RF, Disruption and Thermal Analyses of EAST Antennas*

Plasma Science and Fusion Center (PSFC)
Massachusetts Institute of Technology (MIT)
Cambridge, MA, USA
lhhua@psfc.mit.edu

Q.X. Yang, C.M. Qin, X.J. Zhang, and Y.P. Zhao
Institute of Plasma Physics (IPP)
Chinese Academy of Sciences (CAS)
Hefei, Anhui, P.R. China

Abstract—CAS IPP and MIT PSFC are collaborating on Experimental Advanced Superconducting Tokamak (EAST), the first tokamak with superconducting toroidal and poloidal magnets and a testbed for technologies proposed for the ITER project. Presented in this paper are RF, disruption and thermal analyses of EAST antennas. All were performed by COMSOL commercial software package Version 5. Analyzed are the I port 4 strap and B port 2 × 2 strap antennas, which are currently installed on EAST.

RF analysis over the Ion Cyclotron Range of Frequencies (ICRF) gets insight into the coupling mechanism to optimize antenna plasma coupling. A lossy dielectric model was created which loads the antenna. The Scattering parameters (S-parameter) were extracted. Peak electric field parallel to the magnetic field of the straps, coaxes and other components were determined. Parametric analysis of the operation frequencies on the electric field are also performed.

Disruption analysis addresses the impact of the magnetic field and plasma. Temporal currents of poloidal field and plasma as well as the spatial toroidal field were imported into the electromagnetic (EM) model. The structural analysis afterwards determined the stress due to antenna loads generated during the disruption. The loads resulted from the reaction of circulating eddy currents in the antennas with the toroidal and poloidal magnetic fields.

Thermal analysis, a fluid — heat transfer — structural multi-physics analysis, performed for the strap and Faraday rod by applying heat loads from the plasma, ripple trapped particles and RF heating for steady state, are also presented.

Finally, benefits of a future field-aligned 4 strap antenna were discussed.

Keywords—tokamak; EAST; antenna; RF; coupling; disruption; thermal

I. INTRODUCTION

Among the international collaboration between EAST and MIT, Ion Cyclotron Range of Frequency (ICRF) antennas are one of the essentials. ICRF provides auxiliary heating and potential current drive. Coupling is one of the top priorities for EAST, and it has a goal to couple 70% of the ICRF source power to the plasma. Thus, RF analysis is necessary to evaluate the performance of the existing antennas. Other topics of interest are the electromagnetic stress due to vertical disruption and thermal stress due to the heat load.

Previous work were reviewed. A reference design of ICRF antenna was firstly described [1] followed by more complete design [2, 3]. A typical Faraday shield cooling tube and a typical current strap were selected for heat transfer and structural analysis [3]. An electromagnetic analysis of the 4 strap antenna was performed by use of ANSYS HFSS code, aiming to reduce parallel electric field and to investigate the current drive using fast magnetosonic wave. The S-parameter, RF current distribution and electric filed distribution on and near the antenna were presented [4]. A new electromagnetic code based on the Method of Moments (MOM) for EAST ICRF double loops antenna was presented with antenna power 6 MW during 30-110 MHz, and study frequency range up to 500 MHz [5].

The purpose of this study is to analyze the performance of the antennas in RF, disruption and thermal aspects. RF analysis has been successfully applied to 4 strap antenna on Alcator C-Mod, which is located at MIT PSFC [6, 7]. A linear 3-D coupling of ICRF waves in C-Mod were performed for rotated 4 strap antenna using FEA code, which includes the actual SOL density profiles, the 3-D solid geometry of the launcher, with a cold plasma load, reduced the average RF potential along magnetic field lines [8].

In this paper, we expand the methods in Section II. The analysis results are presented in Section III. Discussion on the benefits of a future field-aligned 4 strap antenna is discussed in Section IV, and conclusions are summarized in Section V.

II. METHODS

Since there will be three kinds of analyses for the antennas, the methods will be described in three sub-sections.

– Method for RF analysis;
– Method for disruption analysis;
– Method for thermal analysis.

