FINAL TECHNICAL REPORT

“Experimental, Theoretical and Computational Studies of Plasma-Based Concepts for Future High Energy Accelerators"

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Introduction

This is the final report on the DOE grant number DE-FG02-92ER40727 titled, *"Experimental, Theoretical and Computational Studies of Plasma-Based Concepts for Future High Energy Accelerators."* During this grant period the UCLA program on Advanced Plasma Based Accelerators, headed by Professor C. Joshi has made many key scientific advances and trained a generation of students, many of whom have stayed in this research field and even started research programs of their own. In this final report however, we will focus on the last three years of the grant and report on the scientific progress made in each of the four tasks listed under this grant.

TASK A: Plasma Wakefield Accelerator Research at FACET, SLAC National Accelerator Laboratory

The U.S. Department of Energy (U.S. DOE) funded the construction of the FACET facility at the SLAC National Accelerator Laboratory for research and development of advanced techniques for charged particle acceleration. In particular the interest has focused on the Plasma Wakefield Acceleration (PWFA) scheme. The main goal of the PWFA program at the FACET facility is to show that high-gradient PWFA can produce a large (10-20 GeV) energy gain for an electron bunch containing a significant amount of charge (~1 nC) while maintaining a narrow energy spread.

The FACET facility came on-line in 2011. It has provided a 20 GeV electron beam in either a single bunch, compressed mode or in a drive beam-witness beam configuration. In the past 18 months we have used both of these configurations and made key advances towards our goal stated earlier.

The basic concept of the PWFA involves producing an accelerating structure in a plasma column by the

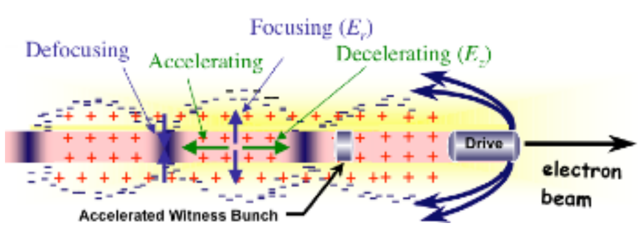


Figure 1. The schematic of the plasma wakefield accelerator showing the drive beam that produces the wake and a witness beam that extracts energy from it.

passage of a high-current, relativistic electron (drive) bunch. Now an appropriately placed second bunch of electrons within this accelerating structure can gain energy from the wake at a rate that is up to 1000 times greater than if a conventional microwave accelerating cavity is used.

The PWFA program at FACET is called the E200 experiment and is a collaboration between UCLA, SLAC, University of Oslo (Norway), Tsinghua University (China), and MPI (Germany). During the first run we used a rubidium (Rb) plasma source to mitigate two potential issues with PWFA. These are gradual shortening of the electron drive bunch as it propagates through the plasma (a process known as head erosion) and plasma ion motion. Both of these deleterious effects can be minimized by using Rb. The head erosion effect is reduced because the Rb atoms have a very low ionization potential and can thus be more easily ionized by the electric field of the drive beam pulse producing a plasma. The rest of the electrons in the bunch then blow out these plasma electrons and produce an ion cavity that focuses rest of the electron bunch and prevents it from spreading. The relatively larger mass of the Rb atoms (compared to H or Li say) also helps the keep ions stationary even in light of the strong radial electric field of the electron beam.

During the first FACET science run in 2012, we discovered that while Rb indeed mitigated the head erosion effect, a new physical effect manifested itself that can limit the maximum accelerating gradient. This is the further ionization of the Rb atom caused by the combined effect of the wakes and the beam's electric fields. This ionization process injects unwanted electrons into the already fully formed accelerating structure where they are accelerated. In a normal RF cavity this process is called "dark-current." The dark current injection can lead to a significant extraction of energy from the wake (a process known as beam-loading) and reduces a key figure of merit known as the transformer ratio T which is simply the ratio of the accelerating field and the decelerating field.

We have quantitatively studied this beam loading effect due to continuous injection of dark current in a Rb wake. We correlated the amount of dark current exiting the plasma with the energy gain and loss and showed that as the excess charge increased the transformer ratio went down (See Figure 2). These results have been submitted for publication.

