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High-performance computing in accelerating structure design and analysis

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Abstract

Future high-energy accelerators such as the Next Linear Collider (NLC) will accelerate multi-bunch beams of high current and low emittance to obtain high luminosity, which put stringent requirements on the accelerating structures for efficiency and beam stability. While numerical modeling has been quite standard in accelerator R&D, designing the NLC accelerating structure required a new simulation capability because of the geometric complexity and level of accuracy involved. Under the US DOE Advanced Computing initiatives (first the Grand Challenge and now SciDAC), SLAC has developed a suite of electromagnetic codes based on unstructured grids and utilizing high-performance computing to provide an advanced tool for modeling structures at accuracies and scales previously not possible. This paper will discuss the code development and computational science research (e.g. domain decomposition, scalable eigensolvers, adaptive mesh refinement) that have enabled the large-scale simulations needed for meeting the computational challenges posed by the NLC as well as projects such as the PEP-II and RIA. Numerical results will be presented to show how high-performance computing has made a qualitative improvement in accelerator structure modeling for these accelerators, either at the component level (single cell optimization), or on the scale of an entire structure (beam heating and long-range wakefields).

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1. Introduction

Particle accelerators are among the most important and most complex scientific instruments in use, and are critical to research in fields such as high-energy physics, nuclear physics, materials science, chemistry, and the biosciences. As new and existing facilities continually strive towards higher energy, higher beam current, and greater efficiency, accelerator physicists and engineers are faced with increasingly demanding specifications on the RF system to improve performance and reduce cost. As a result, the emphasis of designing the accelerating structures for these machines has been placed heavily on numerical modeling as the cost-saving approach to their R&D. This means the accuracy and reliability of the modeling software are becoming of paramount importance in order that the structures can meet the stringent design requirements.

The Damped, Detuned Structure (DDS) shown in Fig. 1 is the baseline linac design for the warm Linear Collider (NLC) [1] scheme. In the DDS, the frequency of the accelerating field must be accurate to within 1 part in 10,000 to maintain acceleration efficiency. This requirement has to be met in a complex cavity geometry that optimizes the accelerating field gradient while suppresses the long-range dipole wakefields. To provide the desired

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Fig. 1. Model of the 55-cell NLC DDS design.

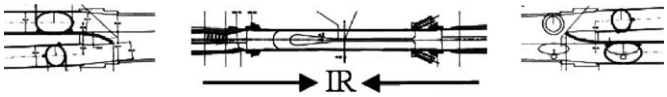

Fig. 2. Beamline complex of the PEP-II Interaction Region (IR).

accuracy in the DDS cell frequency and to verify the wakefield suppression by damping and detuning over the entire structure are modeling challenges that are beyond the capabilities of standard electromagnetic (EM) codes (e.g. MAFIA [2] and HFSS [3]) running on limited computing resources like desktop computers.

2. High-performance computing

Besides the NLC DDS design, the PEP-II [4] Interaction Region (IR), the RIA [5] RFQ cavity and the PSI [6] ring cyclotron are additional examples for which more advanced simulation tools other than available software are needed. In the PEP-II, beam heating in the IR due to trapped modes is an obstacle to high current operation, and thus high luminosity. Fig. 2 shows the IR beamline complex which consists of a central vacuum chamber of complicated, varying cross-sections (due to the synchrotron masks) that connects to the positron and electron beamlines via a crotch junction at both ends. Modeling the entire geometry is necessary to fully account for the beam heating effect. The proposed RIA plans to employ RFQ structures such as those shown in Fig. 3 in its low-energy linacs. Presently, provisions have to be made for tuners to compensate for frequency errors of about 1% from using existing design software. New modeling tools that can improve the accuracy by an order of magnitude would lead to a significant reduction in tuners required and a much simplified operation as well.

To address these modeling challenges, SLAC has embarked on a code development effort that was first initiated in 1997 under the support of the DOE Grand Challenge on Accelerator Physics, with the goal to implement high-performance computing (HPC) capabilities in accelerating modeling tools. This work has expanded with the follow-up DOE SciDAC Accelerator Simulation project in which SLAC leads the team that specifically targets high accuracy, large-scale electromagnetic applications.

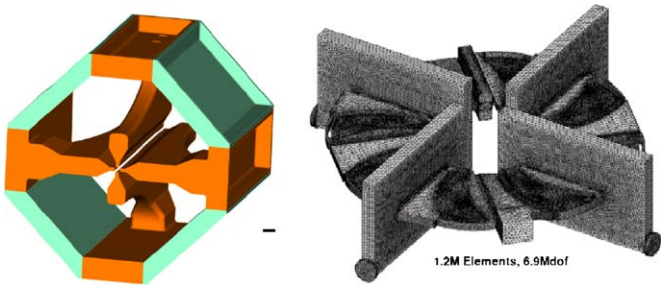

Fig. 3. The RIA RFQ and the PSI ring cyclotron.

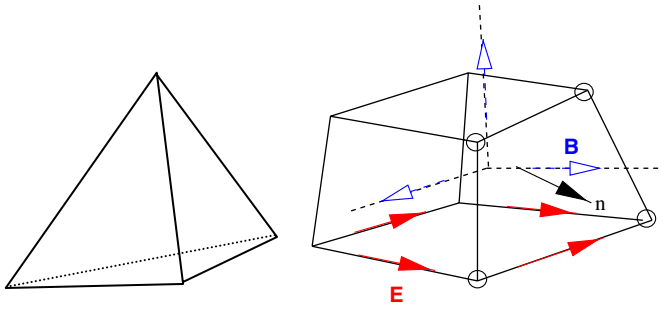

Fig. 4. Tetrahedral mesh for Omega3P/S3P/T3P and hexahedral mesh for Tau3P.

3. Parallel electromagnetic codes on unstructured grids

The suite of 3D, parallel electromagnetic codes that are finite element based consists of:

(1) Omega3P—eigenmode solver for finding normal modes in lossless and lossy cavities.
(2) S3P—solver in frequency domain to calculate S parameters of open structures.
(3) T3P—time-domain solver for modeling response due to beam, dipole and waveguide excitation, and it also includes:
(4) Tau3P—time-domain solver following the Discrete Surface Integral (DSI) formulation with same functionalities as T3P.
(5) Track3P—module for dark current simulation with surface physics using fields from solvers above.
(6) Viz3D—analysis and graphics package.

The finite element codes employ tetrahedral mesh elements while the DSI-based Tau3P uses hexahedral cells (Fig. 4), both unstructured grids able to conform to curved surfaces for very high accuracy modeling. The set of codes is developed under C++ with a unified data structure to facilitate geometry input and partitioning, and uses MPI for communication on distributed memory architectures.

The code development at SLAC is supported by an extensive and coordinated R&D program in computer science and applied mathematics that is sponsored by SciDAC and carried out in designated national laboratories and universities. Among these efforts include parallel meshing at Sandia and University of Wisconsin, partitioning at Sandia and Lawrence Berkeley Lab (LBL), linear solvers and eigensolvers at Stanford and LBL, adaptive refinement at RPI, and visualization at UC Davis. They contribute to the success of the large-scale simulations required for the challenging accelerator applications described above. We will next present two examples of