Final Report on the Advanced Acceleration Techniques Working Group, T8

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(Dated: October 12, 2001)

Convenors of Subgroups:
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I. OVERVIEW

There is a small but vigorous community working on advanced accelerator concepts in the United States. This effort, principally supported by the DOE, is deemed important for the long term vitality of High Energy Physics (HEP). In addition, the program contributes essential technology and accelerator science to the benefit of all fields using accelerators in their research. Although the research is not directed at any particular project, such as the NLC, its long term focus, i.e., 10 years or more, is to advance the state-of-the-art for HEP. It addresses fundamental issues which could lead to new or improved, high-gradient accelerators, rf sources, computational techniques, beam control devices and new diagnostic tools. The advanced accelerator research provides an exciting and stimulating field of physics, which continues to attract young and talented researchers. This community is also responsible for a large number of high quality scientific publications and is invaluable as a training ground for new Ph.D. students.

Over 80 invited talks were presented within the T8: Advanced Acceleration Techniques Working Group. These talks highlighted the recent progress, developments and results in the field. The schedule for the T8: Working Group on Advanced Acceleration Techniques was

Subgroups	**# of Talks**	**Subgroup Convenors**
Plasma Based Acceleration	38	P. Sprangle, A. Ting, E. Esarey
Plasma Based Injectors	8	W. Leemans, D. Umstadter
Computational Techniques (Joint with T7)	8	T. Antonsen, W. Mori
Non-Plasma Based Acceleration	13	T. Marshall
Plasma Based Processes	5	P. Chen
Advanced RF Sources (Joint with T3)	8	J. Hirshfield

The Europeans and the Japanese have extensive programs on advanced accelerators, which are receiving large funding from the European Union and various Japanese government agencies. The present report addresses the US effort.

The advanced accelerator program is progressing along many fronts, one of which is the techniques for next generation of advanced accelerators. Experiments are being designed to produce an electron beam of well-defined energy in the multi-GeV range. The first generation laser wakefield accelerator (LWFA) has generated (100 MeV electrons with an accelerating gradient of 100 GeV/m and energy spread of 100%. The second generation LWFA will require optical guided beams, properly controlled phased beam injection and stable wakefield generation.

To increase the acceleration length, the high intensity laser pulse must be optically guided in a plasma channel. This has been demonstrated over distances of many ten's of Rayleigh lengths (several centimeters) at several institutions, e.g., NRL, U. MD, U. Texas, LBNL and U. Mich. A tapered plasma channel with a drive laser of ten's of TW and optical laser injection may lead to a final energy of several GeV in a distance of several ten's of cm. To have a well-defined accelerated beam energy an injected beam occupying a small phase angle is necessary. Several all-optical injection concepts are being investigated that may be capable of producing such pulses (U. Mich, NRL, LBL, UCLA).

The plasma wakefield accelerator (PWFA) mechanism utilizes a relativistic electron beam propagating in a plasma to excite a large amplitude wakefield which accelerates the tail end of the beam. A number of

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laboratories (UCLA, FNAL, SLAC, ANL) are presently performing experiments on this concept. One of these experiments is the E-157 project at the FFTB of SLAC. This joint effort (SLAC/UCLA/USC/LBL) involved the propagation of a 30 GeV electron beam through a 1.4 m plasma column in the blowout regime of the PWFA. Simulations indicate that an accelerating gradient of 1 GeV/m can be achieved. The experiment has already observed, a) the betatron oscillation of the electron beam and related synchrotron radiation, b) induced transverse effects such as oscillation of the beam tail, and c) electron beam refraction as the beam crosses the plasma-gas boundary. An ongoing related experiment is the E-162 joint project (SLAC/UCLA/USC), in which a 30 GeV positron beam propagates through the plasma column. Experimental results clearly demonstrate that the plasma column acted as a focusing lens for the positron beam. Results on a related experiment, E-150, were presented in which focusing of both electrons and positrons by a factor of 2 was observed using a thin plasma lens.

Recently proton acceleration experiments (GA, U. Mich., LLNL) have observed high energy 10-50 MeV protons from hydrocarbon surface contaminants when a high intensity laser pulse is focused onto a thin solid target. The resulting proton beam can have a small energy spread and emittance (1mm-mrad), but a significant bunch charge (1nC). The accelerated proton pulse may find applications in basic nuclear physics studies, fast ignitor fusion, production of radionucleides, and injectors for ion accelerators.

The computational community is developing a hierarchy of new codes for advanced accelerator research. Full-scale 3D modeling is presently at hand, and it is expected that the computational run time can be reduced from a month to minutes with a combination of reduced description particle models and parallelized algorithms.

New rf sources are being developed either as candidate tubes for future colliders operating from 11.4 to 91 GHz, or simply to carry out high-power tests of structures and components. High frequency gyroklystrons are being developed at the U. MD (80 MW design at 17 GHz) and Calabasas Creek Research (10 MW design at 91 GHz). Magnicons are being developed at 11.4 GHz (NRL/ Omega-P, Inc.) and 34 GHz (Omega-P, Inc.)

The three largest areas of work in the non plasma area are the inverse free electron laser (IFEL) accelerator, dielectric wake field acceleration (DWFA), and small vacuum structures. The STELLA IFEL experiment at the ATF facility at BNL has demonstrated phasing of two IFEL stages which required the first stage to bunch the picosecond long beam into 3fs microbunches. These microbunches were subsequently injected into the next IFEL stage with precise phase control. The IFEL, while it cannot achieve TeV energies, can contribute to parts of a staged accelerator system, or as an injector for plasma-based accelerators. A new method of chopping ps bunches into fs pieces by the LACARA (Yale/Omega-P/Columbia) has been devised and will be tested. Tests of optical structures (Stanford U.) for vacuum acceleration, are planned for the near future.

The field of structure-based wakefield accelerator research is demonstrating great progress (ANL, BNL, Columbia U. and Omega-P). The upgraded ANL facility for wakefield studies was presented. A successful test has been made of their two-beam accelerator concept, and higher energy tests are planned that may soon demonstrate gradients in excess of 100 MeV/m. A test at NRL of the ANL dielectric-loaded TM01 slow-wave structure using high power X-Band microwaves generated by a magnicon is planned soon. Whereas most wakefield work involves exciting a spectrum of microwave TM modes in a cylindrical dielectric wakefield device, it was pointed out (Columbia) that one might well imagine tall rectangular dielectric structures having optical-scale dimensions, that would be excited by fs bunches containing pC of charge. If the issues of stability and breakdown can be resolved, the dielectric wakefield accelerator (DWFA), which may have gradients of 100 MeV/m to 1 GeV/m, may play an important role in accelerator physics of the future.

Laser wakefield schemes have demonstrated jets of electrons and ions with broad energy spectra and impressive acceleration gradients, exceeding 100 MeV in a mm. Presently research is directed towards a 2nd generation of wakefield device employing various injection and channel guiding schemes to produce relatively monoenergetic beams in the GeV range. Several facilities around the country are engaged in this research, including, NRL, ATF (BNL), Neptune (UCLA), L'OASIS (LBNL), AWL (ANL) and the planned ORION facility at SLAC. From the E-157 experiments, an idea for an energy doubler for a linear collider has emerged, called the Afterburner. The advanced accelerator community may, within 3-5 years, propose application of these ideas to the HEP community.

II. PLASMA BASED ACCELERATION

A. Laser Wakefield Accelerators (LWFA)

In a laser wakefield accelerator a single laser pulse is used to drive a large amplitude plasma wave (wakefield) that can accelerate injected electrons to high energies. Experimentally, the first generation LWFAs have typically generated 100 MeV electrons with an accelerating gradient of 100 GeV/m. Since the background plasma electrons are accelerated the resulting beam has a large energy spread. The generated beams have an energy spread of 100% and electron distribution which monotonically decreases with respect to energy. These self-modulated LWFA (SM-LWFA) experiments operate in a highly unstable regime where the pulse length is much longer than the wakefield period. The energy limitation is primarily due to diffraction and dephasing. Research groups in the US that have measured accelerated electrons in the SM-LWFA include NRL, LBNL, Michigan, and UCLA.

