Coupled EM/Thermo/Mechanical Analysis of a High Frequency Current Detector for Use in the International Thermonuclear Experimental Fusion Reactor (ITER)

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Abstract

Standard high frequency voltage and current monitoring equipment is currently used, for automatic control and protection of the power coupling equipment, in thermonuclear plasma heating experiments. In a fusion reactor experiment such as ITER (International Thermonuclear Experimental Reactor), these devices would have to operate in the reactor vessel and therefore would be submitted to severe electromechanical, thermal and nuclear loads. The development of new equipment, capable of operation in a reactor environment, is therefore necessary. The use of a high frequency coaxial resistive current probe, operating on the principle of a coaxial current shunt, has been recently proposed [1]. In this paper the detailed coupled high frequency, electromagnetic, thermal and structural analysis of the probe is presented.

Introduction

The ITER Ion Cyclotron Heating and Current Drive (ICH&CD) is a system designed to couple 20MW of power from a single antenna (equivalent to a power density of ~9.3 MW/m^2) in the frequency range 40-65 MHz for a variety of ITER plasma scenarios. Reliable coupling at high power density, particularly in the presence of rapid changes in loading resistance, is regarded as the critical issue [2] for the performance of the ITER ICH&CD system.

The IC launcher proposed in the ITER reference design [3] is an array of eight structures - hereafter referred to as ITER-Like Structures (ILS) - having properties of load resilience useful to maintain an efficient power flow also when the loading of the antenna changes.

Each ILS is itself an array of two short circuited current straps, in series with two tuning capacitive reactances, connected in parallel to a low characteristic impedance feeder (Fig. 1).

Recently, the design of a Compact Vacuum Tuner (CVT), intended for application in tuning networks in Ion Cyclotron systems and suitable for ITER applications has been proposed [1]. Substantially, the CVT is an adjustable two port coaxial device, with different input and output characteristic impedances Z_{in} and Z_{out}.

The ITER Ion Cyclotron array requires, for an efficient operation, the real-time vectorial measurement of voltages and currents in all array elements. In this paper it is proposed to provide these measurements within the design of the Compact Tuner. A reliable detection/protection system against the occurrence of voltage breakdowns is also necessary.

The RF voltage measurement is performed by a capacitive RF voltage by using usual techniques and will not discussed any further here.

High frequency vectorial current measurements are in general obtained using B-flux loops of small dimensions which provide a local measurement. This may be a source of significant error in the vectorial measurement of the total currents, which is necessary for the control of the impedance matching process. A local B-field measurement is representative of the total current only in areas of the circuit where

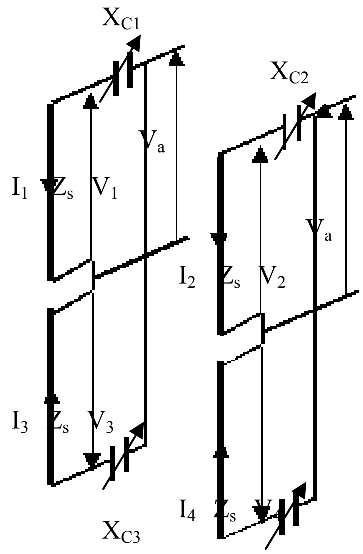

Figure 1. Sketch of a toroidal array of two ILSs

Transversal Electromagnetic Mode (TEM) propagation takes place, but the phase measurement, in particular, is inaccurate where the magnetic field pattern and/or the local current density are strongly inhomogeneous. The location and the geometry of current probes are therefore an important issue.

In the ITER vessel the monitors are exposed to high magnetic fields (which prevent the use of magnetic circuits e.g. for the construction of wideband current transformers), temperatures and neutron radiation field. They should therefore be rugged, insensitive to mechanical, thermal and nuclear loads and should not require frequent maintenance and/or recalibration.

The concept of a high frequency, wideband resistive current monitor (shunt), suitable for the vectorial current measurement, is described in the next section.

The Current Monitor

The proposed current monitor is simply a short resistive section of the inner conductor of a coaxial transmission line. The monitor operates with the principle of the coaxial current shunt. The (high) RF current flowing in a coaxial cable is passed through a thin and short section of resistive metal (shunt). A small resistive E-field component parallel to the surface of the shunt is produced and propagates through the thickness of the metal. If the thickness of the wall is comparable with one of the skin depth, a measurable voltage

$$V = k\,R\,I$$

(where R is the shunt total resistance and k is dependent on the square root of the frequency) can be detected inside the (hollow) inner conductor. The (much larger) TEM field component normal to the shunt wall is instead shielded by the wall and does not contribute to the measured voltage.

