TECHNICAL PROPOSAL

Full-Scale Numerical Experiment to Test a Future Plasma-Based Accelerator

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Abstract

This is a proposal for a 36-month program to develop a testbed computer simulation laboratory with the capacity to determine the viability of plasma-based accelerators as 21st century accelerator technology. If successful, the prototypes developed in this project will lead to a full-scale numerical test of a future plasma-based accelerator on a teraflop machine in the mid-1990's. Such a test would provide critical direction to an experimental program to realize accelerators that would allow the field of high-energy physics to progress beyond the SSC without the associated cost of an $8 billion machine.

The essential elements of the program are the following:

1. Algorithm Development. The goal will be to develop a prototype PIC algorithm including collective plasma behavior, gas ionization, and a moving mesh. Special effort will be directed to reducing numerical dispersion, enabling accurate propagation of laser pulses over 10^6 laser wavelengths.
2. Parallel Processing Implementation. The speed of the particle push will be optimized by employing domain decomposition of particles and fields. Improvements in pusher speeds of .97 times the number of processors has already been achieved on 100 processor computers.
3. Software Development and Software Engineering. Software to permit interactive data management, data modification, and code steering will be designed.
4. Diagnostics for Tera-scale Output. Diagnostics will include 3-D visualization and require processing of Gbytes of data per data snapshot.

PROPOSED PROGRAM

I. Introduction

The goal of high energy physics is to theoretically describe and experimentally observe the most fundamental particles of matter. This partnership between theory and experiment has existed since the discovery of the electron in 1896. Experimental observations have kept up with theoretical predictions because of the exponential increase in the output energy of high energy accelerators. These increases in energy have been achieved by technological advances and increasingly larger accelerators. However, as is evident from the $8 billion price tag and 60 km size of the Superconducting Super Collider, current accelerator technology has reached the limit of feasibility. Therefore, future progress in high energy physics will require new techniques of accelerating particles to ultra high energies over short distances.

Plasmas can provide accelerating gradients that are orders of magnitude larger than conventional technologies[1]. Therefore, plasma-based accelerator concepts are being investigated world-wide because of the potential to miniaturize colliders from kilometer scales to meter scales.[2,3,4,5] This extensive[6,7,8,9,10] effort involves both experiments[11,12,13] and computer simulations. Present state-of-the-art experiments and simulations have demonstrated extremely high gradients over distances of only millimeters. Extending the experiments to meter long devices will require a major initiative to develop the appropriate laser, particle beam, and plasma source technology.

The advent of parallel supercomputing makes it possible to dramatically improve the computational speed of plasma simulation codes[14], so that a full-scale numerical experiment of a future plasma-based accelerator is possible by the mid 1990's. Such a numerical experiment could demonstrate the viability of plasma-based accelerators as 21st century accelerator technology, before and at considerably less cost than conventional experiments; and if successful the numerical experiment would provide direction for a major initiative to develop the laser and plasma technology needed to realize these compact accelerators. Moreover, compact light sources based on compact plasma-based accelerators could have a major impact on applications[15,16] ranging from x-ray lithography of micro-chips to biomedical imaging.

In this proposal we describe a three year plan to develop an elaborate particle-in-cell computer simulations laboratory in which a full-scale numerical experiment of a plasma-based accelerator can be carried out. This plan requires the fusion of plasma physicists, computational physicists, and computer scientists in a grand challenge environment. Many of the required advances in each discipline already exist, but a mechanism is needed to bring these advances together and to focus them on a project of grand challenge proportion. The computer simulations lab outlined in this proposal would provide this mechanism. The simulation lab will consist of a computer program made of physics-based algorithms written to run efficiently on parallel supercomputers. The sophisticated algorithms will be managed and maintained by using advanced software engineering techniques. Programs will be run on a remote supercomputer while being controlled from local workstations. Diagnostic routines will run at both the remote supercomputer and local workstation. The lab will also contain advanced visualization and data reduction programs designed to quickly determine the physical state of the running program so that program steering and tuning can be done.

This proposal is outlined as follows: In section II we describe the science issues to be addressed by this project. The status of and outstanding questions on plasma-based accelerators is given. In section III we describe the computational issues to be addressed by this project. The present capacity of existing plasma accelerator simulation codes and the grand challenge requirements for modeling a future plasma accelerator are presented. In section IV the Project Plan is delineated. The computer code software development required to meet those challenges is described.

II. Science Issues

Theoretical work on plasma accelerators has progressed to the point that the critical physics issues have been identified which will ultimately determine the viability of these accelerator concepts. These issues are highly nonlinear and many of them cannot be studied in present experiments because of limitations in existing technology. However, computer experiments on parallel supercomputers provide a means of studying these issues now. The results will help to guide the direction of future technology development and will enable the best new ideas to be identified and tested without the major expense of laboratory experiments. We next discuss the physics issues which will guide our development of numerical algorithms and computer software.

In order for particles of charge q to attain ultra-high energies, the work done on the particle $W = q\int d\vec{l} \cdot \vec{E}$ must be large. This requires that the accelerating electric field, $\vec{E}$, point along the direction the particle is moving and that the field act on the particle for large distances. In conventional accelerators this is done by generating time oscillating electric fields in cavity sections and phasing the fields in the cavities so that the particle always feels an accelerating field. The phase velocity of the accelerating electric field must be nearly the speed of light, c, because otherwise, particles moving at c will quickly outrun the wave. The accelerating electric field in current accelerators is limited to the breakdown field of the accelerating structure. Plasma-based accelerators do not suffer from this limitation because they are already ionized. Furthermore, plasmas support longitudinal space charge waves with phase velocities near the speed of light[17]. The maximum accelerating gradient of a plasma space charge wave is given by the formula[3] $eE \cong \sqrt{n_o}$ eV/cm where n_o is the plasma density in cm^{-3}. Plasmas of density between 10^{16} cm^{-3} and 10^{18} cm^{-3} can therefore support coherent electric fields between 10 GeV/m and 100 GeV/m. Hence, it may be possible to accelerate electrons to 1 TeV energies in a distance of only 10 meters using a plasma wave.

The energy gain from a plasma accelerator depends on three properties of the plasma wave. These are: (a) the electric field amplitude; (b) the phase velocity; and (c) the spatial extent of the plasma wave. Property a) provides the maximum accelerating gradient while b) and c) determine the interaction distance. These properties depend on the manner in which the wave is generated.

There are currently two methods being seriously considered to excite the plasma wave. They are the Laser Wakefield Accelerator[2] (LWFA) and the Plasma Wakefield Accelerator[4] (PWFA) methods, originally proposed at UCLA in 1979 and 1984, respectively. We next briefly describe these two methods.

A) Laser Wakefield Accelerator

In the simplest LWFA concept[2,18], the plasma wave is generated from the ponderomotive force (light pressure) of an intense short pulse laser. The ponderomotive force of the leading edge of the laser pulse pushes plasma electrons forward. The electrons acquire a maximum forward velocity of $c/4\ I\lambda^2 \times 10^{-18}$, where I is the laser intensity in W/m^2 and λ is the laser wavelength in μm's. The space charge of the ion pulls the electrons back after half a plasma period. If the pulse length is half a plasma period, then the ponderomotive force of the trailing edge of the pulse reinforces the electrons restoring motion. After the pulse passes by, the electrons continue to oscillate, creating a plasma wake behind the pulse of amplitude $eE/mc\omega_p = 1/2\ I\lambda^2 \times 10^{-18}$. The phase velocity of the wake is tied to the velocity of the laser pulse which is the group velocity of light in plasma. This is analogous to the wake left behind a motor boat. The length over which the plasma wave is excited is limited by either pump depletion or diffraction.

There has been extensive theoretical work performed during the past decade on the LWFA. The amplitude of the wake is very well understood[19]. However, the critical issues left for the LWFA are accurately calculating the wake's phase velocity and developing definitive techniques to optically guide the laser pulse over hundreds of diffraction lengths. Therefore, the numerical algorithms must accurately model the phase and group velocity of light propagation in plasma and vacuum over unprecedented distances.

Recently a new nonlinear LWFA concept has been proposed[20] in which the plasma oscillations are generated by radially expelling the electrons to make an evacuated channel. This can be done by using intense laser pulses focused to spots c/ω_p in radius. The accelerating and focusing fields of this wake have ideal properties for accelerating a collection of electrons. We show 3-D surface plots of the laser field E_z and the accelerating field E_x in Fig. 1. The peak accelerating field is still equal to those found in 1-D calculations.

Since the accelerated particles travel at speeds nearly equal to c, acceleration over large distances requires the wake's phase velocity to be as close to c as possible to avoid dephasing. The wake's phase velocity is approximately the group velocity of light in plasma. The linear group velocity $d\omega/dk = v_g = c\,(1 - \omega_p^2/\omega^2)^{1/2}$ is obtained by differentiating the dispersion relation $\omega^2 = \omega_p^2 + c^2k^2$. For a given laser frequency, v_g/c is closest to unity for small ω_p. On the other hand, the accelerating gradient is proportional to ω_p. For nonlinear electromagnetic waves, this conflict may be less restrictive because the relationship between v_g and the dispersion relation is no longer valid. We have previously shown[21] that for nonlinear waves the wakes phase velocity, v_w, is larger than $c\,(1 - \omega_p^2/\omega^2)^{1/2}$. We have recently[22] begun theoretical and numerical work to accurately determine v_w in terms of ω/ω_p and $I\lambda^2$. When this is understood, techniques to control the phase velocity can be developed. This issue cannot be investigated in real experiments because lasers with pulse lengths less than ω_p^{-1} and accurate diagnostic techniques do not yet exist.

