Query-driven Analysis of Plasma-based Particle Acceleration Data

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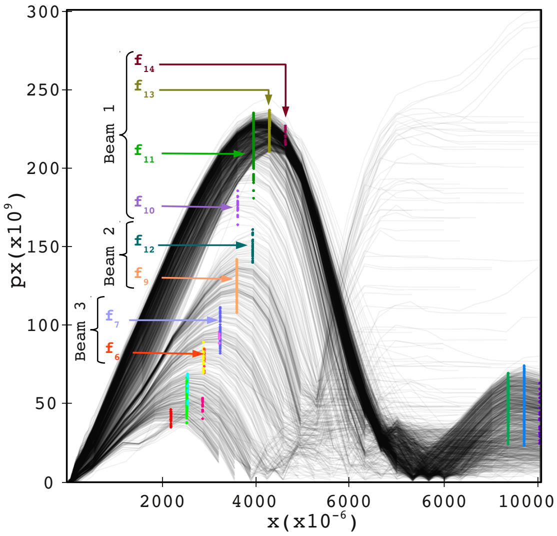

Figure 1: Plot of an example 2D dual colliding pulse accelerator simulation showing 17 acceleration features (colored groups of particles) identified by the automatic feature detection. The traces of the relevant particles in x/px space are shown in addition in black.

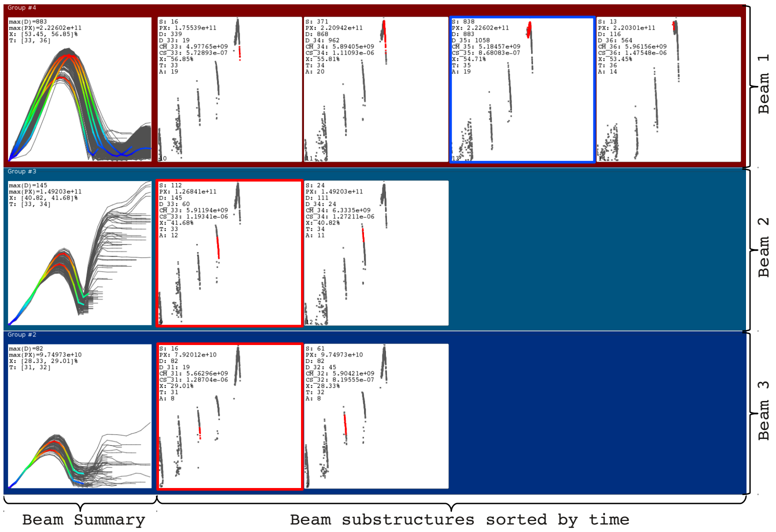

Figure 2: Matrix view showing the three main particle beams marked also in Fig. 1. Each horizontal box represents a group of features that are part of the same particle beam and shows: i) a summary x/px trace plot (left) and ii) one x/px scatter-plot for each sub-feature (right). Each group box is colored by the estimated compactness (quality) of the beam it represents (red=high, blue=low).

ABSTRACT

Plasma-based particle accelerators can produce and sustain thousands of times stronger acceleration fields than conventional particle accelerators, providing a potential solution to the problem of the growing size and cost of conventional particle accelerators. There is a pressing need for computational methods that aid in scientific knowledge discovery from the ever growing collections of accelerator simulation data generated by accelerator physicists to investigate next-generation plasma-based particle accelerator designs.

To address this challenge we describe in this poster a novel approach for automatic detection and classification of particle beams and beam substructures due to temporal differences in the acceleration process, here called acceleration features. By combining the automatic feature detection with a novel visualization tool for fast, intuitive, query-based exploration of acceleration features, we enable an effective top-down data exploration process, starting from a high-level, feature-based view down to the level of individual particles. We describe the application of our analysis in practice to study the formation and evolution of particle beams using simulations modeling different plasma-based accelerator designs.

Index Terms: I.6.6 [Computing Methodologies]: Simulation and Modeling—Simulation Output Analysis J.2 [Computer Applications]: Physical Sciences and Engineering—Physics I.5.4 [Computing Methodologies]: Pattern Recognition—Applications

1 INTRODUCTION

Plasma-based particle accelerators utilize an electron plasma wave driven by a short ($\leq 100fs$) ultrahigh intensity ($\geq 10^{18}W/cm^2$) laser pulse to accelerate charged particles (e.g., electrons) to high energy levels [3]. A central goal in designing plasma-based accelerators is to achieve reproducible, high-density particle beams with low energy spread. To enable optimization of accelerator designs, the physicists need to be able to understand the origins, injection processes and evolution of the particles that form the particle beams. However, while large numbers of particles are needed for accurate simulation of plasma-based particle accelerators, only a small fraction ($< 1\%$) of the particles are accelerated to high energy levels and subsequently form particle beams of interest. Accurate and efficient analysis of plasma-based particle accelerator simulations, hence, relies on the ability to accurately extract the particles of interest and to classify the particle beams and their temporal substructures (here called acceleration features) To address this challenge we: i) developed an automatic, query-based algorithm for detection and classification of acceleration features (Sec. 2) and ii) designed a tool for visual, query-driven feature exploration (Sec. 3). In contrast to previous manual [5] and automated beam analysis methods [4, 6], our algorithm makes temporal coherency an integral part of the beam detection, which allows us to i) avoid the complex and error-prone tracking of feature, ii) detect particle beams independent of their level of energy, and iii) identify temporal beam sub-structures that cannot be detected using previous methods.