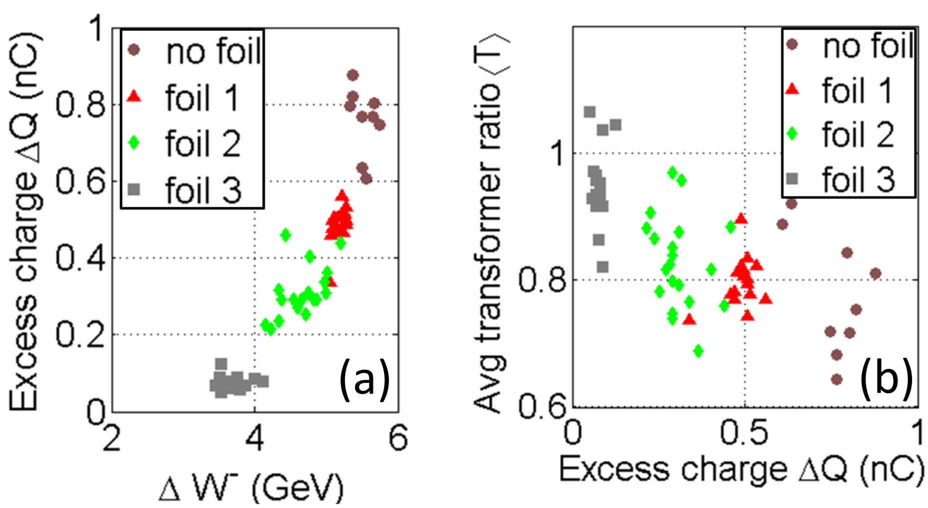
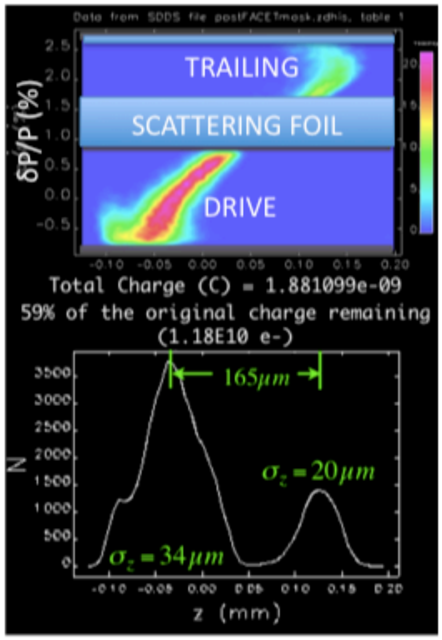


Figure 2. (a) Excess charge due to ionization of Rb to Rb^{+2} as the wake amplitude increases and (b) the reduction of the average transformer ratio <T> as the excess charge increases.

More recently, we have generated a drive-beam/trailing beam combination using techniques that are familiar in the photonic world but very hard to do with GeV-class charged particle beams. We first impose a +ve chirp on the beam in the dispersion plane. We then insert a metallic foil at the center of this dispersed beam to induce a large scattering angle on the electrons as they go through the foil. We also use collimators to block non-linear portions of the dispersed beam. When the beam is reassembled it has a double-hump charge distribution that acts as a drive-witness bunch combination (see Figure 3). The pulse width of each of the two bunches is less than 100 fs and the separation is about 300 fs. These bunches have been measured directly in time using a RF-streak camera and confirm that we can deliver a two-bunch structure to the plasma source. Unfortunately, a significant amount of charge is lost in this process and the peak current of the drive beam is insufficient to produce the plasma via self-field ionization.



(a)

(b)

Figure 3. (a) Simulation of the energy spectrum of the electron beam in the dispersion plane of the chicane in sector 20 and the selected portions of this spectrum perturbed by the scattering foil and (b) the resultant drive and the trailing bunches produced upon recompression.

We have therefore implanted a laser ionization scheme using a Bessel beam produced by an axicon focus to produce the plasma. Initially a 5 x 10^{16} cm^{-3} density, 35 cm long plasma was produced in a lithium (Li) vapor column. When the drive-witness bunch combination was propagated through this plasma, the drive beam was seen to lose energy while the witness beam was seen to lose energy while the witness beam was seen to gain energy by up to 2 GeV.

These results are very exciting and we hope to increase the interaction length in the upcoming experiments to increase the energy gain even further. All indications are that this work is indeed on the right track.

