

Generation of relativistic intensity pulses at a kilohertz repetition rate

O. Albert

Laboratoire d'Optique Appliquée, Centre National de la Recherche Scientifique, Unité Mixte de Recherche 7639, Ecole Polytechnique, École Nationale Supérieure des Techniques Avancées, 91761 Palaiseau Cedex, France

H. Wang, D. Liu, Z. Chang, and G. Mourou

Center for Ultrafast Optical Science, University of Michigan, 2200 Bonisteel Boulevard, Ann Arbor, Michigan 48109-2099

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By using adaptive optics to correct the wave-front distortion of a 21-fs, 0.7-mJ, 1-kHz laser, we are able to focus the pulses to a 1- μm spot with an $f/1$ off-axis parabolic mirror. The peak intensity at the focal position is $1.5 \times 10^{18} \text{ W/cm}^2$, which is to the authors' knowledge the first demonstration of generating relativistic intensity at a kilohertz repetition rate. © 2000 Optical Society of America

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Relativistic intensity refers to a new regime in optics in which the nonlinear character of a laser-matter interaction is dominated by the relativistic motion of the electrons characterized by a ponderomotive energy comparable with the electron's mass at rest.¹ It is a fundamentally new optical regime, in which the product of the laser intensity times the square of the wavelength exceeds $\sim 10^{18} (\text{W/cm}^2) \mu\text{m}^2$.² It extends the traditional realm of ultrafast optics investigation—limited so far to the valence and core electrons, with characteristic energy of a few electron volts, and which has dominated the ultrafast field for 25 years—to the nuclear regime. This intensity level has been possible because of the technique of chirped pulse amplification combined with the refinement in short-pulse generation.³ However, this novel regime could be reached previously only with relatively large and expensive lasers working at relatively low repetition rates, i.e., single-shot to 10-Hz. Currently there are only a small number of such big laser systems available for relativistic physics studies.^{4–8}

Kilohertz, millijoule, femtosecond lasers are commercially available and relatively cheap. For many experiments it is desirable to use lasers with kilohertz repetition rates because of their high stability (1% rms fluctuation) and compactness. To focus the millijoule level laser pulses to 10^{18} W/cm^2 or higher requires small- f -number optics. However, it is difficult to obtain a diffraction-limited focal spot because the geometric aberrations of such optics are highly sensitive to alignment. The wave-front distortion of the laser beam as a result of thermal effects and imperfection of the optics also affects the focusability. In this Letter we show that relativistic intensities are now accessible with kilohertz Ti:sapphire lasers, as we have shown by correcting the aberrations of an $f/1$ focusing mirror and wave-front distortion with the adaptive optics.

The Ti:sapphire laser system used in this experiment can produce 0.7-mJ, 21-fs pulses with a repetition rate of 1 kHz. The whole system is compact and oc-

cupies only a little more than half of a $1.2 \text{ m} \times 2.4 \text{ m}$ optical table. A schematic diagram of the system is shown in Fig. 1. The front end is a Kerr-lens mode-locked Ti:sapphire oscillator (FemtoSource Scientific Pro; FemtoLasers GmbH) that can generate broadband spectra pulses (120 nm FWHM), pumped by a Spectra-Physics Millennia laser at 5 W. The pulses are then stretched to 40 ps by an all-refractive grating stretcher. A Faraday isolator is used after the stretcher to isolate the oscillator from any possible feedback. After the Faraday isolator is a Pockels cell, which selects 1-kHz seed pulses. The seed pulses are then injected into a multipass Ti:sapphire amplifier.

The amplifier consists of only two curved mirrors. The radii of curvature of these mirrors are 75 and 60 cm, respectively. The separation of the two mirrors is the sum of their focal lengths, i.e., 67.5 cm. The beam is injected to the edge of the 75-cm radius-of-curvature mirror. The beam is then closer to the center of the mirror after each round trip because of the difference of the radii of curvature of the two mirrors. After seven passes, the amplified beam will exit from a

