Final Technical Report: DOE grant number DE-SC0007970

Award Recipient: University of Maryland, College Park

Project title: *Application of Plasma Waveguides to High Energy Accelerators*

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Experiment and simulation accomplishments (Milchberg and students)

Goals

The major goals of the project were

(1) Generation of extended axially modulated plasma waveguides in cluster jets using multiple techniques,
(2) Generation of radially polarized laser pulses for injection into the waveguide to serve as the driving field for direct laser acceleration (DLA),
(3) Demonstration of high efficiency guiding of intense linearly polarized and quasi-radially polarized laser pulses in modulated plasma waveguides
(4) Demonstration of an optical injection source to seed DLA
(5) Demonstration of DLA. These experiments were to take place on our 10 Hz laser system. In parallel, we were to
(6) build a 1 kHz, ~20 mJ laser and
(7) Develop a high repetition rate cluster jet for modulated waveguide generation and DLA experiments at 1 kHz. In the last reporting period, our task was extended to

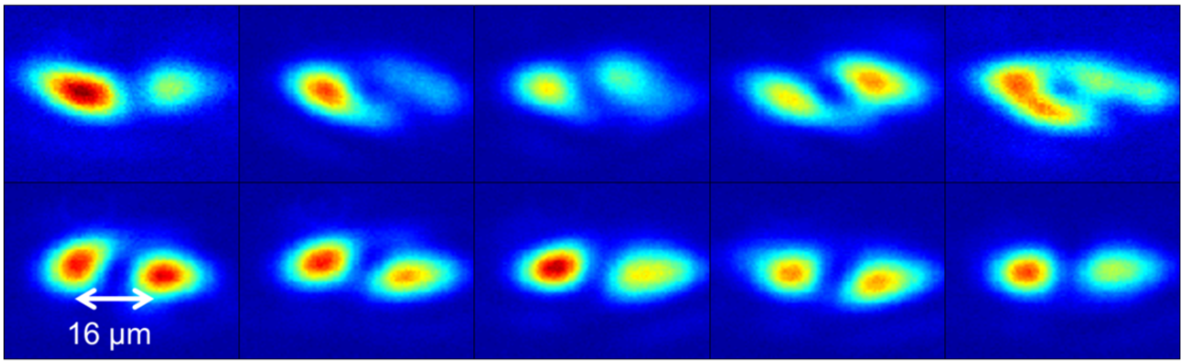
Accomplishments (regarding the numbered items above):

(1) This task was completed. Axially modulated waveguides with fixed spatial features have been demonstrated using (a) ring gratings producing modulated laser profiles to heat uniform cluster jet flow, (b) uniform laser profiles heating wire-modulated cluster jet flow. (c) Waveguides with dynamically controllable modulations have been produced in uniform cluster flows using a spatial light modulator-based interference technique.

(2) This task was completed, using quasi-radially polarized light produced by a 'half-pellicle'. In the prior grant period, we attempted another method: making our own fixed liquid crystal film-based radial polarizer using the local fab-lab at UMd. However, the quality of the resulting

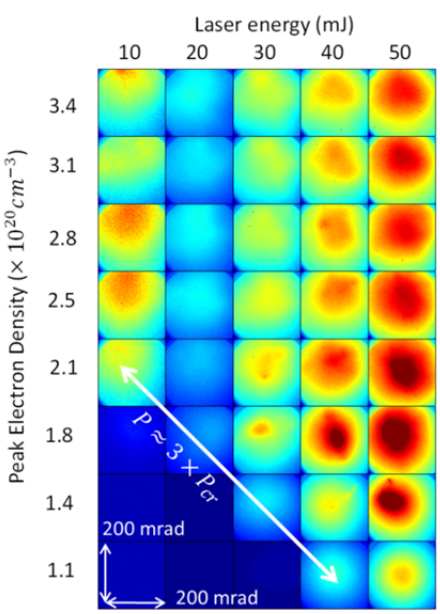
optical surfaces was insufficient to support the required precision of polarization rotation. So this approach was dropped. This precluded testing of the liquid crystal susceptibility to laser damage.

