can be used to compute other mechanical magnitudes of interest (e.g. stresses and displacements).

The workflow detailed above requires the evaluation of the quasi-static Maxwell equations for any modification of the design. These evaluations are usually slow and computational expensive, and they can delay significantly the design process. Moreover, the uncertainties in the definition of the worst-case scenario often do not justify such an accurate an expensive calculation.

To make things faster and simpler we follow a different path. From every worst-case scenario we just take the initial and final current distribution. These current distributions are used to compute the magnetic flux density **B** around the tokamak machine (see Fig. 1). The magnetostatics fields obtained are used to calculate the spatial gradients of each **B** component and their variation with time (see Fig. 2). This process is done for every scenario of interest and the values obtained saved in files which store a list of nodes with its corresponding set of fields and gradients values.

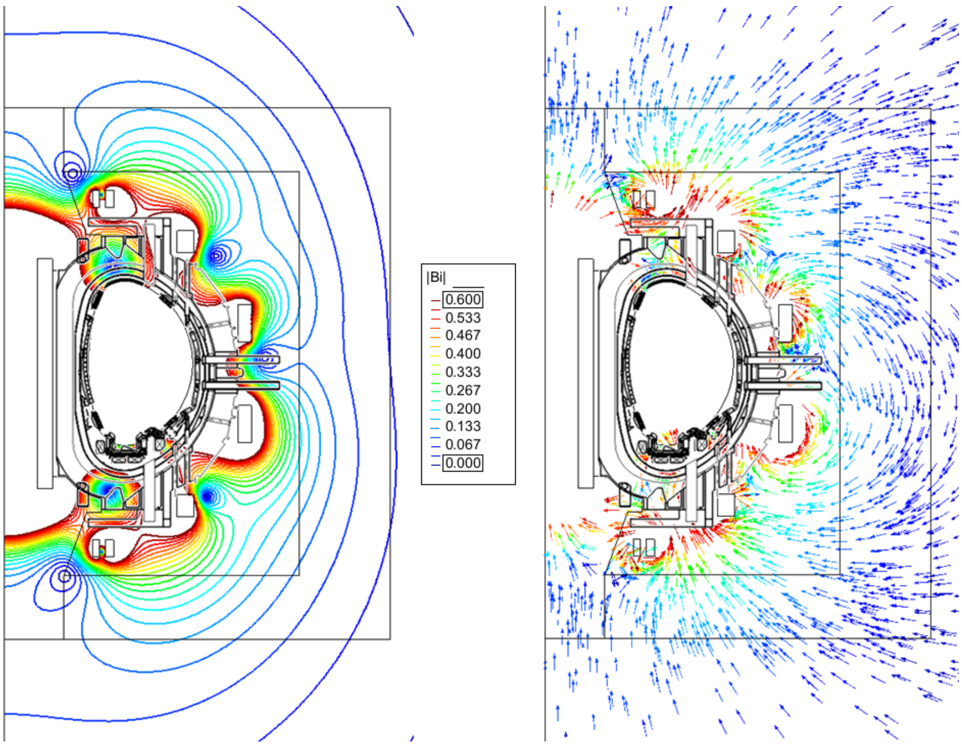

*Figure 1: Magnetic flux density **B** before a 10 ms 6 MA plasma disruption scenario at JET.*