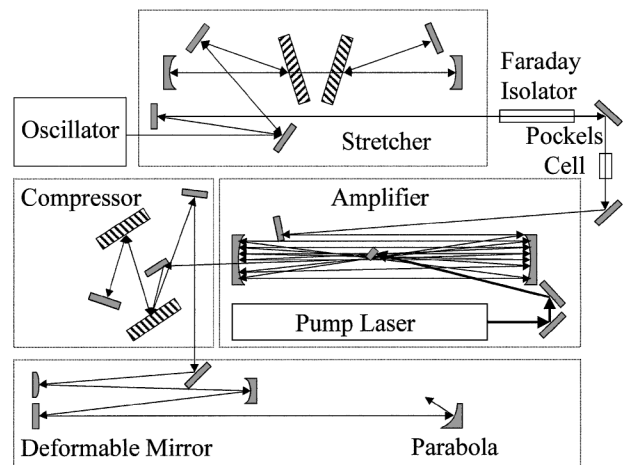


Fig. 1. Schematic diagram of the laser system.

hole in the center of the 60-cm radius-of-curvature mirror. The Ti:sapphire crystal is put at the focal spot, which minimizes the effect of thermal lensing. The crystal is water cooled and is maintained at $\sim 20^\circ\text{C}$. A mask with seven holes that match the beam sizes of the seven passes is placed in the amplifier to reduce amplified spontaneous emission. This amplifier is pumped by the second harmonic of a diode-pumped LiYF₄ laser (Spectra-Physics Lasers, Evolution X), which can generate 10-W average power at a 1-kHz repetition rate. More than 1 mJ of pulse energy can be obtained for a pump energy of 9.5 mJ. This amplifier design is easy to align because of its simplicity. Furthermore, there are only two mirror reflections for each round trip, which minimizes the loss that is due to mirror reflection.

After the beam is amplified, it is compressed by a grating compressor. The output pulse's energy is 0.7 mJ. The spectrum of the output pulse has a FWHM of 40 nm. An autocorrelation measurement was made with a 50- μm β -barium borate crystal. The autocorrelation trace in Fig. 2 shows that the pulse has a FWHM of 21 fs, assuming a sech² pulse shape.

To generate intensities greater than 10^{18} W/cm^2 we use an $f/1$ off-axis parabola to focus the beam. A deformable mirror is used to correct the wave-front distortion from the laser system and to precompensate for the aberration caused by the focusing optics. The deformable mirror is a 5.08-cm-diameter silver mirror with electrostrictive actuators (from Xinetics). The deformation of the mirror is controlled by 36 actuators. The maximum displacement is $\sim 10\ \mu\text{m}$. The laser beam is expanded to match the active size of the deformable mirror. In most traditional adaptive optical systems, one determines the optimal shape of the deformable mirror that will compensate for wave-front aberrations by first using a wave-front sensor to measure the distorted wave front, thus obtaining a wave-front error correction, which can then be fed to the deformable mirror to produce a flat wave front.⁹ Because it is extremely difficult to measure the wave front at the focus of a high-numerical-aperture parabola, we designed a scheme with which one can determine the optimal correction by the deformable mirror without the necessity to perform a wave-front measurement.¹⁰ The scheme that we implement here uses nonlinear optics in conjunction with machine learning through an evolutionary algorithm described below. Strong nonlinear effects occur at the focus spot of an ultrashort pulse. A stronger nonlinear signal generated at the focus corresponds to a smaller focal spot. Thus we can obtain diffraction-limited focusing by maximizing the nonlinear signal, using the deformable mirror, without the necessity to know anything about the wave front of the laser on the parabola.

We implement the nonlinear correction scheme by using second-harmonic generation in a thin β -barium borate crystal at the focal spot. The second-harmonic signal is used as feedback for the computer-controlled deformable mirror. The shape of the deformable mirror is optimized by an evolutionary algorithm, which is used as a form of machine learning to permit the

optimization of nonlinear systems with a large number of variables. The specific kind of evolutionary algorithm utilized in our experiment is a genetic algorithm, so named because it mimics the mechanism of evolution in nature. The basic idea is to create a population of individuals represented by their genes and then to test this population on the system under study. The best individuals of the initial population are then selected as parents of the new generation. The next generation goes through the same selection process, and the population converges, after a few generations, to a population of individuals that perfectly fit the system. As the algorithm can converge to a local minimum, a few individuals are mutated so they are randomly spread out of the convergence and then probe the system for a better convergence.

