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ComPASS final report

Tech-X Corporation

"Community Project for Accelerator Science and Simulation"
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Activity description and overall status

Tech-X participated across the full range of ComPASS activities, with efforts in the Energy Frontier primarily through modeling of laser plasma accelerators and dielectric laser acceleration, in the Intensity Frontier primarily through electron cloud modeling, and in Uncertainty Quantification being applied to dielectric laser acceleration.

In the following we present the progress and status of our activities for the entire period of the ComPASS project for the different areas of Energy Frontier, Intensity Frontier and Uncertainty Quantification.

Energy frontier: Plasma-based acceleration

For advanced accelerators, our deliverables are to perform large-scale simulations of laser plasma accelerators (LPAs) in order to design production of high quality 10 GeV electron beams. As described in previous progress reports, we have developed, implemented, and tested an algorithm for control of numerical dispersion in LPA simulations, and also implemented an implicit PIC method.

Since the last progress report, we have developed new infrastructure components for solving the linear and nonlinear systems involved in implicit PIC, the laser envelope model, and similar algorithms. This is a flexible system, in which the user specifies arbitrary sets of field components as degrees of freedom via input blocks (this allows for solvers on non-rectangular regions, such as the interior of RF cavities, relevant for other accelerator applications). The user then specifies vectors and matrices, with arbitrary stencils, over those degrees of freedom. A matrix-vector multiply or a matrix solve can be performed, with solver parameters also specified by the user. This allows the user complete control over the update, and enables combining linear and nonlinear solves with other types of updates, such as finite-difference evaluations. For higher-level algorithm, such as implicit PIC or the laser envelope model, the needed input blocks for the solvers are encapsulated in macros.

Energy frontier: Dielectric laser acceleration

For dielectric laser acceleration (DLA), our deliverables are to improve techniques for linear solvers for fields in photonic crystal accelerator structures and for computations of dielectric laser accelerators relevant to ongoing SLAC experiments. As described in previous progress reports, we have developed advanced linear solvers for frequency-domain photonic crystal problems and implemented material interactions for simulating electrons in a dielectric grating structure experiment.

Since the last progress report, we developed full-scale simulations of a more recent experiment, which uses a shorter laser pulse (90 fs) than previously to achieve a record gradient in a DLA structure. We added diagnostic planes to the simulation that can track the trajectory of particles crossing those planes. Using this information, we created a post-processing tool that adds a transverse kick from multiple scattering in the material. We can then propagate the particles to the position of the spectrometer screen for direct comparison with experiment, finding good agreement with the experimental data. We are also able to examine the dynamics of the acceleration, including optical phase dependence, and from the data we can show that the acceleration occurred over a short distance, verifying the high observed gradient.

Intensity frontier: Electron cloud

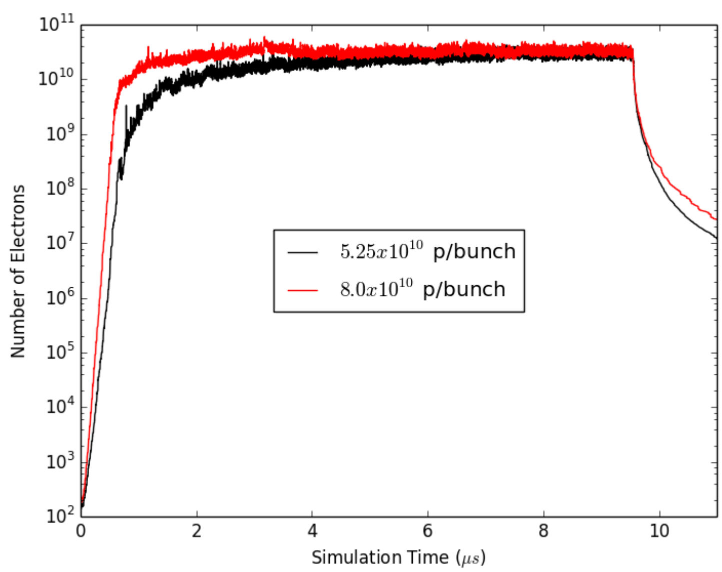
Electron clouds can pose a serious threat to accelerator performance, and understanding cloud buildup and the effectiveness of different mitigation techniques can provide cost-saving improvements in accelerator design and fabrication, especially on the intensity frontier, where electron clouds can be a limiting factor in accelerator performance. Microwave diagnostics of electron clouds are a non-destructive way to measure cloud buildup, but it is very difficult to measure the absolute cloud density from spectral signals alone due to uncertainties in rf path lengths, the role of reflections and attenuation, and large inhomogeneities in spatial and temporal distributions of electrons. Modeling travelling-wave rf diagnostics is needed to be able to interpret ongoing electron cloud experiments at many accelerators, but is very difficult because of the computational requirements to resolve both rf and electron cloud modulation time scales. As described in previous progress reports, we have developed new numerical models based on simulations of modulated dielectric properties of electron clouds in order to generate synthetic spectra, and demonstrated new modeling capability that simulates travelling wave rf diagnostics of electron clouds including the effects of cloud buildup over many bunch crossings.

