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LASER WAKEFIELD EXCITATION AND MEASUREMENT ON A FEMTOSECOND TIME SCALE: THEORY AND EXPERIMENT

Progress Report

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THEORETICAL INVESTIGATIONS

1) *SUPERLUMINOUS WAKE EXCITATION*: For possible control of the excitation of wake in the longitudinal and transverse directions, the employment of active media in situ of the laser propagation can be advantageous. In light of recent pulse propagation over 20m in air by Mourou's group and a large gain in collisionally excited x-ray laser, a possibility of superluminous laser pulse in active media may have become nonnegligible. We wrote a follow-up paper[1] to the last year letter paper.[2]

2) *PHOTON FREQUENCY-SHIFT ("PHOTON ACCELERATOR") SPECTROSCOPY:* We developed a computational tool which can track the frequency shift of the probe laser pulse in the gas that ionizes at the front of the pulse and later in a fully ionized plasma that sustains the wakefield. The theoretical expression of the coulomb barrier suppression ionization is inserted into each "model" atom. Then the PIC code with fully self-consistent electromagnetic fields can track the spectral shift due to ionization, wakefield, third (or higher) harmonics as well as the initial laser's third order spectral distortion. Test spectra from the experiments are compared with the code results with semiquantitative agreements.[3]

The simulation results had similar structures of the main spectrum of the laser pulse, the blue shifted main spectrum, the third harmonic, and the blue shifted third harmonic of the laser pulse. Higher harmonics of the fundamental frequency were observed for the first time in a numerical simulation. The fine structure of the spectrum could be reproduced by allowing a higher order disturbation in the frequency domain of the incoming laser pulse. Good qualitative and quantitative agreement with the observed date in the main spectrum and in the 3rd harmonic was achieved when allowing a cubic frequency distortion in the frequency domain of the pulse.

3) *FOCUSING, DIFFRACTION, AND 2D SPECTRAL SHIFT:* 2D code with self-consistent laser complitude and phase equations has been constructed. We evaluated the laser diffraction due to the ionization, plasma density modulation etc., which were found to play a small role in our experimental setup. The probe photon frequency shift diagnosis á la 2) is also incorporated in this code.

Additionally, pump depletion due to ionization has also been shown to have little effect on the experimental setup. Channel depth and shape necessary for channel guiding in the experimental regime has been demonstrated through simulation.

4) *RAMAN SELF-MODULATION EFFECTS:* The KEK (National Lab for High Energy Physics, Japan) scientists and their collaboration (UT Austin included) have carried out a wakefield acceleration experiment using an Osaka University ILE's glass laser. The standard wakefield excitation with a low density plasma was carried out with expected results,[4] in agreement with theory. However, when they shot the same laser (at focus the estimated intensity was $I=2x10^{16}$ W/cm^2) in 1 atmosphere gas ($ne=1.5x10^{19}$ cm^{-3}), they observed much higher energy electrons unexpectedly. After experimental analysis, it was determined that the accelerating gradient over 1.5 mm. propagation with focus amounted to 30 GeV/m. Injected electrons with 1MeV/c momenta reached as much as 18 MeV.

In order to understand this unexpected experimental result, we carried out 1D PIC simulation. Under the parameters similar to the experiment we find that strong Raman forward instability sets in and this strongly modulates the laser pulse profile and induces intense wakefield (much more so than in the standard less dense plasma) which corresponds to about 30 GeV/m in good agreement with the experiment. The resultant laser pulse is sharply bunched and cleanly shredded with the periodic length of $2\pi c/\omega_p$. Accelerated electrons are equally strongly bunched. With a slight seed pulse with frequency shift of ω_p with 0.1 % of intensity of the main pulse, the above modulation process is even more pronounced and clean. In the case of $I=10^{17}$ w/cm^2 in 10^{19} cm^{-3} density plasma, with 0.1% seed we observe the accelerating field of 300 GeV/m.[5] Applications of such bunched electrons to coherent radiation in Wigglers and others have been considered.