It should be noted that a substantial amount of power would be dissipated in the shunt, which needs to be intensively water-cooled in steady state operation. This is however already provided in ITER, where all in vessel components need to be water cooled to remove volume and surface thermal loads.

The detected signal is transmitted by a dielectrically insulated cable running in the cooling channel to an exit point outside the vacuum vessel (such as a service stub or used to drive an opto-link).

A high frequency electromagnetic, a thermo-mechanical and a mechanical analysis of various types of coaxial shunt have been carried out by using the ANSYS finite-element code. In particular the geometry of commercial bellows such as the one shown in Fig. 2 (in Inconel®625, 0.3 mm thick) has been investigated.

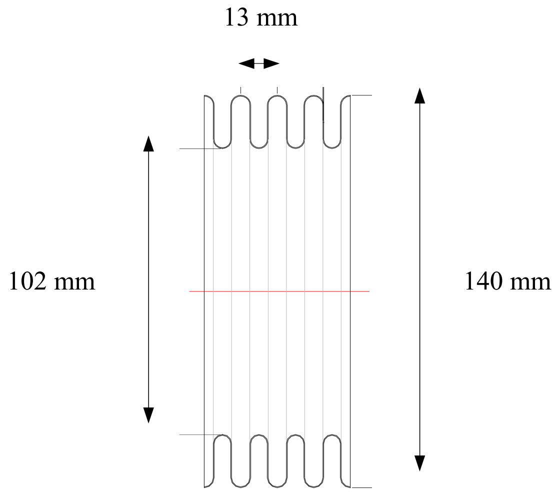

Figure 2. Bellows geometry

The Inconel®625 bellows has been assumed inserted in the middle of a 0.25 m long copper coaxial cable with 0.14 m inner diameter and 0.23 m outer diameter. The inner conductor of the coaxial cable has been assumed made of 1mm thick Oxygen Free Copper.

High Frequency Electromagnetic Analysis

A high frequency (60 MHz) finite element electromagnetic analysis has been performed in order to compute the electric field and the current density distribution in the shunt. Moreover, by performing several analyses, the Total Current-Voltage relationship as function of frequency has been obtained. The finite element model of the shunt is shown in Fig. 3 and Fig.4. The inner conductor of the coaxial cable has been assumed made of 1mm thick copper (ρ=1.7e-8 Ohm m) shell, the outer conductor has been flagged with a surface impedance boundary condition. The input port has been voltage loaded, the output port has been matched. The inner conductor of the coaxial transmission line has been assumed filled up of distilled water (ρ=5000 Ohm m, εr=81). Due to the symmetry just a slice of 1 degree of the actual geometry has been modeled. The voltage at the input port is about 30 kV, the total current, as computed by ANSYS, is about 1kA, the input impedance is Z = (29.9+j 0.5) Ohm.