* The work was supported by U.S. Department of Energy (US DoE) with award DC-SC0010720 and Chinese National Academy of Sciences.
A. Method for RF Analysis

1) Geometry for RF analysis

The EAST antennas to be studied are shown in Fig. 1.

To get a RF analysis performed, plasma and air need to be added to the geometry. Table I lists the overall dimension of the antenna, air, and major/minor radius of the plasma.

With reference to the front surface of the strap, the plasma is about 10 mm in front of the strap. The overall width and height of the air is about twice those of the antennas.

![EAST antennas](image)

**Fig. 1. The EAST antennas.**

<table>
<thead>
<tr>
<th>TABLE I. THE GEOMETRY FOR RF ANALYSIS</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>EAST Antennas</strong></td>
</tr>
<tr>
<td>Port location on EAST</td>
</tr>
<tr>
<td>I-antenna</td>
</tr>
<tr>
<td>Number of straps</td>
</tr>
<tr>
<td>4</td>
</tr>
<tr>
<td>Metal (straps and the support box)</td>
</tr>
<tr>
<td>overall dimension, width x height x depth, mm</td>
</tr>
<tr>
<td>966 x 846 x 551</td>
</tr>
<tr>
<td>Air overall dimension, width x height x depth, mm</td>
</tr>
<tr>
<td>2284 x 2000 x 1933</td>
</tr>
<tr>
<td>Plasma major, minor radius, mm</td>
</tr>
<tr>
<td>1623, 760</td>
</tr>
</tbody>
</table>

* Radiation stripline antenna (RSA)

2) Material properties of the components for RF analysis

Table II lists the material properties of the components (antenna, plasma and air). The straps and the support box are made of stainless steel 316L.

The interest of this study is the magnetic and electric field of the antennas, not the plasma itself. The detailed property or result of the plasma is not of interest in this study. Thus, the relative permittivity ($\varepsilon_r$) and electrical conductivity ($\sigma$) of the plasma is set such a way that the antenna is loaded. For I antenna, $\varepsilon_r = 250$, $\sigma = 0.15$ S/m is used [6]. For B antenna, water is selected, that is, $\varepsilon_r = 80.2$, $\sigma = 5.5 \times 10^6$ S/m [4].

3) Boundary conditions for RF analysis

The default boundary conditions is perfect electric conductor. The walls of the coaxes are treated as perfect electric conductors. This is appropriate when the skin depth and the losses in the conductors are insignificant. The power input ports are numbered as #1, 2, 3 and 4. By viewing from the vessel center, top left is #1, bottom left is #2, top right is #3 and bottom right is #4. For each simulation, one port is activated, type “coaxial” and input power is 1 MW. The other ports are off. In addition, regarding B antenna, pair #1 & 2 or pair #3 and 4 are activated simultaneously.

For 2.5 T operation, H minority frequency is 38 MHz, and for 3 T operation, H minority frequency is 45.6 MHz. The antennas sometimes run at frequency of 34-35 MHz, so a series of frequencies are selected, 34, 38, 45.6 and 50 MHz [9]. Then, a parametric analysis of these operation frequencies were also performed, when port #1 is activated for either I or B antenna.

**TABLE II. MATERIAL PROPERTIES**

<table>
<thead>
<tr>
<th>Material Properties</th>
<th>Stainless steel 316L</th>
<th>Plasma</th>
<th>Air</th>
</tr>
</thead>
<tbody>
<tr>
<td>Relative permittivity, $\varepsilon_r$</td>
<td>1</td>
<td>250</td>
<td>80.2</td>
</tr>
<tr>
<td>Relative permeability</td>
<td>1</td>
<td>1</td>
<td>1</td>
</tr>
<tr>
<td>Electrical conductivity, $\sigma$, S/m</td>
<td>1.35 x 10^6</td>
<td>0.15</td>
<td>5.5 x 10^6</td>
</tr>
<tr>
<td>Density, kg/m^3</td>
<td>7990</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Thermal conductivity, W/(m.K)</td>
<td>16.2</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Specific heat, J/(kg.K)</td>
<td>500</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Coefficient of thermal expansion, x 10^-6/1/K</td>
<td>16.0</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Max. service temperature, ºC</td>
<td>2620</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Young’s modules, GPa</td>
<td>193</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Poisson’s ratio</td>
<td>0.25</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Tensile strength, yield, MPa</td>
<td></td>
<td></td>
<td>290 at room temperature and 190 at 427 ºC</td>
</tr>
</tbody>
</table>

B. Method for Disruption Analysis

The material properties of the antennas and air are the same as those listed in Table II, so only geometry and boundary conditions are described as follows.