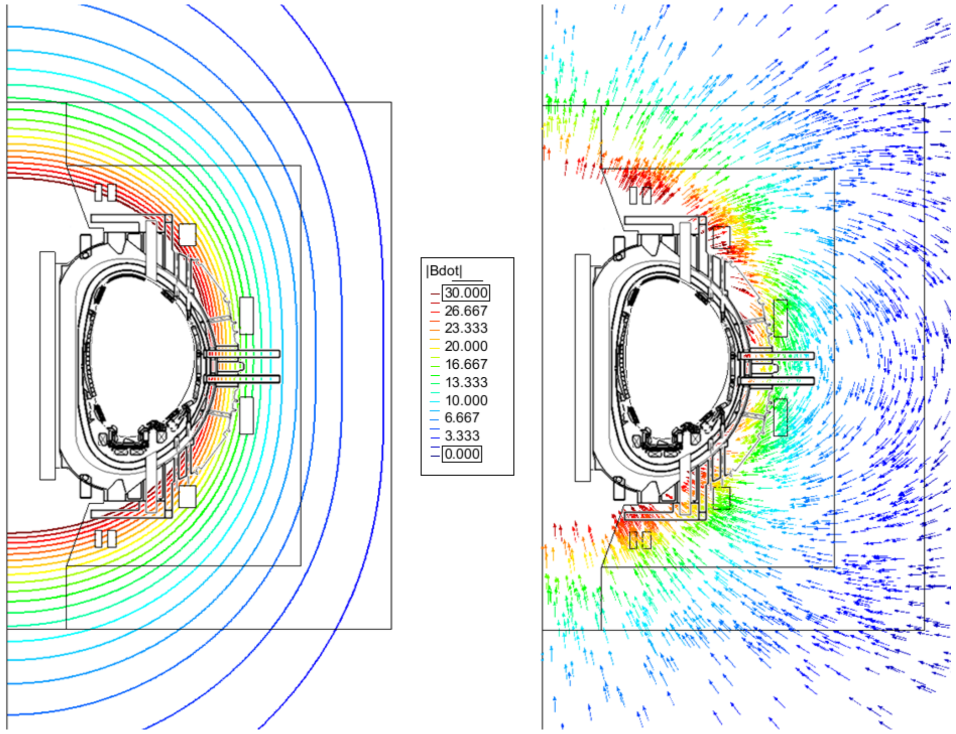

*Figure 2: Time derivative of the magnetic flux density **B** for the 10 ms 6 MA plasma disruption scenario at JET.*

When the evaluation of a new design is required, we first take the fields and gradients from the position where the new design is going to be installed. Then, the new design is discomposed in a set of simplified geometries (rectangular plates, cylinders and rings). Finally, we apply analytical formulas to those geometries (Otin, 2015b; Otin, 2014b) assuming a quasi-static induction-less regime (i.e. the fields generated by the induced currents can be neglected when compared with the applied fields). These analytical formulas are valid for slow time variations of the fields and relatively small pieces and always provide a conservative value of forces and torques, which is beneficial for structural safety assessments. The whole process is very fast because the fields are pre-calculated and therefore, we only need to read a file before applying the analytical formulas, so the design interactions are greatly accelerated. This procedure has been widely used in JET and it is part of the operation and fault condition design criteria for JET components.

In this process ERMES is used to compute the fields and provide the pre-calculated files. A python script is used to read the files and apply the analytical formulas. ERMES calculates the magnetostatic fields from the current distributions using a very low frequency (1 Hz or lower) and setting to cero the electrical conductivities of all the materials present in the computational domain. Examples of the fields obtained are shown in Figures 1 and 2.

4. Electromagnetic compatibility

When installing diagnostics that measure electromagnetic fields is important to evaluate the perturbations on these fields produced by the surroundings structures. Nearby components can shield the signal and make the diagnostic to produce erroneous results.

ERMES can perform this type of evaluation easily. First, we must generate the fields that the diagnostic is supposedly going to measure. This can be done by a proper current distribution. Then, we perform a frequency sweep and calculate the fields inside the diagnostic for the different frequencies and design proposals. Finally, we can analyse which frequencies are the most affected and which tokamak components are inducing larger error fields.

As an example of application, in Fig. 3 is shown two Mirnov coils design proposals. These coils measure the magnetic field at the edge of the plasma. Their measurements are an important part of the real time networks that control the shape and position of the plasma. The operation of a tokamak reactor depends greatly in the accuracy of their measurements.

The main difference in the designs shown in Fig. 3 is the configuration of the metallic frame that supports the coils. The frames have been designed taking into consideration easy remote maintenance accessibility. The configuration at the right of Fig. 3 has the advantage of requiring less space for its installation (which is necessary considering the busy walls of a tokamak, cramped with loads of different diagnostics and actuators). The configuration at the left uses more space, but as can be seen in Fig. 4, its measurements at high frequencies are less affected by the metallic frame. Therefore, when possible, the design at the left would be preferred. On the other hand, if the installation space inside the tokamak is too tight to allocate this configuration, we can use the design at the right, but allowing as much distance as possible between the bolt and the coil. In Fig. 4 is shown the effect on the measured fields of the distance between the bolt and the coil.