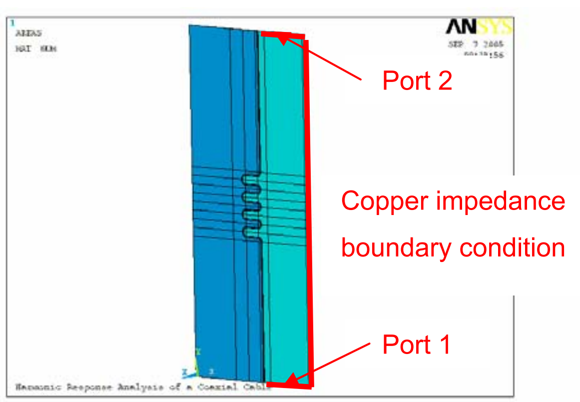

Figure 3. FE Shunt Model

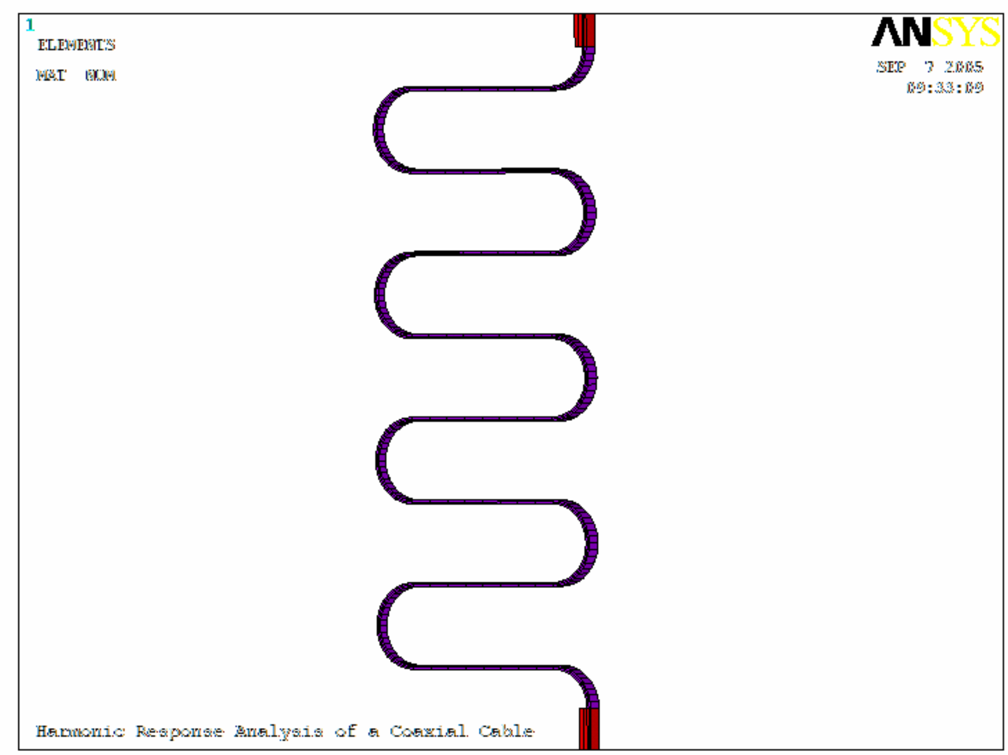

Figure 4. FE bellows model

In Fig. 5 and 6 the real and imaginary parts of the electric field distribution in the region of the bellows have been reported. In the graph below (Fig.7) the electric field on the inner conductor boundary water-copper surface (which has essentially only a tangential component) has been reported.

The integral of the electric field along the curvilinear coordinate of that water-copper boundary surface is by definition the voltage along the path, which results:

$$\Delta V = -\int_{along\ bound\ surf} \vec{E} \cdot d\vec{l} = 0.68\ V$$

Several analyses have been performed in order to compute the variation of the voltage with the frequency and the total current in the shunt. The frequency has been varied between 20 and 80 MHz. The current range considered is between 100 and 1700 A. In the graph below (Fig.8) is reported the voltage amplitude versus the total current in the shunt. As can be noted the relationship is linear and the curves slope decreases as the square root of the frequency.