The second generation LWFA will require optically-guided laser beams, properly controlled phased beam injection and stable wakefield generation. Research results on these issues as well as intense laser pulse propagation were discussed in the working group.

To increase the acceleration length the drive laser pulse must be optically guided. To have a well-defined beam energy an injected beam occupying a small phase angle is necessary. Optical guiding can be achieved in plasma channels. Optical guiding in plasma density channels has been experimentally demonstrated at U.MD, NRL, LBNL, UT Austin, and Michigan. To date, intensities as high as the mid 10 17 W/cm2 have been guided over distances corresponding to tens of Rayleigh lengths (on the order of a few cm). Future challenges include guiding at ultrahigh intensities (¿10 18W/cm2) over long distances (many cm), and the further development of plasma channel technology aimed at producing long channels (many cm) with control over the plasma density profile including the ability to generate lower on-axis denisties (1016-1018 cm-3).

To produce stable, strong wakefields, it is expected that future experiments will have shorter pulse lengths and/or lower plasma densities so that the pulse length is shorter than the wakefield period. Lasers with suitable power and pulse length already exist at a number of institutions. Presently, short pulse lasers with powers in excess of 10 TW are in operation at Michigan, LBNL, and NRL.

Phased injection of electrons in the LWFA is difficult because the required pulse length is typically tens of femtoseconds. Using photocathode RF Linac technologies, including high frequency (X-band) RF Linacs, as well as bunching technologies such as Inverse Free Electron Laser and magnetic compression via chicanes (BNL, UCLA), electron bunches with these timing characteristics could be achieved. However, the best timing synchronization can be obtained when the electron bunches are generated optically.

Several all-optical injection concepts are being investigated that may be capable of producing such pulses. These concepts include LILAC that uses a transverse propagating injection laser pulse (U. Mich.), injection using two co-linear, counter-propagating laser pulses (LBNL), injection by ionization and ponderomotive acceleration LIPA (NRL), injection using density transitions (UCLA, LBNL) and injection using transversely propagating beat waves (UCLA), and injection using density transitions(UCLA, LBNL), which is also applicable to the plasma wakefield accelerator. Theory and simulation of these concepts indicate the production and acceleration of high quality electron bunches. To date, however, a definitive experiment demonstrating the production and acceleration of a high quality electron bunch in a laser driven accelerator has not been performed. The LIPA concept has been demonstrated experimentally at sub-MeV energies.

In addition to diffraction, which can be controlled using density channels, phase slippage between the accelerated electron and the accelerating plasma wakefield as well as energy depletion from the drive (pump) laser pulse ultimately limits the final electron energy. In the mildly nonlinear limit, the dephasing distance is smaller than the depletion distance. However, the phase velocity of the accelerating bucket can be made equal to the speed of light and hence postpone the dephasing limitation by tapering the density of the plasma channel (NRL). A tapered plasma channel with a drive laser of ten's of Terawatt and optical laser injection can lead to a final energy of several GeV in a distance of several ten's of cm. Other concepts for mitigating dephasing have been proposed as well, such as by using drift spaces in conjunction with appropriately phased laser pulses (Princeton). In the highly nonlinear limit (high laser power and high intensity), the excited wakefield can be high enough so that the dephasing and depletion lengths are comparable, thus allowing for high final electron energies in a single stage with a nearly uniform plasma channel (LBNL).

B. Plasma Wakefield Accelerator (PWFA)

The plasma wakefield acceleration mechanism utilizes a highly relativistic electron beam propagating in a plasma to excite a large amplitude wakefield (plasma wave). In principle, a second, trailing electron bunch is injected into the wakefield for acceleration to high energy. However, it is possible to design the experiment such that the tail end of the drive electron beam can experience acceleration by the wakefield. A number of laboratories (SLAC, UCLA, FNAL) are presently performing experiments on this concept. One of these experiments is the E157 project at the FFTB of SLAC. The primary goal of this experiment is to address the key issues associated with a high gradient plasma-based accelerator. This collaborative effort of SLAC/UCLA/USC/LBL involves the propagation of the 30 GeV electron beam of SLAC through a 1.4 meter long plasma column in the blowout regime of the PWFA. Simulation indicates an accelerating gradient of 1 GeV/m could be achieved. This experiment has observed a variety of beam-plasma interaction phenomena. These include a) the betatron oscillation of the electron beam due to mismatch between the electron beam and the plasma channel and the related synchrotron radiation, b) induced transverse effects of the electron beam tail that could not be distinguished from possible longitudinal energy gain, and c) the observation of electron beam refraction as the beam crosses the plasma-gas boundary. An ongoing related experiment is the E162 joint project of SLAC/UCLA/USC where a 30 GeV positron beam propagates through the plasma column. The wakefield generation physics is quite distinct from that using an electron beam because the plasma electrons are attracted to the positron beam instead of being expelled. Experimental results showed that the plasma column acted as a focusing lens for the positron beam.

C. Plasma Beatwave Acceleration (PBWA)

Plasma beat-wave experiments, in which the plasma wave is generated by beating two long-pulse lasers with a frequency difference equal to the plasma frequency, are being carried out at the Neptune facility (UCLA). The Neptune facility is a unique state of the art, laser, electron beam and plasma laboratory for advanced accelerator research. Presently, the Neptune laboratory is exploring the plasma beatwave accelerator using two lines from a high power CO2 laser system. In addition, experiments being planned at the Neptune laboratory include: a) plasma wake field generation and acceleration, b) plasma lenses, c) IFELs and d) Cherenkov waves in magnetized plasmas

D. Ion Acceleration

Recent experiments (LLNL, Michigan, GA) have observed monochromatic high energy 10-50 MeV protons from surface contaminants when a high intensity laser pulse is focused onto a thin solid target. The resulting proton beam exhibits accelerator quality emittance (1 mm-mrad) and bunch charge (1 nC). The mechanism appears to be due to electrostatic fields generated by the laser-plasma electrons accelerated through the target and form a dense plasma sheath on the rear (non-radiated) surface. A large sheath electric field ionizes surface layer. The accelerated proton pulse (1 ps, ¿ 1013protons) can have energies as high 50MeV. The presence of a pre pulse may have important effects on the final proton energy. These unique proton beams may find applications in basic nuclear physics studies, fast ignitor fusion, production of radionucleides, and injectors for ion accelerators.

E. Backward Raman Pulse Amplification

Backward Raman pulse amplification involves the interaction of a short seed pulse with a counter propagating long pulse of low intensity in a plasma. Amplification of the short pulse takes place at the expense of the pump laser energy via the backward Raman instability. The frequency of the pump laser is greater than the amplified seed laser by the plasma frequency. This process has been proposed as a way of achieving ultra high power short laser pulses without damaging optics (Princeton). However, the amplification mechanism is only applicable for low intensities, i.e., less than the relativistic intensity. High power amplification can be achieved only by going to large laser and plasma spot sizes.

III. PLASMA BASED PROCESSES

The plasma lens was proposed as the final focusing element in linear colliders in order to achieve high luminosity. When a bunched beam enters a plasma wakefields are excited. The initially uniform plasma electron distribution is perturbed in such a way as to neutralize the space charge of the beam and cancel the radial electric field. For an electron beam the plasma electrons are expelled, leaving behind the less mobile ions that neutralize the beam. For a positron beam, neutralization is produced from plasma electrons that are attracted towards the beam. When the beam radius is much smaller than the plasma wavelength neutralization of the beam current by the plasma return current is not complete and the azimuthal magnetic field is unbalanced. Thus the beam pinches, i.e., focuses. This process has been modeled using particle-in-cell simulation codes at several laboratories.

