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THERMAL ANALYSIS OF SRF CAVITY COUPLERS USING PARALLEL MULTIPHYSICS TOOL TEM3P[2]

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Abstract

SLAC has developed a multi-physics simulation code TEM3P for simulating integrated effects of electromagnetic, thermal and structural loads. TEM3P shares the same software infrastructure with SLAC's paralell finite element electromagnetic codes, thus enabling all physics simulations within a single framework. The finite-element approach allows high-fidelity, high-accuracy simulations and the parallel implementation facilitates large-scale computation with fast turnaround times. In this paper, TEM3P is used to analyze thermal loading at coupler end of the JLAB SRF cavity.

INTRODUCTION

In the design of the next generation accelerators, optimizing the performance and cost effectiveness of RF cavities require precise thermal and mechanical analyses along with accurate electromagnetic (EM) design. Many failures in accelerator operations are caused by excessive heating arising from high power or high current operations. Mostly, EM, thermal and mechanical calculations are carried out separately with different modeling tools. It is important in the accelerator community to build an integrated modeling package with capabilities of EM, thermal, and mechanical modeling using the same data structure.

Under the support of the U.S. SCIDAC program, SLAC has been developing high fidelity 3D parallel finite element codes for the design of next generation particle accelerators [1]. Recently we have developed a multi-physics simulation tool, TEM3P, for the design and analysis of thermal, structural and electromagnetic effects such as cavity wall heating, structural deformations, and Lorentz force detuning simulations [2]. TEM3P shares the same finite element code infrastructure with the existing EM finite-element codes developed at SLAC, and enables all multi-physics calculations to be done in a single framework, and provides a complete toolset for engineering prototyping. The new solvers for thermal and mechanical simulations have been implemented, tested and validated independently against the commercial package ANSYS [3]. The parallel implementation of TEM3P allows large-scale computations on massively parallel supercomputers so that high-fidelity and high-accuracy simulations can be performed with a fast turnaround time.

In the following, we perform multi-physics study of the SRF cavity couplers that includes electromagnetic and thermal analyses.

THERMAL ANALYSIS OF JLAB HCCM COUPLER

Thermal analysis of JLAB (High Current Cryomodule) HCCM cavity Higher Order Modes (HOM) coupler has two main computational challenges. The first is extreme large scale. This is due to the need to resolve very small features of cavity walls and HOM couplers. A typical finite element discretization ends up with millions of degrees of freedom. Single processor simulations may limit simulations accuracy to details due to both memory requirements, and slow turnaround time. Thermal simulation of HCCM cavity with single processors may take days to converge. A fast turnaround time is essential for the design of accelerator cavities, since design process may require many simulations. The second computational challenge is nonlinearity. Thermal simulations of superconducting cavities are highly nonlinear due to temperature dependent thermal conductivity, surface resistance and Kapitza conductance. Solving nonlinear thermal equation requires efficient and robust nonlinear solvers. TEM3P addresses both challenges through parallel implementation of an inexact Newton method.

For the JLAB HCCM cavity HOM coupler, the surface magnetic fields of the accelerating mode produce RF heating on the cavity and coupler walls. This heating, if not properly dissipated may result in catastrophic cavity quench. The multi-physics simulation for HCCM cavity HOM coupler is done in two steps

- Electromagnetic simulation for the vacuum region.
- Thermal simulation for the cavity metal body.

These two steps are performed in sequence. The result of EM simulation is used as input for the thermal simulation. The analysis starts from a CAD model of JLAB HCCM cavity HOM coupler shown in Fig. 1. The second order finite element meshes are generated using CUBIT [4] for the vacuum and metal body region of the cavity-coupler structure. The EM simulation is performed to the vacuum region of the mesh and the thermal analysis is conducted in metal region. The two regions share the same common surface meshes at their interfaces, so that heat flux can be transferred directly between two analyses.

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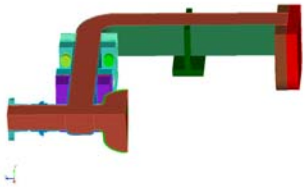

Figure 1: The CAD model of JLAB SCRF cavity HOM coupler including metal and vacuum regions.

Electromagnetic analysis is performed using Omega3P. The mesh for the vacuum region has 113K elements. The wall is assumed perfect conductor during EM analysis. Using second order FEM discretization, the resulting accelerating frequency is 1.497 GHz, and electric field distribution is shown in Fig. 2.

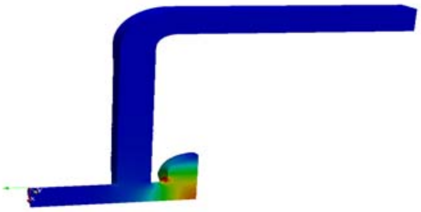

Figure 2: Electric field distribution for the accelerating mode.

The heat source for the thermal simulation is the thermal loss of the accelerating mode at the wall. The heating power P_S is calculated using perturbation method

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

Where R_S is the surface resistance, and G is the surface boundary between the vacuum region and the metal part. The magnetic field is scaled to an effective gradient of 20 MV/m. The power loss computed with Eq(1) is applied as heat flux load to the RF surfaces of the metal. In Eq(1), the surface resistance depends on material type. For HCCM cavity, the interface between EM field and metallic part is made of various materials such as copper, stainless steel, and Nb-Ti alloy. All these materials have temperature dependent surface resistance properties, their values vary significantly.

