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This grant F49620-96-1-0095:
Development of a high repetition rate elongated gas jet for plasma waveguide generation.
Guiding of terawatt level laser pulses in plasma waveguides produced in gas jets.
Complete measurements of pulse shortening resulting from ionization-induced refraction.
Upgrade of our ultra high power Ti: sapphire laser system.
Plasma structural electromagnetic resonances.
Laser-driven implosion of a cylindrical plasma.
Resonant plasma absorption of Bessel beams.

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Final report AFOSR grant F49620-96-1-~~0193~~ 0075

Progress since 96-97 report:

1. **Development of a high repetition rate elongated gas jet for plasma waveguide generation**: Efficient injection into the plasma waveguide of laser intensities greater than 10^{15}W/cm^2 is not possible if the waveguide is created in an ambient static gas. Pulses higher than this intensity limit tend to self-refract (in effect, spatially blow up) from the sharp electron density gradients they generate through field ionization as they propagate through neutral gas. To solve this problem, we developed an elongated, high repetition rate pulsed gas jet operating in vacuum, so that the laser pulse could be focused through vacuum before encountering the plasma waveguide entrance. We have demonstrated operation of a 1.5 cm long jet and we plan later this fall to demonstrate a 3 cm long jet. This work was published as *Applied Physics Letters 73, 3064 (1998).*

2. **Guiding of terawatt level laser pulses in plasma waveguides produced in gas jets:** We continued our guiding experiments, now using the pulsed gas jet (see above) in which to generate the waveguide. We demonstrated guided powers up to 0.4 terawatts (almost 10^{17}W/cm^2, a weakly relativistic intensity) over a 1.5 cm long waveguide, at 52% coupling efficiency. (It should be noted for comparison that coupling efficiency of low power laser beams to ordinary glass fibers is typically 50-60%!). This is almost a factor of two better coupling and over 20 times the guided intensity than achieved with channels generated in a gas backfill (described in our paper *Opt. Lett. 22, 1787 (1997)*). This work was eventually published as Phys. Rev. E **59**, **R**3839 (1999). Later this year, after upgrading the laser system to higher energy, we will attempt to guide pulses of intensity ~10^{18} W/cm^2.

3. **Complete measurements of pulse shortening resulting from ionization-induced refraction:** Ionization-induced refraction is an important consideration in the coupling of intense pulses to plasma waveguides (see 1 above). Aside from its relevance to plasma waveguide coupling and propagation, ionization-induced refraction is interesting in its own right, and we spent some time studying this phenomenon with short helium and argon gas jets. The FROG (Frequency Resolved Optical Gating) diagnostic we built last year (which can measure the field envelope and phase of a pulse on a ~3 femtosecond time scale) was modified to what we called a TI-FROG configuration. This enabled us to extensively investigate ionization-induced refraction *and* retardation in time of intense pulses. Retardation resulted from the pulse slowing down in the plasma it generated from field ionization as it propagated. Our wave propagation simulations (T. Antonsen) agreed well with experiment. This work was published as *Optics Communications **157**, 139 (1998).* We also developed an alternate FROG-like diagnostic, and this work was published as *Optics Communications **156**, 43 (1998).*

4. **Upgrade of our ultra high power Ti:Sapphire laser system:** We have added a second power amplifier to the Ti:Sapphire laser system, nearly doubling the energy to

80 mJ (in a 90 femtosecond pulse). We will be further doubling this energy later this year, to bring the pulsed power level to almost 2 terawatts.