Plasma lens focusing of high energy, high density electron and positron beams has been demonstrated in the SLAC E-150 experiment. Laser and/or beam ionization of neutral nitrogen or hydrogen gas generated a plasma lens with density in the range 4-5x1018 cm-3. Best focusing was obtained with a combination of laser and beam-generated ionization, and reductions in beam spot size (focusing) by factors 2 were observed. Design studies for linear collider applications are now in progress.

Johnny Ng (SLAC) gave a detailed report on the physics motivation, the design and construction, and the data analysis of the SLAC E150 Plasma Lens Experiment, which was carried out at the Final Focus Test Beam at SLAC from 1998 to 2000. The experiment was done with both high energy (28.5 GeV) electron and positron beams penetrating a plasma, which is either ionized by the beam or laser pre-pulse. The plasma density, which is of the order 1018 cm-3., as well as the beam energy, are more relevant for the parameter regime of the future linear colliders. The E150 experiment has clearly demonstrated the principle of self-focusing plasma lens, first proposed by P. Chen in 1987. The focusing strength of the plasma lens was measured to be around 1 Tesla/(m, which is more than 100 times stronger than the conventional magnetic quadrapoles.

Kathy Thompson (SLAC) gave a talk on the tolerance of jitters in future linear colliders assuming that a plasma lens is applied. As the beam-induced self-focusing plasma lens defines its own axis of symmetry, any offset of the incoming beam cannot be reduced by the plasma lens. Kathy simulated this effect and calculated the effective luminosity deliverable when a plasma lens is invoked. Her results showed that a parameter space does exists in which the desired luminosity is not severely degraded, yet the incoming beam size were much relaxed. This implies that perhaps the utility of a plasma lens lies not in enhancing the linear collider luminosity, but in reducing the upstream tolerances of the machine is general, for the delivered beam to the plasma lens would not have to be as small.

Andy Charman (UC Berkeley) presented his investigation into the effect of shaped laser pulse on the efficiency of Laser Wakefield Accelerators (LWFA). He confirmed the initial findings made by P. Chen and A. Spitkovsky in the linear and nonlinear regime for the optimum laser pulse shape. However, he called to the attention the subtleties of what physical quantity is one really supposed to optimize.

IV. NON-PLASMA BASED ACCELERATION

A. Inverse Free Electron Laser (IFEL)

The IFEL is the most developed of all the areas, as its roots are in the theory and hardware technology of FEL which developed rapidly in the 1980's. In the 1990's, proof-of-principle experiments were done. Recently, a microwave IFEL experiment at Yale successfully related experimental data to 3D theory, and the STELLA IFEL experiment at ATF demonstrated prebunching on an optical scale of distance and injection/capture/acceleration of the short (3.5(m) bunch in a following IFEL stage using higher CO2 laser power related in phase to the first stage. Approximately 50% of the bunch charge can be captured. As a result, the IFEL now is ready for some ambitious acceleration tests using higher power (100 GW - 1 TW) CO2 lasers (ATF [Pogorelsky and Kimura] and UCLA "Neptune"[Musumeci and Pellegrini]) which can accelerate the bunch 50 MEV and demonstrate gradient 90 MeV/m while maintaining high beam quality. The UCLA IFEL uses an undulator with a very rapid taper. Both these new experiments will use tapered undulators of about 50 cm in length. It is worthwhile to recall that, by using a constant K tapering, an IFEL might ultimately achieve a bunch energy 200 GV given sufficient laser power, without excessive synchrotron radiation from the wiggler.

Given the recent results from STELLA, one would expect that there should not be trouble in staging IFEL sections. Nevertheless, new variations on the IFEL theme keep appearing. An example of this is a "single half-period" wiggler concept presented by Hartemann. In this scheme, the bunch encounters in its axial motion a short region of specially determined transverse magnetic field. Under conditions of very high power, a very favorable scaling of acceleration with laser power is obtained. As with many new ideas, the exploratory work is done with 1D analysis, but further effort on 3D effects is needed to justify an experiment. Clearly, a very high power laser which delivers many joules of energy in a pulse is needed to accelerate a bunch to meaningful energy. There is also the need for several repetitions per second, and for an acceptable overall efficiency for the system. It would appear unlikely that a 1/2TeV accelerator would be entirely made up of IFEL sections; yet the IFEL development has permitted a valuable study of laser acceleration and staging. It has also developed a proven method for producing fsec bunches, which have many applications outside of HEP accelerator physics. A STELLA workshop is planned for December 2001 in Tucson.

B. Dielectric Wake Field Acceleration (DWFA)

These devices use an injected "drive" bunch, or train of bunches, in either a co-linear or two-beam configuration, to develop high longitudinal electric fields which can accelerate a "test bunch" to high energy. As the bunches move in vacuum at nearly the speed of light, they set up in a surrounding low-loss dielectric a co-moving

Cerenkov wake, and thereby experience energy loss or "drag". The wake fields of several drive bunches may be superimposed to build up field pulses 100 MEV/m to 1GeV/m moving at the speed of light. No plasma or laser sources are required, or for that matter new microwave sources either, and thus if dielectric wake field accelerators are successful, they have incredible significance for future linear colliders. The energy-delivering hardware is the conventional rf linac. There would appear to be two very important issues: the matter of dielectric failure, and the question of the "transverse" (or dipole) instability. The performance of the dielectrics when exposed to transient electric field pulses of ¡ 1 psec duration indicates that a gradient 1 GV/m is reasonable to expect. This is far greater than the breakdown field for a dielectric exposed to microsecond pulses of rf. Modern dielectrics such as alumina exhibit very low loss tangent, high dielectric constant, almost zero dispersion in the microwave/millimeter band, and do not accumulate charge on the surface. The matter of the instability is being dealt with in a number of ways. Argonne described an external damping system useful for stabilizing a bunch train. Park and Hirshfield presented results of their calculations showing that a FODO system could be designed that would delay the onset of the instability in the first bunch. Marshall (Columbia U.)described a wake field "resonator" system that, by accumulating the wake field energy of several bunches, would decrease the length of the resonator module below the threshold limit of the instability. The drive bunch train energy in this system could be partly recovered in the original linac that provided the drive bunches. The consideration of the resonator has turned attention to the effect of axial boundaries on the wake fields, now receiving analytical attention by Park. If the DWFA becomes operational, one might expect some cooling problems to emerge.

Argonne [Wei Gai and Conde] described their upgraded facility (new laser and photo-cathode rf gun that should give higher gradients and better stability) for wake field studies and their future research program (which dates back many years). A successful test has been made of their two-beam accelerator concept, and higher energy tests are planned that may demonstrate gradients in excess of 100 MeV/m shortly. Indeed, the drive beam line would be carrying about 500 MW in power in this test! The previous experiment demonstrated a transformer enhancement of about two between the drive beam line (3.5 MeV/m) and the test beam line (7 MeV/m). Their work on hybrid dielectric irises may favorably impact mainline accelerator work by reducing surface fields a factor of two. A test at NRL of a dielectric-loaded slow wave TM01 structure using high power X-Band microwaves generate by a magnicon is planned soon. John Power of ANL described a method to increase the "transformer ratio" (and thus efficiency) of a co-linear wake field accelerator from the canonical value of 2 to as much as 8, using a series of about four carefully timed drive bunches of progressively increasing charge (eg, 1:3:5:7). The method may also be applied to plasma wake field accelerators too. A 40 cell ramped bunch train iris-loaded TW structure experiment is planned for operation this fall.

Whereas most wake field work involves exciting a spectrum of microwave TM modes in a cylindrical dielectric wake field device, Marshall (Columbia) pointed out that one might well imagine tall rectangular dielectric structures having optical-scale dimensions, that would be excited by fsec bunches containing pC of charge. These could deliver wake fields in excess of 1 GV/m; however, new dielectric optical materials must be created, and the use of microfabrication would be necessary.

