SLAC-PUB-11495

High Energy Density Physics and Exotic Acceleration Schemes

Thomas Cowan[1] and Eric Colby[2]

[1]*General Atomics, San Diego, CA 92121*
[2]*Stanford Linear Accelerator Center, Stanford University, Palo Alto, CA*

We summarize the reported results and the principal technical discussions that occurred in our Working Group on High Energy Density Physics and Exotic Acceleration Schemes at the 2002 workshop on Advanced Accelerator Concepts at the Mandalay Beach resort, June 22-28, 2002.

SCOPE OF THE WORKING GROUP

The High Energy Density and Exotic Acceleration working group took as our goal to reach beyond the community of plasma accelerator research with its applications to high energy physics, to promote exchange with other disciplines which are challenged by related and demanding beam physics issues. The scope of the group was to cover particle acceleration and beam transport that, unlike other groups at AAC, are *not* mediated by plasmas or by electromagnetic structures. At this Workshop, we saw an impressive advancement from years past in the area of Vacuum Acceleration, for example with the LEAP experiment at Stanford. And we saw an influx of exciting new beam physics topics involving particle propagation inside of solid-density plasmas or at extremely high charge density, particularly in the areas of laser acceleration of ions, and extreme beams for fusion energy research, including Heavy-ion Inertial Fusion beam physics.

One example of the importance and extreme nature of beam physics in HED research is the requirement in the Fast Ignitor scheme of inertial fusion to heat a compressed DT fusion pellet to keV temperatures by injection of laser-driven electron or ion beams of giga-Amp current. Even in modest experiments presently being performed on the laser-acceleration of ions from solids, mega-amp currents of MeV electrons must be transported through solid foils, requiring almost complete return current neutralization, and giving rise to a wide variety of beam-plasma instabilities. As keynote talks our group promoted Ion Acceleration (plenary talk by A. MacKinnon), which historically has grown out of inertial fusion research, and HIF Accelerator Research (invited talk by A. Friedman), which will require impressive advancements in space-charge-limited ion beam physics and in understanding the generation and transport of neutralized ion beams.

A unifying aspect of High Energy Density applications was the physics of particle beams inside of solids, which is proving to be a very important field for diverse applications such as muon cooling, fusion energy research, and ultra-bright particle

Contributed to 10th Advanced Accelerator Concepts Workshop (AAC 2002) ,
23-28 June 2002, Mandalay Beach, California

Work supported in part by Department of Energy contract DE-AC02-76SF00515

and radiation generation with high intensity lasers. We had several talks on these and other subjects, and many joint sessions with the Computational group, the EM Structures group, and the Beam Generation group. We summarize our groups' work in the following categories: vacuum acceleration schemes; ion acceleration; particle transport in solids; and applications to high energy density phenomena.

1. Exotic Acceleration Schemes

We held 3 joint sessions with the Electromagnetic Structures working group to cover schemes using laser acceleration in vacuum. Much of the recent research has concentrated on methods suitable for high energy physics machines, but the remarkable progress in laser-driven foil target proton sources has sparked interest in developing high gradient low-β acceleration for capture and acceleration. Discussion of initial beam properties (typically 1 nC, E_o~200 MeV, $\varepsilon\gamma$~0.5 μ, $\delta E/E_o$~5-10%) quickly made it clear that for most applications, a high-gradient graded-β microwave accelerator would be a reasonable choice, with the primary challenge being the requirement that the gradient in the first (or first few) accelerator sections needs to be a factor of 2-3 higher than the present state-of-the-art. Although the foil target source produces charge-neutral bunches of electrons and protons, the electrons are rapidly stripped in the capture accelerator, requiring gradients of ~200 MV/m to suppress space charge damage.

Perhaps the most unusual accelerator structure discussed was the transient photoionized silicon structure work done at Stanford University. Smith presented work to produce wavelength scale optical elements by photoionization of silicon. Fresnel zone lenses are routinely, accurately produced for near-field microscopy by illuminating silicon wafers though a mask with a laser. Exposed portions of the silicon ionize and become optically transmissive. These lenses were shown to last a few tens of picoseconds before electron-hole recombination significantly altered the optical properties. Accelerator structures could also be "printed" by a laser on silicon in the same manner by, for example, ionizing a grating pattern on the surface of the silicon and using it to couple laser radiation (at a wavelength below the bandgap) to a particle beam. Since the structure is printed fresh each time, this scheme potentially allows destructive use of the structure and considerably higher gradients as a result.