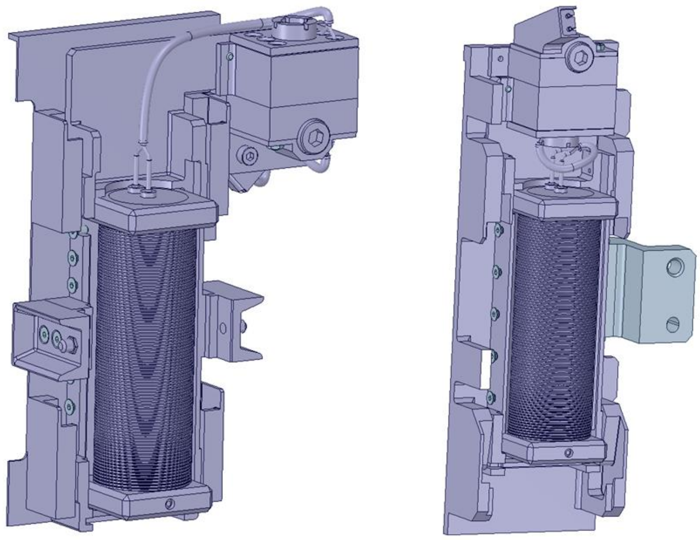

Figure 3: Mirnov coils design proposals.

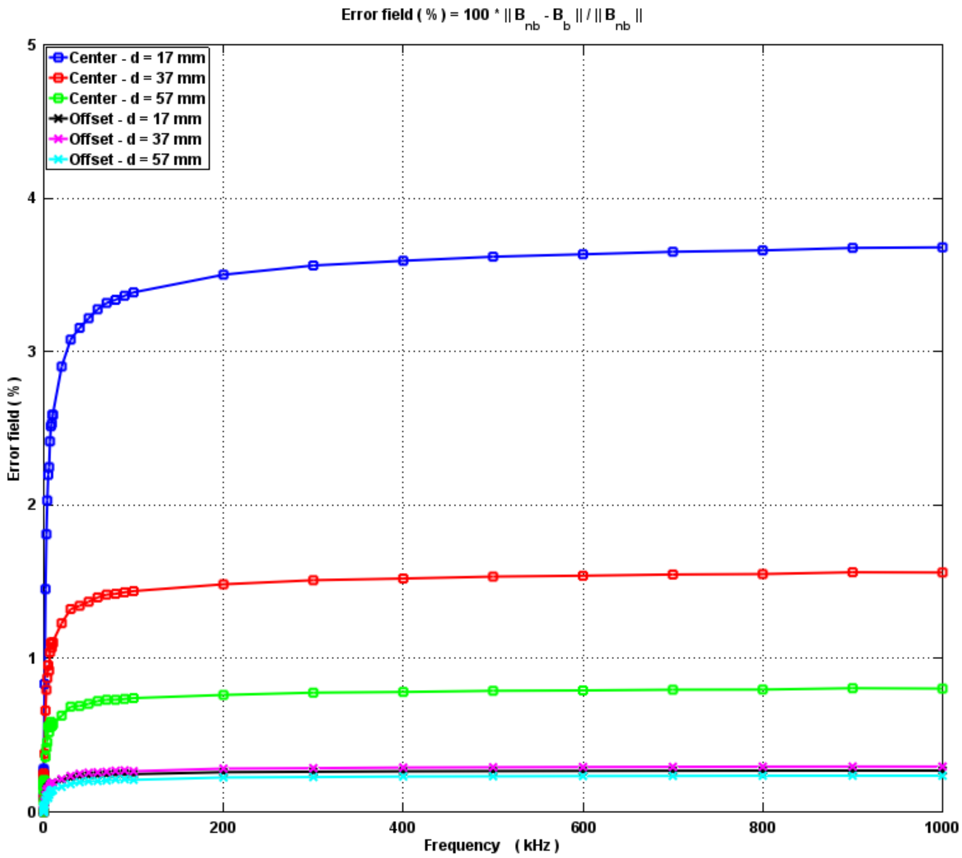

Figure 4: Error field for the two different configurations shown in Fig. 3. $\mathbf{B}_{nb}$ *refers to the magnetic flux density calculated without the frame.* $\mathbf{B}_{b}$ *is the magnetic flux density calculated with the frame.* ***Center*** *is the configuration at the right of Fig. 3.* ***Offset*** *is the configuration at the left.* ***d*** *is the vertical distance between the coil and the bolt.*

5. Electric arcs

Under some conditions the electric fields induced around the tokamak reactor can generate powerful electric arcs able to damage important components of the machine. A detailed analysis of an electric arc requires a multiphysics approach combining fluid dynamics, thermal and electromagnetic equations. These simulations can be unpractically expensive from the computational point view, especially, if we must consider large geometries.

