Application of High-performance Visual Analysis Methods to Laser Wakefield Particle Acceleration Data

Oliver Rübel[1,2,3], Prabhat[1], Kesheng Wu[1], Hank Childs[4], Jeremy Meredith[5], Cameron G.R. Geddes[6], Estelle Cormier-Michel[6], Sean Ahern[5], Gunther H. Weber[1,2,3], Peter Messmer[7]. Hans Hagen[2], Bernd Hamann[3,2,1] and E. Wes Bethel[1,3]

1. Computational Research Division, Lawrence Berkeley National Laboratory (LBNL), One Cyclotron Road, Berkeley, CA 94720, USA.
2. International Research Training Group "Visualization of Large Unstructured Data Sets," University of Kaiserslautern, Germany.
3. Institute for Data Analysis and Visualization, University of California, Davis, One Shields Avenue, Davis, CA 95616, USA.
4. Lawrence Livermore National Laboratory, 7000 East Avenue, Livermore, CA 94550, USA.
5. Oak Ridge National Laboratory, P.O. Box 2008, Oak Ridge, TN 37831, USA.
6. LOASIS program of Lawrence Berkeley National Laboratory, One Cyclotron Road, Berkeley, CA 94720, USA.
7. Tech-X Corporation, 5621 Arapahoe Ave. Suite A, Boulder, CO 80303, USA.

Background

Laser WakeField Particle Accelerators (LWFAs) promise to be a compact source of high-energy electron beams and radiation. Similar to the wake of a boat, the radiation pressure of a laser pulse fired into a plasma displaces the electrons in the plasma, and with the space-charge restoring force of the ions, this displacement drives a wave (wake) in the plasma. Electrons can be trapped and accelerated by the longitudinal field of the wake, forming electron bunches of high energy. LWFAs have been shown to generate electric fields thousands of times stronger than those in conventional particle accelerators, accelerating particles to high energies of 1GeV within *3cm* compared to *~50m* in traditional electromagnetic accelerators.

Simulations are performed over 2D and 3D domains using the VORPAL code. Due to the large amount of particles required to achieve accurate simulation results, it is not possible to simulate the entire plasma at once. Simulations are therefore restricted to a window that covers only a subset of the plasma in *x* direction in the vicinity of the beam. The simulation code moves the window along the local *x* axis over the course of the simulation. Each simulation produces a set of files for the particle and field data (at typically 40-100 timesteps) with the following main characteristics:

- Particle data: scattered data with: x,y,z (particle location), px, py, pz (particle momentum), id (particle identifier)
  - No. of particles per timestep: ~ $0.4*10^6$ – $30*10^6$ (in 2D) and ~$80*10^6$ – 120 $*10^6$ (in 3D)
  - Total size: ~1.5GB – >30GB (in 2D) and ~100GB – >1TB (in 3D)
- Field data: electric field, magnetic field, and RhoJ (defined on a regular grid)
  - Resolution: Typically ~0.02-0.03µm longitudinally, and ~ 0.1-0.2µm transversely
  - Total size: ~3.5GB - >70GB (in 2D) and ~200GB - >2TB (in 3D)

System Design

To accelerate data mining operations, we use FastBit, a state-of-the-art data management technology for indexing and searching. We use FastBit to perform data subsetting/selection and to compute conditional histograms. We implemented these operations using FastBit directly in the file-reader stage of the processing pipeline in VisIt, a production-quality, parallel capable visual analysis system (see Figure a). The conditional histograms serve as basis for the visual presentation of data vis-a-vis histogram-based parallel coordinates.