In our case, each individual has 36 genes, which correspond to the voltages on the 36 actuators of the deformable mirror. The fitness of each individual is the amount of second harmonic that it generates at the focal spot of the parabola. Mirror shapes that yield smaller spots generate more second harmonic and thus must be closer to the optimal mirror shape. This fitness function suits the genetic algorithm well, as it is a smooth function that has a maximum that contrasts well with the local minimum.

Figure 3 shows the close-to-diffraction-limited focal spot with the deformable mirror, which had a diameter of $1.2\ \mu\text{m}$ at FWHM. After unfolding the result with the instrument function, we found a spot size of $1\ \mu\text{m}$. Analysis of the focal spot image shows that 45% of the total energy is within the area surrounded by the $1/e^2$ intensity boundary, which results in a peak intensity of $1.5 \times 10^{18}\text{ W/cm}^2$.

In conclusion, we have shown that by correcting the wave-front distortion with adaptive optics we could reach a spot size of $\sim 1\ \mu\text{m}$ and an intensity higher than 10^{18} W/cm^2 could with femtosecond lasers operating at a kilohertz repetition rate. We believe that the same technique can be applied to kilohertz lasers at the 1-TW power level^{11,12} to produce an intensity that is $>10^{19}\text{ W/cm}^2$. Just as, 30 years ago,

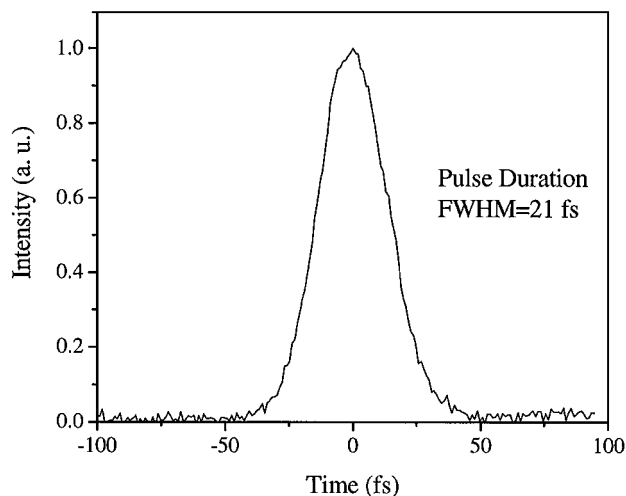


Fig. 2. Autocorrelation trace of the output pulse. The pulse duration is 21 fs, assuming a sech² pulse shape.

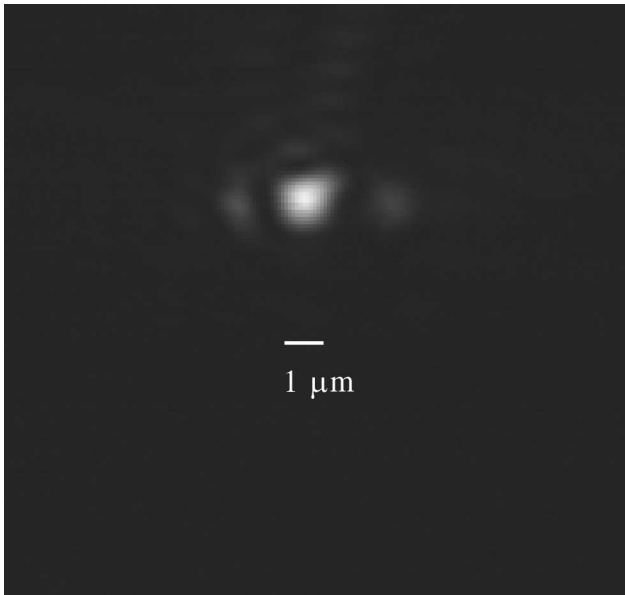


Fig. 3. Near-diffraction-limited focal spot with a diameter of $1.2 \mu\text{m}$.

high-repetition lasers made possible the study of ultrafast reactions in the visible regime, the possibility of studying, at high repetition, physical phenomena with mega-electron-volt characteristic energy will give a second wind to the field of ultrafast phenomena.

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