To reduce the computational cost when doing this type of study, we can make first a quick and cheap electrostatic assessment which will tell us the possible locations where the arc can be initiated and, also, what is the approximate damage that the arc can make on the structures. Once this first assessment is done, we can select the scenarios with a higher probability of arcing and with the more damaging effects and perform a more detailed simulation. This way of proceeding reduces the number of costly simulations and accelerated the overall study.

ERMES can perform this type of preliminary analysis with its electrostatic module. In Figures 5 to 8 is shown an example of electric arcs assessment with ERMES. Figure 5 shows the voltage and electric field generated outside an ITER poloidal coil when a quench develops inside it. A quench occurs when part of a superconducting coil change to its normal resistive state. When this happens, the Joule heating generated at that spot raises the temperature of the surrounding regions, which also become resistive, which leads to further heating and to more areas becoming resistive. This chain reaction transforms the superconducting coil in a normal resistive coil. The change from superconductor to normal can result in high voltages and arcing. The objective of the study shown in figures 5 to 8 is to assess the probability of arcing in case of an unmitigated quench and to estimate the damage that these arcs can make on the surroundings structures. For instance, we would like to know if the arcs can perforate areas which store radioactive materials (e.g. tritium).

To estimate the probability of arcing we first calculate the maximum voltage that the quench can generate and the associated electric field (see Figures 5 and 6). Then, we combine the length of the iso-lines (see Fig. 6) with the Paschen's law to assess the probability of breakdown and the possible arc impact points. Once the impact points are defined, we calculate the current distribution inside the affected structure (see Figures 7 and 8) and estimate the damage caused by the arc.

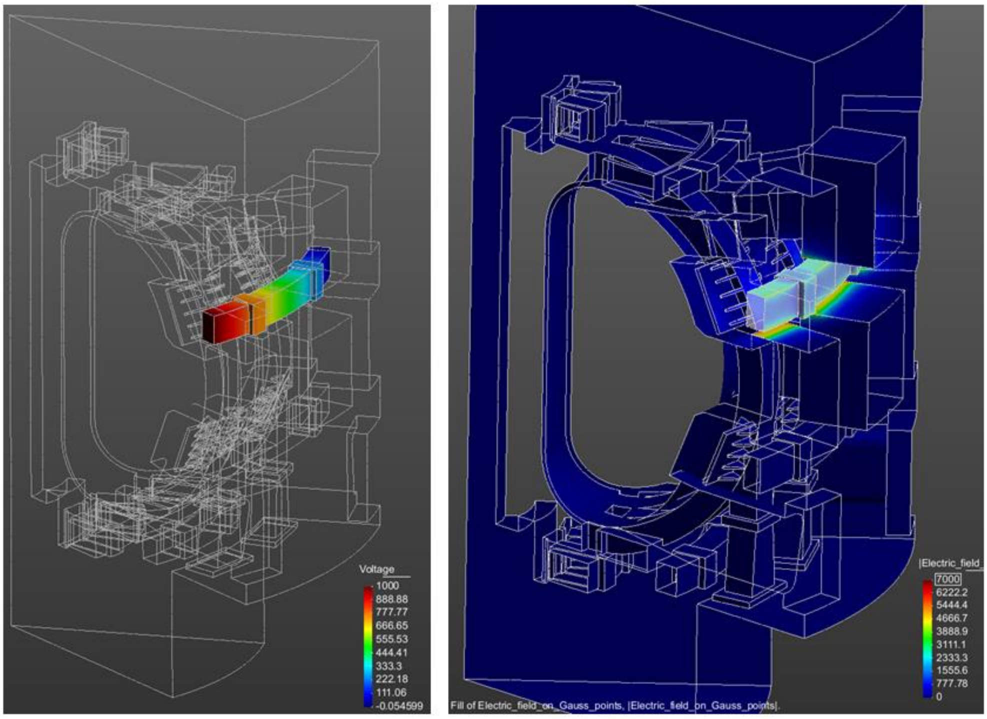

Figure 5: Voltage (left) and electric field (right) generated during a quench in ITER poloidal coil.