5) *OPTICAL PREACCELERATOR:* In order to accelerate electrons in the wakefield whose wave length is of the order of 100μ, it is crucial to preaccelerate electrons and bunch them at precise phase synchronous with the wakefield phase. The beam radial size has to be equally small. This synchronization amounts to the accuracy of less than 10μ corresponding less than 30 fs synchronicity. No accelerator physics technology has accomplished such minuscule time scale accuracy. In order to meet this challenge, we invented the method of chirped backscattering beat wave.

The idea is: (i) to use the same laser system to accomplish the precise synchronicity; (ii) to superimpose the forward propagating laser ω_1 and the back propagating laser ω_2 ($\omega_1-\omega_2=\omega_p$) in a plasma to make a beat phase velocity $v_{ph}=\omega_p/(k_1+k_2)$, which is much less than c; (iii) to pick up a large portion of the bulk electrons to accelerate in a low energy and then to gradually increase its phase velocity by chirping the laser frequencies ω_1, ω_2 downward with $\omega_1-\omega_2=\omega_p$ intact. A following main pulse ω_m can now cause the wakefield whose phase velocity is near c, to accelerate the preaccelerated electrons by the beat described above.

6) *ACCELERATOR PHYSICS DEVELOPMENTS:* We pointed out the importance of the laser efficiency and efficacy of usage of laser energy in wake excitation and subsequent acceleration. (Papers [1] and [2] were written partially out of this concern.) This point has been now well recognized by the laser developer Prof. G. Mourou of University of Michigan and led him to consider CPA (chirped pulsed amplified) lasers appropriate for LWFA. Another crucial issue is the precision and control of the wakefield and plasma. As we discuss in the experimental session, the development of precision optical diagnosis of wakefield, plasma, and the main laser pulse in femtosecond regimes can contribute to the real time diagnosis (and possible feed forward control) of LWFA conditions in the future experiment through a variety of techniques such as the adaptive optics strategy. Our systematic diagnosis technique is targeted to such future direction.

Another precision usage of laser in accelerator physics is to employ the short wide-band laser for optical cooling with laser beatwave. The algorithm for this has been developed and computer simulation has demonstrated that the beatwave laser kick can contribute to rapid electron beam bunch cooling in a storage ring.[6]

In order to promote the awareness and communication of the state-of-the-art scientific review of the current status of accelerator physics and finding the future course of actions and technical developments and the collaboration among the active researchers, one of the PI's (T.T.) organized the Tamura Symnposium on Accelerator Physics in November of 1994 in Austin. In this Symposium we not only reviewed the demise of SSC but its ramifications as well as new directions for future accelerator physics. Many interesting new ideas have emerged and they are compiled in the Summary of the Symposium which, along with authors' papers, will be published in the Symposium Proceedings by AIP on LWFA.

One emerging theme that attracted strongest interest was the recent T^3 laser development and its application. A group of people from many institutions decided to examine critical technical issues on LWFA in a short while. Prof. G. Mourou (T.T. helping) took charge to have a follow-up meeting at the University of Michigan under the auspices of NSF Center for Ultrafast Optical Center. There now emerges an active collaboration group of institutions (UT Austin, U of Michigan, U of Maryland, NRL, LLNL, UCLA, UC Berkeley, LBL, USC, KEK) complementing each other's strength and lack of resources etc., presenting a loosely knit working group. One of our roles was to stimulate the convergence of mutual interaction and interest.

REFERENCES

1. D.L. Fisher, T. Tajima, M.C. Downer, and C.W. Siders, *Envelope Evolution of a Laser Pulse in an Active Medium*, to be published in Phys. Rev. E (1995).