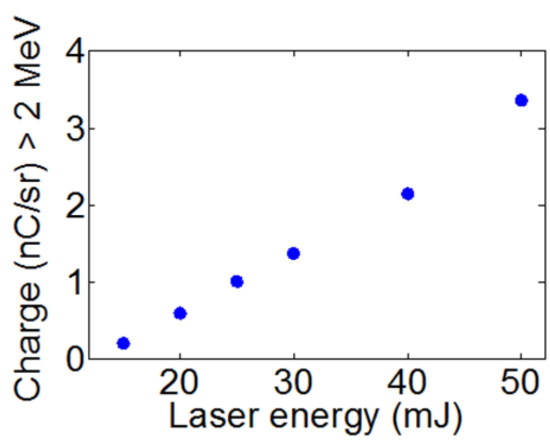
(3) This task was completed with both low power and high power guiding of linear and quasi-radially polarized pulses.



The figure above shows stable guiding of (0, 1) modes observed over 19 successive shots for a 1.5cm long plasma waveguide. Average energy throughput is ~ 30% for 10mJ, 40fs injected pulses. Estimated peak E_z fields of exit modes is ~100 MV/cm

(4) In 2013-14, we demonstrated a compact ionization-seeded <100 MeV injection source from a He-like nitrogen plasma waveguide. The 2013-14 report shows those results. In 2014-15, we demonstrated a laser wakefield acceleration injector that produces high charges of up to 10 MeV-scale electrons with pump pulse energies as small as 10mJ. See figure below. As DLA requires injected electron energies > 5MeV, this completes our development of an efficient electron injector that can operate at very high rep rate. In early 2016, we demonstrated generation of ~1MeV electron bunches at 1 kHz using 1.3 mJ laser pulses.





Single shot electron beam images for energies > 1 MeV for a range of laser energies and peak profile electron densities. The colour palette was scaled up by 10× for the 10 mJ column. The onset laser power for detectable electron beam

Total charge >2 MeV as a function of laser energy generation was ~3P_{cr} across our range of conditions

We have also found that a 1:1000 prepulse ~ 3 ns in advance of the main pulse is sufficient to generate a guiding channel in the high density jet that stabilizes the e-beam and narrows its divergence.

(5) Owing to time dedicated to development of the low energy injection source (see (4) above), DLA has not been demonstrated as yet. This is a goal for the next year under perhaps DoE funding. Our experiments demonstrating that high density hydrogen jets enable acceleration with >10 mJ pulses was ported to the 1 kHz laser in Kiyong Kim's lab. It appears that even without a boost from DLA, the injection source alone is promising for radiography applications. As mentioned, in early 2016, 1 kHz generation of ~1 MeV bunches was demonstrated using 1.3mJ laser pulses.

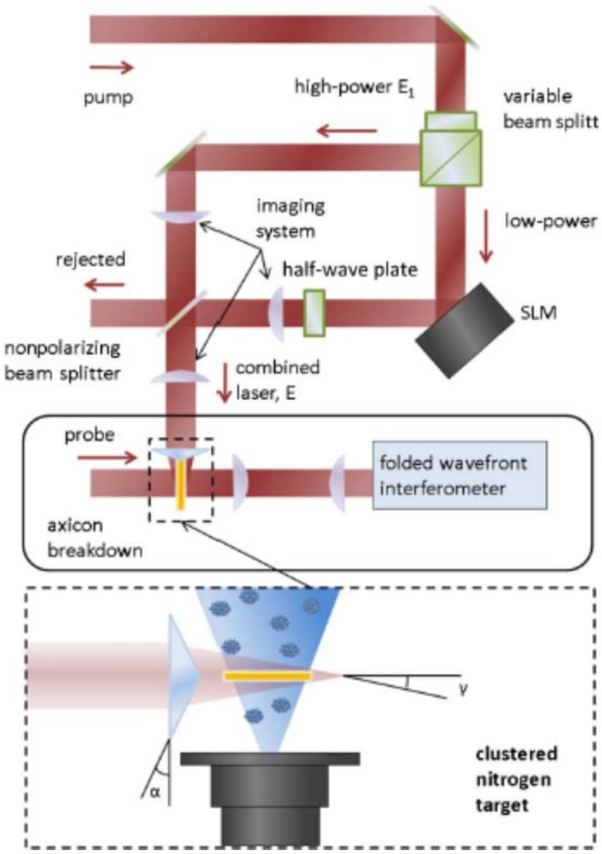
(6) This laser was completed in 2013 in Prof. Kiyong Kim's lab with 15mJ/pulse @30fs and 1 kHz rep rate. Our high density hydrogen gas jet was ported to this laser to generate a high repetition rate relativistic seed electron pulse.