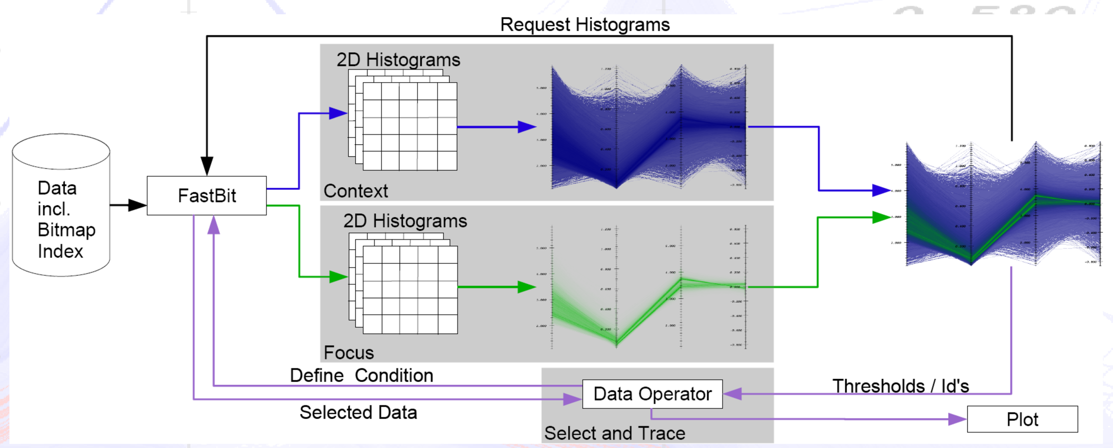


Figure a: System design

In contrast to earlier work, we employ a histogram-based parallel coordinates rendering for both context and focus views of large, complex data. Via FastBit, we can recompute conditional histograms fast, thus enabling support for fast data selection and smooth drill-down into finer level of detail in very large datasets. As a further improvement, we also support adaptively binned (equal-weight) histograms. As illustrated in Figure b, adaptively binned histograms are especially useful for display of low-level-of-detail views where the number of bins per variable is much smaller than the number of pixels per parallel axis.

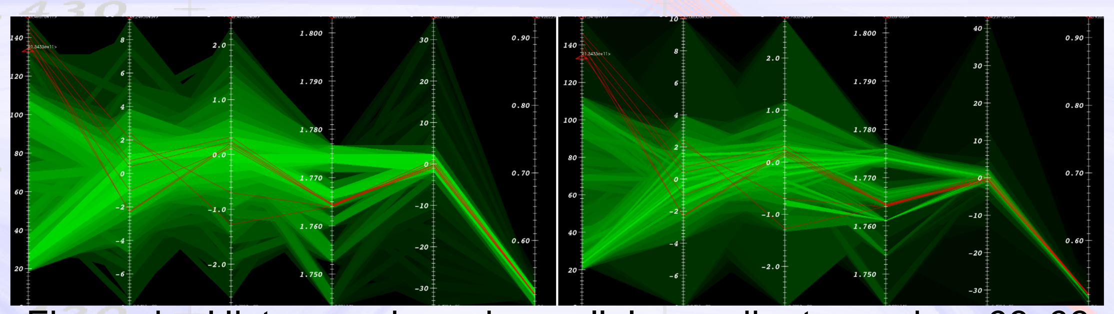


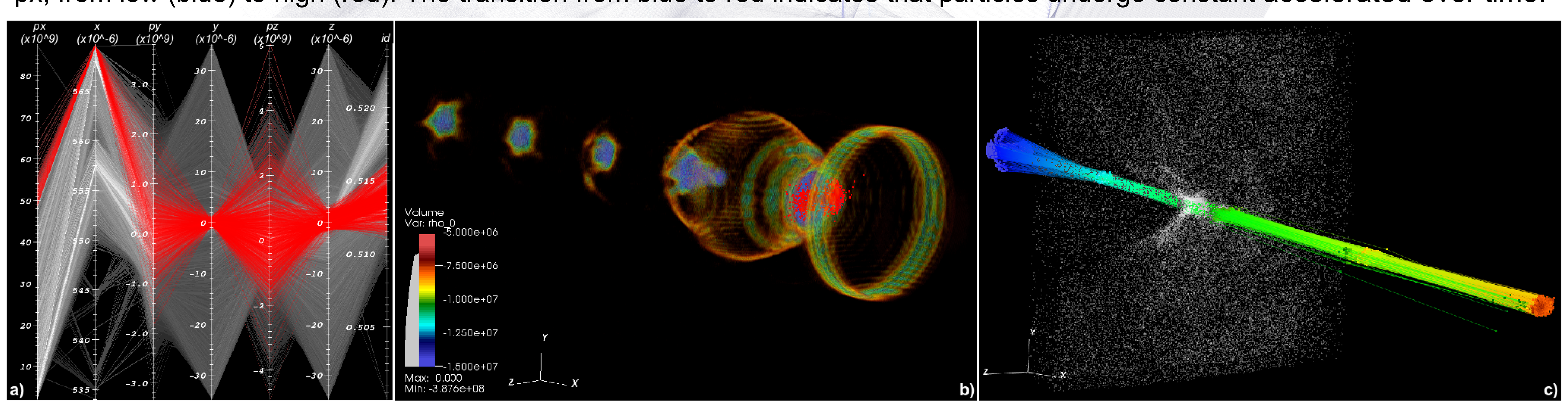
Figure b: Histogram-based parallel coordinates using *32x32* uniform binning (left) and adaptive binning (right)