5. **Plasma structural electromagnetic resonances:** We demonstrated the first direct observation of electromagnetic resonances of a plasma structure. This involved the side-coupling of subpicosecond, broadband visible continuum laser pulses to the plasma fibre. The work was published as *Phys. Rev. Lett. **81**, 357 (1998).* This phenomenon has an immediate consequence in the breakdown and heating of a gas with a Bessel beam, and the results of that experiment have been submitted to Phys. Rev. Lett. (see 7 below)

6. **Laser-driven implosion of a cylindrical plasma:** We demonstrated the first direct observation of a laser driving a concentric compression of a plasma. Although inertial confinement fusion or 'laser fusion' relies on laser-driven compression, no direct time-resolved measurement had ever been made of the density evolution in that situation. We did this measurement for a lower density case with a high degree of symmetry. This was published as *Phys. Rev. E 57, 3417 (1998).*

7. **Resonant plasma absorption of Bessel beams:** While performing the experiments of #5 above, we discovered that plasma channel generation can take place through a resonant coupling process, where the channel generation and heating can proceed with lower laser energy requirements. This work has been submitted to *Physical Review Letters.*.

Publications since 96-97 report:

1. *Frequency-selective tunnel coupling to the plasma fiber*
T. R. Clark and H.M. Milchberg
Phys. Rev. Lett. **81**, 357 (1998).
2. *Laser-driven implosion of a cylindrical plasma*
T.R. Clark and H.M. Milchberg
Phys. Rev. E **57**, 3417 (1998)
3. *Ionization-induced pulse shortening and retardation of high intensity femtosecond laser pulses in a neutral gas*
S.P. Nikitin, Y. Li, T. M. Antonsen, and H.M. Milchberg
Optics Communications **157**, 139 (1998)
4. *Generation of a plasma waveguide in an elongated, high repetition rate gas jet*
J. Fan, T.R. Clark, and H.M. Milchberg
Appl. Phys. Lett. **73**, 3064 (1998)
5. *Tracing the phase distortion of a single ultrashort light pulse from angularly resolved second-harmonic generation*
V. Kabelka, M. Masalov, S.P. Nikitin, and H.M. Milchberg
Optics Communications **156**, 43 (1998).

unrefereed conference proceedings:

Plasma waveguide: density development and high intensity guiding

T.R. Clark, S.P. Nikitin, Y. Li, and H.M. Milchberg

Proceedings of OSA conference on Applications of Field and Short Wavelength Sources, eds. L. DiMauro and M. Murnane, Plenum Press, 1998

High efficiency coupling and guiding of intense femtosecond laser pulses in preformed plasma channels in an elongated gas jet

S.P. Nikitin, I. Alexeev, J. Fan, and H.M. Milchberg, to be published in the proceedings of the Advanced Accelerator Conference 1998

invited talks:

Mode control in the plasma waveguide

APS spring meeting, Columbus, OH April 1998 (30 min.)

Weakly relativistic, high intensity guiding in a gas jet waveguide

Advanced Accelerator Conference, Baltimore, MD July 1998 (1 hour)

contributed talks:

Mode control in the plasma waveguide

Laser-driven implosion of a cylindrical plasma

APS Division of Plasma Physics Meeting, New Orleans, LA Nov. 1998 (30 min.)

Awards received under this grant

Tom Clark (PhD 1998) received the APS division of Plasma Physics Dissertation Award for 1999, for his dissertation entitled *Hydrodynamical and Optical Properties of the Plasma Waveguide*, work partially supported by this grant.