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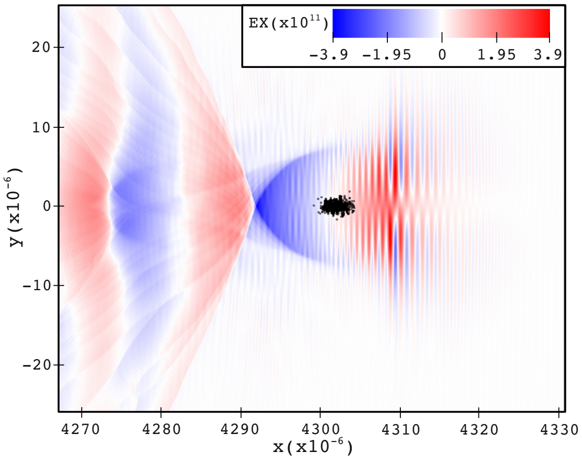

Figure 3: Visualization of timestep $t = 35$ showing: i) all particles of Beam 1 (black particles, see also Fig. 1 and 2) and ii) the electric field Ex in acceleration direction x (color).

2 FEATURE DETECTION

The algorithm for automatic detection of acceleration features proceeds as follows: i) compute the set of accelerated particles, ii) compute the traces of the accelerated particles, and iii) detect and group particles with similar local maxima in energy.

Temporal Query: To detect the particles that become accelerated, we evaluate the temporal query: $P = \{i \mid \exists px(p_i(t)) > 10^{10}ms^{-1},\ t \in [0,n]\}$, with px being the momentum in acceleration direction x. This query retrieves all particles p_i that reach energy levels several times above the plasma wave's phase velocity v_ϕ,

Particle Tracing: Next, the algorithm traces all particles returned by the temporal query over time. To enable efficient analysis of even large 3D particle datasets, we use bitmap indexing based on FastBit [1] to accelerate the queries required to compute the temporal query and particle traces. Based on the particle traces, the algorithm then computes for each timestep t the set of particles with a stable local maximum in energy.

Compute Acceleration Features: Using a density-based clustering approach, we then group the trace maxima identified at each timestep into clusters of particles that are: i) condensed in space and energy and that ii) reach a peak in energy at the same timestep of the simulation. As illustrated in Fig. 1, each particle cluster c_k then corresponds to a unique acceleration feature.

Feature Grouping: In practice, different sets of particles of a beam may reach their peak in energy at different points in time and are, hence, identified by the automatic feature detection as distinct acceleration features. To facilitate the analysis of particle beams, we group acceleration features based on their spatial location, timepoint of peak energy and peak energy level.

3 FEATURE EXPLORATION, VISUALIZATION AND ANALYSIS

To facilitate visual exploration of the space of acceleration features we use a matrix view (see Fig. 2). Groups of features are represented in the matrix view as horizontal boxes showing a summary trace plot for the group and a plot per acceleration feature contained in the group showing either: i) a particle scatter-plot, illustrating the structure of the feature at its timepoint of peak energy (see Fig. 2, *beam substructure plots*) or ii) a particle trace plot, illustrating the temporal evolution of the feature. The main (i.e., most condensed) feature, which best represents the beam, is highlighted in the view via a thicker red/blue frame.

Based on a variety of derived feature characteristics —such as, the timepoint of peak energy, the main temporal phase of acceleration, the estimated density/compactness of the feature, and other feature statistics— physicists can then define advanced feature queries to quickly identify the main features of interest, e.g., the features of highest energy and density. Once a user has identified a feature of interest, we extract the particles associated with the feature for further detailed analysis. The particles of interest may be defined based on: i) the set of reference particles of the feature, ii) the set of reference particles of a group of features, or iii) using particle queries based on derived particle-to-feature distance fields and/or original particle quantities.

To study the formation, evolution and acceleration of the selected particle feature, we trace the particles over time and perform further detailed analysis of the particle feature using the high-performance, parallel visualization system VisIt [2]. As illustrated in Figure 3, using this capability we can study, e.g., the evolution of the main particle beam in the context of the electric field data and its location in the wake of the laser pulse. Using feature statistics we can then study and compare the quality and evolution of particle features.

4 CONCLUSION

The suite of methods we have developed enables rapid knowledge discovery from large and complex plasma-based particle accelerator simulations. We have presented a novel algorithm for automatic detection and classification of acceleration features which enables for the first time automatic detection of subtle temporal sub-features of particle beams not easily detected otherwise [4, 5, 6]. We have demonstrated how the automatic feature detection in combination with dedicated methods for query-based visual exploration enables detailed feature-based analysis of plasma-based accelerator simulation data. In the future we plan to explore different avenues for parallelizing the feature detection algorithm and to apply our methods to automatically process large collections of accelerator simulations in order to compare different simulation designs.

ACKNOWLEDGEMENTS

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