The field of structure-based wake field accelerator research is demonstrating great progress, and results permitting an assessment of its ability to develop an advanced accelerator technology should be obtained in the next 3-5years.

C. Vacuum Acceleration Techniques

This has always been an attractive method because of the simplicity of the hardware. A variety of approaches are being examined.

At ATF, Pogorelsky described several configurations of vacuum accelerators which are a "byproduct" of the discontinued ICA experiment. These use a combination of axicon or spherical focusing of radially-polarized annular CO2 laser beams. A 0.5 nC bunch with a diameter 10(m has been achieved, and will be propagated through tiny holes in mirrors and screens that restrict the bunch-optical interaction to the dephasing length; tests begin this fall. A collaboration with Tsinghua University (Taiwan), which will develop a TEM01 "lens" array was described. If the laser power were 50 GW, it is believed that an energy gain of 2 MeV might be demonstrated in a proof of principle experiment. There are challenges, such as adjusting the angle of injection between the electrons and the photons correctly. In experiments of this type, one must deal with diffraction of the light from apertures, formation of plasmas and erosion at mirrors pierced by holes which transmit the bunches, and in the broader context of a TeV device, the issue of coherent diffraction radiation (CDR) from the bunch as it passes through tiny holes in mirrors. This could considerably reduce the energy gain per stage. Steinhauer has begun to model acceleration in the optical bounded medium.

Calculations by Ho (Fudan University, China) have revived interest in exploiting a finite path electron interaction in an intense optical beam. In certain parts of the radiation field, it turns out that the phase velocity of the light is ¡ c, and so there is potential to accelerate electrons there. The electrons must be injected in a particular way, and it is not clear now, given the substantial ponderomotive forces which can scatter electrons, that acceleration of more than a few electrons can be achieved. Nevertheless, Cline (UCLA) has proposed to examine the feasibility of such a technique, given that the potential payoff could be high.

Another technique, LACARA, is in a special class. It was described by Hirshfield (Yale, Omega-P). Acceleration of an entire psec bunch can occur in a solenoidal magnetic field, using a circularly-polarized TW CO2 laser beam which sets up a cyclotron auto-resonance with the electrons. In the 2 m length of a 6 T field, an energy increase of over 50 MeV is to be expected, with little synchrotron radiation. The LACARA is being assembled at ATF. Apart from its use as an accelerator component, the LACARA can be configured to produce a series of ultrashort current pulses, containing about 1 pC of charge each within an envelope of 3.5 fsec duration, with 10.6(m spacing. These current pulses might be injected into tiny dielectric structures which minimize the problem of CDR (Marshall), injected into a LWFA as a "test bunch", injected into a PWFA as a train of "drive bunches", or used in a variety of spin-off applications, such as producing a train of short X-Ray pulses (competing with Compton backscattering of laser pulses off of relativistic charge bunches). The short bunch technique in LACARA is referred to as "chopping" rather than "bunching", since it is geometrical in origin, and indeed it may be superior in some respects to the bunching that is produced in the FEL and IFEL at present insofar as applications are concerned.

Mikhailichenko (Cornell) described an accelerator system in which a series of coupled open-sided cavities is illuminated by an intense laser beam which is swept as a traveling-wave focus over the structure synchronous with the bunch. The accelerator hardware is a microfabricated structure, and the laser beam is moved electro-optically. The question of laser damage in such a structure is important, but that is also true of conventional structures, and relates to the expected lifetime of the system. Damage tests would yield guidance in this connection.

D. Summary of Non-Plasma Based Acceleration

In summary, the areas of IFEL and DWFA are becoming mature, and are capable of proof-of-principle demonstrations in the next few years. Tests of the smaller optical structures are planned for the near future, and it is too early to reach a conclusion about their prospects. The IFEL, while it cannot achieve TEV energies, can contribute to parts of a staged accelerator system, or as an injector for plasma-based accelerators. New tests are planned which should obtain large energy increases and gradients approaching 100 MeV/m. A new method of chopping psec bunches into fsec pieces by the LACARA has been devised and should be tested, as it may have some advantages over methods in current use. Providing issues of stability and breakdown can be successfully resolved, the DWFA may play an important role in accelerator physics of the future, as it uses no plasma, and does not require power from a laser source but rather from a conventional rf linac which is capable of very high efficiency. One might anticipate gradients in the range of 100 MeV/m to 1 GeV/m from the DWFA. All areas of this topic have contributed "spin-offs" to the rest of accelerator physics, and potentially to the science community at large.

V. ADVANCED RF SOURCES

At Snowmass 2001, advanced RF technology concepts (similar in spirit to other topics within T8) were discussed jointly with Working Group T3, wherein "mainline" current RF issues were the central theme. This merge was intended to insure that participants who focus on research for advanced concepts could cast their work in an intellectual and parameter-space framework familiar to people associated with goal-oriented RF projects (notably for NLC and CLIC), and engender commentary from those goal-oriented scientists. Conversely, the merge was also intended to provide an opportunity for goal-oriented scientists to be exposed to some of the latest ideas for next-generation RF technology that might apply to a future linear collider.

Presentations given at Snowmass2001 on advanced RF technology can be categorized into (i) expositions on alternate RF sources other than round-beam klystrons; and (ii) expositions on miscellaneous topics that included active RF pulse compressors mainly at 11.4 GHz, sheet beams, accelerator structures at 17.1 and 34.3 GHz, and dielectric accelerator structures.

A. RF Sources Other than Conventional Klystrons

Steven Gold (NRL) delivered an overview of "alternate" advanced RF sources that are conceived as finding application with a future high-gradient electron/positron collider. Such RF sources (amplifiers by necessity) include gyroklystrons, magnicons, CARM's, and gyroharmonic frequency converters. These can be divided into two categories: (a) those that could evolve into RF drivers for actual accelerators by virtue of high peak and average powers, high phase and amplitude stability, high intrinsic efficiency, and moderate to low eventual production cost; and (b) those that might fill needs as "one-off" high-power sources for testing RF components and accelerator structures at frequencies where no other sources exist. For example, the savings in power costs for operation of TESLA over a 15 year span would amount to about $100 million, if the 1.3 GHz RF sources could have an efficiency of 73%, rather than the present 63% for the multi-beam klystrons, assuming an electricity cost of $ 0.10/kW-hr. Specifications for devices in category (b) might not be as stringent as in (a), with intrinsic efficiency often not considered crucial. However, toleration for low intrinsic efficiency for either (a) or (b) should perhaps be limited in pursuing development of alternate RF sources, whenever a justification is used that overall efficiency can eventually be increased by use of a depressed collector. This remedy for inefficiency can be faulted on two counts, namely (i) added cost for construction of the tube itself together with the complexity of the modulator, and (ii) increased susceptibility of the tube to spurious oscillations driven by the higher current needed to overcome intrinsic inefficiency. Prudence may suggest that future consideration of new ideas for alternate RF sources be scrutinized with these considerations in mind, if the underlying fundamental physics can be shown to impose a severe limitation on intrinsic efficiency or some other critical parameter.