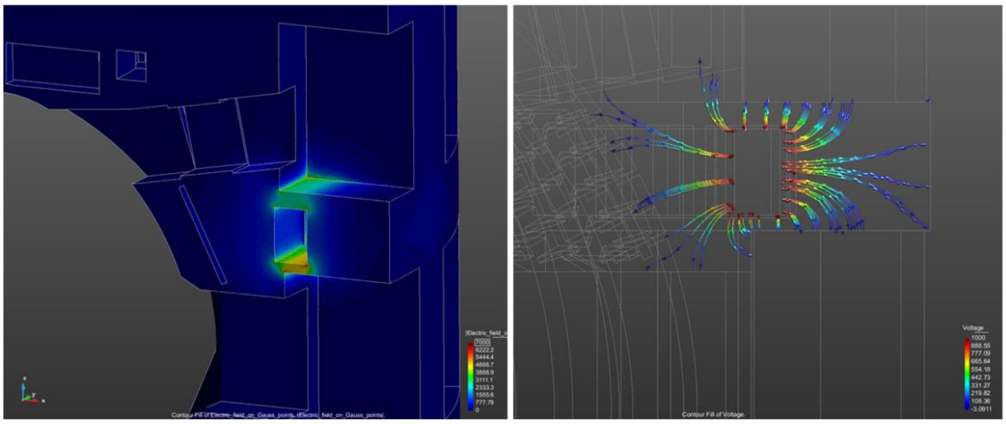

Figure 6: Detail of the electric field module (left) and electric field iso-lines (right).

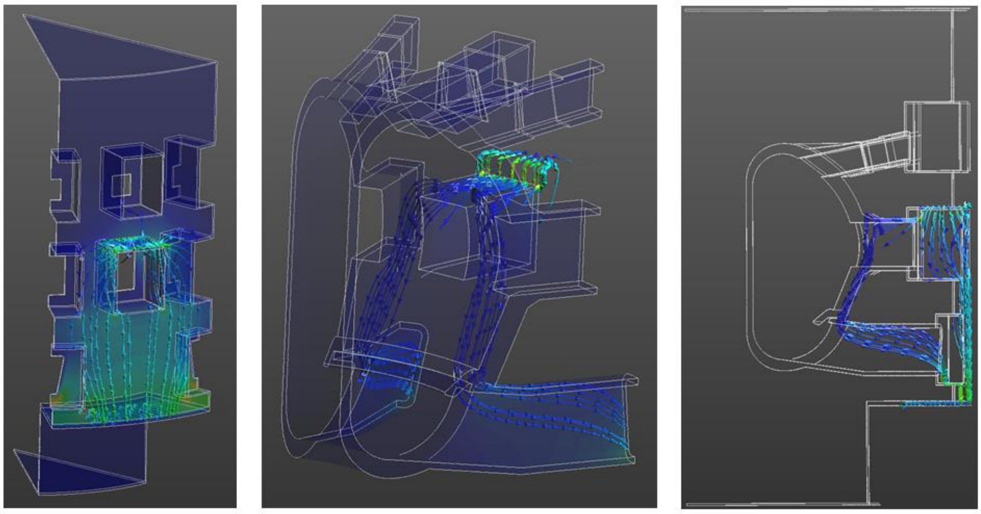

Figure 7: Electric current distribution inside the ITER cryostat and vacuum vessel.