Our system uses two main types of data selection that are implemented by FastBit: i) multi-variate thresholding, and ii) identifier-based selection. Multivariate thresholding is used for defining "interesting" data subsets. ID-based selection is the basis for tracing of particles over time. We parallelize computations over the temporal domain to accelerate, e.g., particle tracking.

Beam Analysis

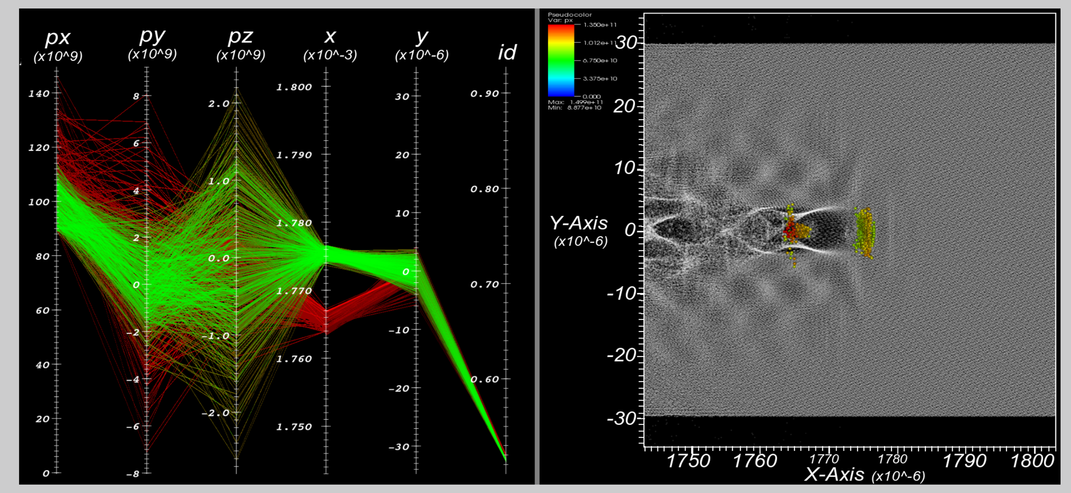
In order to gain a deeper understanding of the acceleration process, we need to address complex questions such as: i) Which particles become accelerated? ii) How are particles accelerated? and iii) How is the beam of highly accelerated particles formed and how does it evolve? To identify those particles that were accelerated, we first perform a selection of particles at a given timestep when the beam has already formed. By tracing the selected particles over time (using ID-queries) we can effectively analyze the temporal behavior of the beam. By refining selections based on information from different timesteps, we are then able to identify characteristic substructures of a beam. An example analysis of a 3D LWFA dataset is shown below.

Figure a) shows a parallel coordinates plot of timestep *t=12* of the 3D dataset with particles with x-direction momentum $px>2*10^9$ as context (gray) and particles satisfying the condition $(px>4.856*10^{10})\&\&(x>5.649*10^{-4})$ as focus (red). Figure b) shows a volume rendering of the plasma density and the focus particles (red). Clearly, the selected particles form a compact beam in the first wake period following the laser pulse. Figure c) shows the traces of the selected beam at *t=9* to *t=14* colored according to px, from low (blue) to high (red). The transition from blue to red indicates that particles undergo constant accelerated over time.