Experimental work to test metallic structures for vacuum laser acceleration at 10 μm was discussed by Yakimenko. Significant progress has been made in all aspects of the experiment, including optical testing of the accelerator cell (showing a damage threshold of ~5 J/cm^2 at 200 ps), initial beam tests with permanent-magnet quads which provide final focusing down to 30 μm spots to pass through the accelerator cell, and studies on the effects of coherent transition radiation (CTR) from the diamond entrance and exit windows of the accelerator cell enclosure. Initial timing between the laser and electron beam will be established by introducing gas into the accelerator cell (hence the windows) and looking for inverse Cerenkov acceleration. The gas will then be pumped out and the residual vacuum acceleration signature measured.

Dielectric structure research is the focus of efforts at Stanford and National Tsinghua University in Taiwan. Kimura presented the work of Huang to produce a ZnSe lens based laser accelerator for use at λ=10 μm. Damage threshold testing of

CVD diamond, ZnSe, and Ge was conducted (1.20 J/cm^2, 0.45 J/cm^2, and 0.19 J/cm^2 at 200 psec, respectively), with the lenses ultimately being constructed from ZnSe for reasons of material and machining costs. The structure is composed of 16 accelerator cells designed to guide the TEM_{01} mode, with a cell length of 2/3 z_R (f=5/3 z_R) and a 50 μm hole laser machined in the center of each lens for the beam to pass through. The lenses are independently temperature-controlled to allow phase advance correction, which will be measured by embedding the accelerator structure in one arm of an interferometer.

Barnes presented work at SLAC to design an optical injector suitable for 1 μm laser accelerator tests as part of the newly approved vacuum laser acceleration experiment, E163. Detailed simulations of a compact IFEL prebuncher and chicane using Elegant and Genesis have been conducted to establish that beams from a microwave linac source (the NLCTA in this case) may be microbunched and focused into a 1 μm accelerator with reasonable capture efficiency. An optical bunching factor of I_1/I_0~0.6 and tight focus (25x25 μm rms) were obtained for 50 pC bunches with very narrow energy spread (16 keV rms on a 60 MeV beam).

Cowan presented work at Stanford to produce accelerator structures by standard lithographic techniques in silicon. Such structures would be suitable for use in the 1.5-2.5 μm wavelength band where silicon is transparent and low-loss. Anisotropic KOH etching[1] of Si_3N_4-masked-silicon has proven capable of producing clean, vertical walls, with very high feature aspect ratios. Work to date has succeeded in producing 12:1 aspect ratio slits with straightforward etching techniques. With improved process control, significant improvement in feature aspect ratio is expected. Methods for producing photonic band gap structures and an example structure[2] were also discussed.

Xie gave a tutorial on general principles guiding laser accelerator design, and presented parameters developed at LBNL for both a proof-of-principle plasma inverse transition radiation (PITA) accelerator and for a staged PITA accelerator. Thin plasma jets with density n_o~10^{17}/cc are proposed for use as transition radiators to couple a laser mode guided in an overmoded waveguide to an electron beam. The plasma jets are spaced such that the phase slip between the particle beam and laser mode builds up to π. During the decelerative phase, the ε<1 plasma speeds up the phase slip, decreasing the energy the beam loses to the laser mode. A proof-of-principle experiment using a single plasma jet placed at the focus of a laser is outlined. For a 1 TW laser focused to a 15λ spot in a 353 μm thick 10^{18}/cc plasma jet, an energy gain of 100 MeV is predicted, corresponding to a gradient of 44 GeV/m. Questions of absorption and refraction of the laser pulse in the plasma jets and wakefields within the plasma remain to be looked at.

Ho from Fudan University, Beijing presented simulation work on nonlinear Compton scattering in extremely intense laser fields. For highly relativistic laser pulses (a_o~100) simulations showed that a very low energy (γ_o~10-40) electron beam would scatter from the location of the laser focus as with the usual ponderomotive interaction, but would briefly bunch and trap in the EM wave under gradients predicted to reach ~1.4 TeV/m. The scattered electron bunch was calculated to reach γ_f~7000 and to have become strongly optically bunched.