In order to generate plasma waves over meter long distances, laser pulses must propagate for millions of wavelengths. These distances are generally thousands of Rayleigh lengths. Therefore, the realization of a LWFA requires techniques to optically guide laser pulses. Relativistic self-focusing[23] is the simplest method to guide pulses. This effect occurs because relativistic mass corrections increase the index of reflection causing a reduction in the phase velocity of light in plasma. This causes wave fronts to curve such that the laser energy is focused towards the axis. Unfortunately, this effect is significantly reduced for laser pulses less than c/ω_p in length.[24] Optical guiding in plasma channels may overcome this problem.[25] The plasma channel could be completely hollow. In this case the physics of wake excitation is altered. The wake will be supported by the fringe fields of plasma oscillations at the edge of the channel. The creation of plasma channels will require that the short pulse laser self-produce a hollow plasma via tunneling ionization. Therefore, the computer testbed will require an ionization package. Plasma production from tunneling ionization[26,27] is a rapidly emerging field and unprecedentedly uniform plasmas of millimeter size have already been produced. However, plasma channels and meter long plasmas are beyond the scope of real experiments. Computer simulations will provide the crucial insight necessary to develop a plasma channel design to optically guide for thousands of Rayleigh lengths.

B) Plasma Wakefield Accelerator

The Plasma Wakefield Accelerator[4,28] is similar to the Laser Wakefield Accelerator except that the driving laser pulse is replaced with a short particle beam pulse (see Fig. 2a). The plasma wave is generated when the space charge force of the particle beam displaces plasma electrons. If

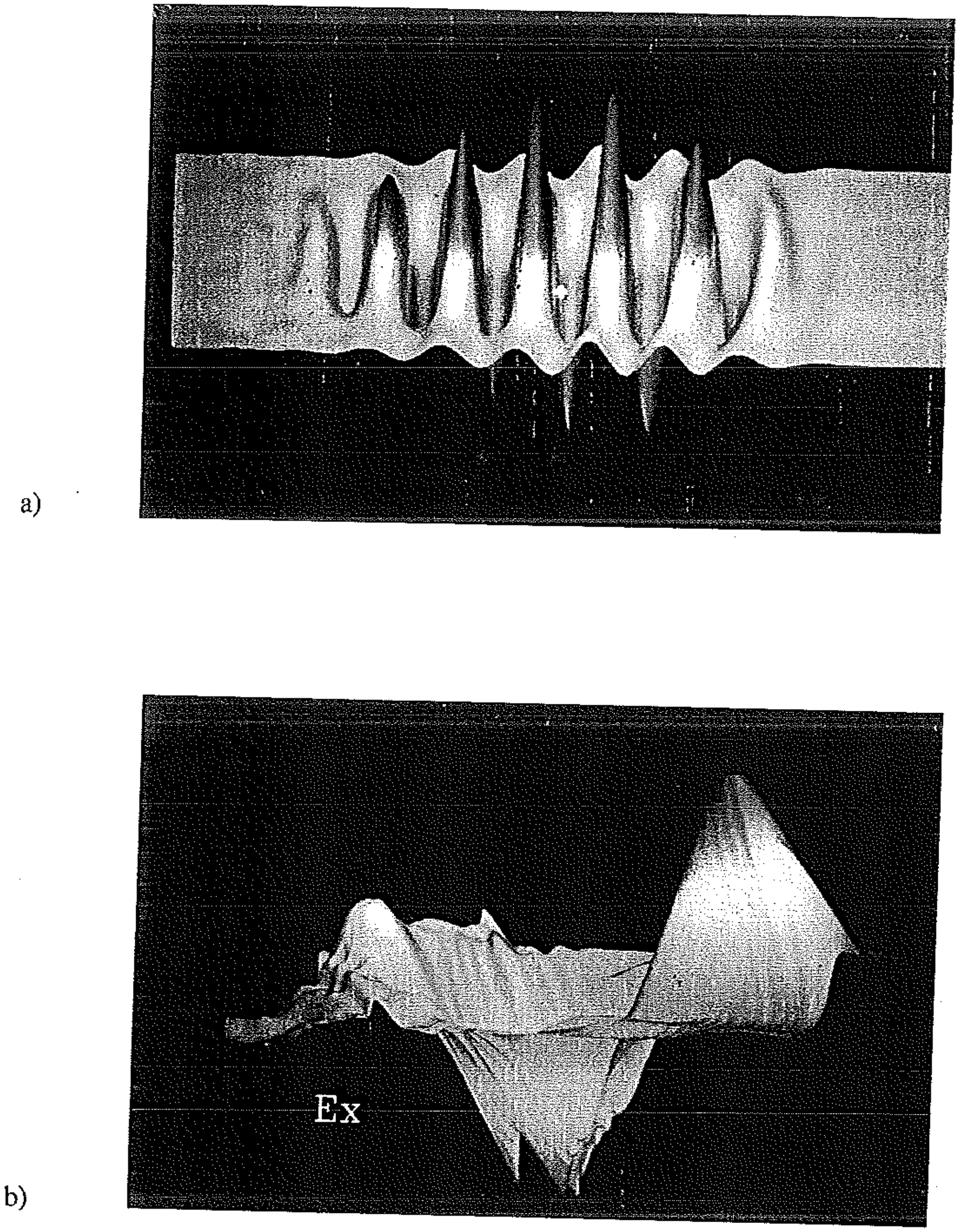

Figure 1. Three-dimensional surface plots of

a) the short laser pulse driver, and
b) the excited accelerating electron field from a two-dimensional PIC simulation

the pulse is sharply cutoff or simply short compared to the plasma skin depth (c/ω_p), the displaced electrons quickly rush back toward their equilibrium positions generating an oscillating wake field. The amplitude of the wake is on the order of $(n_b/n_o)\sqrt{n_o[\mathrm{cm}^{-3}]}$ V/cm, where n_b and n_o are the beam and plasma densities, respectively. The phase velocity of the wake matches the velocity of the driving beam, but can be tuned by ramping the plasma density[29] (analogous to motor boat wakes catching up to the motorboat as it enters shallower water).

The PWFA can be thought of as a transformer. It transforms low voltage, high current drive beams into high voltage, lower average current accelerated beams (though the peak current can actually be higher). The transformer ratio (R) gives the ratio of the energy gain of the accelerated beam to the energy of the drive beam per particle[28]. The transformer ratio is determined by the wake amplitude in and behind the drive beam and the phase slippage of the accelerated particles. Applying these concepts gives an analytic scaling law for the energy gain in the PWFA[29], $\Delta\gamma = R\gamma_b\pi\varepsilon\,\gamma_b/(R + \pi\varepsilon\gamma_b)$, where $\varepsilon \simeq n_b/n_o$ is the normalized wake amplitude, γ_b is the driving beam energy and $R \simeq \omega_p L_b/c$ where L_b is the driving bunch length.

Although the particle acceleration in the PWFA is similar to that in the LWFA, many of the physics issues associated with particle beam propagation differ from those of laser propagation. For example, the key problem of diffraction of the laser is overcome in the particle-driven scheme. In fact, the electron beam is strongly self-focused by a mechanism[29] that has become known as the plasma lens[30]. However, the self-pinched radial and longitudinal beam profiles critically affect the wake amplitude and phase velocity.

Previous simulations in 1-D have demonstrated the viability of PWFA acceleration up to 1 GeV[31]. However, these do not include instabilities and distortions that can be important in the transverse direction. A major advance that can be made with the testbed development proposed here is the extension of the GeV PWFA model to a fully 3-D test. Perhaps the most critical issue to test for a PWFA at high energy is the electron hose instability. Below we briefly describe this instability and show why it cannot be modeled with existing 2-D codes.

A number of longitudinal and transverse beam-plasma instabilities have been studied for the PWFA. These include the two-stream and Weibel (filamentation) instabilities[31]. From the previous computational and analytic work we have been able to identify these instabilities and ways to control them, and an operating regime that is stable with respect to these has been found. This work has generally been in the linear regime in which the beam density is small compared to the plasma density. For reasons of improved acceleration gradient and beam quality, we would like to operate in the nonlinear regime. In the nonlinear regime, the electron beam is so dense it expels nearly every plasma electron from a channel along the beam line (see Fig. 2b). In this regime, the electron hose instability may appear.

The electron hose instability[32] is caused when a part of the electron beam becomes slightly off-axis with respect to the channel (i.e., the head of the beam). The off-axis beam electrons induce polarization of the plasma electrons just outside the channel. The polarization charges produce a deflecting electric field that kicks later particles in the beam causing them to go off axis. In this way the amplitude of the polarization oscillations and transverse beam oscillations feed back and grow. This instability inherently requires a 3-D code to model. The reason is that in 2-D cylindrical geometry, the coordinates are r and z, so that axial asymmetry is precluded. In 2-D slab geometry (x, y), the beam can oscillate asymmetrically about its axis, but the deflecting force due to induced polarization is prevented for the same reason that the electric field between infinite capacitor plates is independent of the plate separation. Thus, 3-D computer simulations are needed to provide the crucial test of the viability of the PWFA.