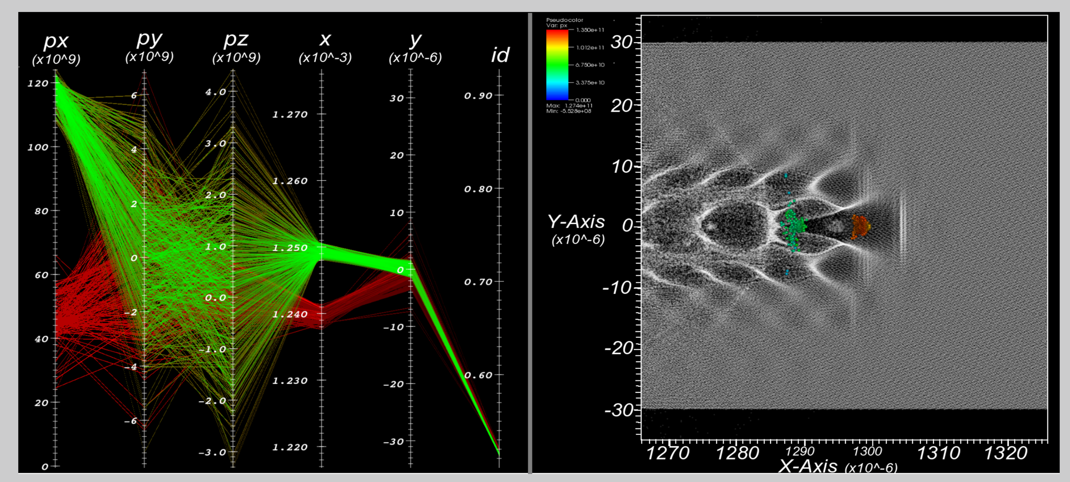
Analysis Example

Beam Selection



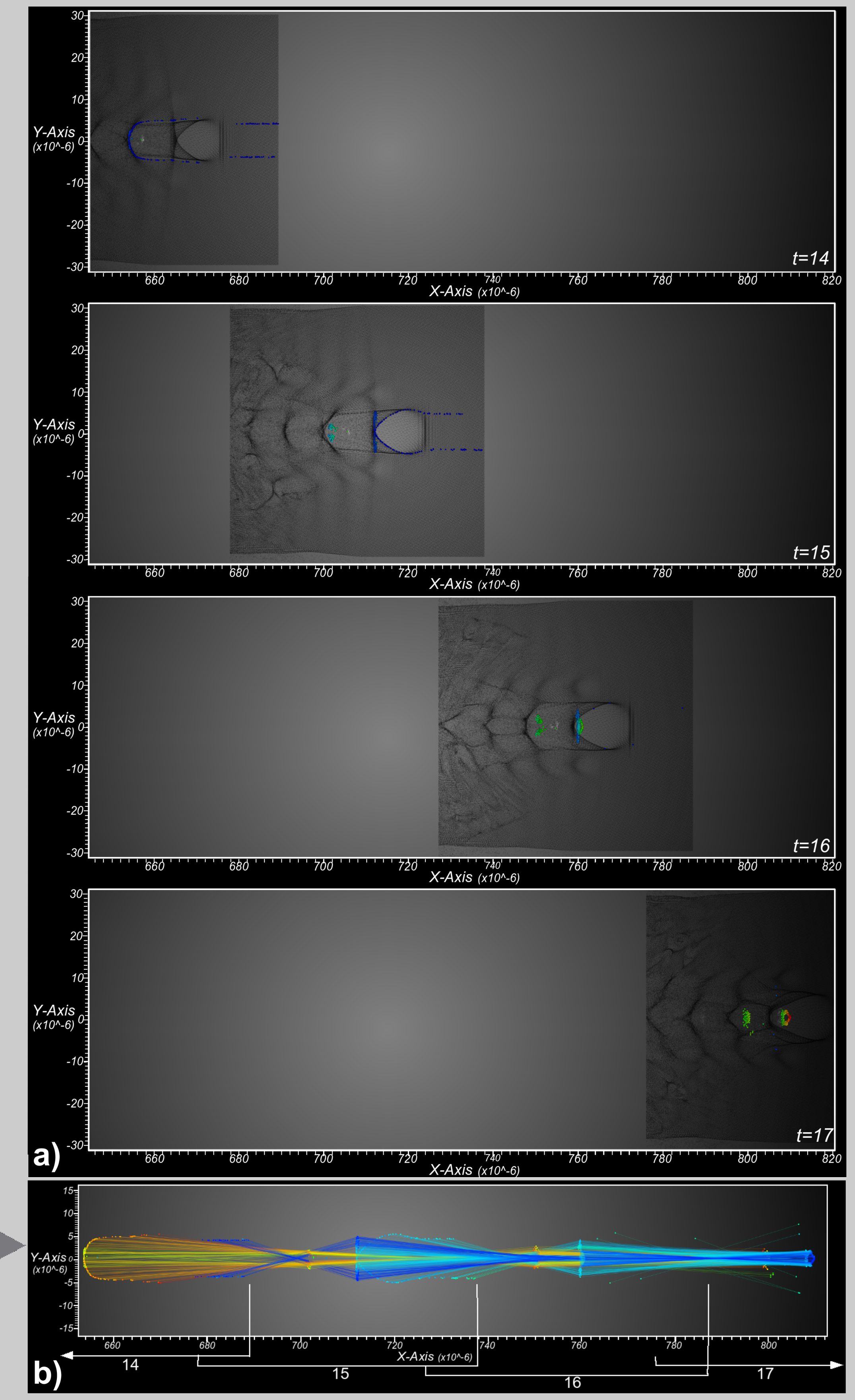
Using parallel coordinates we identify the beam, i.e., find those particles that became accelerated, by applying a condition of $px>8.872*10^{10}$ at the last timestep of the simulation (*t=37*) (left). The selected particles constitute two separate clusters (beams) in *x*-direction. Using a pseudocolor plot of the data, we can then see the physical structure of the beam (right).