Patents received under this grant

A High Intensity Optical through X-ray Waveguide and its Applications

U.S. Patent 5,394,411 issued 28 February 1995

Milchberg

Report 1996-97 for AFOSR grant F49620-96-1-~~0193~~ 0095

1. Summary of progress

- In order to generate high harmonic radiation in ions and to generate sufficient ponderomotive force for large amplitude plasma wave generation (in other experiments in the area of laser-driven particle accelerators), we need to inject and optically guide in the plasma waveguide intense laser pulses from a Ti:Sapphire laser system we have developed. The pulse that makes the waveguide is produced by a different, independently mode-locked Nd:YAG laser system with 100 ps pulses. We had earlier achieved rough synchronization (within 1 ns) and in fall 1996, we successfully synchronized the 2 laser systems to well within 100ps and in a proof-of-principle experiment, injected and guided a low energy pulse from the Ti:Sapphire system. This result was presented in an invited talk to the particle accelerator community (Advanced Accelerator Workshop) in October, 1996 (see invited talks). After further increasing the energy of the Ti:Sapphire laser early this year we are now guiding pulses 50 times more intense, at the level of 10^{17} W/cm^2. We have performed FROG measurements on the output pulse (a diagnostic which can measure the time dependent optical amplitude and phase) and have found that the propagation is linear up to 5×10^{16} W/cm^2, which in retrospect is not surprising given that the guiding medium (the plasma waveguide) has been prepared ionized to a stable shell. Publication on this result is currently in preparation for submission to Optics Letters. We are now in the process of adding our final amplifier to the Ti:Sapphire laser system.

- We set up and demonstrated a time-resolved interferometer for directly measuring the refractive index profile of the waveguide. First results were presented in October, 1996 at the Advanced Accelerator Workshop and the work was published in PRL **78**, 2373 (1997).

- We demonstrated that irradiating the hydrodynamically evolving waveguide with a second pulse after the formation pulse drives an inward compression wave which modifies the waveguide refractive index profile in a controlled manner, resulting at early times in mode cutoff and at later times in the propagation of annular modes. Interferometry of the plasma directly shows the index profile evolution inferred from the guided mode profiles.

Journal and Proceedings Articles

Mode Control in a two-pulse excited plasma waveguide
C.G. Durfee III, T. R. Clark, and H.M. Milchberg
J. Opt. Soc. Am. B **13**, 59 (1996).
Development and Applications of a Plasma Waveguide for Intense Laser Pulses
H.M. Milchberg, C.G. Durfee III, T.R. Clark, T.M. Antonsen, and P. Mora
Phys. Plasmas **3**, 2149 (1996).
Time- and Space-Resolved Density Evolution of the Plasma Waveguide

T. R. Clark and H. M. Milchberg
Phys. Rev. Lett. 78, 2373 (1997).

Channel Guiding for Advanced Accelerators
H.M. Milchberg, C.G. Durfee III, T.M. Antonsen, and P. Mora
The Future of Accelerator Physics, AIP Conf. Proc. No. 356, p. 247-257 (AIP, New York, 1996)

Channel Guided Lasers for Plasma Accelerators
H.M. Milchberg, C.G. Durfee III, T.M. Antonsen, and P. Mora
Proceedings of the 1995 Particle Accelerator Conference and International Conference on High Energy Accelerators, p. 621-625 (APS, IEEE, 1996)

Guiding of sub-100 fs femtosecond pulses in pre-formed plasma channels
S. Nikitin, T.R. Clark, and H.M. Milchberg
to be published in Proceedings of 7th Workshop on Advanced Accelerator Concepts, Lake Tahoe, CA, October, 1996

Invited talks

Review of Intense Laser-Matter Interactions Experiments at the University of Maryland
seminar at RIKEN (The Institute of Physical and Chemical Research), Hirosawa, Wakoshi, Japan, 17 January 1996 (1 hr.)

A Light Pipe for Ultrahigh Intensity and its Applications
AAAS Annual Meeting and Science Exposition, Baltimore, MD, February 22, 1996 (30 min.)

Development and applications of a plasma waveguide for high intensity laser pulses
Plasma physics colloquium, Cornell University, 21 February 1996 (1 hr.)

High Order Frequency Conversion in the Plasma Waveguide
CLEO/QELS '96, Anaheim CA, June 4, 1996 (30 min.)

Guiding of sub-100 fs femtosecond pulses in pre-formed plasma channels
7th Workshop on Advanced Accelerator Concepts, Lake Tahoe, CA, October, 1996 (1 hr.)

High Intensity Laser-Plasma Interactions
Physics Department Colloquium, University of Connecticut, Storrs, CT, Dec. 6, 1996 (1hr.)

Time and Space-resolved density development of the laser-produced plasma waveguide
OSA conference Application of High Field and Short Wavelength Sources, Santa Fe, NM, March 1997 (30 min.)