PARALLEL COMPUTATION OF INTEGRATED ELECTROMAGNETIC, THERMAL AND STRUCTURAL EFFECTS FOR ACCELERATOR CAVITIES*

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Abstract

The successful operation of accelerator cavities has to satisfy both rf and mechanical requirements. It is highly desirable that electromagnetic, thermal and structural effects such as cavity wall heating and Lorentz force detuning in superconducting rf cavities can be addressed in an integrated analysis. Based on the SLAC parallel finite-element code infrastructure for electromagnetic modeling, a novel multi-physics analysis tool has been developed to include additional thermal and mechanical effects. The parallel computation enables virtual prototyping of accelerator cavities on computers, which would substantially reduce the cost and time of a design cycle. The multi-physics tool is applied to the LCLS rf gun for electromagnetic, thermal and structural analyses.

INTRODUCTION

In the design of next generation accelerators, high fidelity thermal and mechanical analyses, along with accurate electromagnetic (EM) design, are essential for optimizing the performance and cost effectiveness of rf components. Many failures in accelerator operations are due to excessive heating arising from high power or high current operations. For superconducting rf cavities (SRF), additional effects come from the Lorentz force exerted by the accelerating mode on the cavity wall, which will lead to detuning of the operating mode frequency. Presently, EM, thermal and mechanical calculations are carried out separately with different modeling tools using different computational meshes. It is highly desirable in the accelerator community to build an integrated modeling package with capabilities of EM, thermal, and mechanical calculations using the same data structures and computing implementations.

Under the support of the U.S. SciDAC program, SLAC has been developing high fidelity 3D parallel finite element codes aimed at electromagnetic and beam physics simulations 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 to compliment the existing electromagnetic simulation tools. 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 [2]. 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 present an example of multi-physics simulation to illustrate the capabilities of TEM3P. We perform multi-physics studies of the LCLS rf gun including electromagnetic, thermal and structural analyses as well as beam quality calculations.

PROTOTYPING OF THE LCLS RF GUN

The prototyping of the LCLS rf gun involves the establishment of an rf design that satisfies EM, mechanical and beam physics requirements. All these effects can be analyzed using TEM3P and other EM codes within SLAC finite-element suite of modeling tools.

Thermal and Mechanical Calculations

The surface magnetic fields of the accelerating mode produce heating on the cavity walls. This heating, if not properly dissipated, may result in excessive structural stress, deformations, and accelerating frequency shift. We use TEM3P for thermal and structural simulations of the rf gun. The multi-physics simulation is done in four steps

- Electromagnetic simulation for the vacuum region
- Thermal simulation for the cavity metal body
- Mechanical simulation for the cavity metal body
- Calculation of thermal frequency drift caused by structural deformations

These four steps are performed in sequence. The results of each step are used as the input for the following step. The analysis starts from a CAD model of the rf gun shown in Fig. 1. Second-order finite element meshes are generated using CUBIT [3] for the vacuum and metal body regions of the rf gun. The EM simulation will be applied to the vacuum region of the mesh and the thermal and mechanical analyses to the metal region. The computational data are transferred between different analyses through the common surface. Since traditional thermal and structural modeling tools use the finite-element method, the integration of the newly-developed thermal and structural codes into the existing EM finite-

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element modeling tools is straight-forward. For the following calculations, we have used the standard commercial software ANSYS for validations and have found excellent agreements for both the thermal and structural solvers in TEM3P.

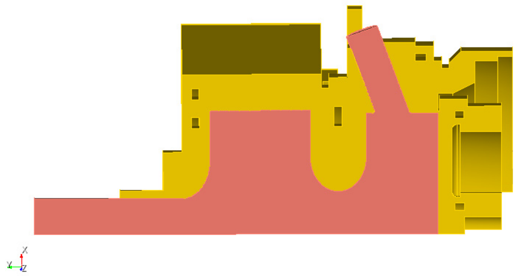

Figure 1: The CAD model of the LCLS rf gun including metal and vacuum regions.

