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

Progress Report

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THEORETICAL INVESTIGATIONS

1) IONIZATION FRONT: We found that over a short period of time the intense laser fields injected in a gas can give rise to an ionization front which, in turn, can generate an electron-rich layer. This layer is propagating with the laser pulse (and thus with speed $\sim c$), yielding a chemical potential $\phi_c \sim T_e$. When the pulse is sufficiently short, this chemical potential can add substantially to the wakefield potential. In our experimental parameters this effect was found to be important.

2) TWO DIMENSIONAL EFFECTS: Through our numerical investigations, we observed the wakefield is much greater in 2D code than in 1D code. At times, the enhancement of the wakefield in the 2D code is as much as five times the value obtained in the 1D code. The enhancement is greater if the transverse size of the laser beam is smaller than the longitudinal size. We identified the reason for this enhancement. A similar effect was found in the auroral electron acceleration and thus is temporarily called the auroral effect. To be more precise, the wake electric field encircling the laser beam has to obey $\nabla \times E \sim \omega$, yielding the geometric enhancement.

3) SUPERLUMINOUS LASER PULSE: We discovered that under appropriate conditions a laser pulse can propagate at a designated speed in an active lasing medium. In order to achieve a significant change in its group velocity, one needs to match the laser frequency with the transition energy ($/\hbar$) and the pulse length needs to be of the order of the Rabi period. By appropriately pre-exciting the laser medium, we are able to propagate the laser pulse faster than (or equal to) the speed of light (superluminous). Such an arrangement allows us also the recovery of pump depletion of the laser. The accelerated laser pulse induces wakefields with accelerated phase velocity. Thus, such a superluminous laser pulse may be able to create a wakefield whose phase velocity is c so that there is no slippage between the wakefield and particles to be accelerated.

4) DEVELOPMENT OF COMPUTATIONAL TOOLS: We are developing a variety of computer simulation codes for analyzing the laser wakefield excitation experiment. As stated in the original proposal, we already had a 1D "fluid" code and particle-in-cell (PIC) code. We are currently developing 2D versions of the "fluid" code. One of these 2D versions includes atomic physics effects such as the ionization effects and internal atomic states, in order to explore the effects described in subsections (1) and (3). We are also streamlining the so-called PIC codes into a code with a larger time-scale integrating over the short laser period. These codes should be capable of analyzing effects such as self-focusing

of laser pulses, atomic physics influence on plasma physics, laser field modifications due to the plasma, etc. These codes are further capable of analyzing the spectroscopic second laser pulse responses to the wakefield. In this regard, we began to convert Dr. V. Wong's (Institute for Fusion Studies) code for a free electron laser for the wakefield spectroscopy analysis.

EXPERIMENTAL INVESTIGATIONS

1) MEASUREMENTS OF GROWTH DYNAMICS OF IONIZATION FRONT: As emphasized in the original proposal, the interaction of a short laser probe pulse with a laser wakefield oscillation closely resembles its interaction with an ionization front. Furthermore, the experimental procedure for observing spectral blueshifts (our primary diagnostic of plasma oscillation dynamics) is similar whether caused by the wakefield or the ionization front. Since the latter can be created with a much lower energy laser pulse from an already existing dye laser system in our laboratory, a comprehensive series of femtosecond time-resolved blueshift measurements which expanded upon earlier preliminary experiments by our group [Phys. Rev. Lett. **67**, 3523 (1991)], was performed using dye laser ionizing pulses focused to 10^{14} to 10^{16} W/cm² peak intensity in atmospheric density samples of each of the five noble gases. These experiments parallel and reinforce the planned wakefield experiments using $\sim 10^{18}$ W/cm² pulses from the more powerful laser/amplifier system under construction (see #2 below). A theoretical analysis of the ionization experiments was carried out, and yielded two main conclusions: (i) for peak intensities $> 10^{15}$ W/cm², collisionless tunneling ionization dominates in the leading edge of the ionizing pulse, and saturates well before the peak of the pulse; and (ii) in the heavy rare gases (Xe, Kr), an extra, slower, density-dependent ionization process occurs near the temporal peak of the ionizing pulse, which cannot be explained by a pure tunneling ionization mechanism. The extra mechanism is believed to be impact ionization induced by electrons quivering in the strong light field. To our knowledge these are the only *time-resolved* measurements of ionization dynamics within an intense femtosecond laser pulse which have been performed. This time-resolved ionization physics relates directly to wakefield generation in several ways: (i) the growth rate of the ionization front determines the importance of ionization-induced wake oscillations described under (i) above; (ii) for effective studies of ponderomotively-driven wake oscillations, the ionization front should grow collisionlessly to saturation early in the pulse so that the intense maximum acts upon a cold, preformed plasma; and (iii) since the ionization front forms early in the pulse, its 2D profile determines the optical guiding or defocusing of the entire main pulse, and thus determines the interaction length for generating and observing wake oscillations.