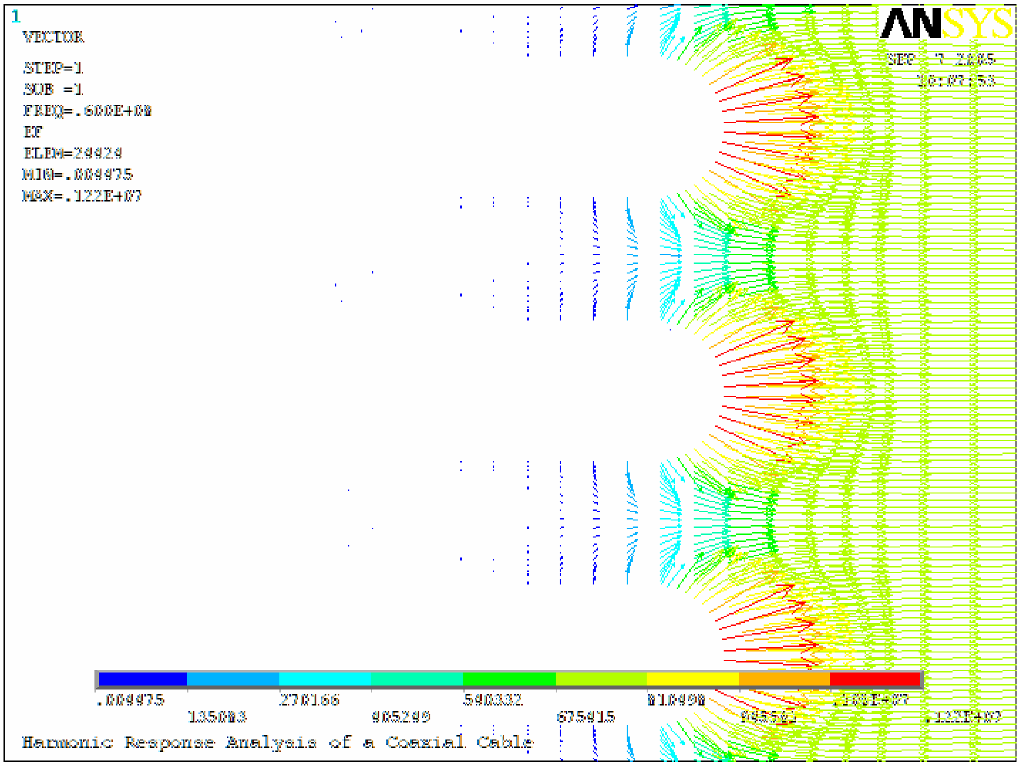

Figure 5. Electric field Real Part

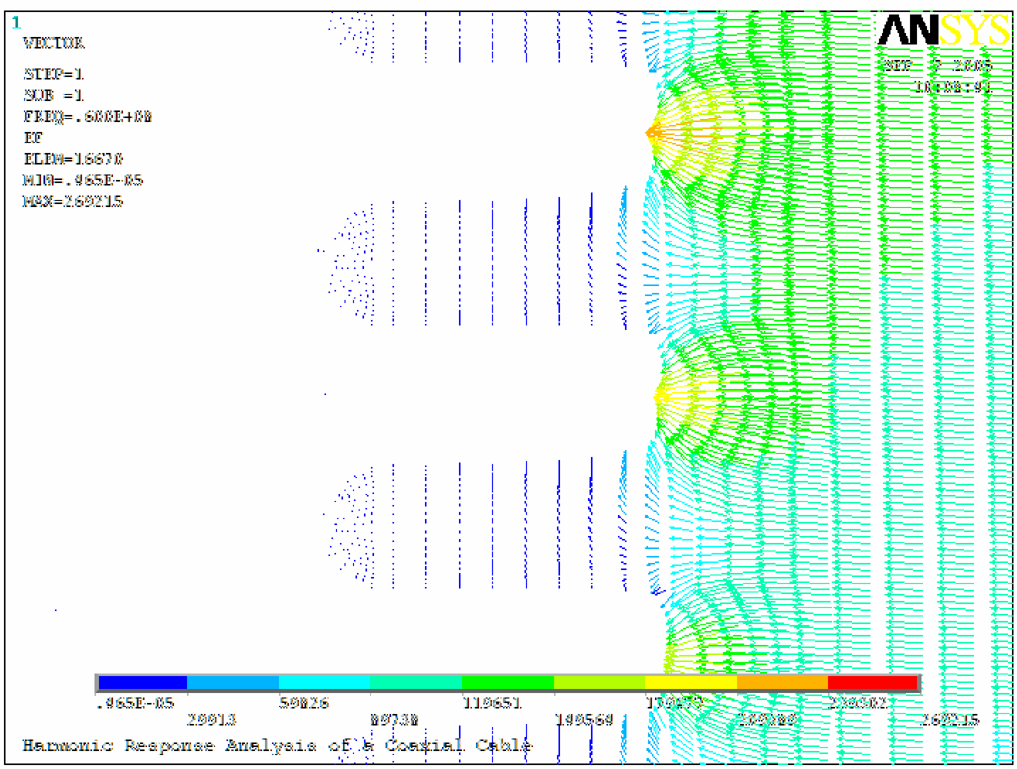

Figure 6. Electric field Imag Part

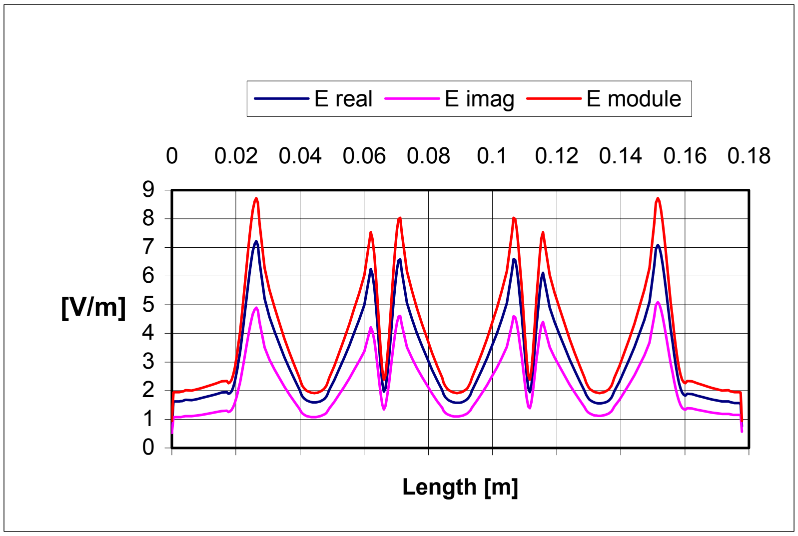

Figure 7. Electric field in the boundary

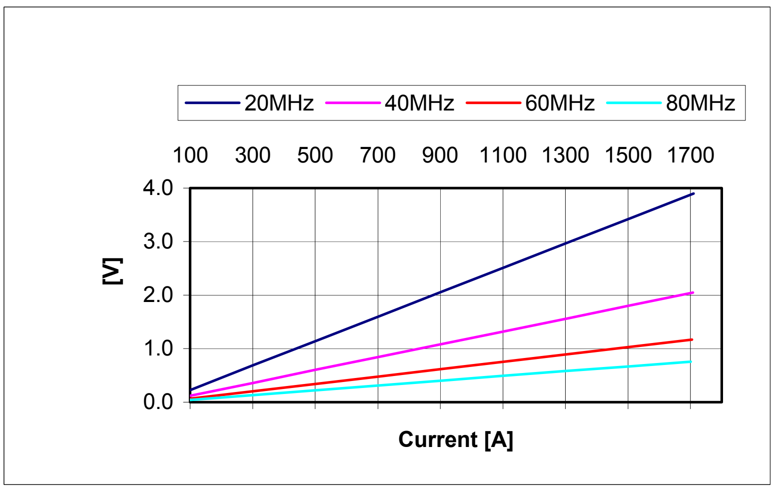

Figure 8. Current-Voltage relationship

Coupled Thermal-Mechanical Analysis

The results of the previous electromagnetic high frequency analysis have been used to calculate the dissipated power in the conducting materials (Inconel®625 and copper) due to the Joule effect in order to perform a following coupled thermal-mechanical analysis. This last analysis has allowed the computation of the temperature and the thermal gradient stresses and deformation distribution. The thermo-mechanical material properties of the Oxygen Free Copper and Inconel®625 are reported in Table 1.

Table 1: Material properties

	Inconel®625	Copper
Thermal conductivity [W/m^2 K]	9.8	390
Thermal expansion Coeff. [1/K]	12.8e-6	17e-6
Poisson Ratio	0.3	0.3
Young modulus [Pa]	200E+9	125E+9

The power distribution [W/m^3] in the Inconel®625 bellows due to the high frequency current density is reported in Fig.9. Water cooling circulation has been considered in the inner region of the shunt: the convective heat transfer coefficient has been assumed equal to 10000 W/m^{2}K with a bulk water temperature of 150 ^{o}C. The temperature distribution is shown in Fig.10: the maximum temperature gradient is about 10 ^{o}C. The results of the thermal analysis have been used to perform a stress analysis in order to compute stresses and deformations in the shunt due to thermal gradients. The model has been constrained in the vertical direction at the two coaxial end points. Results of the analyses are shown in Fig. 11 and 12; the maximum Von Mises stress is about 190 MPa, the maximum displacement is about 0.3 mm.