The electromagnetic analysis is performed using the parallel eigensolver Omega3P, which determines the resonant mode frequencies and field distributions. The mesh for the vacuum region has 78K elements, and second order iso-parametric finite-element discretization is used. The calculated frequency for the accelerating mode is 2.856 GHz, and the magnetic field distribution of this mode is shown in Fig. 2.

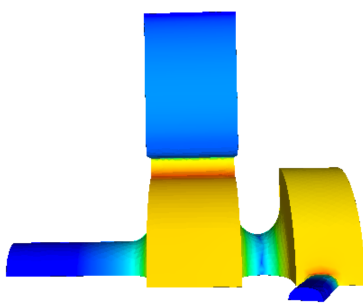

Figure 2: Magnetic field distribution of the accelerating mode.

The heat source for the thermal simulation is the power loss of the accelerating mode on the cavity wall. The wall loss power P_S is calculated as

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

where R_S is the surface resistance, and G the surface boundary between the vacuum and the metal regions. To determine the wall loss arising from LCLS operation, the magnetic field is scaled such that the peak electric field on the gun cathode is 120 MV/m, resulting in a total of 4 kW dissipated power on the cavity wall, computed using Eq. 1. The computed power loss is then applied as heat flux load to the surface of the metal body of the cavity.

The mesh for thermal and structural analyses is shown in Fig. 3. Note that the cooling channels are indicated as holes inside the mesh and appropriate boundary conditions need to be applied to represent their cooling effects. We use a mesh with 215K high-order tetrahedral elements for both analyses. The metal part is comprised of two different materials, copper and stainless steel. The thermal conductivities are k=391 $Wm^{-1}K^{-1}$ for copper, and k=16.2$Wm^{-1}K^{-1}$ for stainless steel, respectively. The coefficient of thermal expansion is $1.7x10^{-5}K^{-1}$ for both materials. We assume that both materials are linear elastic and obey Hooke's law with the following elasticity parameters (the Young's Modulus ε and the Poisson's ratio ν): for copper $\varepsilon=1.15x10^{11}N/m^2$ and ν=0.326, and for stainless steel $\varepsilon=1.93x10^{11}N/m^2$ and ν=0.305.

For the heat analysis of the rf gun we use the following model. The metallic wall has 7 cooling channels, and they are modeled as convective boundary conditions. The bulk temperature for the cooling channels is 25 °C. Other parts of the boundary are modeled using natural convection boundary conditions. In this case, the heat equation is linear, due to the constant thermal coefficients and linear boundary conditions. The numerical linear system of equations of the thermal solver is solved using an iterative solver. It should be pointed out that TEM3P is capable of solving nonlinear heat equation problems, such as those arising from analysis in superconducting cavities. The temperature distribution is shown in Fig. 4. The maximum and minimum temperatures caused by electromagnetic wall-loss heating are found to be 50.3 °C and 27.1 °C, respectively.

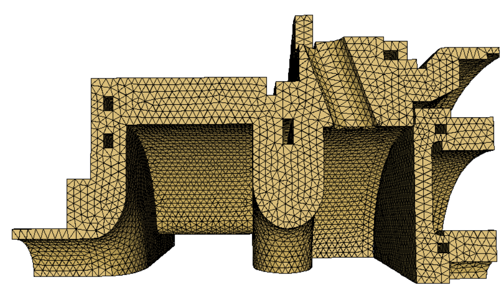

Figure 3: A 3D mesh for the metal part of the LCLS gun.

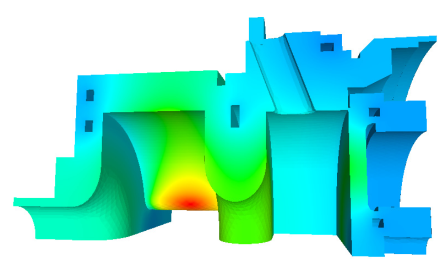

Figure 4: Temperature field caused by EM heating (the hot region represented by red color).

The changes in temperature field cause structural deformations. To simulate this, the thermal load computed in the previous step is transferred to the structural solver in TEM3P. We use symmetric boundary conditions for symmetric planes in the structural solver. In addition, at the right side of the cavity wall, we assume that the displacements along the cavity longitudinal axis are constrained (see Fig. 3). The maximum deformation is found to be 3.7×10^{-5} m. The distribution of the axial stress is shown in Fig. 5.