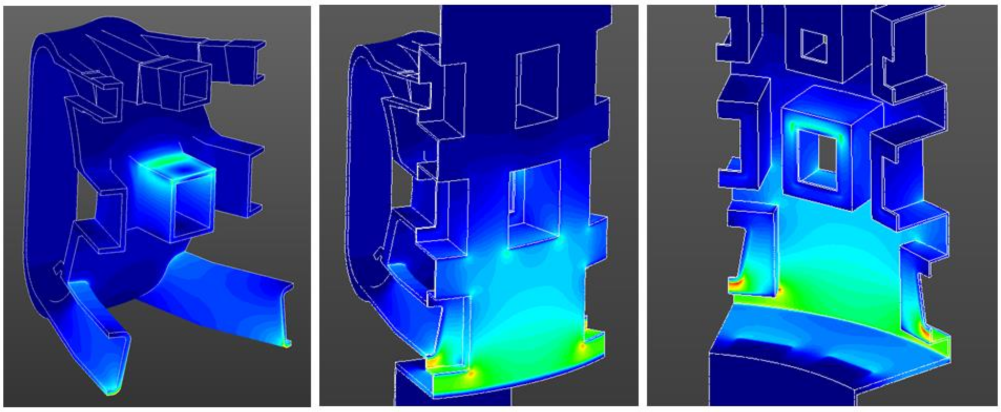

Figure 8: Electric current module inside the ITER cryostat and vacuum vessel.

6. RF waves-plasma-wall interactions

One possible option to heat the plasma up to fusion temperatures is by means of Radio Frequency (RF) waves. But we must be careful when we send these waves to the interior of a tokamak. When RF waves are applied in tokamaks with metal walls, sheath rectification effects associated to the fields induced in the scrape-off layer (SOL) may lead to enhanced plasma-wall interactions which can melt components of the machine and limit the RF power. The prediction of these events is difficult and, although, many codes are available to describe the wave-particle physics in the plasma core, the modelling of the RF wave interactions in the presence of a low-density plasma is much less explored since the RF physics describing the involved mechanisms is not yet fully understood and the solution of the problem is numerically demanding due to the excitation of millimetric waves in the SOL and the close interaction of these waves with the complex antenna and wall geometries (see Fig. 9 and 10). Moreover, the knowledge of the antenna near fields is important from the engineering point view because it allows to improve the design of the antennas and its components. For instance, an estimation of the reflected power from the plasma to the ILA antenna (Fig. 9) allowed us to improve its electric contacts and reduce manufacturing costs (Thompson and Otin, 2015).

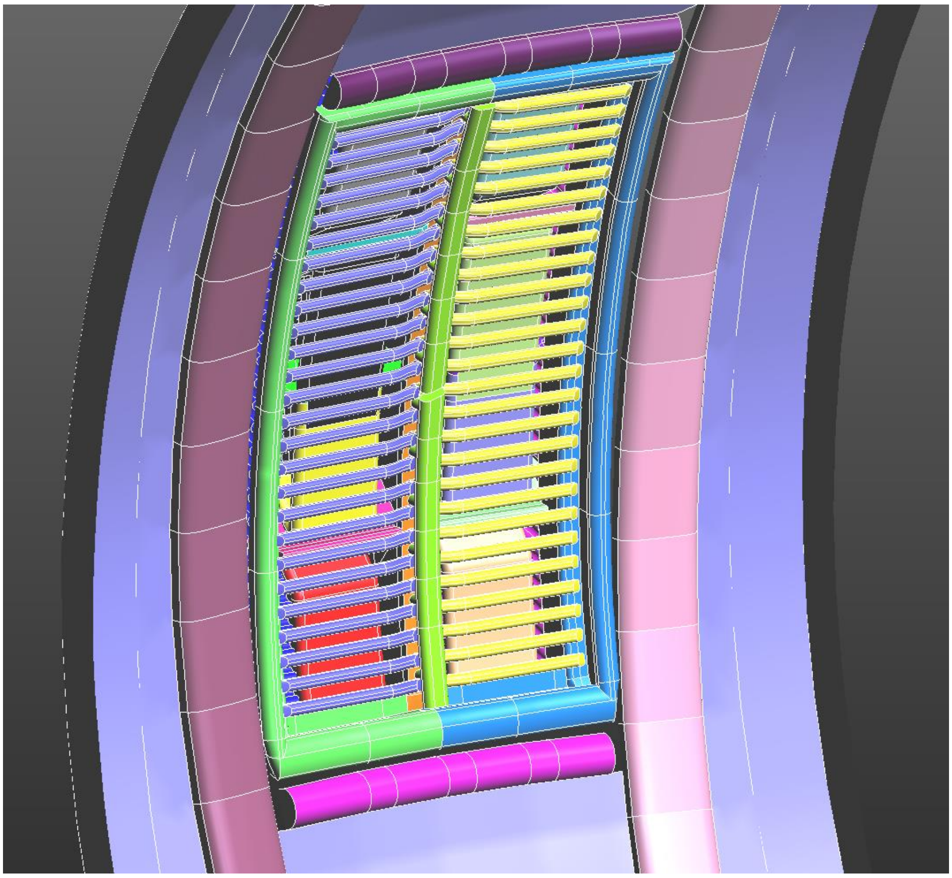

Figure 9: CAD model in GiD of the JET ITER-Like Antenna (ILA).