The most mature advanced RF source beyond the conventional round-beam klystron is the gyroklystron, an amplifier first described over 30 years ago in published US and unpublished USSR work. In fact, development of a 91 GHz gyroklystron by NRL with 100 kW peak, 10 kW average power; and by IAP (Nizhny Novgorod, Russia) of a 91 GHz, 200 kW peak power gyroklystron, both for radar applications, speaks to the versatility of this interaction. Greatest strides with high-power gyroklystrons intended for application as drivers for a future collider have been made at University of Maryland (U. Md), in an effort directed by V. L. Granatstein and W. Lawson. Gold summarized the U. Md achievements, including high-gain amplifiers at 9.9 GHz using TE01 cylindrical cavities that achieved 27 MW peak power with 32% efficiency, and at 8.6 GHz using coaxial TE01 cavities that achieved 75 MW peak power also with 32% efficiency. Work is now underway with a second-harmonic TE01/TE02 progeny of the latter device that is expected to achieve 80 MW with 40% efficiency; to date this device has yielded but 28 MW peak output power at 12% efficiency limited, it is postulated, by difficulties arising from non-uniform cathode emission. Some problems with U. Md coaxial gyroklystrons may also be attributable to use of radial tungsten pins to support the coaxial insert. Conceptual design at CPI for a 30 GHz gyroklystron to yield 50 MW peak power in a coaxial design without radial support pins for the coaxial insert was described; this device is intended to provide power for testing RF components and accelerator structures at CLIC, when used with some type of (undisclosed) RF pulse compressor to achieve peak power levels of 300 MW. Finally, mention was made of a 10 MW peak power TE02 gyroklystron under development at Calabazas Creek Research (L. Ives and W. Lawson) that is expected to operate at 91 GHz with 55 dB gain at an efficiency of 40%, using a 500 kV, 55 A beam. Elaboration of details of gyroklystron developments was provided in separate talks by W. Lawson (U. Md) and M. Blank (CPI).

Gold pointed out virtues of gyroklystrons that include good frequency scaling, a long track record, and achievement of record peak power outputs at frequencies above 11.4 GHz. Possible limitations of gyroklystrons for accelerator applications that still require careful examination include phase and amplitude stability, operation without a circulator into a resonant narrow-band load (such as an RF pulse compressor and/or an accelerator structure), intrinsic inefficiency, and cost and cooling issues attending use of internal absorbing ceramics.

The RF amplifier described by Gold that is second in maturity to the gyroklystron is the magnicon, as subsequently elaborated upon in a talk by O. Nezhevenko (Omega-P). The magnicon is a scanning-beam device descended from Budker's gyrocon, a sub-GHz amplifier that achieved 80-90% efficiency by employing a low-perveance beam with rotating RF cavity TM-modes, wherein electrons at all RF phases interact equally and without bunching. In magnicons, an axial magnetic field is imposed to both guide the beam through a series of drive, gain, and output cavities, and to provide local resonance with the RF fields. The first magnicon, built by Karliner, Nezhevenko, et al at Budker INP, Novosibirsk, Russia (BINP) produced 2.6 MW peak power at 915 MHz using a 300 kV, 12 A beam; it operated with 73% efficiency. This remarkable result engendered further research at BINP on a 7 GHz tube, and at Omega-P and NRL in a collaboration for developing a 11.4 GHz tube. The 7 GHz, 2nd harmonic magnicon built in 1998 at BINP produced 55 MW peak power output at 56% efficiency. The 11.4 GHz Omega-P/NRL tube was designed to deliver 63 MW peak power in a 1.2 (sec pulse with 63% efficiency; however, fabrication errors in the electron gun moderate expectations to 60 MW peak power with 58% efficiency. This tube, still in RF conditioning at this writing, has so far demonstrated 15 MW peak power output in a 1.2 (sec pulse, and 25 MW peak output in a 200 nsec pulse. No impediments to achievement of full peak output power have yet arisen. The Omega-P/NRL tube, once it achieves full output power, is to be the key element in an X-band test facility being established at NRL, available to the accelerator community for testing of accelerator components and structures, and second only to SLAC with high-power X-band capability. Initially, the facility is being used for evaluation of high-power X-band RF active pulse compressors designed and built by Omega-P in collaboration with IAP, and of dielectric accelerator structures designed and built by a group led by W. Gai (ANL). The RF active pulse compressor program was expanded in June 2001 to include NRL as a direct scientific participant.

Nezhevenko described conceptual and engineering development of a 10 MW peak, 400 kW average power magnicon with 76% efficiency suitable as the RF driver for TESLA. However, there are no current plans to build this tube. He also described conceptual and engineering development of a 3rd harmonic magnicon at 34.3 GHz that is currently under construction, which is predicted to achieve a peak output power of 45 MW in a 1 (sec pulse at a 10 Hz prf with 45% efficiency. This 34.3 GHz high-power source is intended to be the centerpiece for a test facility at the Yale Beam Physics Lab (YBPL) for evaluation of components and structures at a frequency significantly higher (3() than the NLC frequency. This magnicon utilizes a 500 kV, 215 A beam with an area compression ratio of 2500:1; the beam diameter in the RF interaction region is 0.8-1.0 mm, close to the Brillouin limit. This gun, with an appropriate beam collector in a diode configuration, is installed at YBPL, where it has been tested to nearly 100 MW peak power and shows a measured perveance of 0.62 (10-6 A-V-3/2, precisely in agreement with predictions. This gun result is significant, since it demonstrates the possibility of building high-area-compression 100 MW level guns without unexpected errors due to differential thermal expansion, as in earlier high-compression guns. Geometrical beam emittance due to aberrations in this gun is estimated to be only about 20% of the irreducible thermal emittance. Further contributions to the increasing maturity of magnicon development lie in the supporting design codes (V. Yakovlev, Omega-P) that are steadily evolving in precision and flexibility. The 56% efficiency value measured for the BINP 7 GHz tube is in precise agreement with the value predicted using these codes. Nezhevenko stated that ever-increasing confidence in these design codes, with confirmation from experimental tests at 7 and 11.424 GHz, should allow the magnicon to emerge as the leading competitor to the conventional klystron for future application in driving an advanced collider. Discussing fabrication issues, Nezhevenko pointed out that magnicons are topologically identical to conventional klystrons: each employs a Pierce gun with perveance (1(10-6 A-V-3/2, an all copper rf cavity chain, and a beam collector. Magnicons could even play a role in NLC, since Omega-P has a preliminary design for a 150 MW peak power magnicon at 11.424 GHz, with cathode current loading as low as in the 5045 S-band SLAC klystron, and peak RF fields in the cavities lower than in the SLAC 75 MW X-band klystron. Such a tube could in principle replace two 75 MW SLAC X-band PPM klystrons in NLC, with a cost savings that could more than justify the added cost for the required dry superconducting solenoid. Virtues of magnicons include higher intrinsic efficiency than for any other known contender, fastwave interaction in TM cavities that are larger than cavities in klystrons at the same frequency, short drift tunnels between cavities, good control over spurious modes, no internal lossy ceramics with attendant cooling challenges, good amplitude and phase stability, and experimentally-proven ability to operate without a circulator into narrow-band resonant loads without generation of spurious oscillations. The major challenge in construction of magnicons, especially at short wavelengths, is the high area compression required for the electron beam; but this challenge seems to have been met with successful design and operation to date of three high-compression magnicon guns.

Gold briefly described CARM amplifiers, which have so far operated at multi-MW peak output powers at frequencies up to about 35 GHz, but with efficiencies that did not exceed about 27%. The intrinsic efficiency in a CARM is severely limited by beam axial velocity spread. But a new approach in a dual-mode CARM has recently been proposed by V. Bratman (IAP) that may overcome this velocity-spread limitation and allow a CARM to operate in a parameter range with peak power and efficiency suitable for future accelerator applications. Beam-mode coupling is near cutoff where velocity spread effects are small, while mode-mode coupling provides significant Doppler up-shift. Gold further described work carried out by M. LaPointe et al (Yale/Omega-P) on harmonic converters. Such devices might find application for testing RF components and accelerator structures at high power at frequencies where no other sources exist. Experiments carried out by LaPointe showed high power output (¿ 1 MW) at harmonics 3, 4, and 7 of the 2.856 GHz driver frequency (from a former SLAC XK-5 klystron) using a gyroresonant traveling wave interaction. But absence of frequency selection led to mode competition in this device that would limit its practical utility. Presently, a two-cavity 7th harmonic converter is under construction by LaPointe, based on a simulation by Yakovlev using Omega-P magnicon design codes, that is expected to produce 4 MW peak output power at 20 GHz with 40% RF conversion efficiency without serious mode competition. This approach could allow generation of multi-MW pulsed RF power at a variety of desired harmonics of 2.856 GHz, by replacing the output cavity and modifying the magnetic field profile.