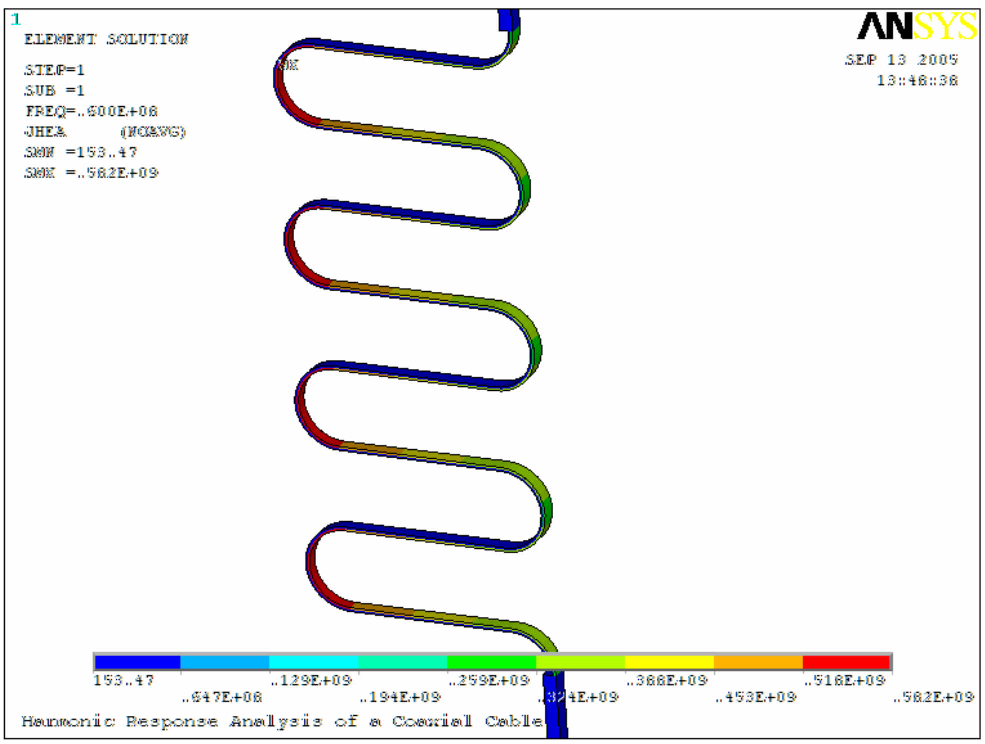

Figure 9. Shunt Power deposition

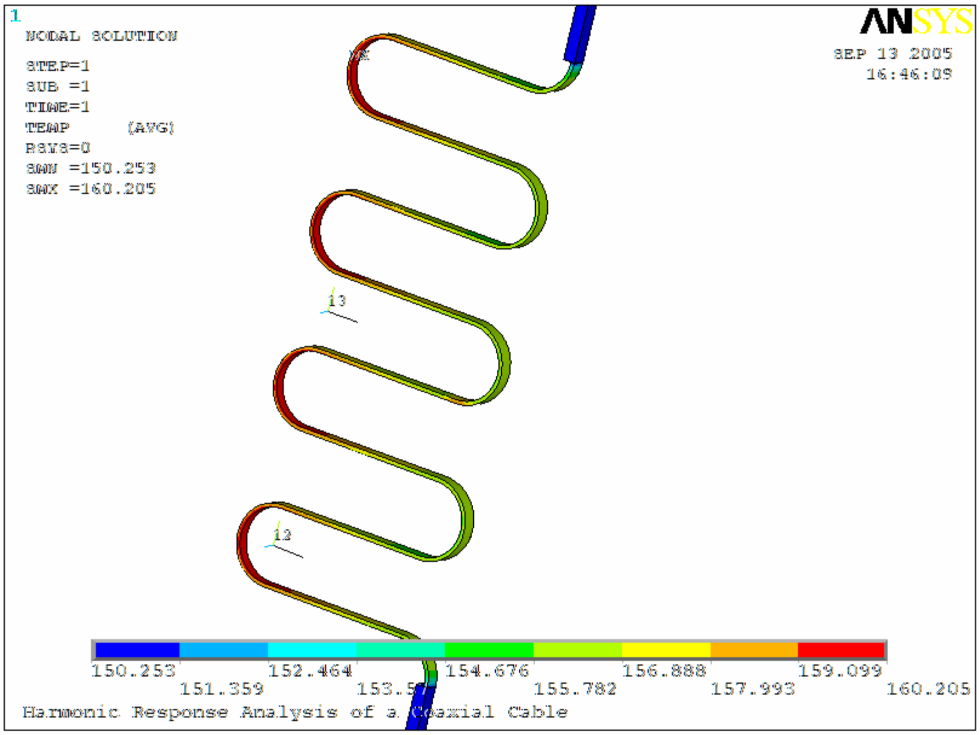

Figure 10. Shunt Temperature distribution

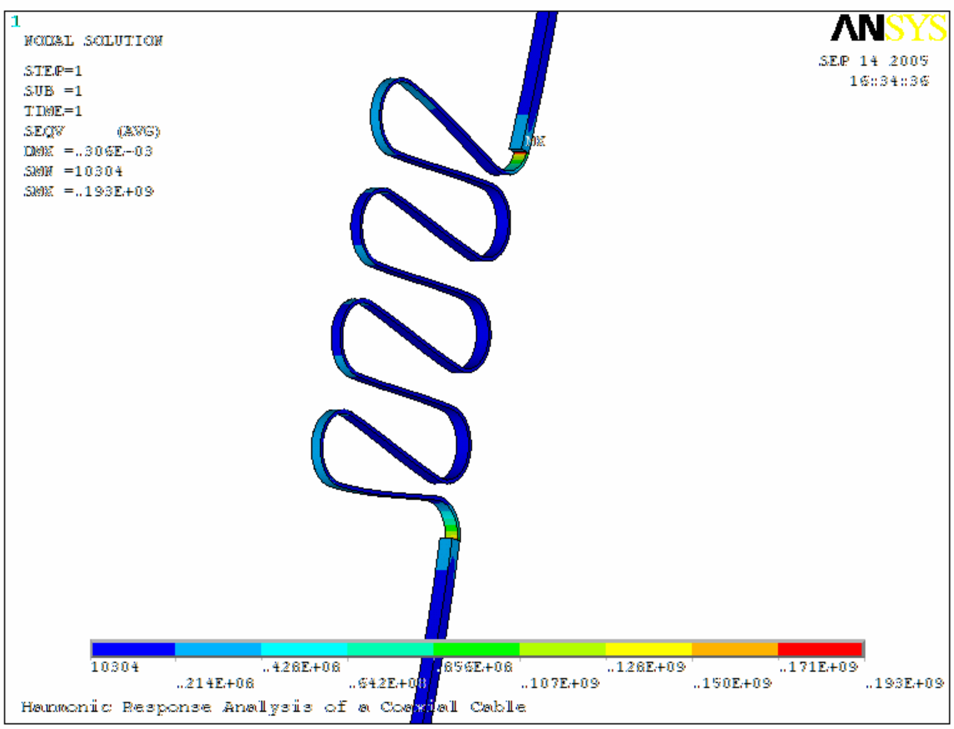

Figure 11. Von Mises stresses

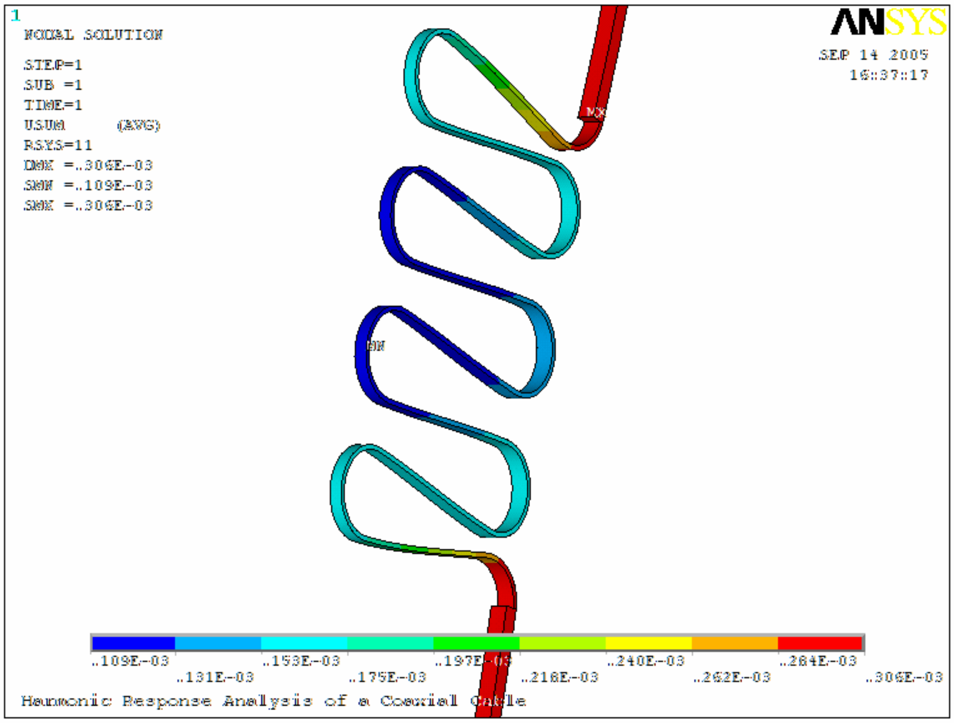

Figure 12. Displacement amplitude

Coupled Thermal-Mechanical Analysis

At last, a mechanical finite element analysis has been performed in order to compute the stress and deformation distribution due to the water cooling pressure. Due to the symmetry a 2-D axial-symmetric model has been built. In the inner surface of the conductor a 0.3 MPa pressure has been applied. The model has been constrained in all the direction at the coaxial two end points. Results of the analysis are shown in Fig. 13 and 14; the maximum Von Mises stress is about 330 MPa, the maximum displacement is about 0.3 mm.

Conclusion

In this paper a high frequency coaxial resistive current probe for current measurement, for automatic control and protection of the power coupling equipment, in thermonuclear plasma heating experiments has been studied.

Several coupled finite element analyses have been done in order to demonstrate the feasibility and reliability of the system.

The relationship of the measurable voltage V and the total current I following in the conductor has demonstrated to be linear and dependent on the square root of the frequency.

Results of the analyses have also shown that stresses due to the power loss dissipation thermal gradients and due to the water coolant pressure are below the materials yield tensile strength limit; displacements are always limited to some fraction of millimeter.