TASK B: In House Research at UCLA's Neptune and 20 TW Laser Laboratories

The Neptune lab and the 20 TW (Ti–Sapphire) laser lab at UCLA have been fully operational during the present grant period. During this time (FY 11 and 12) these laboratories served as a training ground for students who are doing their MS projects, while the Group's focus has been on experiments at FACET. These two laboratories have been central to our scientific program and have led to the Ph.D. thesis work of Dan Haberberger and Art Pak. The Neptune lab in particular has undergone two major upgrades. The first led to generation of 15 TW peak power output, making the Neptune CO_2 laser the most powerful in the world. The second was a 30 GW, 1 Hz capability upgrade supported by the ARRA funds. It should be noted that although only the experimental work is listed under this task, all Professor Joshi's students learn to do the necessary theory and simulations work. Some examples of which are included in the theory/simulations, Task D section. On a day-to-day basis Dr. Sergei Tochitsky oversees experimental work in the Neptune lab while that in the 20 TW lab is overseen by Ken Marsh.

Generation of narrow energy spread protons by collisionless shocks

There is a very significant worldwide effort on high-energy proton generation using intense lasers. Most of this work is carried out using either Nd:glass or Ti-sapphire lasers. Furthermore almost all the groups in the world are working on either the target normal sheath acceleration (TNSA) mechanism or the radiation pressure acceleration (RPA) mechanism. It has been known for some time that the CO_2 laser has certain advantages over other lasers such as higher pulse energy and a few picosecond pulse width that is more suited to ion acceleration. It is also known from PIC simulations that collisionless shocks can reflect and thereby accelerate ions in a plasma. What was not known is how to create such shocks using a CO_2 laser. This is what the Neptune experiments have managed to accomplish. We generated shocks in a near critical density plasma by efficiently generating very high-energy electrons and sending them streaming through a much colder long scale-length plasma. The latter reduces the TNSA fields that would otherwise smear the energies of the ions accelerated by the shock

Figure 4 below shows the data obtained in the Neptune lab. Protons with about 1% energy spread but 20+ MeV energy were observed at a modest laser intensity of 5×10^{16} W/cm^2. These results were published in *Nature Physics* and featured on the cover of the January 2012 issue.

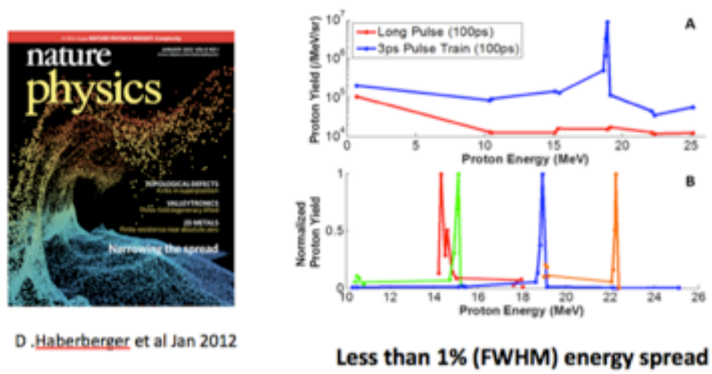


Figure 4. Generation of less than 1% energy spread protons by reflection off a collisionless shock wave in a plasma produced by an intense laser pulse. The blue plot in A shows the energy spectrum of protons with a 3 ps pulse train and the red curve in A shows the data when a single smooth 100ps pulse containing the same energy is used.

Upgrading the Neptune CO2 laser to give 15 TW peak power

The key improvement in the Neptune Lab during this period was the successful upgrade of the CO_2 laser to 15 TW peak power making it the world's most powerful CO_2 laser. This was shown to be possible by first amplifying 3 ps (FWHM) pulses in an 8 atmosphere regenerative amplifier and then triple passing these pulses in the e-beam pumped 2.5 atmosphere amplifier. The collisionally broadened bandwidth at 2.5 atmospheres of pressure is not sufficient to support 3 ps pulses but the power broadening caused by the laser pulse itself provides additional bandwidth with the net result that a 100 ps macropulse containing 3 ps micropulses separated by 18 ps is produced containing up to 100 J of energy. When focused intensities exceeding 5×10^{16} W/cm^2 are produced. Moreover this unique pulse structure made it possible to do the ion acceleration by collisionless shock experiment described above.

