ACE3P COMPUTATIONS OF WAKEFIELD COUPLING IN THE CLIC TWO-BEAM ACCELERATOR *

A. Candel†, Z. Li, C. Ng, V. Rawat, G. Schussman and K. Ko, SLAC
I. Syratchev, A. Grudiev and W. Wuensch, CERN

Abstract

The Compact Linear Collider (CLIC) provides a path to a multi-TeV accelerator to explore the energy frontier of High Energy Physics. Its novel two-beam accelerator concept envisions rf power transfer to the accelerating structures from a separate high-current decelerator beam line consisting of power extraction and transfer structures (PETS). It is critical to numerically verify the fundamental and higher-order mode properties in and between the two beam lines with high accuracy and confidence. To solve these large-scale problems, SLAC's parallel finite element electromagnetic code suite ACE3P is employed. Using curvilinear conformal meshes and higher-order finite element vector basis functions, unprecedented accuracy and computational efficiency are achieved, enabling high-fidelity modeling of complex detuned structures such as the CLIC TD24 accelerating structure. In this paper, time-domain simulations of wakefield coupling effects in the combined system of PETS and the TD24 structures are presented. The results will help to identify potential issues and provide new insights on the design, leading to further improvements on the novel CLIC two-beam accelerator scheme.

INTRODUCTION

The Office of Science in the U. S. DOE is promoting the use of High Performance Computing (HPC) in projects relevant to its mission via the 'Scientific Discovery through Advanced Computing' (SciDAC) program which began in 2001. Since 1996, SLAC has been developing a parallel accelerator modeling capability, first under the DOE Grand Challenge and now under SciDAC, for use on HPC platforms to enable the large-scale electromagnetic and beam dynamics simulations needed for improving existing facilities and optimizing the design of future machines.

T3P is the time-domain module within SLAC's parallel electromagnetic code suite ACE3P, and is used for simulations of wakefields and transient effects. T3P solves Maxwell's equations via the inhomogeneous vector wave equation for the time integral of the electric field $\mathbf{E}$:

$$\left(\varepsilon\frac{\partial^2}{\partial t^2}+\sigma_{\mathrm{eff}}\frac{\partial}{\partial t}+\nabla\times\mu^{-1}\nabla\times\right)\int^{\mathbf{t}}\mathbf{E}\,\mathrm{d}\tau=-\mathbf{J},\quad (1)$$

with permittivity $\varepsilon=\varepsilon_0\varepsilon_r$ and permeability $\mu=\mu_0\mu_r$. For simplicity in the computations, a constant value of the effective conductivity $\sigma_{\mathrm{eff}}=\tan\delta\cdot 2\pi\mathrm{f}\cdot\varepsilon$ is assumed by fixing a frequency f, and the losses are specified by the loss tangent $\tan\delta$. The computational domain is discretized into potentially curved tetrahedral elements and $\int^t \mathbf{E}\,\mathrm{d}\tau$ in Eq. (1) is expanded into a set of hierarchical Whitney (tangentially continuous) vector basis functions $\mathbf{N_i}(\mathbf{x})$ up to order p within each element:

$$\int^t \mathbf{E}(\mathbf{x},\tau)\,\mathrm{d}\tau=\sum_{i=1}^{N_p} e_i(t)\cdot\mathbf{N_i}(\mathbf{x}).\quad (2)$$

For illustration, N_1=8, N_2=20 and N_6=216. Higher-order elements not only significantly improve field accuracy and dispersive properties, but they also generically lead to higher-order accurate beam-cavity coupling equivalent to, but much less laborious than, complicated higher-order interpolation schemes commonly found in finite-difference methods. Time integration is performed via the implicit Newmark-Beta scheme which is unconditionally stable, but requires the solution of a sparse matrix problem at every time step, typically performed with a conjugate gradient method using a suitable preconditioner. More detailed information about the methods used in T3P and their parallel scalability has been published earlier [1].

RESULTS

In the following, numerical verification of transverse wakefield damping in the CLIC two-beam accelerator is presented - for the PETS decelerator structure, the TD24 accelerator structure and a simple combined system. More information about the structures can be found at [2], [3].