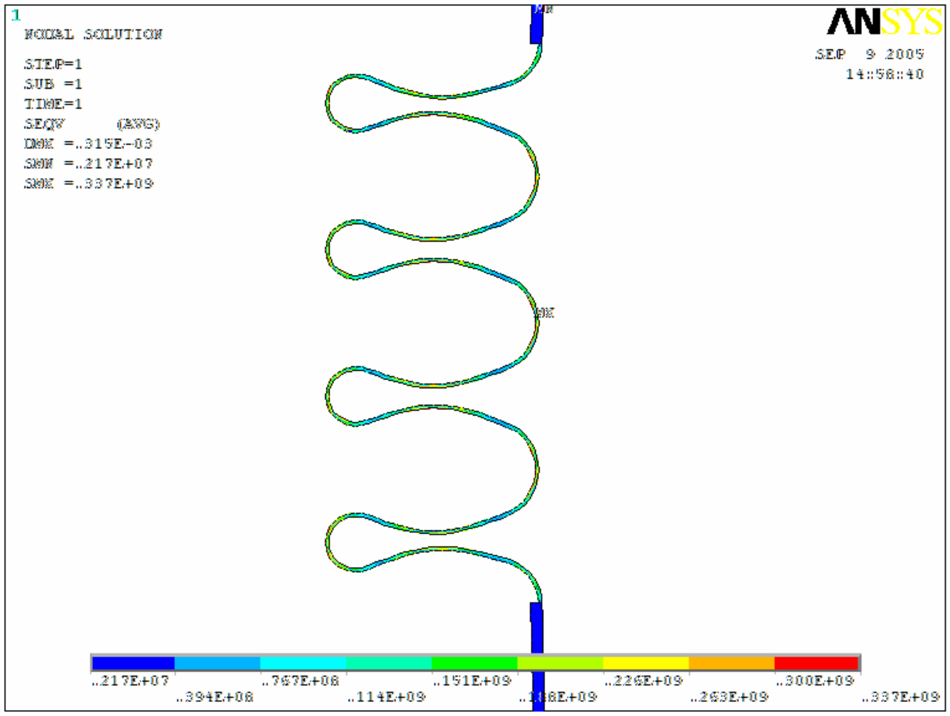

Figure 13. Von Mises stresses

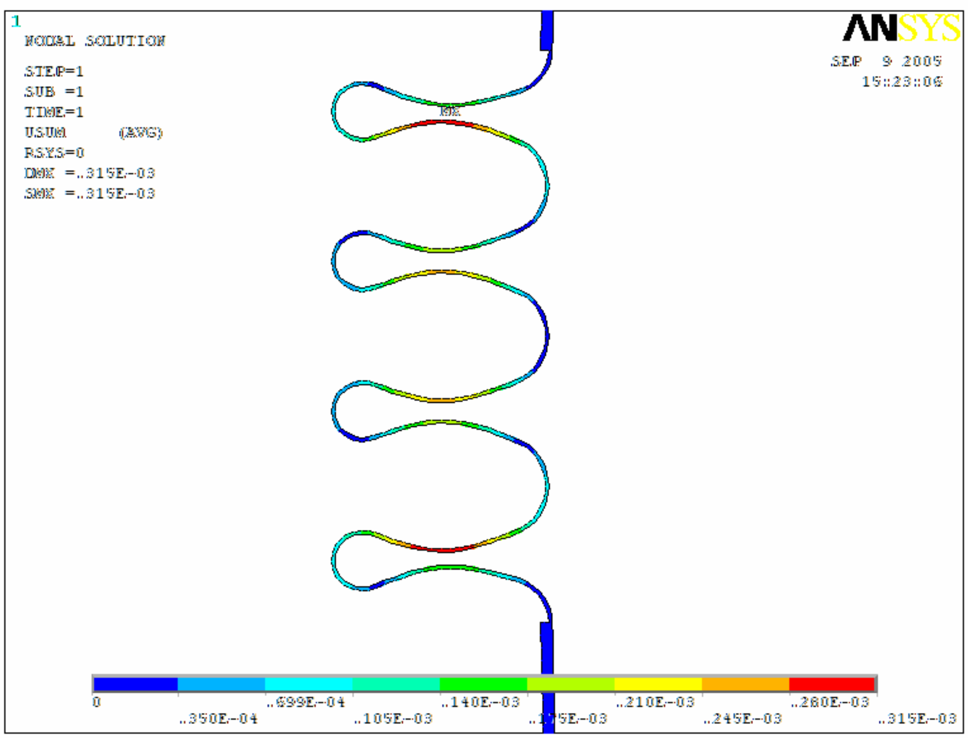

Figure 14. Displacement amplitude

References

[1] G. Bosia, P.Testoni, K.Vulliez. "Development of a compact tuner" CEA CH/NTT –Technical Report (2005)

[2] Technical Basis for the ITER Final Design Report (in partic, PDD Section 2.5, Additional Heating and Current Drive), July 2001.

[3] ITER Design Description Document 5.1, Ion Cyclotron Heating and Current Drive System, July 2001.