Neptune high-rep rate, 30 GW, picosecond CO_2 system using ARRA Funds

At 15 TW power the Neptune CO_2 laser is the most powerful CO_2 laser in the world. It is however a single shot laser with a rep rate of once every 10 minutes. This puts a limit on the kind of experiments that can be preformed at Neptune. There is a whole class of experiments (e.g. electron micro-bunching using the IFEL mechanism) that need only a modest laser power, say 10s of GW but a higher repetition rate. We therefore undertook an upgrade of the front end of the Neptune CO_2 laser to increase its repetition rate to 1 Hz but to give peak powers of greater than 10 GW with the help of ARRA funds. This was done by adding one more multi-atmospheric amplifier followed by two, 1-atmosphere TEA lasers. It is by no means obvious that a few picosecond pulses can be amplified in a 1 atm. amplifier and in fact conventional wisdom says that this is not possible. But we have shown that coherent amplification based on power broadening can generate a sufficient bandwidth to support such short pulse amplification. The upgrade of the laser has now been successfully completed and the amplified pulse has been time resolved using a streak camera (after frequency mixing) and shows the characteristic 3 ps micropulses separated by 18 ps in a 100 ps envelope. The schematic of the new laser front end is shown in Figure 5. This is the world's first ever demonstration of amplification of ps long CO_2 pulses in a 1-atm, TEA amplifier.

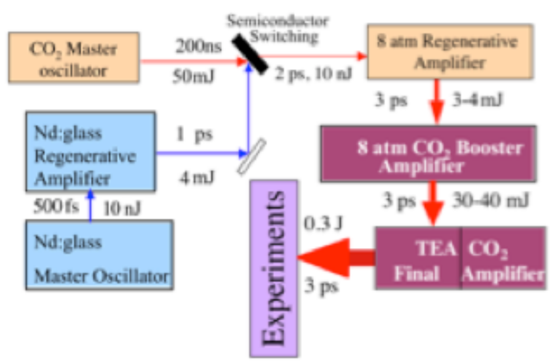


Figure 5. The schematic of the upgraded front end of the Neptune CO_2 laser system.

TASK C: Laser-Wakefield Acceleration (LWFA) in Self Guided Regime: Experiments at the Callisto Laser at LLNL

We established collaboration with Drs. Dustin Froula (now at LLE, Rochester) and Siegfried Glenzer (now at SLAC) of LLNL to carry out LWFA experiments in the self-guided regime using the 250 TW Callisto laser in October 2007. Access to this laser gives us the ability to carry out experiments on LWFA at a power level comparable to other large Ti-Sapphire laser systems such as those at Rutherford Lab (U.K.), I.O.P. (China), G.I.S.T. (Korea), U. Nebraska, U.T. Austin and other places. The UCLA LLNL collaboration is a natural fit because of the proximity of Los Angeles to Livermore, recruitment of UCLA students (Joe Ralph, Catalan Filip and Art Pak) by LLNL and the expertise in plasma acceleration that the UCLA group brings to the table. Within a period of less than 5 years, the collaboration has published 5 papers in *Physical Review Letters* on LWFA that have brought this group to the top rank of groups in the world working in this area.

Injector-Accelerator LWFA Experiment

We have brought to fruition a two-stage, injector-accelerator concept capable of generating 0.5 GeV, narrow energy spread electron beams in a roughly 1 cm long plasma. The injector section is typically a 3-4 mm long gas cell containing a mixture of helium and nitrogen gases. The 5 mm long accelerator section contains only helium. The plasma density in the two sections is kept as uniform as possible which means that the pressure in the injector section is slightly higher than that in the accelerator section. The positive pressure in the accelerator section meant that the nitrogen gas was indeed confined to the injector section. A novel spectroscopic diagnostic technique was developed to confirm this. A 1 mm diameter aperture separated the injector and accelerator sections.

We first determined the lowest density at which electron self-injection was observed in pure He plasma in the injector section when the LWFA was operated in the self-guided, blowout regime. We then showed that it was possible to inject electrons at even lower densities by adding 5% nitrogen impurity. The spectrum of electrons from the injector section alone obtained in this manner is shown in Fig. 6 with a purple curve. The electron spectrum of these injector only electrons was typically broad out to 140 MeV. We then showed that the laser pulse with an a_o of about 3 could be guided through the entire length of the injector accelerator combination, i.e., over 8-9 mm. We also measured the spectral modifications to the laser pulse, which is indicative of wakefield excitation. When the densities in the two sections were carefully matched the output spectrum of the electrons showed a relatively narrow energy spread with maximum energies of around 500 MeV demonstrating the validity of this concept.