In addition to the question of what physical mechanisms can lead to higher accelerating gradients are always the essential questions of what accelerated beam current and beam quality are possible, and for high energy physics machines, what power efficiency is possible. These issues were discussed in joint session with the EM Structures working group, and an outline of the discussion may be found in their working group summary.

2. Ion Acceleration Physics

Laser generation of intense proton and ion beams is an extremely active area of research worldwide, and we had excellent talks from groups working in the U.S., Europe and Japan. Some of the key issues presently facing the community are to understand the production of ultra-low emittance proton beams from the rear-surface of solid foils, understand the very robust generation of beams at low energies from the front surface of irradiated foils, and to reconcile apparently conflicting experimental results as to the dominant acceleration mechanism. Many applications of laser accelerated protons and ions were also discussed, which will be detailed in section 4 below.

A MacKinnon (LLNL) provided a comprehensive overview of ion acceleration with lasers in his plenary talk. He featured data from an IC-RAL-Belfast-LLNL collaboration working at the RAL Vulcan laser, and from subsequent work at LLNL with the JanUSP laser. His group showed proton acceleration to >25 MeV, which could be switched off by perturbing the rear surface of the target with a pre-heating laser pulse. He showed that the so-called Target Normal Sheath Acceleration mechanism could explain the results from his groups, as well as those of the earlier LLNL-Petawatt laser group (Snavely et al.), and the GA-GSI-LULI-MPQ group (Cowan et al.). And he showed very impressive pump-probe applications of laser-accelerated ions to image strong electric fields in plasmas, and plans for experiments to image shock waves in solids with laser-accelerated protons. In the working group, K. Flippo (Univ. Mich.) showed data from CUOS group on front-surface ion acceleration. They accelerated deuterons from the front surface of a plastic foil, through the target substrate and into a ^{10}B catcher to produce ^{11}C by the (d,n) nuclear reaction. When they turned the foil to accelerated deuterons from the rear surface, they did not observe nuclear reactions. Moreover, they developed a model for the acceleration mechanism that involved sheath field generation within the target foil, assuming the foil remained non-ionized during the laser pulse. They were able thereby to explain the systematic dependence of the observed proton energy on target type and target thickness. K. Kinoshita (Univ. Tokyo) introduced new work by a Japanese group on laser-ion acceleration, using also a 1 J-class short pulse laser. They observe low energy protons only (up to 100 keV) from the front and rear surfaces of their target foil. A large prepulse in these experiments probably produced a large density scale length pre-plasma, which inhibited proton acceleration to higher energies. T. Cowan (General Atomics) presented data from a GA-GSI-LULI-MPQ collaboration working at the Ecole Polytechnique LULI 100 TW laser. They observed ultra-low emittance proton acceleration (normalized rms emittance < 0.006 μm) at 10 MeV, as

evidenced by the formation and preservation of 100 nm scale structures in the proton beam by patterning the rear surface of the laser-target foil. They also demonstrated heavier ion acceleration, for example He-like Fluorine acceleration up to 100 MeV, by coating CaF_2 on the rear surface of a 50 μm tungsten foil. Resistive heating up to 1200 K was required to completely remove contaminant hydrogen which otherwise "poisons" the heavy-ion acceleration by virtue of its higher charge-to-mass ratio. The LULI experiment also reproduced the Univ. Michigan deuteron acceleration experiment, and showed that with much larger laser pulse energy (up to 20 J), acceleration of deuterons from the rear surface of the target foil was not only possible, but also more efficient at producing ^{11}C radioisotopes than by the front surface acceleration mechanism. Similar results were obtained by $^{48}Ti(p,n)^{48}V$ reactions. MacKinnon presented additional data by the LLNL group in the working group session regarding the enhancement of rear surface acceleration by matching the target thickness to the laser pulse duration, allowing for the recirculation of hot electrons, thereby enhancing the sheath field strength. We discussed that this model appeared nominally consistent with the target-thickness dependence data of the Michigan group (Flippo et al.).

