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An All Optical Laser Wakefield Electron Injector

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DISCLAIMER

1 Summary

The personnel who were supported by the grant included the P.I. (Prof. Umstadter), several research scientists (A. Maksimchuk and V. Yanovsky), a postdoc (P. Zhang) and several graduate and undergraduate students.

Although there were several setbacks in developing the novel laser technology required to produce a monoenergetic beam of electrons from an all-optical accelerator, several important steps were taken towards reaching that ultimate goal. The most important outcome of this project was that we demonstrated the principle of optical control of laser accelerators, namely, that one laser pulse could modify the properties (e.g., emittance and electron number) of an electron beam accelerated by a separate but synchronized laser pulse. Another recent highlight was that, using our new 30-fs 10-TW laser system, we accelerated with a laser accelerator an electron beam with a record low divergence (0.2 degrees). This is more than 100 times lower than the 30-degree divergence that was reported recently by a French group using a laser with similar parameters [V. Malka et al., *Science*, **298**, 1596 (2002)]. A detailed discussion of the results of the project are presented below.

1.1 Detailed Discussion of Results

S.-Y. Chen, M. Krishnan, A. Maksimchuk, R. Wagner and D. Umstadter, Phys. of Plasmas **6**, 4739 (1999).

The electron beam generated in a self-modulated laser-wakefield accelerator was characterized in detail. We measured an electron beam divergence angle of $< 1°$ from a single-stage laser-driven electron gun. The electron beam was observed to have a multi-component beam profile and energy distribution. The latter also undergoes discrete transitions as the laser power or plasma density is varied. In addition, dark spots that form regular modes were observed in the electron beam profile. These features are explained by analysis and test particle simulations of electron dynamics during acceleration in a three-dimensional plasma wakefield.

S.-Y. Chen, M. Krishnan, A. Maksimchuk, and D. Umstadter, Phys. of Plasmas **7**, 403 (2000).

Spatially, temporally and angularly resolved collinear collective Thomson scattering was used to diagnose the excitation and damping of a relativistic-phase-velocity self-modulated laser wakefield. The excitation of the electron plasma wave was observed to be driven by Raman-type instabilities. The damping is believed to originate from both electron beam loading and the modulational instability. The ion wave driven by the modulation instability was directly observed in this experiment. The collective Thomson scattering of a probe pulse from the ion acoustic waves, resulting from modulational instability, also allows us to measure the temporal evolution of the plasma temperature. The latter was found to be consistent with the damping of the electron plasma wave. Fortunately, this instability takes many electron plasma periods to grown and thus should not play a significant role during the time of injection (only a single plasma oscillation period after the laser pulse).

J. K. Kim and D. Umstadter, "Cold Relativistic Wavebreaking Threshold of Two-Dimensional Plasma Waves," *Advanced Accelerator Concepts: Eighth Workshop*, edited by W. Lawson, C. Bellamy, and D. Brosius, AIP Conference Proceedings **472** (AIP Press, New York, 1999), p. 404.

We also investigated theoretically and numerically the two-dimensional wave-breaking of relativistic plasma waves, which can result from a transverse nonlinearity. This phenomenon occurs below the 1-D wavebreaking threshold and may ultimately limit the maximum achievable amplitude of a plasma wakefield. Our studies resulted in an analytical expression for the threshold of 2-D wavebreaking. More complete studies are required to determine whether this will limit the possibility of injection, but 2-D PIC simulations indicate that it will not.

D. Umstadter *et al.*, "New Development in Laser Acceleration of Beams," *PAC 2001*, Proceeding of the 2001 Particle Accelerator Conference, Chicago, Illinois U.S.A., June 18-22, 2001, Editors, P. Lucas, S. Webber, (IEEE, New Jersey, 2001), p. 117.

We have conducted a proof-of-principle experiment of the injection concept. While this was done with a long duration laser pulse and thus did not result in a reduction of the energy spread, it did demonstrate that with injection the energy of electrons could be increased and the beam emittance decreased. These studies also allowed us to perfect the techniques required for the short pulse experiments being proposed. It also led us to a new injection concept, which will be explored in the proposed project.

X. Wang, M. Krishnan, N. Saleh, H. Wang and D. Umstadter, Phys. Rev. Lett. **84**, 5324 (2000).

We studied the propagation of an intense (1×10^{19} W/cm^2) ultrashort (30-fs duration) laser pulse in plasma conditions that are similar to those that will be encountered in an injection experiment. The plasma density was varied in such a way that the parameters of the interaction crossed for the first time the transition from the resonant to the self-modulated regime. In so doing, we found that under certain conditions, self-focusing into multiple filaments accompanies self-trapping and acceleration of electrons, both of which must be avoided if injection is to be successful. This same experiment demonstrated electron acceleration at a repetition rate of 10 Hz, which is an improvement of several orders-of-magnitude in the duty cycle of laser accelerators, bringing a practical injector closer to reality.

N. Saleh *et al.*, "Low Divergence Laser-Plasma-Based Beams," *PAC 2001*, Proceeding of the 2001 Particle Accelerator Conference, Chicago, Illinois U.S.A., June 18-22, 2001, Editors, P. Lucas, S. Webber, (IEEE, New Jersey, 2001), p. 4029.

More details on experiments first descibed in Wang, et al., above.

K. Nemoto, A. Maksimchuk, S. Banerjee, K. Flippo, G. Mourou, D. Umstadter, V. Yu. Bychenkov, Appl. Phys. Letts. **78**, 595 (2001).

We have observed deuterons accelerated to energies of about 2 MeV in the interaction of relativistically intense 10 TW, 400 fs laser pulse with a thin layer of deuterated polystyrene deposited on Mylar film. These high-energy deuterons were directed to the boron sample, where they produced atoms of positron active isotope ^{11}C from the reaction ^{10}B(d,n)^{11}C. The activation results suggest that deuterons were accelerated from the front surface of the target.

E. Dodd and D. Umstadter, Phys. Plasmas 8, 3531 (2001).

A method for the control of stimulated Raman scattering and hot electron production in short-pulse laser-plasma interactions was proposed. It relies on the use of a linear frequency chirp in nonbandwidth limited pulses. Theoretical calculations show that a 12% bandwidth will eliminate Raman forward scattering for a plasma density that is 1% of the critical density. The predicted changes to the growth rate are confirmed in two-dimensional particle-in-cell simulations.

1.2 Societal Benefits

Besides providing valuable training of accelerator physicists in a growth area of research, considerable technology transfer has also resulted from the first contract. For instance, we have collaborated with Drs. Alex Trifunac and Robert Crowell at Argonne National Laboratory on demonstrating the feasibility of using laser-produced electron injectors for the purpose of time-resolved radiation chemistry experiments. Consequently, Argonne has now duplicated our laser system and accelerator instead of building an RF-injector. This is an example of the synergy obtained by collaboration between universities and national laboratories. The results are also relevant to the next generation light sources.

2 Budget

The amount of unexpended funds for this project was $31.