C. Chen (MIT) discussed equilibrium and stability for a sheet beam that may be suitable for a sheet-beam klystron. Suppression of beam halo was shown to be crucial to practical application of sheet beams. Unfortunately, a late cancellation of a presentation by G. Caryotakis (SLAC) on a design for such a tube prevented discussion of this topic in its full complexity.

B. Other Advanced High-power RF Technology

R. Temkin (MIT) described design and construction of a 1-1/2 cell RF gun at 17.1 GHz that operates with an accelerating gradient approaching 200 MV/m. This gun is driven by the 17.1 GHz klystron built by J. Haimson and installed at MIT. Beam bunches from the RF gun can be injected synchronously with RF applied to a Haimson RF linac installed nearby. So far tests of this advanced accelerator configuration have been at a power level not exceeding 4 MW, due to concern for structure damage. Higher applied power could allow a gradient of 60 MV/m to be reached in this structure. Work at MIT at 17.1 GHz has also includes development of a photon band-gap cavity with fields near the axis resembling those of a TE04 mode cylindrical cavity. In the photon band-gap cavity this mode is the lowest mode, and competing modes are far away. This new cavity has been operated by Temkin et al as part of a gyrotron oscillator with an output power of 25 kW. Temkin also described a conceptual accelerator structure based on use of a similar photon band-gap structure with built-in damping of higher-order modes; this could be an attractive feature for suppression of transverse wake forces. However, further study of photon-gap structures is needed to determine whether ohmic losses and/or fatigue due to pulse heating in the structure's thin rods would restrict its power handling capacity at the power levels required for accelerator applications (Photon band-gap structures were first introduced by Schultz, Kroll et al at UCSD).

A. Vikharev (Omega-P, IAP) described design and first high-power experimental results with active RF pulse compressors at 11.4 GHz. High-power plasma switches are at the heart of these designs, complementary to the solid state and ferrite switch elements studied by S. Tantawi (SLAC). Tantawi has christened a successful high-power switch the "holy grail" of RF pulse compression, and points out unique virtues that would attend the use of such a switch, through the added flexibility in RF system design that can be provided using high compression ratio. A single-channel active Bragg compressor (ABC) was described by Vikharev that utilized mode converters with a TE01 energy storage cavity having a quality factor of about 24,000. Cylindrical quartz tube plasma switches, fired by a high-voltage nsec-risetime kA pulser, allow rapid energy extraction by lowering the reflection coefficient at one port of the storage resonator ("Q-switching"), with attendant compression of the incident RF pulse. Tests during April 2001 using the Omega-P/NRL X-band magnicon showed compressed pulses with both triggered and non-triggered switching, but with evidence in some tests of multipactor breakdown on the exterior of the quartz plasma discharge tubes. Peak output in compressed pulses of 14.5 MW was observed, with a compression ratio ¿6:1. Redesign of the plasma switch tubes is underway with improved precision in the tube dimensions, TiN coating to inhibit multipactor discharges, and slightly larger major diameter to reduce the magnitude of RF field at the tube's location. Operation in the near future is planned of single- and double-channel ABC's with compression ratios ¿10:1 and peak compressed pulses of 100-150 MW; designs were described for a 2nd generation ABC with a peak output power of 500 MW. Preliminary work on quasi-optical passive and active RF pulse compressors for use at 34 GHz was also briefly described by Vikharev.

W. Gai (ANL) described designs and planned experiments where smooth-wall dielectric-loaded structures are employed for accelerator structures. He characterized these structures as being of simple design and fabrication, of comparable shunt impedance as disk-loaded structures, with easily damped higher-order modes (using wall slots), and with the axial accelerating field being the maximum field in the structure. Dielectric-loaded structures are of interest in wake field studies, where the accelerating fields arise from Cerenkov radiation from a drive bunch or bunches; as well as where the accelerating fields are externally driven from an RF source. The former approach was discussed by Gai, Powers and Conde elsewhere within T8, while the latter approach was discussed in the context of advanced RF structures. General unsolved issues with dielectric-loaded structures include dielectric breakdown limits, ohmic heating and attendant cooling of the dielectric, and gas absorption. A further issue brought out in the discussions concerned breakdown at an internal gap at the interface between dielectric and metallic wall, or between two sections of dielectric; breakdown at such gaps has been observed by Fang et al (Columbia) in experiments at YBPL. A variety of candidate structures was described by Gai, with the first of these scheduled for initial high-power tests in Fall 2001 using the Omega-P/NRL magnicon. This structure consists of an annular dielectric liner with (= 20 in a smooth conducting pipe, with radii adjusted for a group velocity of 0.05c at 11.424 GHz. The liner is tapered at each end where magnetic coupling to external WR-90 waveguides occurs. Cold tests of the structure show 1% power reflection and 70% power transmission, with cause for the 29% power loss not clear. The structure is to be exposed to external RF at 11.424 GHz to determine its power handling capacity. If such tests are successful, a small beam injector and beam energy analyzer will then be installed to observe actual acceleration up to 10 MeV and, with a longer structure, up to 40 MeV. Further structures described by Gai included a hybrid disk-loaded waveguide with dielectric inserts to reduce fields at the iris tips, and alternately-rotated rectangular waveguides with slabs of dielectric along the long faces to provide FODO-like alternate-gradient focusing. Goals of this work include studies of dielectric breakdown up to 100 MV/m, standing- and traveling-wave structures, and variation amongst three different dielectric materials. W. Gai emphasized the need for a dedicated facility, such as that at NRL using the Omega-P/NRL magnicon, for careful systematic tests of these advanced accelerating structures.

O. Nezhevenko (Omega-P) described designs, cold tests, and future plans for high-power tests of accelerating structures at 34.272 GHz, using the Omega-P 34.272 GHz magnicon as the RF source. One objective of this program is to determine the maximum accelerating gradient that can be sustained by a disk-loaded structure at a frequency three-times higher than the NLC frequency. One structure, which has been designed and cold-tested for high-power tests up to a surface field of 650 MV/m using 45 MW of magnicon output, is a 2(/3, 57-mm long structure containing 19 TM010 cells that operate in the standing-wave mode. This structure has a group velocity of about 0.05c. The input coupler to the structure is a TM020 cavity with four symmetric WR-28 waveguide inputs to provide highly-symmetric fields near the axis, and to avoid surface field enhancements that have characterized other input couplers using TM010 cavities. A further goal of this program is development of a test device for subjecting surfaces to high peak RF magnetic fields to explore pulse heating and metal fatigue limits. In a particular pulse heating test structure that was described, application of a few MW at 34.373 GHz can allow surface temperature excursions up to 500(C, more than three times that in 11.424 GHz tests conducted at SLAC. The goals of these structure and pulse heating tests is to add data to that collected at lower frequencies in the expectation of establishing reliable scaling laws for high-gradient RF accelerator structures and components.

C. Summary of Advanced RF Sources

In summary, recent discoveries at SLAC, CERN and KEK show that long-held beliefs on scaling laws for breakdown in high-gradient accelerator structures require revision for prediction of performance at X- and Ka-band, and presumably at higher frequencies. A lesson that can be drawn from the last decade's evolution of superconducting high-power RF technology is that remarkable advances can result from a broad fundamental R&D program. A similar broad RF technology R&D program has not been a practical option at microwave and mm-wave frequencies for normal-conducting structures and components, because no suitable high-power amplifiers were available, other than SLAC X-band klystrons. This situation is changing, with development of advanced high-power sources and dedicated test facilities at 11.424 GHz (Omega-P/NRL), 17.1 GHz (U. Md and Haimson/MIT), 30 GHz (CPI), 34.272 GHz (Omega-P), and 91 GHz (Calabazas Creek). Laboratory facilities are emerging, aside from those at National Laboratories, for development of advanced high-power RF components and for testing of high gradient accelerator structures. Progress towards the international goal of a future high-gradient electron-positron collider is likely to be more rapid if means can be found to nurture and strengthen this nascent research community.