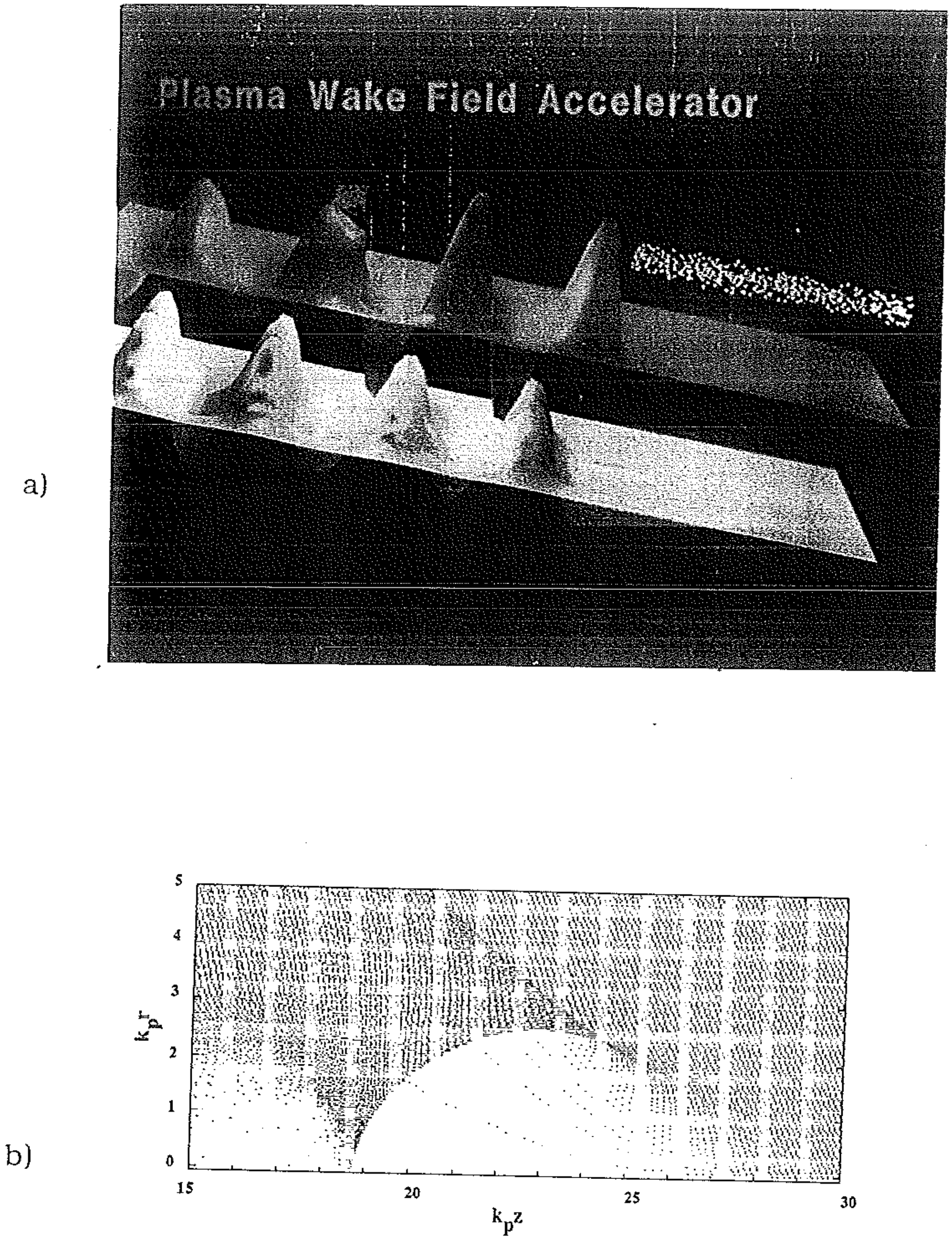

Figure 2. a) the accelerating and focusing fields from the PWFA, and b) electron phase space showing blow-out for the nonlinear PWFA from a simulation using a cyclic mesh

Grand Challenge Science Aspects

The new physics that can be accomplished with this project will make key advances toward the grand challenge goal of realizing a compact high-energy super collider. The grand challenge physics issues that can be addressed with future teraflop supercomputers are:

1.) Modeling laser pulse propagation over millions of wavelengths in 3-D. The long term evolution of the laser pulse in the LWFA, can be characterized, including pulse distortion due to pump depletion, nonlinear dispersion, diffraction and optical guiding in evacuated channels.

2.) Modeling inherently 3-dimensional behavior of the driving beam in the PWFA over meter distances (10^4 plasma wavelengths). This includes the electron hose instability and self-pinched beam propagation.

3.) Characterization of the overall beam quality and efficiency of a plasma accelerator over full-scale lengths. This will require modeling the long-term evolution of the wake's phase velocity, including determination of phase slippage for accelerated electrons over meter distances.

III. Computational Issues

Computer experiments have already had a major role in plasma-based accelerator research. The seminal letter in this field[2] used simulations to test the concept. The computer codes used are explicit particle-in-cell codes[33]. They are relatives of the original codes developed 20 to 30 years ago to model laser-plasma interactions[34]. Since plasma accelerator physics requires resolving both high frequency electromagnetic waves and low frequency plasma waves, the full set of Maxwell's equations need to be solved with an explicit algorithm. Furthermore, because the electrons (both plasma and accelerated) can move with relativistic speeds, the particle push must be relativistic. Thus, these algorithms use the fewest approximations of any plasma simulation codes.

Simulations using 10^5 mesh points and 10^6 electrons and ions have already been undertaken[35,36]. These state-of-the-art simulations have been run for 2×10^4 time steps and at speeds of 5×10^{-6} sec/particle/timestep on the fastest Crays for a run time of 10^2 hours. As successful as these simulations have been the largest computer runs have managed to simulate plasmas of length equal to only 10^2 laser wavelengths (1mm for a CO_2 laser) in two-dimensions. Clearly, these fall short of the simulations necessary to answer the critical physics issues for a meter long plasma accelerator.

The computer time and memory requirements on a sequential computer of a PIC code for simulating meter distances can be expressed by the CPU time formula

$$(N_x N_y N_z) \times P \times T \times R$$

where N_i is the number of cells in the i^{th} direction, P is the number of particles per cells, T is the duration of the simulation in time steps, and R is the speed of the particle push in CPU seconds per particle per time step. The first five quantities are determined by the physics, while R is determined by the processor speed and the product $N_x N_y N_z \times P$ is limited by computer memory.

In the LWFA the simulation size in the laser propagation direction (x) must be on the order of 10^6 laser wavelengths. The *minimum* number of cells per wavelength is 10 so N_x needs to be at least 10^7. The simulation dimensions in the directions orthogonal to the laser propagation direction must be several laser widths (unless absorbing boundary conditions exist in all directions). The minimum width for the laser is a collisionless skin depth c/ω_p. If we assume that $\lambda_o = 1\mu m$, $n_e = 10^{18}\ cm^{-3}$ and a simulation width in the orthogonal direction of 5 laser pulses, then N_y and N_z must be on the order of 10^2. The number of particles per cell must be at least 5. For an explicit field solver, the time step must be less than the time it takes light to move one cell. This requires T to be at least N_x. Therefore, in terms of R, the amount of CPU time necessary for a full scale

LWFA experiment on a fixed simulation grid is 10^{19} R. Existing supercomputer speed corresponds to an R of 5 x 10^{-6}/particle/time step. Such a simulation would take 5 x 10^{13} sec or 1.4 x 10^{10} hours, and require 40 Terabytes of computer memory.

Clearly, even with future teraflop speed, simulating meter long laser-plasma interactions with a PIC code on a fixed grid is not possible. Therefore, we are proposing a novel algorithm that performs computations both on a cyclic grid and in a Lorentz transformed frame. In this scheme the simulation box need only contain the laser pulse and several plasma oscillations. No physical phenomena is lost because the accelerated electrons and the laser pulse move together at the speed of light, and because signals left behind in the plasma can never catch up to the laser. In the Lorentz transformed frame, there is an additional reduction in computing time. This reduction has a physical interpretation. It is for the same reason that a short-lived muon can reach the earth from the upper atmosphere, a time of 30 μs, even though the muon lifetime is only 2 μs. The explanation is that in the reference frame of the muon, time dilation and length contraction occur in accordance with special relativity theory. The Lorentz transformed algorithm takes advantage of this effect to reduce the computing time by the factor $\gamma = (1 - v^2/c^2)^{-1/2}$.

