MULTIPHYSICS APPLICATIONS OF ACE3P*

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Abstract

The TEM3P module of ACE3P, a parallel finite-element electromagnetic code suite from SLAC, focuses on the multiphysics simulation capabilities, including thermal and mechanical analysis for accelerator applications. In this paper, thermal analysis of coupler feedthroughs to superconducting rf (SRF) cavities will be presented. For the realistic simulation, internal boundary condition is implemented to capture RF heating effects on the surface shared by a dielectric and a conductor. The multiphysics simulation with TEM3P matched the measurement within 0.4%.

INTRODUCTION

In the next generation accelerator design, it is crucial to have a multiphysics solver capable of carrying out precise thermal and mechanical analyses based on the accurate electromagnetic (EM) design. The accelerator operation under high current or high power often involves excessive heat and mechanical problems, some of which lead to many operational failures. Performance optimization[1] and cost effectiveness of RF cavities in the multiphysics environment helps to identify the coupled multiphysics effects not easily isolated in single physics simulations. It is beneficial to the accelerator community to have an integrated modeling package with EM, thermal, and mechanical modeling and simulation under the same data structure. Under the support of the U.S. SciDAC program, SLAC has been developing ACE3P, a suite of high fidelity 3D parallel finite-element codes for the design of next generation particle accelerators.

Recently, the heating and structural effects caused by high gradient electromagnetic fields, are analyzed with TEM3P, a multiphysics moule of ACE3P[2]: cavity wall heating, structural deformation, and Lorentz force detuning problems are studied[3]. TEM3P compliments the existing EM finite-element code developed at SLAC and is built upon the same code infrastructure as the EM solvers, such as Omega3P[4] and S3P, in the ACE3P suite. The ACE3P code suite provides a complete analysis toolset for engineering prototyping in a single development framework.

TEM3P, a thermal and mechanical solver, has been implemented and validated against ANSYS, the widely accepted commercial package. Parallel implementation in TEM3P allows large-scale computations on massively parallel supercomputers, and its fast turnaround time enhances computational efficiency. In the following sections, TEM3P's capabilities are illustrated through HOM feedthrough simulation. The HOM feedthrough simulation is carried out including electromagnetic and fully nonlinear thermal analysis.

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RF-THERMAL COUPLED ANALYSIS OF JLAB FEEDTHROUGH

Previous studies[5] from JLAB found the thermal impedance of HOM coupler caused thermal instabilities in the superconducting cavity. To have a better understanding of RF heating and thermal impedance in the coupler, JLAB analyzed and tested various HOM coupler designs for the cryomodule. In this paper, HOM feedthrough, the portion of the HOM coupler except HOM can and hook, is simulated with realistic boundary conditions.

In order to address the thermal problems occurring in the HOM Feedthrough, accurate simulation of temperature distribution with nonlinear material properties at the superconducting temperature is crucial. The accurate resolution of the effects requires large scale simulations, and the finite-element discretization could end up with millions of degrees of freedom. Due to memory allocation and slow turn around time, single cpu simulation is not adequate since the fast turnaround time is essential for the design cycle of the accelerator cavities. The multiphysics effects include nonlinear thermal conductivities, surface resistance and Kapitza conductance. Due to the nonlinear nature of these conditions, the successful resolution requires an efficient and robust nonlinear solver. TEM3P addresses both challenges through parallelization and implementation of inexact Newton method[2].

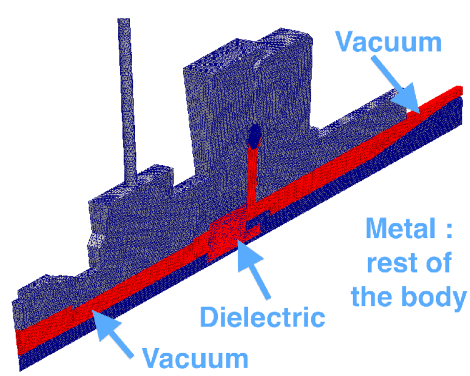

Figure 1: HOM feedthrough CAD model.