The metal part is comprised of copper, stainless steel, Nb, Nb-Ti alloy and AlMg. HOM waveguide part is made of stainless steel. The heating surface of HOM waveguide is covered with very thin copper coating with 5 μm thickness. The coating has smaller surface resistance than that of stainless steel to decreases the heating caused by EM fields. In addition copper also has larger thermal conductivity than stainless steel. The coating can not be modeled with volume elements such as tetrahedron due to extremely small thickness comparing to its substrate. TEM3P uses shell elements for FEM modeling of very thin layers.

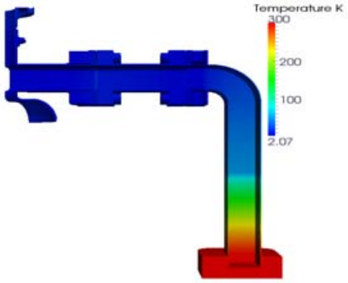

Figure 3: Temperature field caused by EM heating

Thermal conductivities of the metallic part vary for part to part and with temperature. For example at 2.1K temperature, the thermal conductivity of stainless steel is 0.11 $Wm^{-1}K^{-1}$, and at the same temperature, copper's thermal conductivity is 66.2 $Wm^{-1}K^{-1}$, and for stainless steel the thermal conductivity at 300 K is 15.3 $Wm^{-1}K^{-1}$ [5].

Cooling of the HOM waveguide is performed by liquid Helium. The heat transfer coefficient is modeled based on Kapitza conductance [6]. The bulk temperature for liquid Helium is at 2.07 K at Nb-Ti flange, and 2.1 K at cooling channel of HOM waveguide. The liquid Helium convective film coefficient is also temperature dependent.

In addition to the RF heating boundary condition and Kapitza conductance, the temperature at the end of HOM coupler is set to 300K. There is also a 50 K heat station at the warmer end of HOM waveguide. The rest of the boundaries are modeled as natural convection.

Due to strong nonlinearity, care must be taken in the solution of nonlinear thermal equation. TEM3P uses Newton method for solving the nonlinear equation. It is known that Newton method needs robust implementation for strongly nonlinear problems. We use an inexact Newton method for solving the nonlinear equations [7]. Each nonlinear equation requires solution of linear system of equations. The resulted linear equations are solved using iterative preconditioned Krylov space methods, such as GMRES.

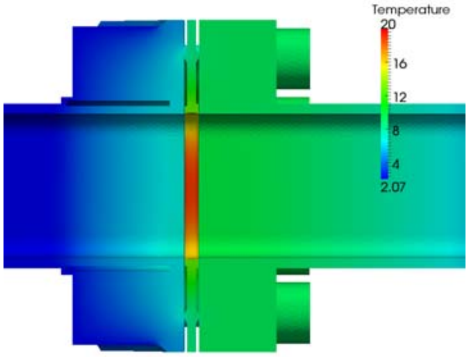

Figure 4: Temperature field around AlMg seal.

Result of the thermal simulation using second order FEM discretization is shown in Figure 3. Temperature field changes between 2.07K and 300K as expected. An important part for thermal analysis is the region around AlMg seal. Temperature distribution for this part is shown in Fig. 4.

CONVERGENCE STUDIES

To perform convergence studies we use two meshes with different mesh sizes. The fist one has 1.35 M (coarse mesh) tetrahedron elements, and the second one has 4.3 M (fine mesh) tetrahedron elements. Thermal simulations are performed with both linear and quadratic discretizations. The temperature results along a charecteristic line are plotted and compared (Fig. 5). Numerical results indicate that, the simulations converge when quadratic finite element discretization is used.

The largest simulation model has 7.07 M dof's, and uses 256 processor (on NERSC's Franklin), and converges in 25 minutes, within 12 nonlinear iterations.

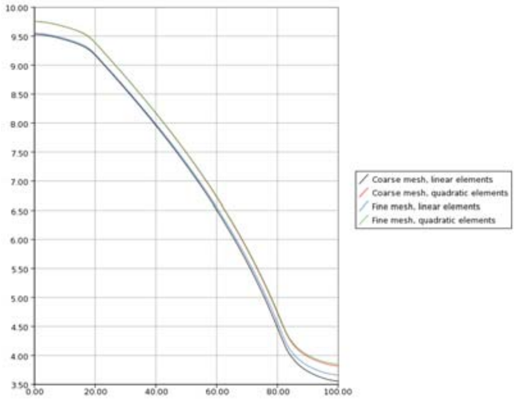

Figure 5: Temperature along a line using different mesh schemes.

SUMMARY

TEM3P is a parallel multi-physics simulation tool including integrated electromagnetic, thermal and structural effects. It allows accurate and fast analysis for accelerator component design and performance evaluations. Nonlinear problems such as that arising from the convective cooling of cavity-coupler surfaces can be solved efficiently in TEM3P. Further code verification and validation will be carried out for the SRF cavity in collaboration with JLAB scientists.

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