2. D.L. Fisher, and T. Tajima, *Superluminous Laser Pulse in an Active Medium*, Phys. Rev. Lett. **71**, 4338 (1993).

3. B. Rau, D. Fisher, T. Tajima, C. Siders and M.C. Downer, *On the Effects of Gas Ionization on Spectral Intensity Distributions of Short, Intense Laser Pulse*", presented at the Tamura Symposium (Austin, Nov. 1994).

4. D.L. Fisher, "*Laser Wakefield Accelerator*", Ph.D. Dissertation (May 1995).

5. K. Nakajima, T. Kawakubo, H. Nakanishi, A. Ogata, Y. Kato, Y. Kitagawa, R. Kodama, K. Mima, H. Shirage, K. Suzuki, T. Zhang, Y. Sakawa, T. Shoji, Y. Nishida, N. Yugami, M. Downer, D. Fisher, B. Newberger, and T. Tajima, *A Proof-of-Principle Experiment of Laser Wakefield Acceleration*, Physica Scripta **T52**, 61 (1994).

6. K. Nakajima, D Fisher, et al., submitted to Phys. Rev. Lett. (1994)..

7. Y. Kishimoto, T. Tajima, D.L. Fisher and K. Mima, *Laser Beatwave Cooling*, submitted to Phys. Rev. Lett. (1994).

8. J.K. Koga and T. Tajima, *Collective Effects of Beam-Beam Interaction in a Synchrotron Collider*, ed. by Y.T. Yan et al. (AIP, NY, 1995) p. 215.

EXPERIMENTAL INVESTIGATIONS

1) *EXPERIMENTAL FACILTIES:* Several major experimental facilities have been designed, built, and operated as part of our project of mapping laser wakefield microstructure using "photon acceleration" measurements:

a) ***Terawatt laser system*** - The laser system is the central instrument of our experiment, and has been built using the chirped pulse amplification principle by graduate students Craig Siders and Ticy Turner and Russian collaborators A. Babine and A. Stepanov. It provides high intensity (~10^{18}W/cm^2) focused light pulses which generate Langmuir waves in an underdense plasma via the ponderomotive force, and weaker synchronized pulses which optically probe the wakefield structure via the "photon accelerator" effect. Our terawatt laser system is now fully operational and provides output pulses of 50 mJ, <100 fs duration FWHM, at 30 Hz repetition rate. The unique point-stabilizer system which we built to guide the Nd:YAG pump laser to the Ti:sapphire oscillator has recently been commercialized [see Technology Transfer]. Recompressed 80 fs pulses of ~ 3 mJ from the regenerative Ti:S preamplifier were used to generate pressure tunable radiation [see Experimental Results] in an important preliminary experiment. Fully amplified recompressed pulses are being used in the current experiments, which utilize an elaborate time-domain interferometry technique developed by graduate student Craig Siders to achieve unprecedented sensitivity to the photon accelerator effect ;see Experiment in Progress].

b) ***Multi-pass cell and dual diode array detector*** - A multipass cell consisting of two slightly off-axis confocal spherical mirrors has been used to achieve five consecutive high-intensity foci of a single laser pulse. A three-fold multiplication of ionization-induced blueshifting of the ionizing pulse was demonstrated. In addition, M.S. student T. Turner designed, built, and operated a dual diode array detector for our .275 m spectrometery which simultaneously acquires frequency-shifted signal and unshifted reference spectra for each laser shot at 30 Hz repetition rate. This detector yielded sensitivity of $\Delta\omega/\omega<10^{-5}$ in the measurement of centroid blueshifts $\Delta\omega$ of an ionizing pulse [see Experimental Results], adequate for wakefield detection. This detector is also central to our current time-domain interferometry measurements, which aim for $\Delta\omega/\omega<10^{-6}$ and for wakefield mapping.

c) ***THz emission optics and detector*** - Russian collaborators A. Babine, A. Kisselev, and A. Stepanov have provided parabolic collection optics and a liquid-helium-cooled Ge: Ga detector to detect THz emission resulting from wakefield charge oscillations in the focal region. Such emission has been reported by Hamster et al., and if useful as a coarse space-time integrated indicator of the existence and approximate average amplitude of wakefield oscillations, to support the more difficult space-time-resolved measurements of wakefield microstructure from the photon accelerator. The THz collection/detection system has been set up and is currently being tested.

d) ***Time-domain Rayleigh interferometer*** - A dual channel probe/reference interferometer designed, computer-modeled, and by C. W. Siders has been set up together with Russian collaborators. It is being tested in photon accelerator experiments now in progress [see Experiment in Progress].