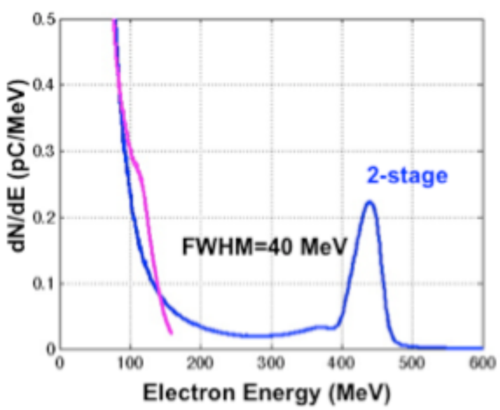


Figure 6. A mono-energetic electron beam is observed when an ionization injection-based “injector” stage injects a 100 MeV electron beam (purple) into a 5 mm long accelerator stage. (2 stage or blue curve)

Developing Betatron Radiation as a Directional Source of X-rays

The development of efficient x-ray probes with energies greater than tens of keV is of enormous interest to plasma diagnostics, material science, medicine and many other research fields. Betatron x-ray radiation produced when relativistic electrons oscillate in a beam-driven or laser-driven plasma channel holds great promise in this spectral range. Betatron x-rays are ultra-short, spatially coherent, directional and have a high peak brightness. The discovery of the betatron radiation was done by our group at the PWFA experiment on the FFTB facility at SLAC. Since then race is on for developing the betatron source as a practical x-ray source for the myriad applications described above.

We have been working on fully understanding the spectral and angular distribution of betatron x-rays from a laser-driven electron accelerator. We are using the Callisto laser facility to do these experiments in collaboration with Dr. Felicie Albert of LLNL. Recently we have recorded the complete spatial (angular) distribution of the betatron x-rays in the 10-100 keV range using a novel spectrometer that uses multiple x-ray image plates sandwiched between attenuating metallic foils. We simultaneously measure the betatron spectrum and the accelerated electron spectrum and show that the measured angular distribution of the betatron spectrum can only be reconstructed by

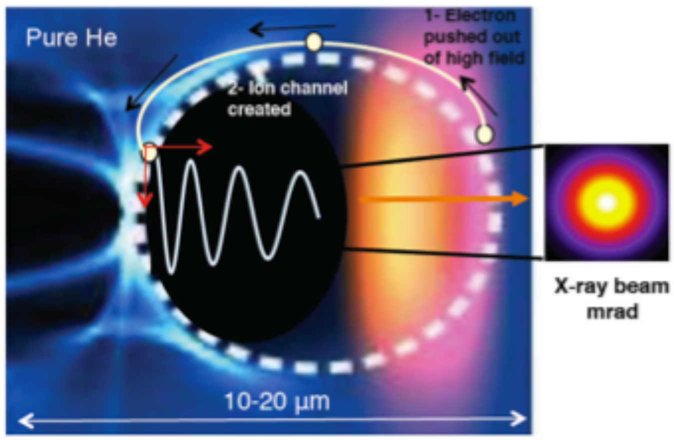


Figure 7. Schematic of how betatron motion of a trapped electron due to the transverse focusing force of the ion column causes forward emission of x-rays.

assuming different angular distributions for different energy electrons. The highest energy electrons oscillate about the ion column axis predominantly along the direction of the laser polarization vector, whereas lower energy electrons oscillate more isotropically. The on axis spectrum of the photons can be fitted with synchrotron-like spectrum emitted by the highest energy electrons oscillating with an initial radium of 5 µm when they are trapped in the wake. These results have been submitted for publication.

TASK D: Theory and Simulations

The theory and simulation effort is lead by Prof. W. Mori. The effort is focused on supporting the interpretation and design of experiments (described above) at UCLA, FACET, and Livermore, on ensuring that the necessary computational tools are available, and on studying fundamental physics involved in plasma-based acceleration.