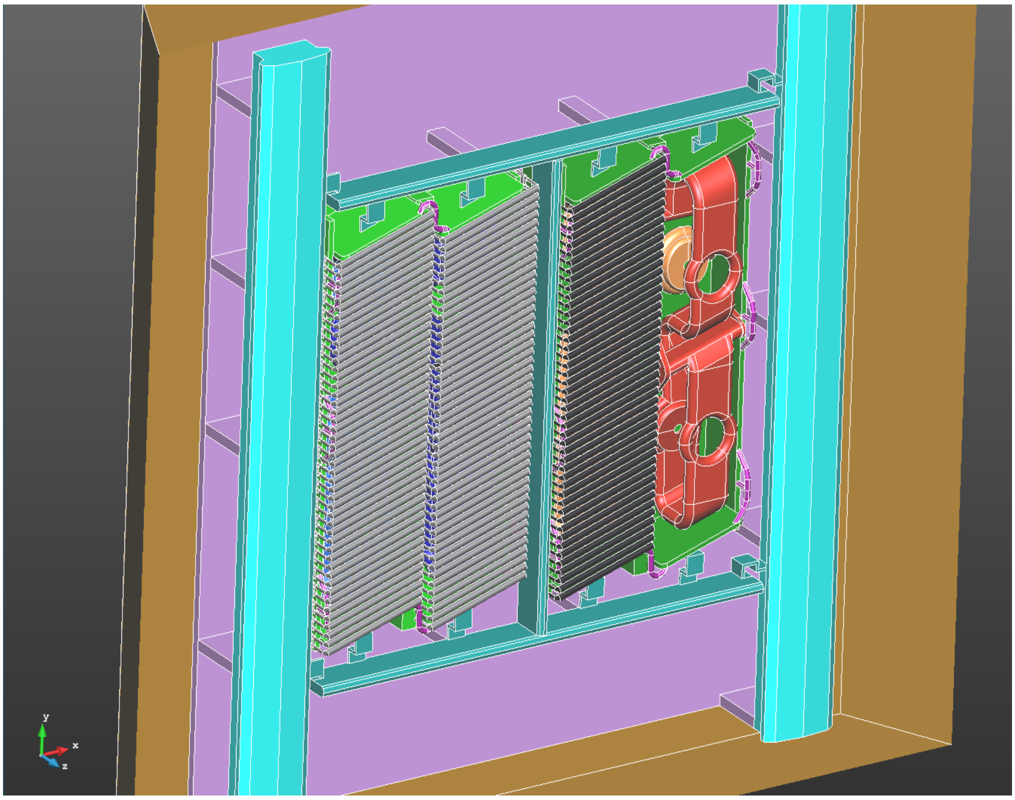

Figure 10: CAD model in GiD of the JET A2 antenna.

Currently, some numerical tools are being used to simulate the RF antenna near fields in the presence of magnetized plasmas, but they have their limitations. For instance, the well-known in-house code TOPICA (Lancellotti et al., 2006), which is typically used to couple realistic antenna geometries with the hot plasma inside the reactor, needs a vacuum buffer area of separation between the antenna and the plasma. Therefore, it neglects all the physical phenomena related to the interaction of the RF waves with the low-density plasma close to the antenna (as the Lower Hybrid Resonance (LHR)). Other software, as the commercial packages CST, HFSS and COMSOL (Lu et al., 2016) or in-house codes as MFEM (Wright and Shiraiwa, 2017), have been customized to consider the close interaction of the near-fields with the low-density plasma, but they fail to find a solution around the LHR due to numerical instabilities associated with the finite element formulation implemented inside them. Simplifications can be used to reach convergence (neglect gyrotropy, increase electron density to avoid LHR), but the fields obtained can be very different to the real ones (even if the input impedance of the antennas are similar to the ones measured) and this difference can affect the accuracy of derived magnitudes as the sheath rectification effects, which use these fields as an input. For instance, Fig. 11 shows how just a change in the plasma species composition can have a huge effect the RF field distribution.