2) *EXPERIMENTAL RESULTS - PRESSURE-TUNABLE HARMONIC GENERATION:* This past year we have completed the first major round of experiments with our new laser system. In these experiments we demonstrated generation of frequency up-shifted, pressure-tunable third harmonic pulses during ultrafast ionization of subatmospheric noble gases at moderate peak

intensities ($\sim 10^{16}$W/cm^2) corresponding to barrier suppression ionization. These experiments were of direct interest for demonstrating a new concept, proposed by us, for an easily tunable source of coherent VUV radiation, and for providing a pathway to attosecond pulse generation, as described further below. However, they simultaneously provided an ideal "dry run" for our main photon accelerator experiment because their realization required development of two key components of the photon accelerator: 1) detection techniques for measuring frequency centroid shifts as small ($\Delta\omega/\omega<10^{-5}$) as those anticipated in probing of small amplitude wakefields, and 2) a multi-pass cell consisting of two slightly off-axis spherical mirrors for 5-fold multiplication of interaction length. In addition, they involved full operation of the laser and vacuum systems which have been prepared for photon accelerator experiments.

While high harmonic generation (HHG) of ultrashort laser pulses offers the potential of table-top VUV light sources, with brightness comparable to synchrotrons, existing HHG systems are not easily tunable. We proposed theoretically via 1D simulations that widely continuously tunable harmonics could be efficiently generated at ionization fronts driven by short laser pulses at intensities $10^{15} < I_{peak} < 10^{16}$W/cm^2. By contrast, previous HHG experiments had been performed at lower intensities, with the prevailing opinion that significant ionization hinders efficient generation of harmonics. Our recent experiments have confirmed that main features of these predictions: 1) blueshifted third harmonic which is widely pressure tunable from $10^{-5} <\Delta\omega/\omega<10^{-1}$, corresponding to a pressure range of $0.1 < p < 700$ torr, is observed; 2) its frequency shift and broadening scale with ease of ionization (i.e. heavier gases evidence more shift and broadening); 3) the observed bandwidth of blueshifted harmonics is consistent with pulse durations $\tau \sim 20$ fs and with a generation source localized at the ionization front; 4) its measured efficiency is consistent with theoretical prediction, and with conversion efficiencies as high as 10^3 for harmonic orders $N < 20$ under optimized focus conditions. In addition, we observed unexpected preferential self-guiding of the blueshifted portion of both the fundamental and harmonic pulses over part of the experimental pressure range ($100 < p < 500$ torr). Such a correlation between blueshifting and guiding had not been observed previously. Though not understood quantitatively, this guiding appears to involve a complex interplay among self focusing, diffraction, and plasma-induced defocusing. The effect is very useful in allowing the blueshifted harmonic to be separated from the unshifted background harmonic by a simple spatial filter. These experiments are described in the accompanying manuscript which has been submitted for publication to the Journal of the Optical Society of America B.