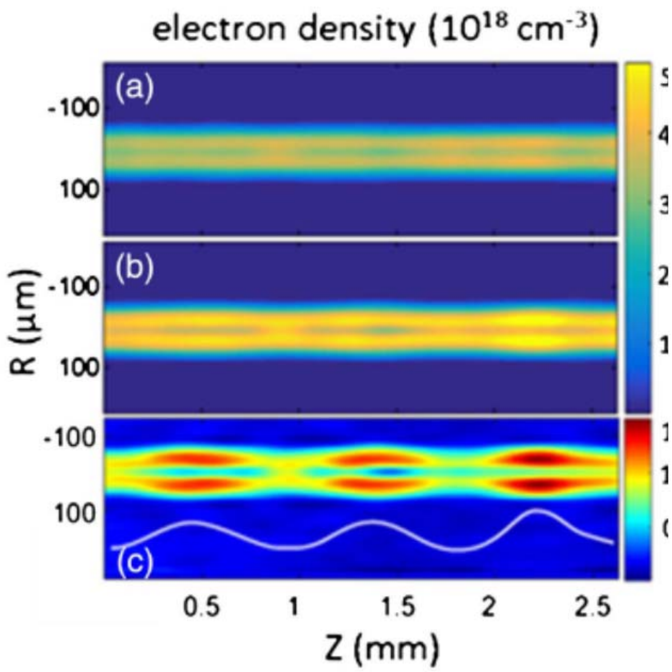
(7) We have developed continuous flow and burst-mode gas jets (N_2 , Ar, He, H_2) for 1 kHz experiments. The high density 100μm H_2 and He jets enabled <10 MeV acceleration with 10 mJ pulses and 1 MeV acceleration with 1.3mJ pulses.

Additional experimental highlights

High power laser patterning and generation of axially variable modulation period plasma waveguides using a spatial light modulator

Up until recently, we used ring gratings with fixed periods and/or wires to produce axially modulated plasma channels. We have now successfully employed a spatial light modulator to impose an adjustable phase pattern on a beam to interfere with the axicon-generated Bessel beam. Even though the phase shifted beam is <10% of the energy of the main Bessel beam, we can generate plasma density modulations up to ~100% contrast (because ionization is very nonlinear in the laser field strength) and also dynamically control their period. This work was published as Opt. Lett. **41**, 3427 (2016).