VI. COMPUTATIONAL TECHNIQUES

The past five years has witnessed a watershed of experimental results on both laser and particle beam driven plasma wave acceleration. Much of this work was summarized in the T8 working group talks. This experimental work has demonstrated that ultra-high gradients can be achieved, and that large numbers of electrons can be accelerated. Recent Plasma Wake Field Accelerator (PWFA) experiments at SLAC have indicated that coherent wakes can be excited over meter distances, while Laser Wake Field Accelerator (LWFA) experiments at several institutions (Rutherford Laboratory, University of Michigan, NRL, LBNL, LOA, Garching) have demonstrated gradients on the order of several hundred to 1000 MeV/cm. Based on these results there are proposals for GeV LWFA stages and energy doubler afterburner designs for existing linear colliders.

Along with the experimental advances, there have been breakthroughs in high-performance computing. Since the first parallel 2D particle-in-cell (PIC) code results five years ago there has been an explosion of advances in physics algorithms, parallel computation algorithms, and computer hardware. Presently, the community has developed a hierarchy of particle models, and full-scale 3D modeling is possible for existing experiments (results from OSIRIS were presented in the T8 working group). Using this base, the simulation community has already shown the codes to be accurate and useful in interpreting and guiding existing experiments. However, to model in full scale and three dimensions the plasma-based accelerator experiments currently being planned will require advances in software engineering and the development of high-fidelity reduced description models. To model 100 GeV plasma accelerator stages will require ensuring that the high parallel efficiency currently obtained on hundreds of processors be extended to thousands or even 10's of thousands of processors. The goal for the simulation community for the next five years is to build a suite of high fidelity electromagnetic particle-in-cell

(PIC) simulations in two and three dimensions that can support and guide further theoretical and experimental efforts to make plasma-based accelerator technology practical for real world applications. The final stage will be to integrate the plasma accelerator code suite into mainline accelerator codes so that one can seamlessly model an RF Linac with a plasma lens or plasma afterburner incorporated into its design.

There was an afternoon session, together with working group T7, dedicated to talks on the current status and future plans of those currently doing high-performance computing.

From these talks there were clear goals and some clear paths towards their achievement. For example, by there very nature 3D PIC simulations of plasma-based accelerators require effective use of parallel processing on teraflop scale computers, with flexible domain decomposition and, for particular problems, dynamic load balancing. Other critical features include a moving window to follow the driving laser pulse or electron bunch, electromagnetic wave launchers and particle beam emitters, and absorbing boundary conditions. Laser ionization models are required to accurately model propagation of the drive laser pulse through a neutral gas jet. Similarly, electron impact ionization models will probably be required to model the plasma afterburner designs. It was also clear that accurate reduced description particle based models will be essential for real-time 3D modeling of experiments and for modeling GeV stages and beyond.

To understand the challenges for high-performance computing we can estimate the computer requirements for modeling 1 GeV plasma accelerator stages. We use the known scaling of the peak accelerating fields, E mc(p/e. For practical reasons the peak gradient is typically a fraction of this, e.g., 0.5. In order to gain 1 GeV then an electron must move 4000 c/(p. Since the accelerated particles and the driver are both moving at the speed of light, it is not necessary to model the entire region of plasma.

Instead all that is required is to model the driver and a few wavelengths of the wake. This requires a moving window which has already been incorporated into several of the existing codes. This scheme was pioneered by the members of the existing SciDAC team. The simulation region also needs to be about 1 plasma wavelength wide and 3 plasma wavelengths long. If we assume that the cell size is .05 c/(p then the simulation requires a 500 x 200 x 200 grid and .5 to 1 x 108 particles (4 particles per cell). The Courant condition limits the time step to .025 (p-1 (in 3D) so that to follow a relativistic beam for 4000 c/(p requires 1.6 x 105 time steps. Such a 3D run requires 1-2 x 1013 particle-steps and on the current SP2 and T3E nodes, and assuming 5-20 (s/particle-step (depends on the code dimension and current deposition scheme), it would take 1 x 104 node hrs. Higher resolution runs with 10 times as many particles but fewer time steps might be needed to ensure convergence. To scale this upward toward 100 GeV afterburner stages will require 100 times the CPU time but the same amount of computer memory. Therefore to scale this problem to a 10 or 100 GeV PWFA afterburner stage will require work on the parallel algorithms. Modeling laser-plasma accelerators is a greater challenge because the laser frequency needs to be resolved. The above estimates would have to be multiplied by a factor 10 to 25 to estimate the requirements to model a GeV laser stage. Based on the talks in simulation session the field has already begun to run massively parallel PIC simulations of PWFA and LWFA stages in 3D using the code OSIRIS and in 2D using OSIRIS, XOOPIC, and turboWAVE. Furthermore, turboWAVE is now running in 3D and there are various other serial 3D codes that are useful for benchmarking and certain physics studies.

Storing, processing and visualizing the data generated by 3-D PIC simulations of plasma accelerators is also a daunting challenge. For example, the memory footprint can be estimated using 48 bytes per particle and 80 bytes per cell, multiplying by 1.5 to account for additional diagnostic data, dividing this among processors and adding about 3 MB of overhead for each processor. For the 3-D PWFA and LWFA simulation parameters discussed above, each checkpoint file would be on the order of 50 GB, which implies time-sequenced data sets of order terabytes. Effective preprocessing of data will be critical to reduce the amount of saved data. High-performance post-processing of the data will also be critical, so that interactive visualization tools can be used to fully explore the results of these large simulations. Groups from UCLA, IST in Portugal, and tech-X have already been addressing some of these issues during the past few years. We also heard of some 3D visualization routines from NRL. There is a clear need for the community to work together to solve these common problems.

The estimated number of required CPU-hours presented above are daunting, so although we currently push the limits of existing parallel computers available we still have far to go. We further note that these estimates are for full PIC simulations, which are required in many cases to model the relevant physics. Therefore, there is clearly a need for reduced models, which average over the laser frequency and/or treat the fields of the plasma wake in the quasistatic (frozen field) approximation. Fluid codes in 2D and 3D are also being developed as a less computationally demanding alternative to PIC codes for use in modeling problems in which kinetic effects are unimportant. However, it is also clear that fully explicit models will be needed to verify the reduced description models and to identify the parameter regimes for which they are valid.

As indicated in the program there were several reduced description particle models that were discussed, turboWAVE, WAKE, and quickPIC. In addition, fluid models were also discussed in several talks. TurboWAVE already has a ponderomotive guiding center model embedded into it, WAKE is an existing 2D quasi-static code for modeling laser drivers, and quickPIC is a parallelized, 3D quasi-static PIC code for modeling beam drivers.

A 3D set of equations using this approach has already been successfully included into turboWAVE. In addition, for many situations of interest the drive beam evolves on a much longer time scale than the plasma frequency. In these cases the beam appears static or frozen for long periods of time. Under these conditions one can make the quasi-static or frozen field approximation. For example, the code WAKE successfully uses these equations in a 2D code for laser drivers. In one talk we heard about quickPIC, which is the beginning of a 3D quasi-static parallel code. This novel code embeds a 2D parallel code inside a 3D parallel code. Preliminary results look promising. However, it is anticipated that the field description will have to be expanded to include the plasma current to more accurately determine the wake properties. Based on lessons learned from WAKE, there was some discussion that implementing such an algorithm will require predictor corrector routines and it might require using another gauge for laser drivers.