1) Geometry for disruption analysis

In disruption analysis, air needs to be added. A wedge (30º) model of air is used. Its radius is 4 m.

Due to the size of the problem, Faraday rods cannot be in a single model together with the straps and the support box. So, there will be multiple models, one includes the straps and the support box. The others model the Faraday rods screen by screen. While viewing from the vessel center, starting from left side, the screens are named A, B, C and D. For each of the screen, there are 43 rods. So, there are total 176 rods.

2) Boundary conditions for disruption analysis

Data from experiment shot #43884 was used. The poloidal field was simulated by imported PF currents. There are total 14 coils, which are symmetric about the mid-plane. The max.
total current of 2.94 MA, as shown in Fig. 2 (top plot). The plasma is represented by 31 filaments (four columns) with current for each filament imported, and max. total current is 0.41 MA [10].

The toroidal field varies with radial location and is constant along toroidal direction, as shown in Fig. 2 (bottom plot).

The Lorentz force from the magnetic fields results stress in the antenna, which will be presented in section III “Results”.

C. Method for Thermal Analysis

The purpose of the thermal analysis is to check the temperature and thermal stress in the straps and Faraday rods. Since the straps are water cooled, three physics are involved in this analysis, fluid, heat transfer and solid mechanics. Fluid (water) is simulated by Computational Fluid Dynamics (CFD). The velocity field was incorporated into heat transfer. The temperature from heat transfer was incorporated into solid mechanics to get the thermal stress.

Both the straps and Faraday rods are made of stainless steel 316L, and their properties are listed in Table II.

1) Geometry for thermal analysis

As for thermal analysis, only antenna (neither plasma nor air) is needed. The parts of interest are current straps and Faraday rods.

A typical strap (I antenna, strap #1, when viewing from vessel center and counting from left side) is modeled. The overall dimension of the strap (width x height x depth) is 100 x 780 x 201 mm.

A typical Faraday rod (I antenna, Screen #1 when viewing from vessel center and counting from left side and rod #22 counting from top) is modeled. Outer diameter 10 mm and inner diameter 6 mm.

2) Boundary conditions for thermal analysis

The heat loads are 0.3 MW/m² for the strap and 0.59 MW/m² for the rod [3].

As for watering cooling in the straps and Faraday rods, water inlet velocity is 2 m/s and inlet temperature is 20 °C.

III. RESULTS

Corresponding to section II “Methods”, results will be presented in the same order: RF, disruption and thermal analysis.

A. Result of RF Analysis

Both I and B antenna are analyzed. When a simulation is done, S-parameter is checked to make sure the reflected wave is less than 70%, that is, the antenna is loaded. The results are shown in Fig. 3.

When power input port (#1 to #4) is activated individually, the S-parameter S11, S22, S33 and S44 are 0.58, 0.55, 0.54 and 0.58 for I antenna, and 0.68 for B antenna. Then the electrical field Ey (parallel to the magnetic field direction) was checked. Ey is 1.29, 0.83, 0.84 and 1.45 MV/m for I antenna, and 0.52, 0.49, 0.42 and 0.49 MV/m for B antenna, which are smaller than the permissible level 1.5 MV/m (15 kV/cm).

For I antenna, the Ey near the cutout in the septum between straps is relatively large. It is favorable not to have any cutout on the septa.

Furthermore, for the frequency range 34, 38, 45.6 and 50 MHz, the smaller the frequency, the smaller the electric field Ey, when port #1 is activated. For I antenna, Ey is 0.67, 0.87, 1.21 and 1.29 MW/m; for B antenna, Ey is 0.3, 0.32, 0.43, and 0.52 MV/m. They are all below the permissible level.

B. Result of Disruption Analysis

Only I antenna was analyzed. Two models were created, one was for the straps and the support box, and the other was
the Faraday rods model. The von Mises stress in the straps, the support box and Faraday rods are shown in Fig. 4.