The last step for the rf simulations using TEM3P is to compute the thermal frequency drift caused by structural deformations. This is done first by re-meshing the deformed vacuum region, and re-performing the EM simulation using Omega3P. The computed frequency shift for the accelerating mode due to structural deformations of the cavity is found to be 650 kHz, which is comparable to the bandwidth of the operating mode. In the real RF Gun operation, the water temperature is lowered to compensate this drift [4].

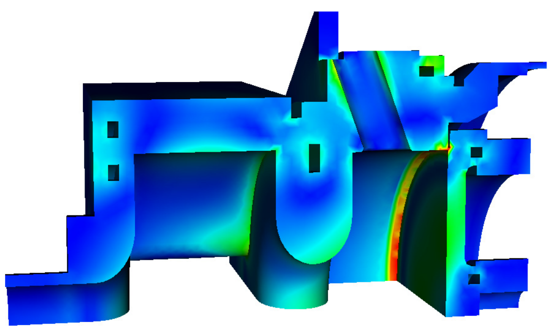

Figure 5: Axial stress distribution calculated using TEM3P.

Beam Emittance Calculations

The complete design of the rf gun has to satisfy beam dynamic requirements. For a given rf design, the emittance of the electron bunch is computed with SLAC's parallel finite-element EM particle-in-cell code PIC3P, the first code of its kind. From first principles, Pic3P self-consistently solves the complete set of Maxwell's equations and includes wakefield and retardation effects that are generally ignored in standard space-charge tracking codes. Pic3P has been highly optimized for efficient rf gun simulations employing various novel computational techniques [5]. Fig. 6 shows a snapshot of the scattered self-fields excited by the bunch computed using Pic3P. Fig. 7 shows the calculated normalized transverse emittance, for a 1 nC, 10 ps long cylindrical bunch of 1 mm initial radius with no initial energy spread.

SUMMARY

We have developed a three-dimensional parallel software TEM3P for integrated multi-physics analysis including rf, thermal and mechanical effects. Together with SLAC existing finite-element suite for capabilities such as beam simulations and the speedup of parallel computations, the toolset provides a unique framework for the engineering prototyping of accelerator components entirely on computers, thus potentially expediting the design cycle in terms of time and cost.

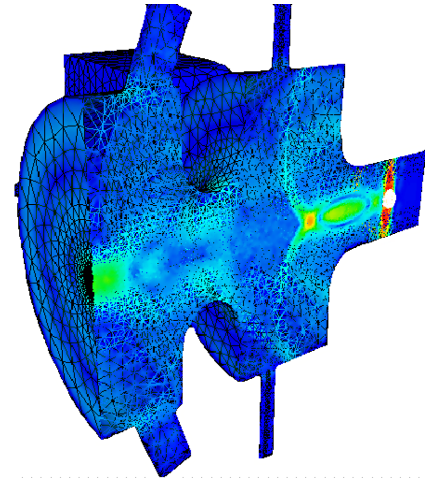

Figure 6: Snapshot of the scattered fields of the bunch using Pic3P.

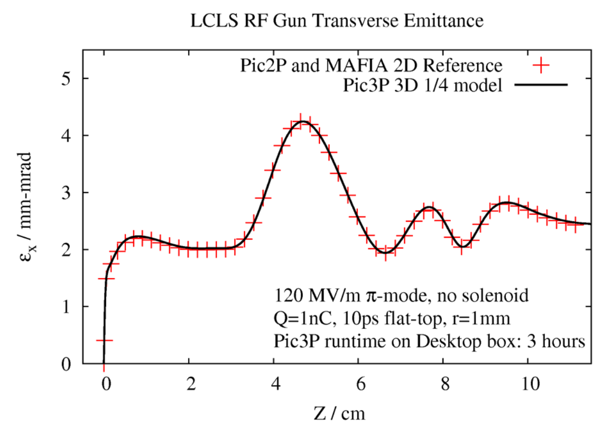

Figure 7: Normalized transverse emittance calculated with Pic3P.

ACKNOWLEDGEMENTS

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