3) *EXPERIMENTS IN PROGRESS: TIME-DOMAIN RAYLEIGH INTERFEROMETRY*

In order to push the detection sensitivity of our photon accelerator to the ultimate limits required for detection and profiling of low amplitude wakefield oscillations ($\Delta\lambda/\lambda<10^{-6}$ in a single laser shot), we have designed, set-up, and are currently running a pump-probe experiment which exploits frequency-domain interference between the pulse probing the wakefield and one or more reference pulses. Related techniques have been developed recently by Kobayashi et al. and Gauthier et al. for measuring fs-time-resolved phase shifts with unprecedented precision in other experimental contexts. The basic idea can be understood by analogy to an interferometer developed by Lord Rayleigh 100 years ago to measure exceedingly small differences in refractive index between two gaseous media (1 part in 10^6). Rayleigh interferometer consisted of a Young's double-slit diffraction experiment with gas cells placed over each slit. With the cells evacuated, the coherently illuminated slits produce a sinusoidal interference pattern on a distant screen. When gas is added to one or both cells, however, the phase shift between the two optical paths shifts the fringe pattern on the screen. By having the cells cover only part of the slits vertically, Rayleigh cast a reference fringe pattern below the "signal" pattern to enhance the measurement sensitivity for small shifts.

Our technique translated Rayleigh's space-domain interferometer into the time-domain. The two slits separated in space are replaced by two collinearly propagating light pulses (probe and reference) separated in time. The two gas cells are replaced by 1. a phase point in the plasma wakefield structure created by the main pump pulse, through which the probe pulse travels, and 2. the reference gas temporally preceding the pump (or alternatively a reference point in the plasma following the pump), through which the reference pulse travels. The spatial interference pattern on a screen is replaced by frequency-domain interference patterns created as the probe and reference pulses interfere inside a spectrometer. Rayleigh's vertically split pattern on the screen is replaced by a dual diode array on the output of the spectrometer, on which the frequency domain interference pattern of the main probe and reference pulses described above can be detected simultaneously on each laser shot with the that of a separate pair of pulses which by passes the interaction region. This last procedure corrects for shot-to-shot phase fluctuations in the laser source.

A diagram of the experimental TDRI set-up, a simulation demonstrating its sensitivity, and preliminary experimental results are described in more detail in an attached document.

4) ***RUSSIAN COLLABORATION:*** The collaboration with the Institute of Applied Physics (IAP), Nizhny Novgorod, Russia, described in last year's report, has continued and expanded over the past year. A formal Scientific Exchange Agreement between IAP and University of Texas has been executed and signed by cognizant officials of each institution. Drs. A. Babine and A. Stepanov have returned (February - May, 1995) for their third collaborative visit, along with first-time visitor A. Kisselev. Group leader A. Sergeev will return this year for the second time. M. Downer visited Russia twice in fall 1993, once as a guest of IAP (9/93), then to attend the US-Russia Workshop on Physics of Plasmas (10/93) in Chernogolovka. During the latter workshop, the participating scientists adopted a memorandum in which they resolved to submit joint proposals on related topics to the Russian Basic Science Foundation (RBSF) and to the US National Science Foundation (NSF). Downer and A. Sergeev submitted companion proposals entitled "US-Russia Cooperative Research: Generation of Tunable, Ultrashort XUV Radiation during Femtosecond Ionization of Gases", which has subsequently been approved and funded by both RBSF and NSF (grant PHY-9417558). This project closely intertwines with the DoE-sponsored wakefield project, and provides the dominant financial support for this continuing collaboration. There have been several joint publications involving the two groups.

5) ***TECHNOLOGY TRANSFER:*** Under DoE support an adaptive optics device which actively stabilizes the directional pointing of the pump beam for the Ti:S femtosecond source laser for our terawatt system was developed in our laboratory. The device greatly improved the amplitude stability of the Ti:S laser output, and enabled synchronously-pumped, self-starting operation. This in turn improved the amplitude and pointing stability of the amplified output. This past year Dr. Drew Nelson of Laser Ionics, Inc., based in Orlando, FL approached us with an interest in marketing the device through a subsidiary company called Technology Transfer Corporation, PO Box 915710, Longwood, Florida 32791 (Tel: 407-365-1733). A consulting agreement to co-develop a commercial product with Technology Transfer Corp. was signed late this past summer. The product is now on the market under the trademark "INLINE", and an advertising brochure featuring the DoE-sponsored University of Texas contribution has been printed and widely distributed to prospective vendors. Several units have been sold as of this writing.