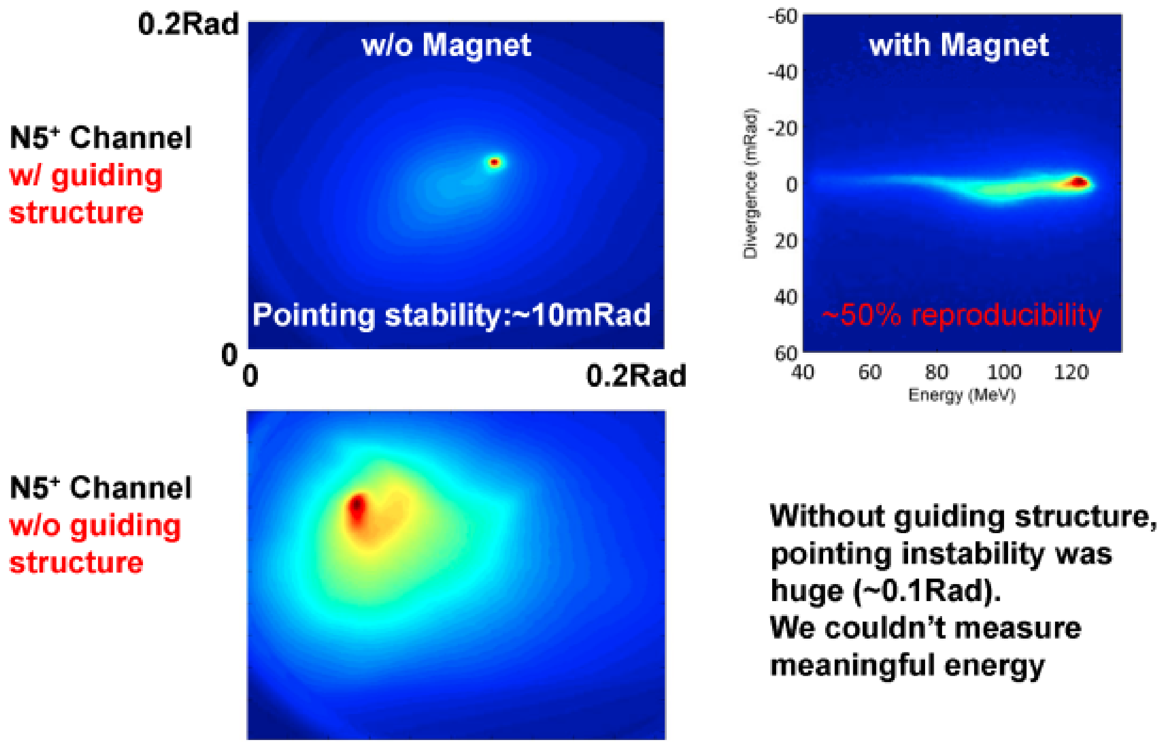


Optical setup for generating axially modulated plasma waveguides in a cluster jet.

Sample of axial plasma waveguide modulations and expanded view.

Installation and calibration of magnetic electron spectrometer and measurement of 120 MeV quasi-monoenergetic spectra

We recently achieved electron acceleration to ~120 MeV in a stable quasi-monoenergetic beam in a pure N^{5+} (He-like nitrogen) plasma waveguide formed by 100ps pulse heating of a nitrogen cluster jet. The accelerated beam was seeded by ionization injection ($N^{5+} \rightarrow N^{6+}$) from the intense, guided wake-generating pulse. See below. The presence of the cluster jet-produced plasma waveguide is essential to the energy gain and beam stability. Very little driving energy was needed: only ~250 mJ. We are using this beam as the e-beam source for direct laser acceleration (DLA) injection. This work has been submitted for publication.



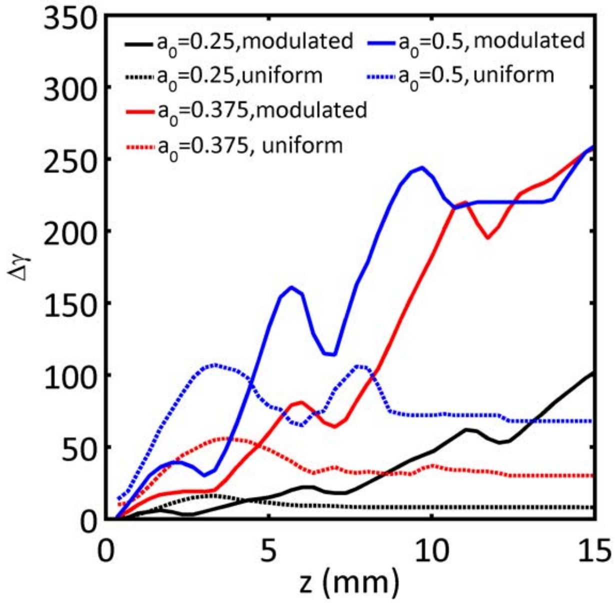
Electron beam spot stability and spectrum from wakefield acceleration in He-like nitrogen plasmas, with and without waveguide structure present.

Installation of supercontinuum spectral interferometry capability onto acceleration chamber

We have performed measurements of relativistic birefringence of plasmas (sensitivity of relativistic phase shift experienced by a probe pulse polarized perpendicular or parallel to the intense drive pulse). In addition, we are measuring the dispersion relation of a modulated plasma waveguide as the propagating pulse transitions to relativistic intensities.