![Fig. 3. RF analysis result. a) I antenna, magnetic field; b) I antenna electric field along direction parallel to magnetic field; c) B antenna magnetic field; and d) B antenna electric field, along direction parallel to magnetic field. In both cases, plots are for case when power input port #1 is activated with operation frequency of 50 MHz.](image)

![Fig. 4. Disruption analysis results. a) I straps and its support box. b) I antenna Faraday rods (screen D, #4 from left side while viewing from vessel center).](image)

The max. stress is 58.3 MPa, which is within the allowable (yield strength of the material at room temperature is 290 MPa). The stress in the straps themselves are benign, smaller than 10 MPa. The max. displacement is less than 0.5 mm.

The stress in the top and bottom row of rods are larger than those of the others. Except the top and bottom rod, stress in the rest rods is within the allowable. For purpose of not distracting the readers’ attention too away from the RF and thermal analysis, only von Mises stress in Screen D is shown in this paper.

C. Results of Thermal Analysis

The yield strength $\sigma_{0.2\%}$ of stainless steel 316L at 427 °C is 190 MPa, so the design strength f is 158 MPa ($\sigma_{0.2\%}/1.2$). As thermal stress is secondary (membrane and bending) stress, thus the allowable is 3f, which is 474 MPa.

The max. temperature of I antenna straps is 424 °C, which is below the melting point of the material (2620 °C). Regarding thermal stress, stress concentration along the sharp edges are not realistic. The real stress in the strap is 383 MPa, within the allowable, as shown in Fig. 5.

The temperature of I antenna Faraday rods is 258 °C, which is below the melting point of the material. And the max. stress is 370 MPa, within the allowable.

IV. DISCUSSION

The existing EAST antennas fall into the category of classic antennas, because they intercept convective cell. A Field Aligned (FA) antenna has been proposed and under design. A FA antenna utilizes symmetry along magnetic field lines to reduce unwanted parallel RF electric fields. Other benefits of a FA antenna includes high couple power, and no need to use low Z coatings. A coating is difficult to verify its thermomechanical properties and flaking is problematic [9].

A successful FA antenna has been developed, installed, functioned in Alcator C-Mod, which would provide reference for the development of an EAST FA antenna.
maximum temperature for the strap and rods are 424 and 258 °C, which are below the melting point of the material (2620 °C). The thermal stress in both the strap and the rod are below the allowable (474 MPa).

The approach described in this paper could be applied to F antenna. Furthermore, a field aligned four strap antenna is under design in collaboration between EAST and MIT.

ACKNOWLEDGMENT
The authors would appreciate the collaborative efforts and support from the EAST and Alcator C-Mod team.

REFERENCES

V. CONCLUSIONS
EAST antennas (I port four strap and B port 2 x 2 strap) are studied in aspects of RF, disruption and thermal analysis.

Regarding RF analysis, when the operation frequency is 50 MHz, the Scattering parameter for I antenna is 0.54–0.58 when various port is activated and 0.68 for B antenna, which are less than 0.7, the level indicating if the antenna is loaded. The maximum electric field parallel to the magnetic field is 0.83–1.45 MV/m for I antenna and 0.45–0.51 MV/m for B antenna, which are within the permissible level 1.5 MV/m (15 kV/cm). Furthermore, parametric analysis with regard to frequency is performed for both antenna when one of the four ports is activated for both antennas. Within the range of 34, 38, 45.6 and 50 MHz, the smaller the frequency, the smaller the electric field.

Regarding vertical disruption analysis, the maximum stress in the straps and the support box of I antenna is 58.3 MPa, which are all within the allowable (yield strength of stainless steel 316L is 290 MPa). Except the top and bottom rod in the screens, the stress in the Faraday rods is also within the allowable.

Regarding thermal analysis, when heat load for the straps is 0.3 MW/m² and that for Faraday rods is 0.59 MW/m², the

![Thermal analysis results. a) strap temperature; b) strap von Mises stress; c) rod temperature; and d) rod von Mises stress. Heat loads for the strap and the rod are 0.3 MW/m² and 0.59 MW/m².](image)