In a joint session with the Computational Accelerator Physics group, H. Ruhl (GA) presented a theoretical analysis of the nano-focusing results from the GA-GSI-LULI-MPQ experiment, showing that they actually arose from a modification of the longitudinal phase space of the protons. This arises from the longitudinal electric field enhancement during the initial virtual cathode phase of the acceleration by accumulation of the ion charge at the initial foci. C. Ren (UCLA) presented a series of OSIRIS simulations of the front surface proton acceleration due to ion shock waves driven through the target plasma by the laser. This joint work with a Lisbon, Portugal group showed that under certain circumstances, front surface proton acceleration could lead to higher energies than rear surface acceleration, and that for underdense plasmas acceleration to very high energies may be possible. Y. Sentoku (Osaka and GA) subsequently showed very similar ion-shock-like phenomena in published simulations of an experiment performed at Osaka (Izumi et al., Phys. Rev. E., 2002), in which deuterons were accelerated from the front surface of a CD_2 foil, and were diagnosed by the D-D beam fusion neutrons produced in the bulk of the target. He showed that for plasma density gradients on the front surface of solid targets, the maximum proton or deuteron energy would be of order of the ponderomotive potential of the laser, due to the quasi-static charge separation field at the critical density surface. Sentoku also provided details of the theoretical modeling he did for the Michigan experiment, and pointed out that a key assumption was the non-ionization of the bulk of the solid target. This led into discussions of the properties of particle transport in solids.

3. Particle transport through Solid-density Matter

As noted above, the propagation of intense beams of electrons, or other charged particles through solids is a pervading issue in HED physics as well as laser acceleration of ions. R. Campbell (Sandia National Lab) presented the LSP code and discussed its use to understand relativistic electron transport through solids in the context of Fast Ignitor research and ion acceleration. He found for example, that at

MA currents of MeV electrons, a hollowing of the transported electron beam appeared to occur, as well as a rapid radial increase in the beam from the initial ~10 μm laser focal spot to of order 100 μm. This is suggestive of recent electron transport experiments conducted at LULI and RAL by a joint European-US group (including A. MacKinnon, T. Cowan and coworkers). H. Ruhl (GA) discussed the use of his PSC code to simulate the initial laser-solid interaction physics on a much finer spatial scale than LSP. He observed rapid filamentation of the laser-generated electrons and a strong inhibition of their initial transport by 100 MG-scale magnetic fields. A rapid coalescence of these filaments was observed, restoring at deeper depths in the target foil a more usual beam transport. Such "anomalous resistivity" was also observed in PIC simulations by Sentoku (Osaka). A picture emerged that the initial phase of the electron transport, which is initially dominated by skin-depth scale electromagnetic instabilities, may not be properly treated in LSP, whose smallest spatial resolution was 0.8 μm. A plan for joint work was identified to resolve the differences between LSP and the PIC codes.

One of the pressing issues identified in beam-solid transport was the role of ionization processes. For example, the electric fields estimated in the bulk of the target by the PIC codes could exceed 100 GV/m, where a large degree of field ionization would be expected. This would bear significantly on the front-surface ion acceleration mechanism postulated by the Michigan group, as well as by another IC-RAL group (Krushelnick, Norreys et al.). D. Bruhwiler and D. Dimitrov (Tech-X) presented new code techniques for including both impact and field ionization in the OOPIC code used to model underdense plasma wakefields. They developed a robust empirical fit to the ionization cross-sections, to facilitate computationally efficient inclusion in PIC. Discussion on the applicability of these routines to solid density plasmas identified several questions such as the role of multiple ionization processes within a single time step. A final analysis of ionization vis-à-vis laser ion acceleration will be pursued as a result of our discussions, and is expected to finally resolve the question of high-energy (>5 MeV) proton acceleration from the front surface of laser-irradiated foils. It appeared that a consensus was reached at this meeting that most all of the front vs. rear surface controversy could be understood simply in terms of the relative efficiency of the competing processes, with front-surface shock-like acceleration dominant at small laser-pulse energy, and sheath formation and rear surface acceleration dominating for higher energy ions and at higher (>5 J) laser pulse energy.