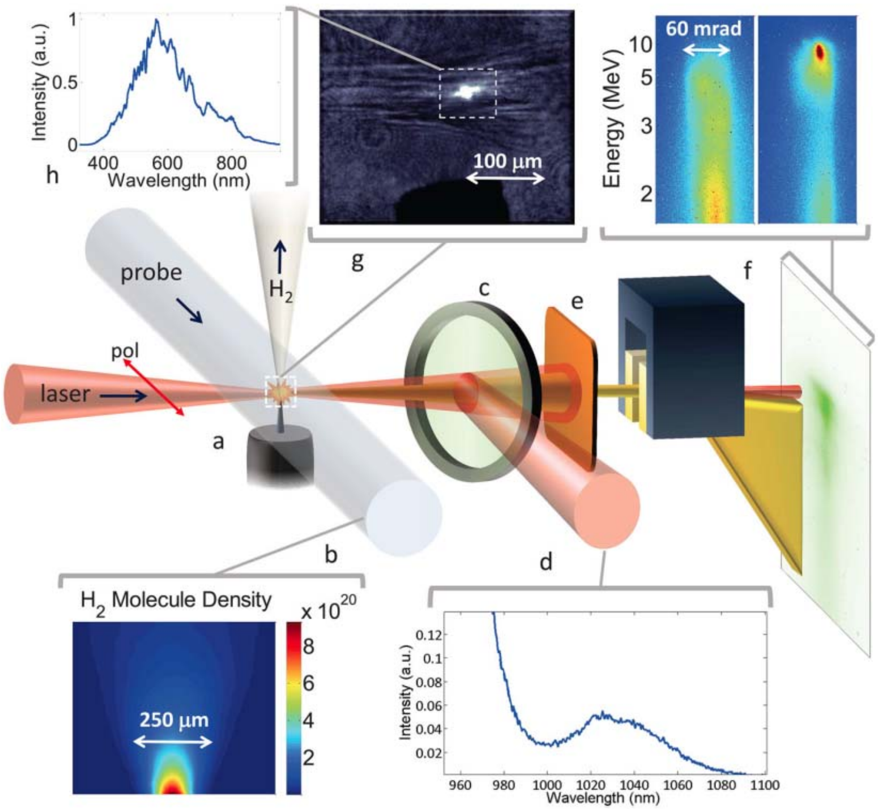
Development of quasi-phasematched laser wakefield acceleration: a new scheme for laser-driven acceleration

The energy gain in laser wakefield acceleration (LWFA) is ultimately limited by dephasing, occurring when accelerated electrons outrun the accelerating phase of the wakefield. We apply quasi-phasematching, enabled by axially modulated plasma channels, to overcome this limitation. We performed calculations and simulations showing that weakly relativistic laser intensities can drive significant electron energy gains, as shown in the figure below. This work was published as Phys. Rev. Lett. **112**, 134803 (2014).



Maximum energy gain as a function of distance in a 1.5cm long plasma waveguide (modulated or uniform). Electrons have initial axial momentum $P_z / m_e c = 30$. The black, red, and blue lines are for initial pulse amplitudes of $a_0 = 0.25$, $a_0 = 0.375$, and $a_0 = 0.5$.

Development of dense H_2 gas jets for laser acceleration using high rep. rate sub-terawatt laser pulses



Experimental setup for experiments demonstrating 10 MeV electron acceleration using ~10mJ laser pulses using near-critical density H2 gas jets Acceleration to ~1 MeV has been demonstrated using laser pulses of energy as low as 1.3 mJ. The jets can be run in continuous flow or burst mode.

Graduate students supported
Sungjun Yoon
Andy Goers
Jennifer Elle
George Hine
Dan Woodbury
Linus Feder

Publications acknowledging DOE support

1. *Shock formation in supersonic cluster jets and its effect on axially modulated laser-produced plasma waveguides*
   S. J. Yoon, A. J. Goers, G. A. Hine, J. D. Magill, J. A. Elle, Y.-H. Chen, and H. M. Milchberg
   Opt. Express **21**, 15878 (2013).

2. *Effect of two-beam coupling in strong-field optical pump-probe experiments*
   J. K. Wahlstrand, J. H. Odhner, E. T. McCole, Y.-H. Cheng, J. P. Palastro, R. J. Levis , and H. M. Milchberg
   Phys. Rev. A **87**, 053801 (2013)

3. *Scaling and saturation of high-power terahertz radiation generation in two-color laser filamentation*
   T. I. Oh, Y. S. You, N. Jhajj, E. W. Rosenthal, H. M. Milchberg, and K. Y. Kim
   Appl. Phys. Lett. **102**, 201113 (2013).

4. *Intense terahertz generation in two-color laser filamentation: energy scaling with terawatt laser systems*
   T. I. Oh, Y. S. You, N. Jhajj, E. Rosenthal, H. M. Milchberg, and K. Y. Kim,
   New Journal of Physics **15**, 075002 (2013).