Beam Assessment



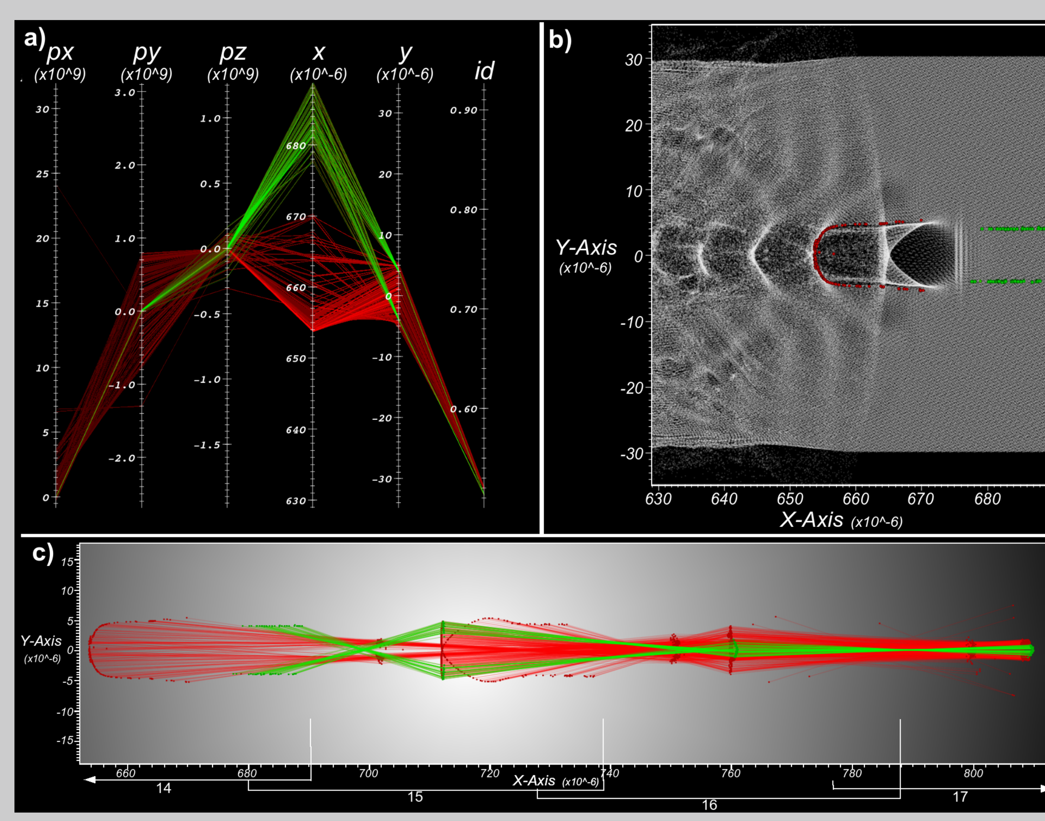
By tracing particles back in time, we observe that the first bunch following the laser pulse (green in parallel coordinates; rightmost in the pseudocolor plot) has lower momentum spread at its peak energy (at *t=27*) than the second bunch. In practice, the first beam following the laser pulse is therefore typically the one of most interest to the accelerator scientists. The fact that the second beam shows higher or equal acceleration at the last timestep of the simulation is due to the fact that the first beam out-runs the wave later in time and therefore switches into a phase of deceleration while the second beam is still in an acceleration phase.