Beam transport through solid matter was the theme of recent work on muon beam cooling design studies presented by D. Cline (UCLA). His groups of collaborators have performed full 6-D phase space studies of ionization cooling of muons within a quadrupole muon cooling ring. Muon cooling relies on using ionization energy loss to damp the energy spread of muons as they transit matter, and subsequent acceleration in an RF structure to restore energy to the longitudinal motion. Ionization cooling is limited by multiple scattering (converting longitudinal to transverse degrees of freedom), so the cooling medium is best situated at a low-beta beam waist. It was noted that longitudinal cooling could simultaneously be obtained if high energy muons are passed through a thicker slab and lower energy muons through a thinner slab. They have identified a novel quadrupole ring design that incorporates a low-beta and energy dispersive section at which point wedge-shaped coolers could be positioned. Both

hydrogen and LiH cooling slabs are under consideration. Simulations suggest that muon emittances down to of order 1 μm may be possible in a cooler-ring geometry, which would significantly reduce the cost of, and strengthen the case for a future muon collider or muon-ring-based neutrino factory.

K. Nakasima (Univ. Osaka & GA) presented a theoretical study of positron generation in ultra-intense laser-solid interactions, based on a new relativistic Fokker-Planck code. He considered the usual Bethe-Heitler pair production from real bremsstrahlung photons in a two-step process, as well as the direct electro-production Trident process. For the first time, he is able to understand the yield of positrons observed in previous LLNL-Petawatt experiments, and showed that post-acceleration of the positrons in the strong sheath electric fields around the target, calculated using a PIC code by Y. Sentoku, is an essential element to understand the data.

Finally, Y. Sentoku (GA) showed how, by using a conical target design, one might significantly enhance the absorption of laser light in solids, as well as generate much higher energy electrons. This arises from intense surface currents of ~500 keV electrons driven along the surface of the cone, which enhances the laser coupling and focuses the laser light to as much as 20 – 100 times higher intensity at the vertex of the cone. This may lead to great enhancement of short pulse laser-radiation sources and much higher efficiency ion generation.

4. Beam Physics in High Energy Density Physics

In his invited talk, A. Friedman (LLNL & LBNL) detailed the crucial role of advanced accelerator physics and beam dynamics in achieving inertial fusion by heavy-ion drive beams. Considerable work is being done in the U.S. and abroad on HIF, particularly in the areas of induction linac technology, merging of many high current heavy ion beams, and beam neutralization and transport in plasma channels to a few mm spot in order to heat a hohlraum to sufficient soft x-ray temperatures to implode a DT fuel pellet. This program leverages the huge investment in ICF target designs using laser drivers, but seeks to achieve much higher efficiency by using ion beam drivers. The end requirements are approximately 5 MJ of beam energy, in ~10 ns, in approximately 100 individual, synchronized 2-4 kA beams. Induction linear accelerators are the present technology of choice, and considerable work is being done to understand multi-beam sources and the physics of beam merging, and space-charge limited beam propagation. On a related topic, we discussed the possibility of using laser-accelerated ions to benefit the HIF program. The laser-accelerated ion option of ICF-Fast Ignition encompasses much of the same neutralized beam physics, and it was pointed out that by scaling beam-plasma interaction studies presently being performed by H. Ruhl (GA), one might begin to address some of the key beam-target issues that are important for HIF, but are presently beyond the capabilities of present ion sources.

Yu-Jiuan Chen (LLNL), presented another application of ultra-high current density beam dynamics in high energy density physics in the limitations of electron-beam short-pulse radiographic machines for advanced hydrodynamics testing. In this class of machines, for example the Dual Axis Radiographic Hydro Test facility (DARHT) at LANL, and the Experimental Test Accelerator (ETA-II) at LLNL, researchers are using 4 kA, 20 MeV electron beams, in 50 ns pulses, to generate huge fluxes of high

energy bremsstrahlung x-rays by focusing on a tungsten target. An important requirement for future machines is the ability to make pulse trains, and a major limitation is the evolution of ion plasmas from the x-ray converter target into the beam line. Even during a single beam pulse, the beam space charge is so large as to ionize and accelerate material upstream from the converter, which creates a plasma channel that focuses the tail of that pulse, and subsequent beam pulses, in an uncontrolled way. Chen and coworkers have characterized the ion back streaming, and have developed empirical ways to minimize its influence on subsequent pulses by creating an axial ion trap in the beam line by inserting a grounded foil a few cm upstream of the x-ray target. This is a particularly dramatic example of intense beam currents affecting the monitoring and control, and similar phenomena should be considered in some of the high current, high space charge beams in use elsewhere in the community.