Over a longer term, this device may be useful in multi-staging of laser wakefield accelerators, where stringent requirements on pointing stability of a recycled, tightly focused pump beam must be met.

REFERENCES

1. E. V. Vanin, A. V. Kim, A. M. Sergeev, and M. C. Downer, *Excitation of ultrashort bursts of harmonics of the radiation during ionization of a gas by an intense light pulse*, JETP Lett. **58**, 900-906 (1994).

2. C. W. Siders, N. C. Turner III, M. C. Downer, A. Babine, and A. Stepanov, *Blueshifted third harmonic generation during ultrafast barrier suppression ionization of subatomic density noble gases*, submitted to J. Opt. Soc. Am. B in February 1995.

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4. A. M. Sergeev, A. V. Kim, E. V. Vanin, and M. C. Downer, *Rapidly ionized atoms as a tunable source of ultrashort coherent VUV radiation*, in High Field Interactions and Short Wavelength Generation, vol. 16, 1994 OSA Technical Digest Series (Optical Society of America, Washington DC, 1994), pp. 130-133.

5. N. C. Turner III, *Dual beam detection of frequency shifted ultrafast pulses*, M. S. dissertation (University of Texas at Austin, 1994).

6. C.W. Siders, E.W. Gaul, M.C. Downer, A. Babine, and A. Stepanov, *Self-starting femtosecond pulse generation from a Ti:sapphire laser synchronously pumped by a pointing-stabilized mode-locked Nd:YAG laser*, Rev. Sci. Instrum. **65**, 3140-3144 (1994).

7. C.W.Siders, E.W. Gaul, M.C. Downer, A. Babine, and A. Stepanov, *Self-starting femtosecond pulse generation from a Ti:sapphire laser synchronously pumped by a pointing-stabilized mode-locked Nd:YAG laser*, In Generation: Amplification and Measurement of Ultrashort Laser Pulses, R. P. Trebino and I. A. Walmsley, eds. Proc. SPIE **2116**, 88-97 (1994).

8. C.W. Siders, E.W. Gaul, M.C. Downer, A. Babine, and A. Stepanov, *A self-starting Ti:sapphire laser synchronously pumped by a pointing-stabilized Nd:YAG laser*, In Conference on Lasers and Electro-Optics 1994, OSA Technical Digest Series (Optical Society of America, Washington, DC 1994), pp. 324-235. Presented at CLEO '94, paper CThl10, Anaheim, CA, May 12, 1994.

9. *INLINE: Laser beam pointing stabilizer*, advertising brochure for Technology Transfer Corporation (1995).

APPENDICES/PUBLICATIONS

THEORETICAL INVESTIGATIONS:

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6. K. Nakajima, D Fisher, et al., submitted to Phys. Rev. Lett. (1994).

7. Y. Kishimoto, T. Tajima, D.L. Fisher and K. Mima, *Laser Beatwave Cooling*, submitted to Phys. Rev. Lett. (1994).

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2. C. W. Siders, N. C. Turner III, M. C. Downer, A. Babine, and A. Stepanov, *Blueshifted third harmonic generation during ultrafast barrier suppression ionization of subatomic density noble gases*, submitted to J. Opt. Soc. Am. B in February 1995.

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8. C.W. Siders, E.W. Gaul, M.C. Downer, A. Babine, and A. Stepanov, *A self-starting Ti:sapphire laser synchronously pumped by a pointing-stabilized Nd:YAG laser*, In Conference on Lasers and Electro-Optics 1994, OSA Technical Digest Series (Optical Society of America, Washington, DC 1994), pp. 324-235. Presented at CLEO '94, paper CThl10, Anaheim, CA, May 12, 1994.

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