2) CONSTRUCTION OF Ti: SAPPHIRE CHIRPED PULSE AMPLIFICATION LASER SYSTEM:

The major capital equipment and essentially all optical components for construction of a laser/amplifier system to generate 100 mJ., 100 fs., 800 nm. laser pulses have been acquired. Highlights of the construction activity so far are: (i) a previous synchronously pumped dye laser oscillator has been replaced with a synchronously pumped Ti: sapphire oscillator. Measured parameters of the new laser oscillator to date are: 75 fs. pulse duration (5x shorter than the dye laser); 300 mW. average power at 76 MHz pulse repetition rate (3x higher than the dye laser); 7 nm. spectral bandwidth around 800 nm. with shot-to-shot spectral stability dramatically improved over the dye laser (this last property is critical for wakefield diagnostic measurements which will be based on spectral blueshifting). With straightforward improvements we anticipate 50 fs., 600 mW. average power should be achievable. The Ti: sapphire oscillator was built by C. W. Siders and Russian collaborators A. Babine and A. Stepanov, the latter contributing the Ti: sapphire crystal and a unique set of wide-bandwidth laser cavity optics coated at Institute of Applied Physics, Nizhny Novgorod; (ii) holographic grating-based pulse stretcher and compressor systems have been set up and are being tested. Stretch factors approaching ~ 1000x are being observed with the 75 fs./70 nm. bandwidth Ti: sapphire laser oscillator pulses, and should be adequate to avoid optical damage to amplifier components and nonlinear pulse distortion during amplification. Precision, heavy-duty rotation-tilt mounts have been designed and built for the compressor gratings, and are critical to control of cubic and quartic dispersion factors which govern final re-compressed pulse duration and, in turn, the peak intensity which can be applied to wakefield generation. Computer ray-tracing programs have been employed to guide the detailed optical design of the grating compressor. Experimental testing of recompression is actively underway; (iii) a Ti: sapphire regenerative preamplifier designed to amplify the stretched (i.e. chirped) femtosecond pulse to several mJ energy at 30 Hz repetition rate is completely constructed and operational. Current activity is focused on optimizing its performance in combination with the stretcher and compressor; and (iv) a large Ti: sapphire crystal for the power amplifier stage, designed to amplify the stretched pulse to ~ 100 mJ. energy, has been supplied at low cost by the Russian collaborators. Other design details of the power amplifier are straightforward. Full system operation is anticipated by end of the summer.

INTERNATIONAL COLLABORATION

1) JAPANESE COLLABORATION: Our project has been carefully coordinated with our Japanese collaborators at KEK (National Laboratory for High Energy Physics, Tsukuba, Japan) and Osaka University Institute of Laser Engineering. In fact, the international coordination has been funded through the National Science Foundation and Japan Society

for Promotion of Science over two years (1992-1994). In this collaboration, several scientists from our group and the Japanese group (in the first year [1992-1993]) travelled and exchanged ideas and technical details. This collaboration aims at enhancing each other's results into different experimental conditions and parameters and at complementing each other's strengths. Our experiment is targeted to evaluate detailed scientific processes of laser wakefield excitation, while the Japanese program emphasizes the actual acceleration and applied experimental consequences. This is partially due to our university setting vs. their national laboratory setting and partially due to the present project's budget limitations. As an example, Professor Nakajima's tracking code of wakefield accelerated particles is useful to predict the energy spectrum of accelerated particles. On the other hand, our code is instrumental to predict the two dimensional wakefield structure for two of the experiments.

2) RUSSIAN COLLABORATION: Scientists at the Institute of Applied Physics (Nizhny Novgorod, Russia) are experts in high-power lasers. We have been in communication with them. However, our collaboration with them has been in high gear since our DOE project began last year. The group leader, Alexander Sergeev, came to give a seminar last year and two of the scientists, A. Babine and A. Stepanov, are now visiting Austin working on the laser system. They provided an excellent laser crystal and exceptionally wide bandwidth optics much below the market price. Two more experimentalists are slated to visit Austin this summer when first experiments with the new laser system are planned. This collaboration allows (i) a stimulating exchange between the two expert laser groups of the first caliber; (ii) our helping the IAP scientists who were previously working on classified defense-related work convert to exciting civilian scientific work; (iii) saving the DOE grant money by taking advantage of the inexpensive and thoroughly professional Russian scientific manpower and products; and (iv) internationalizing this exciting and important research on laser wakefields.

PUBLICATION

Wood, W.M., Siders, C.W., and Downer, M. C., *Femtosecond Growth Dynamics of an Underdense Ionization Front Measured by Spectral Blueshifting*, IEEE Transactions on Plasma Science 21, in press (1 February 1993), (invited paper).

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