Beam Formation



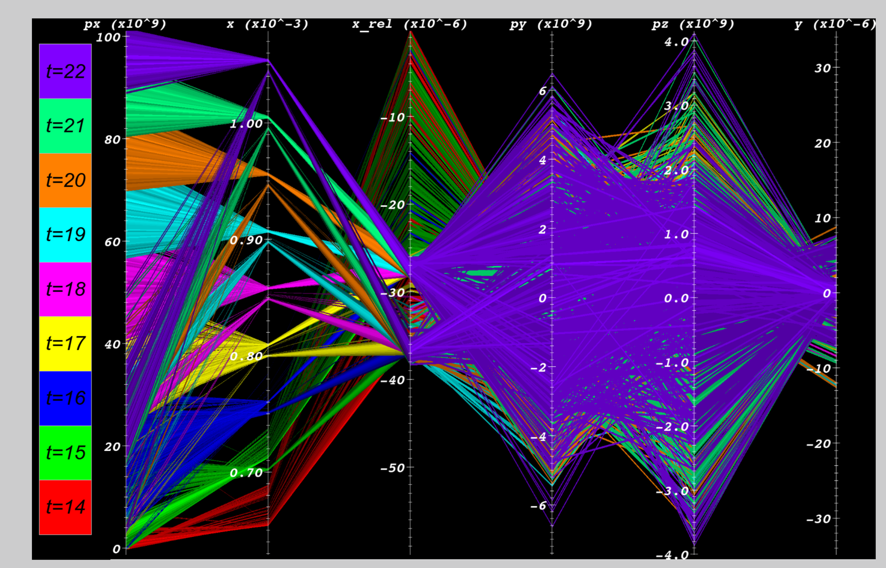
We can analyze formation of the beam by tracing the selected particles back to the time when particles entered the simulation and were then injected into the beam. Figure a) shows all particles (gray) and the selected subset (colored according to *px*) at timesteps *t=14* to *t=17*. Figure b) shows the according traces with color indicating particle ID. Different sets of injection can be seen, e.g., two sets of particles entering at *t=14* and an additional set entering at *t=15*.

Beam Refinement



Based on the information at *t=14,* we refine our initial selection of the beam by applying an additional threshold in *x* to select those particles that are injected into the first wake period behind the laser pulse (a,b). By comparing the temporal traces of the selected particle subset (green) with the traces of the whole beam (red), we can identify important characteristics of the beam.

Beam Evolution



Using temporal parallel coordinates, we can analyze the general evolution of the beam in multiple dimensions. Along the *x*-axis, two separate beams can be seen at all timesteps. At early timesteps, both beams show similar acceleration in *px* while the first beam shows significantly higher acceleration with a relatively low energy spread later on at timesteps *t=18* to *t=22*.