As is common for wakefield computations of rigid beams, the electric current source density $\mathbf{J}$ in Eq. (1) is defined by a Gaussian line current ($\pm 5\sigma_z$), moving at the speed of light along the beam line (along z-direction). For most efficient computation of transverse wakefields, the beam is sent through a symmetric quarter of the structure with a small (e.g., horizontal) offset ($x>0$), with electric boundary condition applied at the vertical symmetry plane ($x=0$) and magnetic boundary conditions at the horizontal symmetry plane ($y=0$).

For the PETS, a beam with bunch length σ_z=2 mm is driven along the beam pipe axis with a transverse offset of 2.5 mm. The effective conductivity σ_{eff} is calculated with parameters f=12 GHz, ε_r=13 and $\tan\delta$=0.2. Figures 1 and 2 show the used mesh model and a snapshot of the excited wakefields in the PETS as calculated with T3P. Figure 3

* Work supported by the U. S. DOE ASCR, BES, and HEP Divisions under contract No. DE-AC002-76SF00515.

† candel@slac.stanford.edu

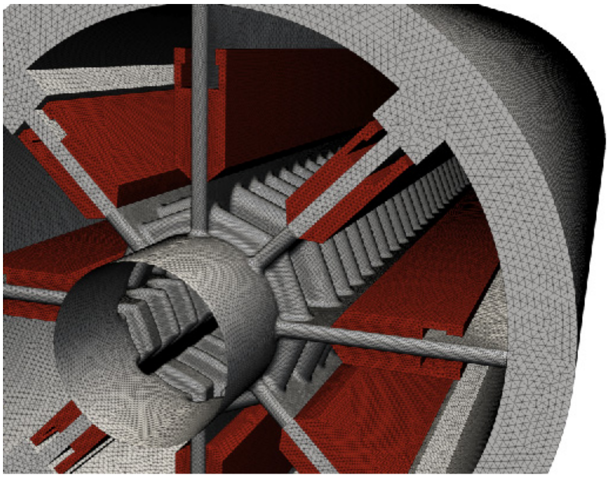

Figure 1: PETS unstructured conformal mesh model used for T3P simulations. A quarter model consists of about 10 million tetrahedral elements, many of which are curved. The mesh for the dielectric loads (highlighted in red) is refined to resolve the smaller local wavelengths.

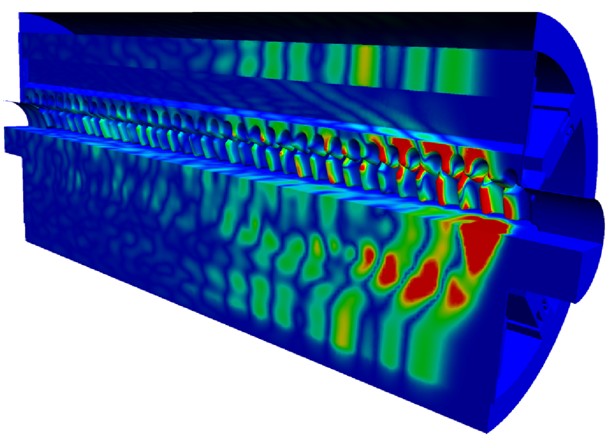

Figure 2: Snapshot of electric field magnitude in the PETS as computed with T3P for a beam transiting at an offset to excite transverse wakefields (via electric/magnetic boundary conditions). Strong damping in the lossy dielectric loads is observed.

shows the transverse wake potential of the PETS computed with T3P and comparison to GdfidL (featuring first-order accuracy in fields and geometry via the finite difference method) results.