Since the last progress report, we worked with Fermilab researchers, using VSim to model electron cloud build up, dynamics, and dissipation, for simulation parameters corresponding to the Fermilab Recycler storage ring in order to understand the survival rate of electrons over more than a single revolution period. For example, in order to model *e*-cloud build up in the Recycler, we executed numerical models simulating the crossing of 504 Gaussian-shaped bunches (84 bunches per batch and 6 batches per beam) with bunch lengths of 60 cm, bunch spacing of 18.94 ns, beam radius of 3.0 mm, and 5.25×10^{10} protons/bunch. The bunches cross during the first 9.545 μs of the simulation, followed by 1.5265 μs where there is no beam, for a total revolution period of 11.0723 μs, in this model. The beam pipe cross-section is elliptical with major radius $a = 0.047$ m and minor radius $b = 0.022$ m. We simulated $l = 0.50$ m of beam pipe in the longitudinal (beam axis) direction and applied an external magnetic field that is primarily a dipole field with an additional quadrupole component:

$$B_x = 0$$
$$B_y = B_0 + Gz$$
$$B_z = Gy$$

where $B_0 = 0.1375$ T and $G = 0.3355$ T/m, x is the longitudinal direction, and y and z are the transverse directions. We seeded the simulation with a low-density, randomly distributed electron cloud, and examined the dependence of build up time and saturation density with initial seed density. We use the Furman-Pivi secondary electron yield model for stainless steel, with max(SEY) = 2.05 at a primary energy of E_{max} = 292.0 eV. We performed simulations for the nominal current Recycler beam charge of 5.25×10^{10} protons/bunch, and compared those results with the beam charge for the PIP-II upgrade of 8.0×10^{10} protons/bunch.

Our simulations show three distinct regions: build up, saturation, and dissipation, as can be seen in the figures below. In our simulations, the rate of build up for the PIP-II beam charge is faster, and there is a somewhat larger density at saturation. In addition, the survival rate is higher for the PIP-II beam parameters. The survivability is especially important for PIP-II since this indicates the potential for electron clouds to affect beam quality across bunch trains, and during the process of slip-stacking for beam loading. This work was presented at the 2015 IPAC conference.



Total number of electrons as a function of time, showing electron cloud build up, saturation, and dissipation, for current recycler (black) and PIP-II (red) beam currents.

Applied Math, Computer Science, Uncertainty Quantification

As described in previous progress reports, we collaborated with the University of Texas at Austin on uncertainty quantification (UQ) applied to advanced particle accelerator development. We shifted the focus of that effort from laser plasma acceleration to dielectric laser acceleration, for applying UQ techniques to establish fabrication tolerances for woodpile photonic crystal DLA structures.

Since the last progress report, we have focused on improving the turnaround time of electromagnetic and particle simulations, which is required for detailed optimization studies. To this end, we have explored techniques for adapting critical pieces of the FDTD and PIC algorithms to advanced architectures, namely GPUs and MICs. We developed methods for using GPU shared memory to efficiently provide field values for interpolation to particle positions. We also developed deposition methods that work robustly in a multithreaded environment.