In a cyclic mesh, the field solve and the particle push are done in the lab frame. When the mesh speed (usually chosen to be c) times some appropriate number of time steps (usually two) exceeds a cell size, then the grid information and the particle positions are backspaced one grid index. Particles at the back cell are placed in the front cell. This algorithm reduces the number of cells, and hence the particle number, by the reduction in the physical size of the box. This reduction is from 10^6 to 10^2 laser wavelengths. The number of time steps does not change because the laser must still move $10^6\ \lambda_o$. The CPU time of the run is reduced to 10^{15} R and the memory requirement is reduced to 4 Gigabytes. We have already successfully implemented this algorithm on a single processor[31,37] at UCLA.

In a Lorentz transformed frame the field solve and particle push are done in a frame with plasma (both electrons and ions) streaming at the stationary laser pulse. The laser's frequency and electric field are Lorentz transformed downward. The frequency becomes ω_p (a Lorentz invariant) and the electric field is E_o/γ. The pulse length and plasma wavelength are Lorentz expanded (lengths contract when going from a rest frame) so that the physical system must be γ times longer in units of c/ω_p. The highest frequency is now ω_p, so that the necessary member of cells is unchanged. However, the necessary number of time steps is reduced because in the Lorentz transformed frame the plasma is contracted by the factor γ_o. The CPU time requirements could therefore be reduced to 10^{15} R/γ_o. For $n_e = 10^{18}$ cm^{-3} and a 1 μm laser, $\gamma_o = 30$ and the CPU time becomes 3 x 10^{13} R. The memory requirements are unchanged from that of the cyclic mesh.

For the PWFA, the Lorentz frame code offers the same factor γ enhancement in computing speed over laboratory frame codes. Here γ is the Lorentz factor of the driving e^- beam (order 10^3). Moreover, the PWFA codes run generally an order of magnitude faster than the LWFA codes because they need only resolve the plasma wave scale length rather than the smaller laser scale lengths in the longitudinal direction.

Grand Challenge Computational Aspects

By restricting the CPU time to 10^3 hours or less, the Grand Challenge computational requirements are:

1) To implement a prototype particle push and field solve using domain decomposition which will provide a three orders of magnitude (R = 5 x 10^{-9} s/particle/time step) improvement in computer speed on projected parallel processing computers of the mid 1990's.

2) To develop prototype three-dimensional algorithms on a cyclic mesh for the field solver, particle push and ionization; the field solver must propagate electromagnetic pulses with tolerable numerical dispersion.

3) To develop prototype three dimensional algorithms in a Lorentz transformed frame, including absorbing electromagnetic boundary conditions in all directions.

4) To develop a flexible distributed computing environment to connect a workstation with the remote supercomputer to steer the large calculation.

IV. Prototype Code Development Plan

A PIC simulation can be logically divided into two major sections: the particle "push" and the field solve. The largest percentage of CPU time is required for the particle pusher because there are typically an order of magnitude more particles than grids. The push has three major phases. In phase I, the forces on each particle in turn are computed by interpolating from a collection of grid points surrounding the particle. Relativistic equations of motion are solved using these forces to advance the position and velocity of the particle a small increment in time (the time step). In phase II, each particle is checked against the simulation boundaries and adjusted as necessary to handle boundary conditions on the particle motion such as periodicity, wall reflection, wall absorption, etc. In phase III, each particle's charge and current (due to its motion) is interpolated back on to the grid in preparation for solving for the new self-consistent electromagnetic fields. The field solve consists of taking the grid-based charge and current information, together with the fields from the previous time, and solving Maxwell's equations to obtain the new fields at the new time step.

The development of the prototype codes will be broken down into four tasks. Special care will be taken to establish a standard set of variable and subroutine names so that these codes can be easily transported to any parallel computing center. Furthermore, user-friendly front end interfaces successfully implemented at UCLA[38] will be installed to make the codes available to other users. Some of the tasks will be done concurrently.

TASK I:

To meet the grand challenge improvements in computer speed by incorporating parallel algorithms into a standard explicit PIC code.

The main routines to be written are 1) charge and current deposition; 2) particle injection and particle boundary conditions; 3) volumetric injection for ionization; 4) field solver; 5) electromagnetic and electrostatic boundary conditions; and 6) particle pusher. A flow diagram is shown in Fig. 3.

The most complicated parts involve the parallelization of the particle pusher and field solver, and maintaining load balance with ionization. This will be done using GCPIC.[14] This has led to parallel efficiencies of 97% on 100 processor machines. Efficiency is defined to be the ratio of the computer speed increase to the number of processors. The parallel efficiency is not necessarily a linear function of the number of processors for a given algorithm. Therefore, extending algorithms to 1000 processor machines is a challenging research topic.

Assuring data locality is an important issue in the efficient implementation of a plasma PIC code, even on single processor machines. In phase I of the push, the particle interacts with the field grid through a "gather" operation, in which an interpolation of field quantities is performed over some set of grid points in the neighborhood of the particle. The reverse operation, a "scatter", is performed during phase III (the charge and current deposition). Optimization by spatial particle binning and grid quantity prefetching will decrease cache misses on machines with cache or hierarchical memory structures. It is also the only way to vectorize phase III of the push. On parallel

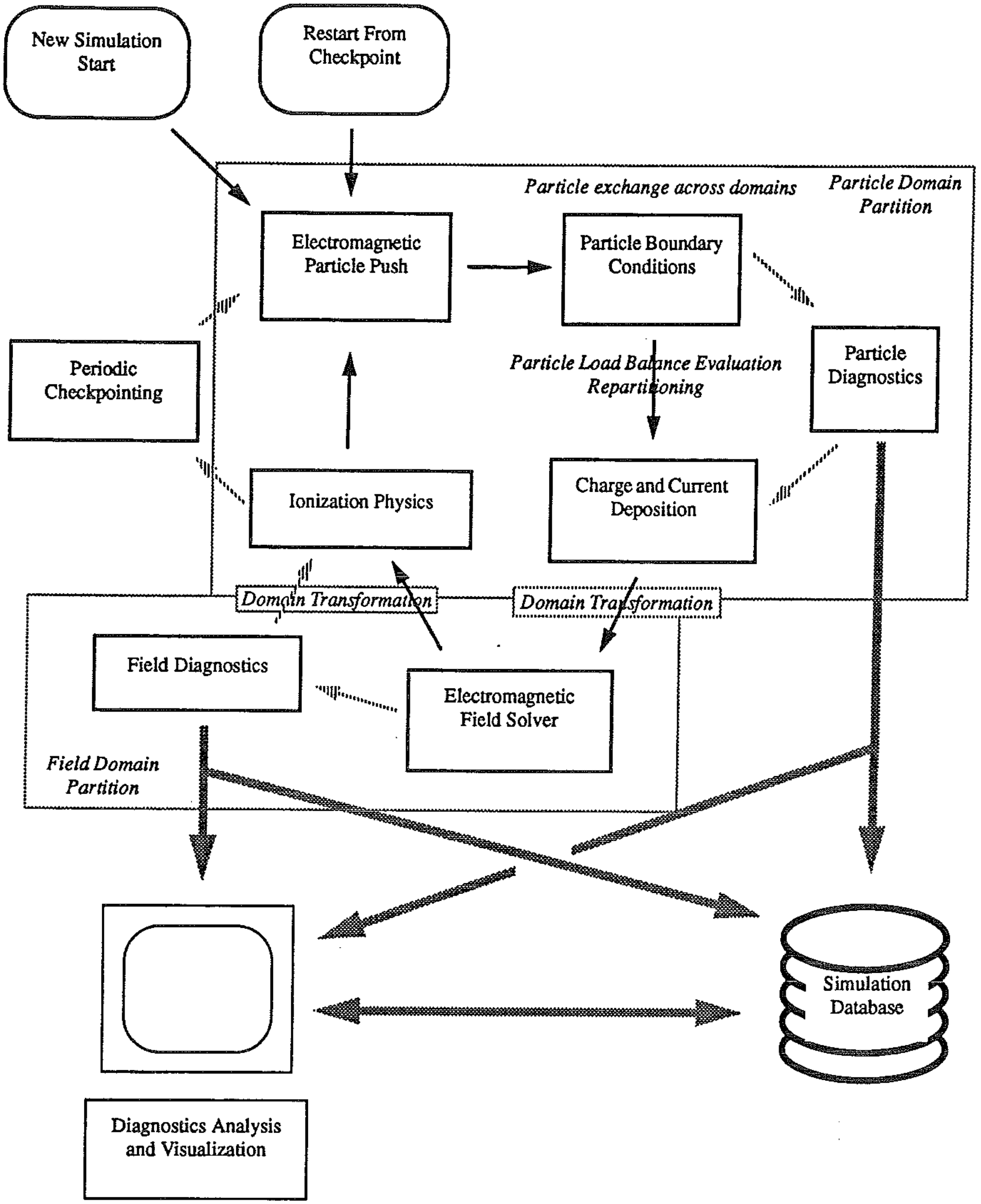

Figure 3. A functional diagram of the plasma simulation, including parallelization issues. Efficient execution of each code module requires a data decomposition appropriate to the module's data access pattern. Two basic data decompositions (domain partitions) are noted in the figure. The ionization package's placement in the particle domain partition is tentative, since its algorithm has not yet been developed.

processors with distributed memory, such as the Intel Hypercube or the NCUBE II, it is essential to avoid having to go "off processor" for gathering and scattering grid quantities. Even on machines with the illusion of shared memory, the cost of accessing data which is not local to a processor is high. For example, recent reports[39] of PIC code execution on a CM200, where no attempt was made to localize particles and fields, place the percentage of execution time spent on just the gather and scatter communication at 70% of the total loop time.