The main source of the multiphysics interaction in the

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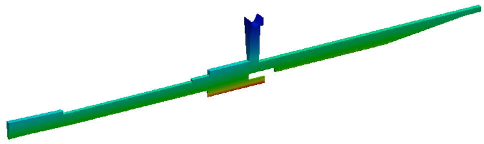

Figure 2: Magnetic fields in the vacuum.

thermal analysis is derived form the surface magnetic fields of accelerating mode, which produces RF heating effects on the cavity and coupler walls. If the heating is not treated properly for superconducting cavities, it leads to catastrophic thermal quenching problems[6]. To capture this effect, the analysis is carried out in two steps. In the first step, an EM field is simulated in the vacuum cavity in the first step. In the second step, the heat input to the cavity body is calculated based on the EM fields obtained in the first step[3].

The analysis starts from a CAD model, as shown in Fig. 1. From this model, CUBIT[7] is used to generate second order finite-element models for the metal body and vacuum. The EM simulation in the vacuum region is performed with S3P for the traveling wave at the frequency of 1497 MHz. The magnetic field distribution is shown in Figure 2. The vacuum mesh in this simulation has approximately 300K, 2^{nd} order tetrahedral elements, which yield approximately 2M degrees of freedom. Perfect conductor is assumed for the metal wall in the EM analysis. The resulting magnetic field on the commonly shared surface is transferred to the thermal solver as a heat input on the surface. The thermal loss of the accelerating mode at the wall is converted to heat generation based on the perturbation method, as shown in Equation 1,

$$P_S = \frac{1}{2}\int_G H^2 R_S dG \qquad (1)$$

where R_S is the surface resistance, and G is the surface boundary between the vacuum region and the metal part. In order to capture the nonlinear effects on the surface, nonlinear surface resistance is applied. The metal structure is composed of copper, stainless steel, aluminum, niobium and other composite materials. Thermal conductivities of these materials vary by several orders of magnitude. The large differences cause severe nonlinearity, which is one of the main difficulties in solving this problem.

Table 1: Boundary Conditions

Type	Value
Static loads	12 and 39.1337 mW
Dynamic loads	2.78 and 8 mW
Nonlinear heat flux	1e-6 to 60 mW
Heat input	503 mW
RF heating	from perturbation method
Fixed T	4.1k and 2.0k

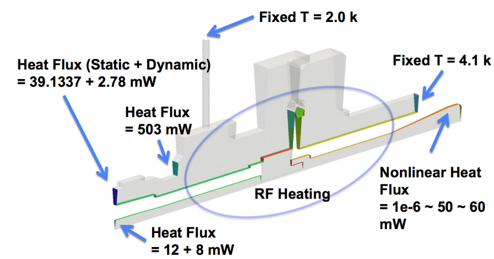

Figure 3: Multiphysics boundary surfaces of HOM feedthrough.

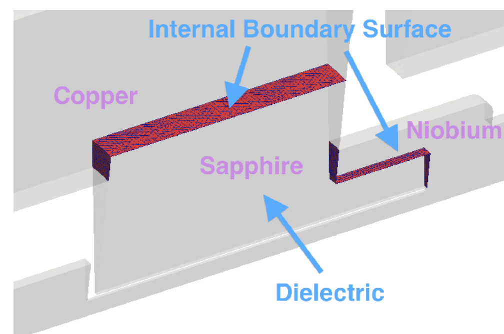

Figure 4: Internal boundary surfaces.

To simulate the performance of a HOM coaxial coupler under static and dynamic loads, a 10 degree model, shown in Figure 1, is created out of the whole model[5] . The original environment is simulated with the boundary conditions summarized in Table 1, applied to the corresponding surfaces in Figure 3. The two values in the static and dynamics loads types in Table 1 are applied to inner and outer connectors, respectively, as shown in Figure 3. The heat flux from RF heating is calculated from the input power of 208 mW. The heater input power of 503 mW is added to simulate the worst case scenario. The fixed temperature of 2.0 K is from liquid helium, and 4.1 K simulates HOM can body attachment. Nonlinear heat flux is used to simulate heat generation coming from the probe tip. RF heating on the external surface is applied to account for the heating on the surface enclosing the vacuum region. Internal RF heating boundary condition is implemented to account for the heating on the surfaces that connect the dielectric, sapphire, and the adjacent conductors, copper and niobium, as shown in Figure 4. Detailed descriptions of the boundary conditions can be found in Cheng's paper[5]. Since the heat input values given above are for the whole model, the $\frac{1}{36}$ of the input values are used for proper scaling of the 10 degree model in the current simulation.