For the TD24 accelerating structure, a beam with bunch length σ_z=2 mm is driven along the beam pipe axis with a transverse offset of 1 mm. Figures 4 and 5 show the mesh model and a snapshot of the transverse wakefields in the TD24 as calculated with T3P. For numerical truncation of the model at the waveguide ports, T3P uses broadband waveguide boundary conditions based on mode expansion into 2D port modes. This leads to much better numerical absorption of excited modes at or near the waveguide cut-off than with the conventional first-order "ABC" absorbing

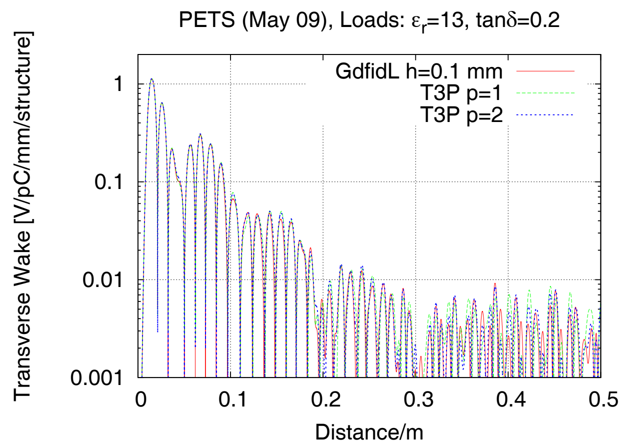

Figure 3: Transverse wake potential of the PETS computed with T3P as a function of the order p of the vector basis functions. For p=2, the time step is halved (to 0.25 ps) for optimal accuracy. Comparison to GdfidL results shows good agreement.

boundary conditions. Figure 6 shows the transverse wake

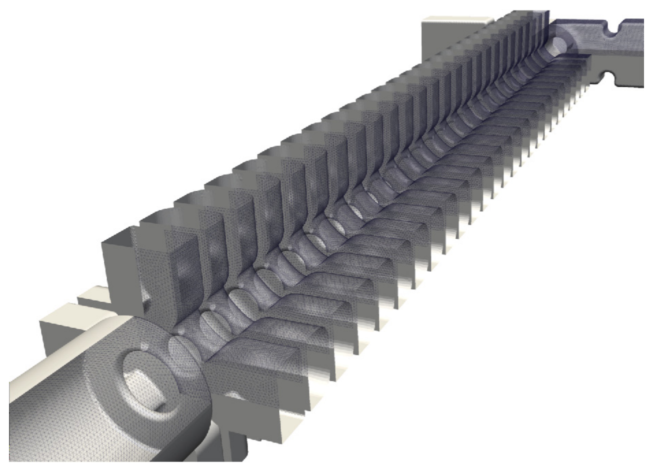

Figure 4: TD24 unstructured conformal mesh model used for T3P simulations. A quarter model consists of about 4 million tetrahedral elements, many of which are curved. Note that by using the broadband waveguide boundary conditions, the waveguides can be shortened without sacrificing simulation accuracy.

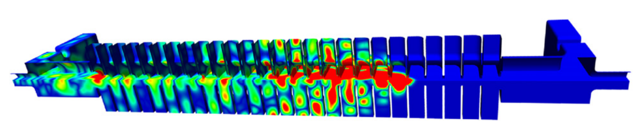

Figure 5: Snapshot of electric field magnitude in the TD24 accelerating structure as computed with T3P for a beam transiting at an offset to excite transverse wakefields (via electric/magnetic boundary conditions).

potential of the TD24 accelerating structure as calculated with T3P and GdfidL. Good agreement is found.

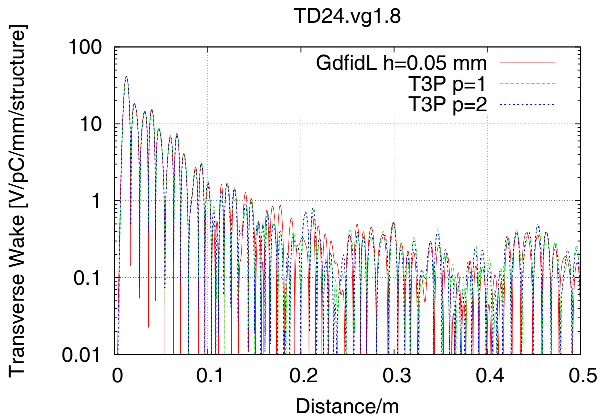

Figure 6: Transverse wake potential of the TD24 accelerating structure computed with T3P and GdfidL.