Previous work[14] with plasma PIC codes on MIMD (Multiple Instruction Multiple DATA) distributed memory machines has demonstrated that the particle push can be parallelized with high (> 90%) efficiency by partitioning the particles into spatial domains distributed among the processors. These spatial domains partially overlap their neighbors so that gather and scatter operations can be performed entirely within a processor's local memory. To attain load balance among processors, these domains should contain approximately equal numbers of particles. In plasma simulations which remain relatively uniform, the domains can be static partitions of equal size. As particle positions are updated at each simulation time step, some fraction of the particles will cross domain boundaries, and must be sent to their new domain via a communication step. This is naturally handled in phase II of the push. Computationally, this is an edge effect while phases I and III are domain volume effects. Also, for simulations which remain relatively uniform, the net flux of particles across a domain boundary is close to zero, maintaining processor load balance.

In the LWFA, there are at least two regions in which the plasma density is not expected to be uniform. At the leading edge of the laser pulse, there is no plasma at all, since the plasma itself is formed by photoionization as the laser pulse propagates through a neutral gas. At the peak of the pulse, the ponderomotive force of the laser pulse is expected to dig a density cavity which could potentially be a vacuum region. To maintain particle load balance among the processors, some means of adapting the particle domains to the plasma density profile will be required. Recent work on dynamic load balancing for plasma PIC simulations on MIMD distributed memory computers[40] has demonstrated that such adaptive partitioning has a high overhead cost if the number of particles/cell is small, and is ineffective compared to static partitions unless the variation in plasma density is large. Research into improved algorithms for dynamic load balancing will be an important part of this project.

Whereas the push execution time is proportional to the number of particles, the field solver execution time is proportional to the number of grid points. To load balance the field solver, grid points should be partitioned equally among processors. In uniform plasma simulations, the field partitions and the particle partitions coincide, so that in switching between the particle push and field solver, only edge information need be communicated between adjacent domains. When the plasma develops a nonuniform density profile, however, maintaining load balance for the push and the field solver requires substantial redistribution of grid information among processors. It is this redistribution which can make dynamic load balancing expensive unless there are a lot of particles. Unfortunately, the PIC algorithm has synchronization points within the main loop which are difficult to avoid. Unless an approximation is made in solving Maxwell's equations, the particle push must terminate in all processors before the field solve can begin. Likewise, the field solver must complete in all processors before the particle push may begin. Some work[41] has been done in which one of the synchronization points between the particle push and field solver is eliminated by using a finite difference field solver, so that load balancing can be done on the combined push-field computation. This work was done on a relatively simple beam-plasma simulation, however, so that it is not clear that it is applicable here. The use of a finite difference field solver is also not desirable due to the numerical dispersion problem.

The ionization algorithm consists of two parts. A rate equation is integrated at each cell to determine the amount of density to be added. A new particle is then added at the cell when this density exceeds that of a single simulation particle. This routine has already been used successfully on a single processor machine[42]. Integrating the rate equation can be done in either the field or particle partition. However, the ionization algorithm needs to be called under the particle partition because, otherwise, when the spatial locations represented by the two partition environments differ significantly, particles might be added to processors representing locations far removed from the particle's position. Ionization could also be modelled by dynamically increasing the charge on existing particles, rather than adding new ones. This would provide better statistical noise. In this case the ionization would be part of the pusher.

TASK II:

To meet the grand challenge requirements of simulating meter long plasmas by including a cyclic mesh and the Lorentz frame algorithms into the parallelization environment.

This will also require field solvers with tolerable numerical dispersion and frame velocity steering.

Maintaining load balance with a cyclish mesh/Lorentz frame can be handled by either keeping particle domains with regular particle flux across domains or by redefining the particle domain boundaries to minimize domain crossing. Either option should work because the particles cycle/flow with constant flux. We will explore both possibilities to determine which internal data structure scheme is more efficient.

The electromagnetic field solver can employ either finite difference or spectral (FFT) methods. In general, finite difference methods are faster, but suffer from numerical dispersion in the large wavenumber end of the spectrum. These errors represent a potential problem in the simulation of the LWFA since the pulses are required to propagate 10^4 to 10^6 wavelengths. Numerical dispersion must be kept less than physical dispersion in plasmas. FFT methods can eliminate numerical dispersion in a vacuum. They require four real to complex and six complex to real inverse FFTs for 3-D simulations. The parallel efficiency can be kept above 50% unless the number of grid points per processor is small. A related issue is numerical phase errors in the orbits of plasma particles in the laser fields. The performance of various FFT and finite difference field solvers and particle pushers with regard to numerical dispersion and phase errors will be measured using the subtraction techniques of Decyk.[43]

For many of these problems the frame velocity, that minimizes the motion of the e.m. pulse through the system may not always be known ahead of time. Since these problems will take many 10's of hours to run, we will need to interact with the application during the run to "tune" the system parameters for the problem. This will be provided by a flexible distributed computing environment which will "attach" to the remote parallel process and extract requisite data structures from the running code to evaluate the physical state of the system. Upon determining appropriate physical changes, the parameters will be sent back to the application to alter some of the numerical parameters to allow the problem to run more optimally. When this task is completed, the graphics process can detach from the running problem to allow it to continue unimpeded. This type of operation has already been demonstrated on a smaller scale between a graphics server and a running distributed application at LANL.

TASK III:

To develop the necessary diagnostics to most efficiently determine the results of a three-dimensional plasma-based accelerator simulation.

In order to understand the plasma simulation, the computer code is outfitted with a set of diagnostics, much like a true plasma experiment. These diagnostics can be particle-based or field-based, and provide far more detail than is available in a plasma experiment. In 2-D simulations of plasma accelerators[35,36], the output consists of 2-D contour plots and 1-D slice plots (field vs. x holding y fixed and field vs. y holding x fixed). In addition, there are fourier plots and phase space plots. A typical snapshot consists of 250 frames. In 3-D these will be 3-D isosurface plots and 2-D contour (slice) plots as well. If the 3-D simulation box is broken into 9 planes for example, then a typical snapshot would consist of nearly 2000 frames. Obviously, some sort of interactive diagnostic package is necessary in 3-D to allow real time data visualization. For example, after viewing a 3-D isosurface rendering, the capability should exist to pick an interesting 2-D or 1-D slice to view.

For simulating plasma-based accelerators, the anticipated data set size from a single simulation run is in the Gigabytes to potentially Terabytes range. Data will therefore need to be stored periodically from the running application and archived to a remote device. The data will then be brought back on line (at least virtually) to allow the problem results to be studied interactively. In some cases, test particles might be placed into the problem after the run has already started to evaluate the accelerator's performance. In some cases the data will be reduced on the parallel machine before being sent to a graphics workstation for display in order to provide for greater interactivity and to allow the workstation to be able to handle a limited data set size. These issues are common to other Grand Challenge problems. We will benefit from ongoing High Performance Data System research going on at various High Performance Computing Research Centers.

Data is typically stored in one of two ways: as raw numerical data, such as the values of the electric field, or as graphical data, such as a graphics metafile. One especially useful form of graphical data are compressed raster images. A related family of compressed raster images form a digital movie file. By reducing pixel depth (number of colors) and screen size, such movie files can be compressed to manageable sizes. These movies files can serve as a "Table of Contents" to a long run, to give a scientist a quick view of what is happening, and serve as a pointer to raw data which needs to be examined in greater detail. They have already been found useful for two dimensional simulations[44]. If the digital movies are made in real time, they can be used to steer a calculation in progress, turning probes and diagnostics on or off, or even aborting a run which no longer seems useful. Unlike visualizations made for formal presentations which need to explain things to others, such digital movies do not need to be sophisticated, since the scientist already has a pretty good idea of what he or she is looking for, but they need to be fast. Thus the ability to create such movies with user controlled pixel depth and and size in real time and archive them in a database must be created. Whether they should be done on the parallel machine itself or on the workstation needs to be researched.

TASK IV:

To develop the necessary software to manage the simulation test bed, communicate between host and high speed environment, and catalog the Gigabyte databases.

This proposal calls for the development of a testbed simulation laboratory. As such it must combine what is already known about such environments, yet it must extend itself in several important respects. In this section we touch upon the various computer science research issues involved and briefly point to technology we can employ to solve the problems.

The use of a massively parallel processor is essential to achieve the speeds necessary to simulate a meter long plasma accelerator. However, the computing environment is actually more complicated than a host computer and a parallel machine. Multiple machines will be cooperating, in a transparent and fault tolerant way. These machines may include vector supercomputers, massively parallel architectures, imaging machines, and database engines. All these components will be linked via a high speed network. The simulation software will reside on the host system, a conventional UNIX workstation, yet it will connect and control all of these components. The task of such an environment is to permit the investigator to directly control all of the factors that affect his experiments. This includes: assisting in the arrangement of a series of test runs, controlling parameters of the experiment both statically and dynamically, displaying the generated data in visual form, and recording the data for post processing. In effect, all of the key elements of the simulation environment must be directly accessible and modifiable from the user interface.