This effort has continued to develop new theoretical models where appropriate and use fully nonlinear simulations. At UCLA we have an in-house simulation infrastructure that is optimal for modeling plasma-based accelerator concepts and physics. This infrastructure includes the codes OSIRIS and QuickPIC as well as UPIC, which is a framework of components (using spectral based solvers) for rapidly developing new codes and optimized algorithms. This set of codes includes full particle-in-cell (PIC), as well as quasi-static PIC tools for both PWFA and LWFA. QuickPIC is the only 3D quasi-static PIC in the world and it is built from UPIC components. OSIRIS and QuickPIC have the framework for ponderomotive guiding center options for modeling LWFA and we continue to develop the ability to model LWFA in a Lorentz boosted frame using both OSIRIS and UPIC. As long as there is no laser light reflection there can be significant reductions in the number particle pushes (larger time steps and shorter propagations distances) needed to model a LWFA stage in a Lorentz boosted frame (the speed ups scale as g_p^2). The UCLA PIC codes have been run on over 100 million core hours at DOE leadership class facilities. They are highly optimized on a single core and scale to 300,000+ cores. The parallelization for QuickPIC relies on a novel-pipelining algorithm. The code development effort is leveraged through other funding such as a SciDAC grant that is used to primarily develop and maintain the PIC code infrastructure.

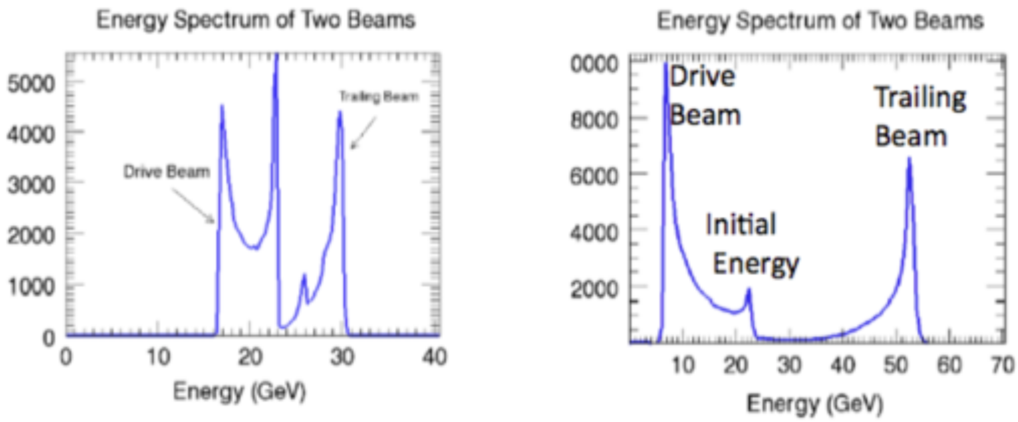
Enhancements to PIC code infrastructure

For OSIRIS, we have optimized the code so that it runs effectively on SIMD units such as the SSE (at 30% of peak speed on the full Jaguar computer for problems with good load balance), added dynamic load balancing in 3D, added a hybrid OpenMP/MPI parallelization strategy, added options for both energy and momentum conserving force interpolation, added the framework for using the ponderomotive guiding center approximation, and developed a new hybrid algorithm for efficiently modeling high density collisional plasmas. In addition, we have developed and enhanced our capability to model laser wakefield stages in a Lorentz boosted frame by adding a moving antenna into OSIRIS as well as theoretically analyzed the numerical instability that limits the use of the boosted frame. As part of this analysis, we have begun to develop the ability to use our spectral codes for boosted frame simulations. For QuickPIC, we have made improvements to the predictor corrector iteration loop. This has reduced the CPU needs by 2-4 for most cases. This work was leveraged from other sources of funding.

Simulations of FACET 2-bunch experiments

Anticipating the availability of drive beam-trailing beam capability at FACET in FY 13-14, we had undertaken an extensive PIC code simulations program to optimize the plasma conditions, so that the trailing beam energy spread could be minimized while maintaining its emittance and efficiently extracting the energy from the wake.