5. *The effect of long timescale gas dynamics on femtosecond filamentation*
   Y.-H. Cheng, J.K. Wahlstrand, N. Jhajj, and H.M. Milchberg
   Opt. Express **21**, 4740 (2013).

6. *Breakthroughs in Filamentation*
   H. M. Milchberg, J. P. Palastro, and J. K. Wahlstrand
   IEEE Photonics Journal 5, 0700405 (2013).

7. *Optical beam dynamics in a gas repetitively heated by femtosecond filaments*
   N. Jhajj, Y.-H. Cheng, J.K. Wahlstrand, and H.M. Milchberg
   Opt. Express 21, 28980 (2013).

8. *Quantum control of molecular gas hydrodynamics*

S. Zahedpour, J.K. Wahlstrand, and H. M. Milchberg
Phys. Rev. Lett. 112, 143601 (2014)

9. *Demonstration of long-lived high power optical waveguides in air*
N. Jhajj, E. W. Rosenthal, R. Birnbaum, J.K. Wahlstrand, and H.M. Milchberg
Physical Review X 4, 011027 (2014)

10. *Direct imaging of the acoustic waves generated by femtosecond filaments in air*
J. K. Wahlstrand, N. Jhajj, E. W. Rosenthal, S. Zahedpour, and H. M. Milchberg
Opt. Lett. 39, 1290 (2014)

11. *Generation of axially modulated plasma waveguides using a spatial light modulator*
G. A. Hine, S. J. Yoon, A. J. Goers, J. A. Elle, and H. M. Milchberg
Opt. Lett. 41, 3427 (2016)

12. *Quasi-phasematched laser wakefield acceleration*
S.J. Yoon, J.P. Palastro, and H.M. Milchberg
Phys. Rev. Lett. **112**, 134803 (2014)

13. *Laser wakefield acceleration of electrons with ionization injection in a pure N^{5+} plasma waveguide*
A.J. Goers, S.J. Yoon, J.A. Elle, G.A. Hine, and H.M. Milchberg
Applied Physics Letters 104, 214105 (2014).

14. *All-optical characterization of cryogenically cooled argon clusters in continuous gas Jets*
D. G. Jang, Y. S. You, H. M. Milchberg, H. Suk, and K. Y. Kim
Appl. Phys. Lett. **105**, 021906 (2014)

15. *Multi-MeV electron acceleration by sub-terawatt laser pulses*
A.J. Goers, G.A. Hine, L. Feder, B. Miao, F. Salehi, and H.M. Milchberg
Phys. Rev. Lett. **115**, 194802 (2015).

16. *Characterization of a micrometer-scale cryogenically cooled gas jet for near critical density laser-plasma experiments*
F. Salehi, A.J. Goers, L. Feder, G.A. Hine, B. Miao, D. Woodbury, and H.M. Milchberg
Submitted for publication

Theory/simulation accomplishments (Antonsen and students)

Pulsed mid-infrared radiation from spectral broadening in laser wakefield simulations
Spectral red-shifting of high power laser pulses propagating through underdense plasma can be a source of ultrashort mid-infrared (MIR) radiation. During propagation, a high power laser pulse drives large amplitude plasma waves, depleting the pulse energy. At the same time, the large amplitude plasma wave provides a dynamic dielectric response that leads to spectral shifting. The loss of laser pulse energy and the approximate conservation of laser pulse action imply that

spectral red-shifts accompany the depletion. In this paper, we investigate, through simulation, the parametric dependence of MIR generation on pulse energy, initial pulse duration, and plasma density. (By: Zhu, W.; Palastro, J. P.; Antonsen, T. M)