An important research issue is exactly how the host and the parallel processors cooperate, what task is appropriate for what machine, what rate of speed of data transfer the host can support, and how dynamic the interaction between host and other components can become. For example, the display of three dimensional data in real-time is a highly computation intensive task that may overwhelm the host computer and is perhaps best done on the massively parallel processor or on some special graphics processor. Another question is whether the host computer will be able to catalog and save the data at the rates it is being produced, or if some form of intelligent pruning will be required?

Task I of this proposal on Computational Issues has outlined the major factors that determine the speed of the algorithms. Serious computational requirements remain. It has been observed that locality of data is quite important, especially for the particle push section of the algorithm. It will be essential to gather execution time profiles, which in turn will identify computing bottlenecks. We expect that this will lead to high parallel efficiency on 1000 processor machines.

Simulation of the plasma accelerator will necessitate a series of tests with many parameter changes, such as the number of mesh points or the frame velocity. Output will be a combination of statistics and visual presentations (3-D) of the data.[45,46] The simulation environment needs to present to the scientist mechanisms for constructing and running his programs that permit him to concentrate on the physics of the experiment and minimize the programming details.

A graphical user interface, based upon X window technology, is an obvious first step to constructing this interface. We then intend to determine those concepts and objects that the scientist wants to manipulate, thereby determining an object-oriented hierarchy. Once this is done, we can investigate what is required to allow him to manipulate those objects via the interface.

Another research effort will be to build the code with interchangeable (plug-in) modules, while employing a visual programming environment for linking these modules. One possible tool we plan to investigate is the Advanced Visualization System software, originally developed for Stardent Computer. This software package is now available on a wide variety of machines. It has several desirable features, that include (i) the ability to divide the computations between the parallel processor and the high speed workstation, and (ii) a mechanism for combining program elements together, thus increasing our ability to develop plug-in/reusable computing elements.

One serious problem in large-scale simulation is the vast amount of data that is produced. This data is not only numerical, but also graphical and in effect represents a movie of the experiment as mentioned in Task III. We estimate that multiple gigabytes of data will be produced for each snapshot or run. It is not enough to simply archive the data for later retrieval and post processing. The challenge is to organize and annotate the data in such a way that one maximizes the scientist's ability to retrieve information he will need at a later time. If one could pre-determine exactly what requests the scientist would make, one could establish a database schema. This schema would permit later retrieval based upon some query as expressed in a query language, e.g. SQL, though current forms of SQL are clearly inadequate. However, it has been observed that the data one wants to retrieve may not have been catalogued when originally collected, and as a result it cannot be retrieved.

We plan to use the object-oriented hierarchy developed for the user interface aspects of this proposal, as a way to characterize the collected data. Fortunately, a relatively new technology in the form of an object-oriented database (OODB) is just now becoming available.[47,48] We hope to use one of the available OODBs as a platform for storing and retrieving the data. New graphical objects and tools may have to be defined to manipulate archived images. In general, this will require intelligent data-base software which has a meta-data description of the data structures to be displayed to optimize the data storage and handling.

Postprocessing tools will need to be very flexible to enable one to explore the anticipated complex features in the simulation and to compare to "in situ" observational data. This work will enable us to evaluate systems and other software involved in data management and make recommendations for future parallel computers, as well as making recommendations regarding parallel I/O and file format standards.

TASK IMPLEMENTATION

Experience has shown that minimizing communication between processors in critical to achieving high performance in PIC codes on distributed memory machines. Message passing gives the user control over this critical function and is better suited for achieving high efficiency. Therefore, we will program on several message passing machines. These are the Gamma at JPL, the Delta at Cal Tech, an IBM Risc Cluster at Cornell, and the CM-5 at Los Alamos. Although the CM-5 uses a data parallel language, CM Fortran, it does permit the user to provide his own message passing. The Gamma and Delta use the standard message passage library Express, so transferring codes between these machines should be straightforward. We do not anticipate any complications when transferring to or from the CM-5 because the message passing calls can be localized to several subroutines.

The code development will be done concurrently at all three institutions. During the first year UCLA will write the 3-D push, JPL will write a 3-D FFT field solver, Los Alamos will write a 3-D low dispersion finite difference field solver, and UCLA and USC will write an ionization package. This effort will be done together to manage the internal data structures necessary for optimal parallelization. USC and Los Alamos will provide the computer engineering tools required to efficiently manage these basic algorithms. During the first year the code will be benchmarked against previously run problems. This will consist of a combination of two-dimensional and three -dimensional runs.

We will implement the cyclic mesh and the Lorentz frame modifications during the second year. This could require changes in the internal data structure as discussed under Task II. Optimization and tuning of the push and field solve will be emphasized. The diagnostics package will be developed. This work will utilize the high speed graphics visualization center at the ACL. During the second year, the benchmark runs of the prototype codes will provide the first simulations of the electron hose instability, relativistic self-focusing in 3-D, and wake excitation in 3-D over tens of plasma wavelengths. During the last year interactive code steering and tuning will be implemented. This will permit simulating meter-long laser-plasma interactions. This effort will also include a careful analysis of the effects of numerical dispersion over long propagation distances.

References

1. M. Tigner, IEEE Trans. on Nucl. Sci., NS-32, 1556 (1985).
2. T. Tajima and J.M. Dawson, Phys. Rev. Lett., 43, 267 (1979).
3. C. Joshi, W.B. Mori, T. Katsouleas, J.M. Dawson, J.M. Kindel, and D.W. Forslund, Nature, 311, 525 (1984).
4. P. Chen, J.M. Dawson, R. Huff, and T. Katsouleas, Phys. Rev. Lett., 54 693 (1985).
5. T. Katsouleas and J.M. Dawson, Phys. Rev. Lett., 51, 392 (1983).
6. Laser Acceleration of Particles (Los Alamos, 1982) AIP Conf. Proc. No. 91, edited by P. Channel (AIP, New York, 1982).
7. Laser Acceleration of Particles (Malibu, 1985) AIP Conf. Proc. No. 130, edited by C. Joshi and T. Katsouleas (AIP, New York, 1985).
8. Proc. of the Symposium on Advanced Accelerator Concepts (Madison, 1986), AIP Conf. Proc. No. 156, edited by F. Mills (AIP, New York, 1987).
9. Special issue on Plasma-Based High Energy Accelerators, IEEE Trans. on Plasma Sci., PS-15, edited by T. Katsouleas (1987).
10. Advanced Accelerator Concepts (Lake Arrowhead, 1989), AIP Conf. Proc. 193, edited by C. Joshi (AIP, New York, 1989).
11. C.E. Clayton, C. Joshi, C. Darrow, and D. Umstadter, Phys. Rev. Lett., 54, 2343 (1985).
12. J. Rosensweig, et al., Phys. Rev. Lett., 61, 98 (1988).
13. Y. Kitagawa, et al., Phys. Rev. Lett., 68, 48 (1992)
14. P.C. Liewer and V.K. Decyk, J. Comput. Phys., 85, 302 (1989).
15. W.A. Hendrickson, Trans. American Cystrolographic Assoc., 21, 11 (1985).
16. J. Kirz and H. Rarback, Rev. Sci. Instrum, 56, 1 (1985) and references therein.
17. A.I. Akhiezer and R.V. Polovin, Sov. JETP, 3, 696 (1956); T. Katsouleas and W.B. Mori, Phys,. Rev. Lett., 61, 90 (1988); W.B. Mori and T. Katsouleas, Physica Scripta, T-30, 127 91990).
18. W.B. Mori, Masters Thesis UCLA (1984); P. Sprangle, E. Esarey, A. Ting, and G. Joyce, Appl. Phys. Lett., 53, 2146 (1988).
19. T. Katsouleas, W.B. Mori, J.M. Dawson, and S.C. Wilks, in SPIE Conf. Proc. 1229, edited by E.M. Campbell (SPIE, Bellingham, WA, 1990), p. 98; P. Sprangle, E. Esarey, and A. Ting, Phys. Rev. A., 41, 4463 (1990); L.M. Gorbunov and V.I. Kirsanov, Zh. Eksp. Teor. Fiz., 93 509 (1987); V.N. Tsytovich, U. DeAngelis, and R. Bingham, Comments Plasma Phys. Controlled Fusion, 12, 249 (1989); V.I. Berezhiani and I.G. Murusidze, Phys. Lett. A., 148, 338 (1990).
20. J. Rosensweig, B. Breizman, T. Katsouleas, and J.J. Su, Phys. Rev. A, 44, 6189 (1991); W.B. Mori, T. Katsouleas, C.B. Darrow, C.E. Clayton, C. Joshi, C.B. Decker, K. Marsh, and S.C. Wilks, Proc. of 1991 PAC Conference, San Francisco, CA.
21. T. Katsouleas, W.B. Mori, and C.B. Darrow, Advanced Accelerator Concepts, (Lake Arrowhead, 1989), AIP Conf. Proc. 193, edited by C. Joshi (AIP, New York, 1989).
22. W.B. Mori, T. Katsouleas, C.B. Decker, and J.J. Su, Bull. Am. Phys. Soc., 36, 2305 (1991).
23. C.E. Max, J. Arons, and A.B. Langdon, Phys. Rev. Lett., 33, 209 (1974); P. Sprangle, C.M. Tang, and E. Esarey, IEEE Trans. Plasma Sci. PS-15, 145 (1987); W.B. Mori, C. Joshi, J.M. Dawson, D.W. Forslund, and J.M. Kindel, Phys. Rev. Lett., 61, 1599 (1988).
24. P. Sprangle, E. Esarey, and A. Ting, Phys. Rev. Lett., 64, 2011 (1990).
25. T. Katsouleas, et al., in preparation; P. Sprangle, et al., to be published.
26. A. Dangor, et al., IEEE Trans. Plasma Sci., PS-15, 161 (1987).