In summary, much progress has been made in high-performance computing since the last Snowmass workshop. This progress includes advances in software, hardware, parallel algorithms, visualization routines, and accurate reduced description algorithms. Currently, it takes 10,000 hours of node hours to model a GeV PWFA stage using a fully explicit PIC code such as OSIRIS in 3D. While this is a major advance, it does not allow real-time feedback between experiments and there is a big gap towards modeling 100 GeV stages. The challenge is to reduce the turn around time from months to minutes and this may be possible through a combination of efficient parallel and reduced description algorithms.

VII. INVITED TALKS PRESENTED AT THE T8 WORKING GROUP

A. Plasma Based Acceleration

"Review of LWFA Experiments", Tony Ting (NRL)
"Overview of Neptune Facility", Sergei Tochitsky (UCLA)
"Overview of PWFA Experiments, E-157", Chris Clayton (UCLA)
"Laser Plasma Channel Guiding", Mike Downer (U. Texas)
"Proton Acceleration using Lasers", Tom Cowan (Gen. Atomic)
"Ion Acceleration", Anatoly Maksimchuk (U. Mich)
"Experiments on laser-plasma acceleration at LBNL", Wim Leemans (LBNL)
"Plasma Channel Guiding of Laser Beams", Howard Milchberg (U. MD)
"Laser-Plasma Acceleration Developments in Japan", Kazuhisa Nakajima (KEK)
"Laser Interaction Experiments at Michigan", Don Umstadter (U. Mich.)
"Laser Pulse Propagation and Ionization", Phil Sprangle (NRL)
"Propagation of Laser Pulses in Plasmas", Eric Esarey (LBNL)
"Laser Ponderomotive Guiding of Laser Pulses", Bahman Hafizi (NRL)
"Particle-in-Cell Simulations of Gas Ionization by Short Intense Laser Pulses", D.A. Dimitrov (Tech-X)
"3D Simulation of LWFA", Dan Gordon (NRL)
"Experimental Results from E-162 Project", Chris Clayton (USC)
"E-157 Experiments", M. Hogan (SLAC)
"Simulation of Plasma Wakefield Acceleration in Three Dimensions", Glenn Joyce (NRL)
"Dynamics of a High Charge Electron Bunch in a Plasma", James Rosenzweig (UCLA)
" Hosing of GeV Class Drive Beams", Evan Dodd (UCLA)
"Particle-in-Cell Simulations of Beam-Induced Ionization in Plasma Wakefield Accelerators and Plasma Lenses", D.L. Bruhwiler (Tech-X)
"Results on Plasma Wakefields from the A0 Experiments at Fermilab", N. Barov (UCLA)
"Diagnostic Techniques", Chris Clayton (UCLA)
"Simulations of LWFA", Tom Antonsen (U. MD)
"Scaling Laws for LWFA", Dick Hubbard (NRL)
"LWFA in Plasma Channels", Joe Penano (NRL)
"Applications of Raman Backscattering for Plasma Wave Generation and Laser Pulse Compression", Gennady Shvets (Princeton U.)
"Backward Raman Pulse Amplication", Dan Gordon (NRL)
"Emittance Growth and Equilibrium in Beam-Plasma Systems", Jonathan Wurtele (UCB)
"Fluid simulations of laser-plasma interactions", Brad Shadwick (LBNL)
"XOOPIC particle simulations of laser-plasma interactions", Peter Mardahl (UCB)
Visionary Talks
"The Continuing Challenge for New Accelerating Concepts", Dave Sutter (DOE)
"Ultra-High Intensity Laser Physics, Present and Future", G. Mourou (U. Mich.)

"Dedicated Facility for Laboratory Astrophysics Using High Intensity Particle and Photon Beams", Pisin Chen (SLAC)

"A Roadmap to the Energy Frontier", Tom Katsouleas (USC)

"Realization of a Hollow Plasma Channel for Accelerating Positrons" Chan Joshi (UCLA)

Plasma Based Injectors

"High-Performance Computing of Plasma Accelerators", Warren Mori (UCLA)

"Laser Ionization and Ponderomotive Acceleration (LIPA)", Chris Moore (NRL)

"Electron Injection using Colliding Laser Pulses", Wim Leemans (LBNL)

"Laser Injected Laser Acceleration (LILAC)", Don Umstadter (U. Mich.)

"Injection into Plasma Wakefields using a Density Transition", Jamie Rosenzweig (UCLA)

"Simulation of beam injection by overlapping laser pulses", John Cary/Rodolfo Giacone (U. CO Boulder)

"Laser Accelerators for Injectors", Rainer Pitthan (SLAC)

Non-Plasma Based Acceleration

"STELLA - Past and Present", Igor Pogorelsky (BNL)

"Vacuum Laser Acceleration Feasibility Tests at ATF", Igor Pogorelsky (BNL)

"The UCLA IFEL Project", Pietro Musumeci and Claudio Pellegrini (UCLA)

"Study of IFEL at 10 GeV", T.C. Marshall/ Rodney Yoder (Columbia U./Yale)

"Laser Vacuum Acceleration", David Cline (UCLA)

"New Laser Acceleration Mechanism Involving a Static Electric Field", Fred Hartemann (LLNL)

"The Dielectric Based Accelerator Concepts Study at ANL", Wei Gai (ANL)

"Enhanced Transformer Ratio Scheme and Experiment Using Ramped Bunch Train", John Power (ANL)

"Argonne Wake Field Accelerator Facility Status and Future Outlook", Manoel Conde/ John Power (ANL)

"Bunch Stability of High Gradient Wake Fields in Dielectric-Lined Waveguides", Jay Hirshfield (Yale/Omega-P) and S.Y. Park (Postech, Korea)

"Laser Cyclotron Autoresonance Accelerator (LACARA)", Jay Hirshfield (Yale/Omega-P)

"Femtosecond Planar Electron Bunch for a Micron-Scale Dielectric Wake Field Accelerator", T.C. Marshall (Columbia U.)

Plasma Based Processes

"The E-150 Plasma Lens Experiment at SLAC", J. S. Ng (SLAC)

"Tolerance to Offsets for a Plasma Lens in NLC", K. Thompson (SLAC)

"Pulse Optimization in Laser Wakefield Accelerators", A. Charman (UC Berkeley)

"The Proposed ORION Advanced Accelerator Research Facility", R. Noble (SLAC)

Advanced RF Sources (Joint with T3)

"17 GHz High Gradient Accelerator", R. Temkin (MIT)

"Sheet Beam Klystrons", C. Chen (MIT)

"Design of a 50 MW, 30 GHz Gyroklystron Amplifier", M. Blank (CPI)

"Overview of Advanced (Non-Klystron) RF Sources", S. Gold (NRL)

"Gyroklystron Development", W. Lawson (U Md)

"Magnicon Performance at 1.3, 7.0, 11.4, 34.3 GHz", O. Nezhevenko (Omega-P)

"Overview of Active and Passive Pulse Compression", S. Tantawi (SLAC)

"Active Pulse Compression with Plasma Switches", A. Vikharev (Omega-P & IAP)

"Multi-Moded High-Power RF Component Development", C. Nantista (SLAC)

"Dielectric Structures", W. Gai (ANL)

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"Overview of High-Performance Computing in Accelerator Physics", Robert Ryne (LBNL)

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"Osiris", Warren Mori (UCLA)

"Plib", Victor Decyk (UCLA)

"Turbowave", Dan Gordon (NRL)

"Xoopic/Vorpal", Chet Nieter (U. CO Boulder)

"Quasi-Static PIC: Wake", Tom Antonsen (U. MD)

"Quickpic", Warren Mori (UCLA)

"Fluid modeling", Eric Esarey (LBNL)