An improved iteration loop for the three dimensional quasi-static particle-in-cell algorithm: QuickPIC
Improvements are developed for the three-dimensional (3D) quasi-static particle-in-cell (PIC) algorithm, which is used to efficiently model short-pulse laser and particle beam-plasma interactions. In this algorithm the fields including the index of refraction created by a static particle/laser beam are calculated. These fields are then used to advance the particle/laser beam forward in time (distance). For a 3D quasi-static code, calculating the wake fields is done using a two-dimensional (2D) PIC code where the time variable is xi = ct - z and z is the propagation direction of the particle/laser beam. When calculating the wake, the fields, particle positions and momenta are not naturally time centered so an iterative predictor corrector loop is required. In the previous iterative loop in QuickPIC (currently the only 3D quasi-static PIC code), the field equations are derived using the Lorentz gauge. Here we describe a new algorithm which uses gauge independent field equations. It is found that with this new algorithm, the results converge to the results from fully explicitly PIC codes with far fewer iterations (typically 1 iteration as compared to 2-8) for a wide range of problems. In addition, we describe a new deposition scheme for directly depositing the time derivative of the current that is needed in one of the field equations. The new deposition scheme does not require message passing for the particles inside the iteration loop, which greatly improves the speed for parallelized calculations. Comparisons of results from the new and old algorithms and to fully explicit PIC codes are also presented. (By: An, Weiming; Decyk, Viktor K.; Mori, Warren B.; T. M. Antonsen)

THz generation by optical Cherenkov emission from ionizing two-color laser pulses
Two-color photoionization produces a cycle-averaged current driving broadband, conically emitted THz radiation. We investigate, through simulation, the processes determining the angle of conical emission. We find that the emission angle is determined by an optical Cherenkov effect, where the front velocity of the current source is faster than the THz phase velocity. (By: Luke Johnson, John Palastro, TM Antonsen, and K.Y. Kim)

Model for the Atomic Dielectric Response in Time Dependent Laser Fields
A nonlocal quantum model is presented for calculating the atomic dielectric response to a strong laser electric field. By replacing the Coulomb potential with a nonlocal potential in the Schrodinger equation, a 3+1D calculation of the time-dependent electric dipole moment can be replaced with a 0+1D integral equation, offering significant computational savings. The model is benchmarked against an established ionization model and \textit{ab initio} simulation of the time-dependent Schrodinger equation. The reduced computational overhead makes the model a promising candidate to incorporate full quantum mechanical time dynamics in laser pulse propagation simulations. (By: T.C. Rensink, T.M. Antonsen Jr., J.P. Palastro, D. Gordon)

Publications acknowledging DOE support

WM An, VK Decyk, WB Mori, TM Antonsen**, An improved iteration loop for the three dimensional quasi-static particle-in-cell algorithm: QuickPIC,** JOURNAL OF

COMPUTATIONAL PHYSICS Volume: 250 Pages: 165-177 DOI: 10.1016/j.jcp.2013.05.020 OCT 1 2013

W. Zhu, JP Palastro, and TM Antonsen, **Pulsed Mid-infrared Radiation from Spectral Broadening in Laser Wakefield Simulations**, *Phys. Plasmas* ***20****, 073103 (2013)*.

L. Johnson, J. Palastro, T. Antonsen, and K-y Kim, **THz generation by optical Cherenkov emission from ionizing two-color laser pulses,** PHYSICAL REVIEW A Volume: 88 Issue: 6 Article Number: 063804 Published: DEC 2 2013

T.C. Rensink, T.M. Antonsen Jr., J.P. Palastro, D. Gordon, **Model for the Atomic Dielectric Response in Time Dependent Laser Fields**, arXiv:1311.5600 Phys Rev. A, to be published.

Conferences and Presentations

55th Annual Meeting of the APS Division of Plasma Physics Volume 58, Number 16 BAPS. (2013))

NP8.00058 Selective emission of low frequency electromagnetic wave due to an interaction between strong laser field and single-walled carbon nanotubes
T. Taguchi, TM Antonsen, M Inoue

UO7.00008 Pulsed Mid-infrared Radiation from Spectral Broadening in Laser Wakefield Simulations
W. Zhu, J. Palastro, T. M. Antonsen

YO6.00003 Simulation of Terahertz Generation in Corrugated Plasma Waveguides
C Miao, A. Pearson, T.M. Antonsen and J. Palastro

YO6.00004 THz Generation by Optical Cherenkov Emission from Ionizing Two-Color Laser Pulses
L. Johnson, J Palastro, T.M. Antonsen and K-Y Kim

UO7.00011 Quantum Model for Atomic Response in Strong, Time Dependent Electric Fields
T. Rensink, T. M. Antonsen, and J. Palastro

Graduate students supported:

Chen Long Miao
Thomas Rensink
Luke Johnson