27. W.P. Leemans, C.E. Clayton, W.B. Mori, K.A. Marsh, A. Dyson, and C. Joshi, Phys. Rev. Lett., 68, 321 (1992); W.P. Leemans, C.E. Clayton, W.M. Bori, K.A. Marsh, P.K. Kaw, A. Dyson, and C. Joshi, accepted by Phys. Rev. A., (1992).
28. P. Chen, J.J. Su, J.M. Dawson, P.B. Wilson, and K. Bane, Phys. Rev., Lett., 56, 1252 (1986); J. Rosensweig, Phys. Rev. Lett., 58, 555 (1987).
29. T. Katsouleas, Phys. Rev. A., 33, 2056 (1986).
30. P. Chen, Particle Accelerators, 10, 171 (1986).
31. J.J. Su, T. Katsouleas, J.M. Dawson, P. Chen, M. Jones, and R. Keinigs, IEEE Trans. Plasma Sci., PS-15, 192 (1987); C. Joshi, et al., Proc. of the Symposium on Advanced Accelerator Concepts (Madison, 1986), AIP Conf. Proc. No. 156, edited by F. Mills (AIP, New York, 1987).
32. D. Whittum, W. Sharp, S. Yu, M. Lampe, and G. Joyce, Phys. Rev. Lett., 67, 991 (1991).
33. C.K. Birdsall and A.B. Langdon, Plasma Physics via Computer Simulation, (McGraw-Hill, New York, 1985).
34. R.L. Morse and C.W. Nielson, Phys. Fluids, 14, 830 (1971); D.W. Forslund, Space Science Reviews, 42, 3 (1985); A.B. Langdon and B.F. Lasinski, in Fusion Research, edited by J. Killeen, Vol. 16 of Methods in Computational Physics, edited by B. Adler, S. Fernbach, and M. Rotenberg (Academic, New York, 1976) p. 327.
35. D.W. Forslund, J.M. Kindel, W.B. Mori, C. Joshi, and J.M. Dawson, Phys. Rev. Lett., 54, 558 (1985); W.B. Mori, C. Joshi, J.M. Dawson, C. Joshi, and J.M. Dawson, Laser Interactions and Related Plasma Phenomena, Vol. 7, edited by H. Hora and G. Miley (Plenum, New York, 1986).
36. W.B. Mori, Ph.D. Dissertation, UCLA (1987).
37. J.J. Su, W.B. Mori, T. Katsouleas, and C.B. Decker, presented at 1992 APS General Meeting.
38. V.K. Decyk, "Student-Friendly Fortran Interface," UCLA-OAC Perspective, Vol. 15, No. 3, p. 39.
39. D.W. Walker, "Particle-in-Cell Plasma Simulation Codes on the Connection Machine," Computing Systems in Engineering, 2, p. 307 (1991).
40. R.W. Huff and J.M. Dawson, "Particle Simulation of the Ncube and other Hypercubes," Proc. of the U.S.-Japan Workshop on Advances in Simulation Techniques Applied to Plasmas and Fusion, Los Angeles, CA, September 1990, UCLA IPFR Report, PPG-1362.
41. R.D. Ferraro, P.C. Liewer, and V.K. Decyk, "Dynamic Load Balancing for a 2D Concurrent Plasma PIC Code", Cal Tech CRPC TEchnical Report 217-50, 1991.
42. J.M. Wallace, et al., Phys. Fluids B, 3, 2337 (1991).
43. V.K. Decyk, "Simulation of Microscopic Process in Plasma," Proc. 1987 Int'l. Conf. on Plasma Physics, Kiev, USSR, April 1987, edited by A.G. Sitenko (World Scientific, Singapore, 1987), vol. II, p. 1075.
44. V.K. Decyk and J.E. Slottow, "Producing Animations on IBM PCs and PS/2s," UCLA-OAC Perspective, Vol. 15, No. 2, p. 40 (1991).
45. Scientific Visualization, edited by G. Nielson, Special Issue, IEEE Computer, vol. 22, No. 8 (1989).
46. Visualization in Scientific Computing, edited by McCormic/DeFanti/Brown, Computer Graphics, Vol. 21, No. 6 (1987).
47. Object-0oriented Databases with Applications to CASE, Networks and VLSI CAD, edited by R. Gupta and E. Horowitz (Prentice Hall, 1991).
48. M. Stonebraker, et al., "Postgres", IEEE Trans. on Know. and Data Engineering, Vol. 32, No. 1 (1990).

APPENDIX A: VITAES

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EXPERIENCE

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PATENTS AND INVENTIONS

Method of Apparatus for Upshifting Light Frequency by Rapid Plasma Creation; U.S. Patent No. 4,975,655; December 4, 1990.

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Publications

1. C. Joshi, W. B. Mori, T. Katsouleas, J. M. Dawson, J. M. Kindel, and D. W. Forslund, "Ultra-High Gradient Particle Acceleration by Intense Laser-Driven Plasma Density Waves," Nature, 311, 525, (1984).

2. W.B. Mori, "On Beat Wave Excitation of Relativistic Plasma Waves," IEEE Trans. on Plasma Science, special issue on Plasma-Based High-Energy Accelerators, ed. by T. Katsouleas (April 1987).

3. W. B. Mori, C. Joshi, J. M. Dawson, D. W. Forslund, and J. M Kindel, "Two-Dimensional Simulations of Intense Laser Irradiation of Underdense Plasmas," Laser Interaction and Related Plasma Phenomena, Vol. 7., ed. by H. Hora and G. Miley (Plenum. New York, 1987).

4. W. B. Mori, C. Joshi, J. M Dawson, D. W. Forslund, and J. M. Kindel, "Evolution of Self-Focusing of Intense Electromagnetic Waves in Plasma," Phys. Rev. Lett., 60, 1298 (1988).

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PUBLICATION LIST

1. Dawson, J.M. and Decyk, V.K., "Particle Modeling of Plasmas on Super-computers," International Journal of Supercomputer Applications, 1, 24 (1987). (20 pages)

2. Decyk, V.K., "Simulation of Microscopic Processes in Plasma," Proc. 1987 International Conference on Plasma Physics, Kiev, USSR, April, 1987, ed. A.G. Sitenko [World Scientific, Singapore, 1987], vol. II, p. 1075 (23 pages).

3. P.C. Liewer, V.K. Decyk, J.M. Dawson, and B. Lembege, "Numerical Studies of Electron Dynamics in Oblique Quasi-Perpendicular Collisionless Shock Waves", J. Geophysical Research 96, 9455 (1991). (11 pages).

4. P.C. Liewer and V.K. Decyk, "A General Concurrent Algorithm for Plasma Particle-in-Cell Codes," J. Computational Phys. 85, 302 (1989) (21 pages).

5. V.K. Decyk, "Student-Friendly Fortran Interface," UCLA-OAC Perspective, Vol. 15, No. 3, p. 39 (1991) (6 pages)

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Resent Research

The development of intense particle beams and high-brightness lasers is leading to an explosion of applications involving beam-plasma interactions. Among these, Dr. Katsouleas is exploring the use of beam-driven plasma waves to accelerate (and focus) a second beam of particles at ultra-high rates, thereby miniaturizing an accelerator by a factor of as much as 100. Other applications include novel light sources based on the interaction of electromagnetic waves with time-varying plasmas and plasma lenses for producing unprecedented particle beam spot sizes.

Selected Publications

1. J.M. Dawson, V.K. Decyk, R.W. Huff, I. Jechart, T. Katsouleas, J.N. Leboeuf, B. Lembege, R.M. Martinez, Y. Ohsawa, and S.T. Ratliff, "Damping of Large-Amplitude Waves Propagating Perpendicular to the Magnetic Field," Phys. Rev. Lett., 50, 1455 (1983).

2. T. Katsouleas and W.B. Mori, "Wavebreaking Amplitude of Relativistic Oscillations in a Thermal Plasma," Phys. Rev. Lett., 61, 90 (1988).

3. T. Katsouleas, J.J. Su, W.B. Mori, and J.M. Dawson, "Plasma Physics at the Final Focus of High-Energy Colliders," Phys. Fluids B, 2 (6) 1384 (1990).

4. T. Katsouleas, J.J. Su, S. Wilks, W.B. Mori, and J.M. Dawson, "The Role of Plasmas in Future Accelerators," Particle Accelerators, 32, 185 (1990).