Complex and physical boundary conditions induce strong nonlinearities in the solution. To overcome these problems, robust implementation of Newton method is required. Inexact Newton method is used for solving the nonlinear equations, and each nonlinear iteration is solved by a linear system of equations. Iterative preconditioned Krylov subspace methods, such as GMRES, are used to solve the

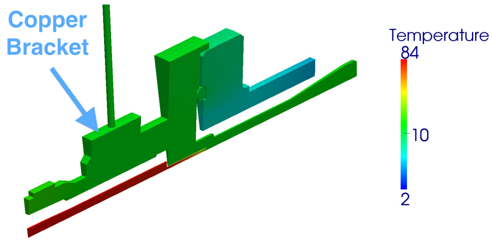

Figure 5: HOM feedthrough TEM3P result.

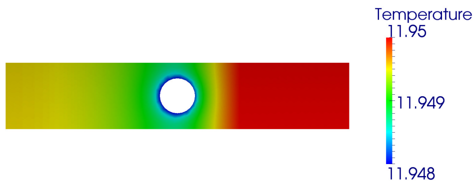

Figure 6: Temperature distribution on the copper bracket surface.

resulting linear systems. The thermal analysis result with a 2^{nd} order FEM discretization is shown in Figure 5. The temperature on the surface of interest, copper bracket, is shown in Figure 6. The average temperature at the copper bracket is compared to the actual measurement from JLAB[5] as well as the result from ANSYS, as shown in Table 2. TEM3P's result shows an excellent agreement with the actual measurement, with the difference of approximately 0.4% of the measured value.

Table 2: Temperature Comparison

Method	Temperature
Measured	11.9 k
TEM3P	11.95 k
ANSYS	11.96 k

CONVERGENCE STUDY

For the convergence study, four different mesh sizes are used: from 0.53 to 3.8 M 2^{nd} order, curved tetrahedral elements. The average temperature at the copper bracket is plotted along the increasing mesh size in Figure 7. The numerical result shows a clear convergence toward 11.95 K as the mesh size increases. The largest simulation, with 5.5 M degrees of freedom, used 160 processors on Hopper at NERSC and converged in 89 mins, within 10 nonlinear iterations. Using desktop computers, this simulation would take a few days, and would not be suitable for realistic design cycles.

SUMMARY

TEM3P in ACE3P code suite is a parallel multiphysics simulation tool including integrated electromagnetic, thermal and structural effects. Its parallel implementation allows accurate and fast analysis for accelerator component design and performance evaluations. Robust implementation of a nonlinear solver enables TEM3P to solve strongly nonlinear problems with physical boundary conditions such as convective cooling near cryogenic environment, nonlinear heat flux and nonlinear thermal conductivities. TEM3P's effectiveness and accuracy in solving large scale, nonlinear multiphysics problems in cryogenic conditions have been demonstrated.

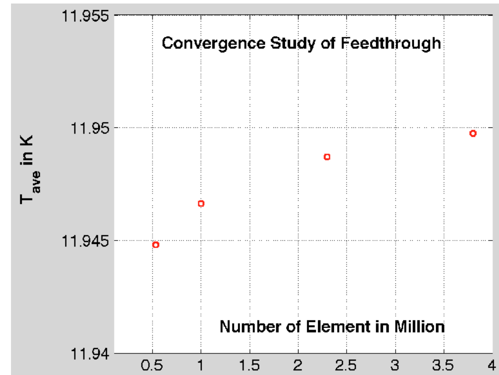

Figure 7: Convergence study of HOM feedthrough.

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