The input parameters for the two bunch simulations were obtained by using the 6D particle tracking code ELEGANT for the SLAC linac together with EGS4 to simulate the masks (collimators) in the dispersion plane of the FACET chicane at Sector 20. Both self-ionized plasmas and pre-ionized plasmas were simulated using QuickPIC and OSIRIS. With the typical drive beam/trailing beam parameters expected at FACET, beam head erosion in self-ionized plasmas will limit the energy gain to about 5 GeV. However when the beams are propagated in a pre-ionized 1.5 m long, Li plasma, it is possible to energy double the trailing bunch from 23 GeV to more than 50 GeV, while the drive bunch energy is reduced to 7 GeV as shown in Fig. 8. Because of the strong beam loading, the energy spread of the trailing bunch is less than 5% and the overall energy transfer efficiency is an asonishing~50%. Conventional microwave based accelerators are never operated in such a high beam loading regime but in a plasma wakefield accelerator high efficiency of energy extraction and small energy spread go hand in hand because of the extremely nonlinear and short scale-length accelerating fields. Of course, it remains to be seen if we can generate 1.5 m long $5\times10^{16}\text{cm}^{-3}$ density plasmas using laser ionization as stated earlier and whether we can accurately propagate the two bunches along the thin plasma column.



(a) (b)

Figure 8. The output spectrum of the initially 23 GeV drive and trailing beams separated by 130 μm using QuickPIC after (a) self-ionization and (b) propagation through a laser pre-ionized 5×10^{16} cm^{-3} density plasma. Other parameters are: Drive beam: σ_r = 10 μm, σ_z = 34 μm, $N_D = 9.57\times10^9$, e_N = 100 mm-mrad. Trailing beam: σ_r = 10 μm, σ_z = 19.3 μm, $N_T = 4.33\times10^9$, e_N = 100 mm-mrad.

Simulations on the generation of collisionless shocks for ion acceleration

Besides using OSIRIS to model the Neptune experiment described earlier, we have also used OSIRIS to understand how collisionless shocks are formed at plasma discontinuities, how they are formed when plasmas interpenetrate, how such shocks can be generated by an intense laser interacting with overdense plasmas with varying density profiles, and under what conditions the electric field associated with these shocks is able to reflect plasma ions and generate a mono-energetic ion beam. Figure 9 shows examples of shock formation when a plasma collides with another plasma. A careful analysis of the simulations for the laser-produced shocks relevant to the in-house experiments indicates that the shock is launched by the density compression at the critical surface and the generation of a relativistic electron temperature.

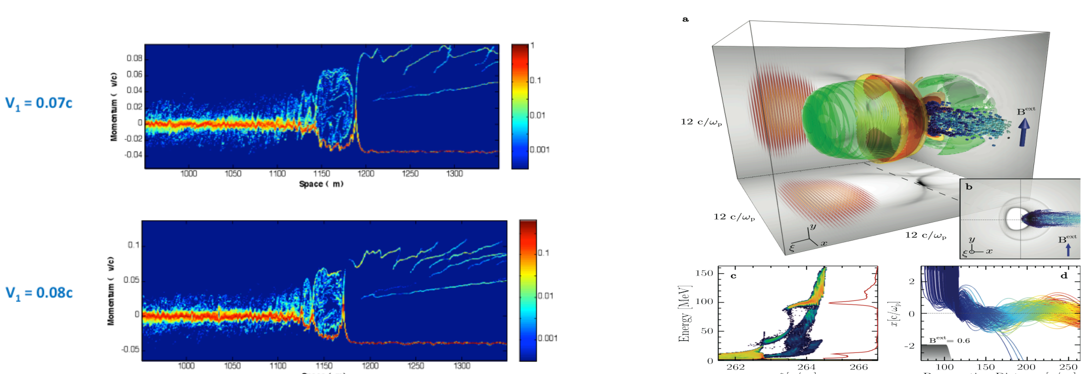


Figure 9. Left: Formation of a shock at the interface between interpenetrating plasmas with differing density ratio of 3:1 and an initial relative drift velocity v1 as shown. In either case a clear reflection of ions from the shock can clearly be seen. Right: 3D simulation for magnetic control of particle injection in plasma based accelerators. a) is wake plus injected particles, b) position of trapped electrons, c) is energy spectra, d) trajectories of trapped electrons.

Students

The following students were fully or partially supported by this grant during the last three years: Chao Gong, Jeremy Pigeon, Navid Vafaei-Najafabadi, Jessica Shaw, and Daniel Haberberger.

Summary

Major scientific results have been obtained in each of the four tasks described in this report. These have led to publications in the prestigious scientific journals, graduation and continued training of high quality Ph.D. level students and have kept the U.S. at the forefront of plasma-based accelerators research field.

Publications: June 1, 2012 – May 12, 2013 (published or submitted)

Journals

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