5. J. Rosenzweig, B. Breizman, T. Katsouleas, and J.J. Su, "Acceleration and Focusing of Electrons in Two-Dimensional Nonlinear Plasma Wakefields," Phys. Rev. A, 44, 6189 (1991).

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Memberships and Honors

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2. D. W. Forslund, "Fundamentals of Plasma Simulation," Space Science Reviews, 42, 3 (1985).
3. D. W. Forslund , J. M. Kindel, W. B. Mori, C. Joshi, and J. M. Dawson, "Two-Dimensional Simulations of Single-Frequency and Beat-Wave Laser-plasma Heating," Phys. Rev. Lett., 54, 558 (1985).
4. C. J. McKinstrie and D. W. Forslund, "The detuning of relativistic Langmuir waves in the beat-wave accelerator," Phys. Fluids, 30, 904 (1987).
5. D.W. Forslund, C. Wingate, P. Ford, J.S. Junkins, J. Jackson, S.C. Pope, "Experiences in Writing a Distributed Particle Simulation Code in C++", 1990 USENIX C++ Conference Proceedings.

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R.D. Ferraro, P.C. Liewer, V.K. Decyk, "Dynamic Load Balancing for a 2D Concurrent Plasma PIC Code," submitted to Journal of Computational Physics

R.D. Ferraro, "Solving PDEs for Electromagnetic Scattering Problems on Coarse Grained Concurrent Computers", in the PIER volume COMPUTATIONAL ELECTROMAGNETICS AND SUPERCOMPUTER ARCHITECTURE, Elsevier Science Publishing Company, Inc. (Chapter, In Press)

J.M. Dawson, R.D. Sydora, V.K. Decyk, P.C. Liewer, R.D. Ferraro, "Physics Modeling of Tokamak Transport, A Grand Challenge for Controlled Fusion," The International Journal of Supercomputing Applications, Vol. 5, No. 3, Fall 1991, pp. 13-35

J.E. Patterson, T. Cwik, R.D. Ferraro, N. Jacobi, P. Liewer, T.G. Lockhart, G.A. Lyzenga, J. Parker, D. Simoni, "Parallel Computation Applied to Electromagnet Scattering and Radiation Analysis", Electromagnetics, Vol. 10, 21 (1990)

R.D. Ferraro, P.C. Liewer, and V.K. Decyk,"A 2D Electrostatic PIC Code for the Mark III Hypercube" in Proceedings of the 5th Distributed Memory Computing Conference, Edited by D.W.Walker and Q.F.Stout, IEEE Computer Society Press, 1990

ELLIS HOROWITZ

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RESEARCH INTERESTS

Software Engineering, methods for improving programming and programmer productivity. CASE environments. Object oriented database systems. Implementation of CASE and document support systems using object technology.

EDUCATION

Univ. of Wisconsin, Madison	Ph.D. - 1/70, Computer Science
Univ. of Wisconsin, Madison	M.S. - 1/67, Computer Science
Brooklyn College	B.S. - 6/64, Mathematics

ACADEMIC EXPERIENCE

9/73 - Present	Computer Science & EE, Univ. of So. Calif.
6/83 - Present	Professor
8/75 - 6/83	Associate Professor
9/73 - 8/75	Assistant Professor
2/80 - 7/80	Lady Davis Fellow and Visiting Associate Professor, Department of Computer Science, Technion
9/79 - 1/80	Visiting Associate Professor, Department of EE&CS, M.I.T.

PROFESSIONAL ACTIVITIES

Member of ACM and IEEE

PUBLICATIONS

1. "Object Database Support for CASE" Object Oriented Databases and Applications to CASE, Networks, and VLSI CAD, Prentice-Hall, Englewood Cliffs, New Jersey, 1990, with Lung-Chun Liu, pp. 261-282.

2. "Building your own software development environment", Software Engineering Journal, vol. 6, Number 5, September 1991, pp. 317-331 (with Y. Sugiyama)

3. "Object Oriented Databases and Applications to CASE, Networks, and VLSI CAD", Prentice-Hall, Englewood Cliffs, New Jersey, 1990, with R. Gupta.

4. "A framework for specification and design of software for advanced sensor systems," Proc. 10th Real-time Systems Symposium, Santa Monica, Ca. December 1989 (with Alice Muntz)

5. "A System for Specifying and Rapidly Prototyping User Interfaces", Taking Software Design Seriously", ed. John Karat, Academic Press, 1991, pp. 257-272.

APPENDIX B: LETTERS OF SUPPORT

Center for Theory and Simulation in Science and Engineering
CORNELL THEORY CENTER

ADVANCED COMPUTING
RESEARCH INSTITUTE

CORNELL NATIONAL
SUPERCOMPUTER FACILITY

CORPORATE RESEARCH INSTITUTE

CORNELL UNIVERSITY

ENGINEERING AND THEORY
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ITHACA, NEW YORK 14853-3801

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FAX: 607/254-8888

April 21, 1992

Professor John Dawson
& Professor Warren Mori
Department of Physics
University of California
405 Hilgard Avenue
Los Angeles, California 90024-1547

Dear Warren and John:

As we have discussed, I am very pleased to invite you to collaborate with the Cornell Theory Center in the exploitation of some scalably parallel computers that we expect to acquire in the next year. At the moment, we have the first 64 Kendall Square machine anywhere. In addition, we will have a 64 processor IBM cluster of advanced Risc processors with an aggregate peak performance of about 6GFlops by the end of this year. We expect that machine to be scaled up to 512 processors about a year later. More specifically, I agree that we will provide the following for a post-doctoral researcher and a graduate student working for you: visitor space, access to these powerful parallel machines, and help in porting and developing problems intended to solve problems in plasma accelerator and laser plasma physics.

Our expectation is that there will be a series of even more powerful parallel prototypes here in years to come and that the collaboration with you will continue as well.

I look forward to a prolonged and fruitful collaboration.

Sincerely,

Malvin H Kalos
Malvin H. Kalos
Director

Jet Propulsion Laboratory
California Institute of Technology

4800 Oak Grove Drive
Pasadena, California 91109

(818) 354-4321

JPL

April 23, 1992
Refer to: 820-9270:CAK:js

Professor Warren B. Mori
University of California, Los Angeles
Physics Department and Engineering Department
Los Angeles, California 90024-1547

Dear Professor Mori:

I am pleased to provide this letter of support for the proposal "Full-Scale Numerical Experiment to Test a Future Plasma-Based Accelerator", submitted by UCLA to the National Science Foundation. Computational Scientists at JPL will participate in the effort. The proposed work, if successful, represents a major advance in the application of High Performance Computing for a proof-of-concept demonstration of a potential GeV accelerator technology. To the extent that other commitments allow us to do so, we will provide access to the Intel Touchstone Delta concurrent supercomputer for code development work by the proposal investigators.

Sincerely,

Carl Kukkonen

Dr. Carl A. Kukkonen
Director
Center for Space Microelectronics
Technology

Los Alamos
NATIONAL LABORATORY

Advanced Computing Laboratory
C-DO/ACL, B287
Los Alamos, New Mexico 87545
(505) 665-4530, FTS 855-4530
FAX 665-4939

April 23, 1992

Dr. Warren B. Mori
University of California, Los Angeles
Physics Department
Los Angeles, CA 90024-1547

Dear Warren:

We believe your NSF HPCC Grand Challenge proposal to develop a testbed simulation laboratory which could conduct a full-scale numerical test of a future plasma based accelerator is an important application and should be a strong contender as one of the NSF Grand Challenges. Los Alamos and UCLA have had a long history of collaboration and exchange on computer simulation of plasma accelerators. To date, these joint simulations reflect the state-of-the-art in computational modeling in this field. Los Alamos and the Advanced Computing Laboratory recognizes the possible impact that this proposal could have on accelerator physics and high speed computing.

We are committed to providing the following resources to this proposed project.

1. Support for Deputy Director David Forslund to oversee the Los Alamos portion of this project, consisting of .1 FTE at $200/FTE.

2. Computational resources for David Forslund and a postdoc to develop parallel processing computer algorithms for this project (see attached table).

3. Access and collaborative development in the use of the high speed visualization facilities within the Advanced Computing Laboratory.

The Advanced Computing Laboratory presently has a 1024-node CM-5 and a 2048-node CM-2. The CM-2 will be upgraded to a CM-200 by this summer and the CM-5 will be fully populated with vector units during the next year. Over the past three years, since the CM-2 arrived at the ACL in February, 1989, Los Alamos has made this resource available to researchers all over the United States. The user profile on the CM-5 will be somewhat different, since it will be used primarily for the solution of Grand Challenge problems. Therefore, access to this resource will be more limited than with the CM-2. We are in the process of discussing with the National Science Foundation the allocation of time for NSF Grand Challenges on the CM-5 at Los Alamos. In addition, the NSF Science and Technology Center for Research on Parallel Computation (CRPC) is very interested in making an investment in resources toward support of the NSF Grand Challenge problems. The CM-5 here at the ACL will undoubtedly be a part of that commitment, but the allocation procedure - which presently is through our Grand Challenge committee chaired by Geoffrey Fox is unclear.

Sincerely yours,

Andy

Andrew B. White, Director
Advanced Computing Laboratory

ABW:egp

att. a/s

cy: File