Figures 7 and 8 show results for the first transverse wakefield coupling calculations performed on a simplified coupled model of the PETS (quarter model) and two TD24 accelerating structures (modeled via a half model). A single drive beam at an offset in the PETS (same parameters as above) excites transverse wakefields that couple to the TD24 (and back). The evolution of the transverse electric field magnitude along the center axis of the TD24 as a function of time is shown in Fig. 8.

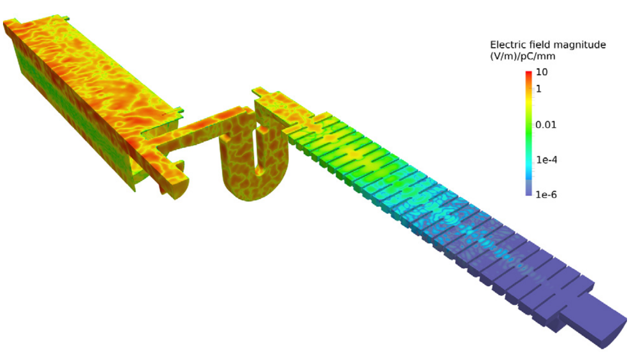

Figure 7: Snapshot of transverse wakefield coupling between the PETS and the TD24 as computed with T3P. A single PETS drive beam is used to excite the fields. The combined mesh model features similar resolution as for the individual structure simulations shown above.

SUMMARY

SLAC's parallel electromagnetic code suite ACE3P employs state-of-the-art parallel 3D Finite Element methods on curved conformal unstructured meshes with higher-order field representation. The scalable time-domain code T3P allows large-scale time-domain simulations of large realistic structures with unprecedented accuracy by using leadership-class DOE supercomputing facilities.

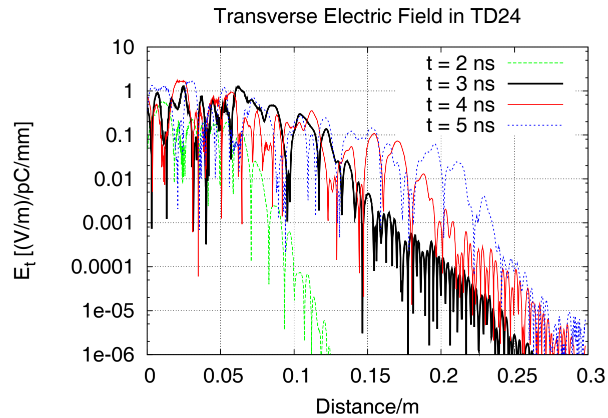

Figure 8: Magnitude of the transverse electric field along the TD24 accelerating structure at various moments after a single drive bunch enters the PETS.

In this study, T3P is used to calculate wakefield damping effects in the CLIC two-beam accelerator module. Single structure simulations of the PETS and the TD24 accelerating structure are benchmarked against GdfidL results. For the first time, transverse wakefield coupling effects are computed on the combined system of PETS and TD24 structures. This capability is an important step toward numerical verification of the electromagnetic performance of the full CLIC two-beam accelerator module. Future work will include calculations on a more realistic model of the coupled system.

ACKNOWLEDGMENTS

This work was supported by the U. S. DOE ASCR, BES, and HEP Divisions under contract No. DE-AC002-76SF00515. This research used resources of the National Energy Research Scientific Computing Center, and of the National Center for Computational Sciences at Oak Ridge National Laboratory, which are supported by the Office of Science of the U. S. Department of Energy under Contract No. DE-AC02-05CH11231 and No. DE-AC05-00OR22725. – We also acknowledge the contributions from our SciDAC collaborators in numerous areas of computational science.

REFERENCES

[1] A. Candel, A. Kabel, L. Lee, Z. Li, C. Ng, G. Schussman and K. Ko *State of the art in electromagnetic modeling for the Compact Linear Collider*, Proc. J. Phys.: Conf. Ser. **180** 012004 (10pp), 2009

[2] I. Syratchev *Progress in the PETS Development*, CLIC09, CERN, October 2009

[3] A. Grudiev and W. Wuensch *Design of the CLIC Main Linac Accelerating Structure for CLIC Conceptual Design Report*, Proc. Linear Accelerator Conference, Tsukuba, Japan, Sep 12-17, 2010