ERMES tries to overcome the limitations mentioned above. It has been customized to read measured plasma density profiles from files, incorporate these measurements in a 3D CAD representation of the RF antennas and calculate the near-fields and other relevant magnitudes in the presence of cold magnetized plasma. ERMES implements a stabilized finite element formulation which allows to simulate near fields of the antenna in a continuous gyrotropic non-homogeneous media without limits in the minimum value of the plasma density. The cold plasma module has also applications in fields outside the nuclear fusion engineering as the helicon plasma thrusters design.

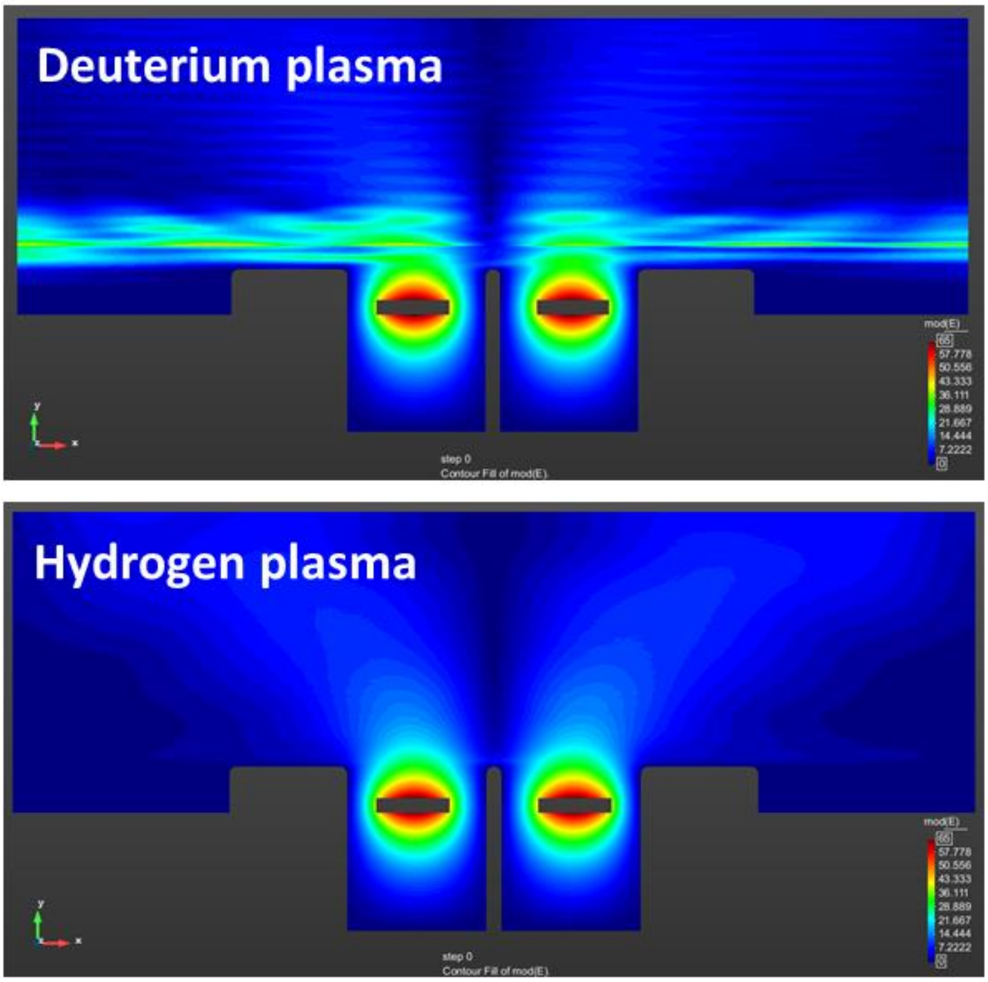

Figure 11: ERMES simulation of RF fields for different plasma compositions.

7. Summary

This paper shows how the finite element code ERMES can help to solve a wide variety of nuclear fusion engineering problems. Due to its C++ object-oriented implementation this code is easily extendable and thanks to its open-source nature more expansions are possible and future researchers could join and create a developers' community to improve and expand the tool.

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