A. MacKinnon (LLNL) described in our working group some more advanced applications of laser-accelerated beams in High Energy Density physics at the national security laboratories. In addition to the plasma imaging discussed previously, he pointed out that laser-accelerated protons can measure very minor areal density modulations, as thin as 1 μm thickness variation of an Al sample, on a transverse spatial scale of ~10 μm. This could be a very sensitive new tool for diagnosing the growth rate of Rayleigh-Taylor instabilities in ICF implosion experiments. He also showed very recent work on developing proton Moire interferometry to precisely measure the divergence of laser accelerated protons after traversing a target implosion plasma. Laser-ions could also be used to measure shock speeds inside of solids, by backlighting a laser-driven shock sample, and benchmarking the particle speed and shock front speed to the breakout time at the rear of the sample using VISAR. Another important application being considered is to use laser-accelerated ions to isochorically heat solid-density matter to a few eV in order to study strongly coupled plasmas. The physics of $\Gamma > 1$ plasmas is important for many aspects of astrophysics and condensed matter physics, and is difficult to produce in the laboratory because of the hydrodynamic expansion of the resulting Gbar pressure material. Rapid, ps heating on a time shorter than the expansion time is required, but direct laser heating is very difficult because the laser is absorbed only in a surface layer and must propagate on a similar hydro time into the bulk sample. Ions could penetrate and heat the entire volume of a sample, which if coupled with a time-resolved x-ray probe would yield novel HED information.

Finally, we discussed at length the prospect of using laser-accelerated ions as a new class of ultra-low emittance beam injectors for heavy-ion fusion and for other accelerator projects. T. Cowan pointed out that in addition to the transverse phase space being exceptionally small, the longitudinal phase space is also usefully small because the initial accelerated bunch is of only ps duration. Even though the energy spread of ions is of order several MeV, the ΔE-Δt product of MeV-ps is the same order as keV-ns, which is typical in conventional RF ion accelerators. A simple PARMILA run showed that a 2 MeV wide slice of proton energies could be captured in a drift tube linac structure simply by allowing the laser-accelerated bunch to drift for one meter, and then capture the velocity dispersed bunch off crest in a DTL of the spallation neutron source (SNS) design. In collaboration with G. Logan (LBNL) and G. Caparasso (LLNL), GA is proposing a capture and post acceleration experiment in

a non-synchronous Dielectric Wall Accelerator (DWA). In a joint session with the EM Structures group, we discussed possible table-top experiments of this type using a laser-driven dielectric structure.

It was also discussed that in addition to HED applications, a laser-based ion injector could be a powerful tool for other beam applications, since it may be possible to preserve the ultra-low transverse emittance of the beams by using a suitably high gradient capture section. One potential opportunity for HEP could be for future high-brightness proton sources for hadron machine upgrades. For example, a reduction in the proton beam emittance from the source from a typical 10 μm by even a factor of two could affect the design of an optimized collider and increase the luminosity at the collision point by a similar factor -- having a major impact on experimental operations. Kinoshita also discussed plans for the Univ. Tokyo group to develop laser-accelerated protons as an injector for C-ion cancer therapy machines in Japan. And several of us discussed the prospect of using laser-accelerated ions to produce medically relevant radio-isotopes, for example the short-lived positron emitting isotopes of ^{11}C, ^{13}N, ^{15}O, and ^{18}F which are used in Positron Emission Tomography.

5. AAC2004 and Beyond

As a final summary of our activities, we identify at least three broad areas of research which we expect will mature rapidly and that hopefully we can expect to be reported on successfully at AAC'2004. These include:

a. Inclusion of realistic matter properties in PIC and hybrid modeling, including full treatment of ionization dynamics;
b. Understanding and taming the physics issues of laser-ion capture and post acceleration; and
c. Developing many more applications of laser-accelerated ions to HED, plasma diagnostics, medical physics and other areas of fundamental research.

ACKOWLEDGEMENTS

We would like to thank John Power and Wayne Kimura of the EM Structures Working group for the productive joint session on exotic acceleration schemes.

REFERENCES

1. K. E. Bean, IEEE Trans. Electron. Devices, **25,** 1185, (1978).
2. S. Y. Lin *et al,* Nature, **394**, 251 (1998).