in which all atoms, by definition, are in the same momentum state. Following a similar procedure but with a different amplitude of modulation, this group also saw the atoms oscillate between modes that feature motions that are 180° out of phase with one another, as seen in figure 3. The discrete diffraction peaks in the figure result from interference between atoms from different cells of the optical lattice; most atoms are found in the peaks centered at 4 and 6 $\hbar k$. By varying the system parameters, Phillips and his colleagues observed as many as seven coherent tunneling oscillations, as well as tunneling periods that varied by as much as a factor of two.

Chaos-assisted tunneling

The Texas group believes that its experiment provides evidence of chaos-assisted tunneling. If chaos-assisted tunneling is involved, one would expect the tunneling rate to be faster when chaos is present than when it is absent. Raizen and company can remove the chaos by turning off the driving modulation of their optical lattice; the resulting motion is simply Bragg scattering. Dynamical tunneling should be manifested by above-the-barrier reflection, or reflection of atoms having a greater energy than the potential walls of the optical lattice. Such reflection is estimated to take about 1 s, much longer than the 360-μs period observed for dynamical tunneling in the driven system. Indeed, the experimenters saw no sign of tunneling oscillations in the undriven system over an interval of 1600 μs.

Raizen and his colleagues also measured the momentum distribution in time steps of 1 μs to study in detail how the tunneling proceeds. They saw a periodically enhanced probability in the chaotic region near $p = 0$, which they believe is evidence that a third (chaotic) state is involved in the transport between the two islands.

Dynamical and chaos-assisted tunneling have been observed in an electromagnetic analog of these quantum mechanical systems: a microwave cavity.[7] They also underlie the fundamental processes in chaos-assisted ionization and may be responsible for the decay of superdeformed nuclei.

Tomsovic thinks that both of the new experiments show clear evidence for dynamical tunneling. Although they are suggestive of chaos-assisted tunneling, he would like to see more evidence, such as determinations of the sensitivity of the tunneling time to variations in the system parameters.

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Experiments Detail How Powerful Ultrashort Laser Pulses Propagate through Air

> Thanks to self-focusing, laser pulses can be launched upward into clouds where they can be used to measure pollutants.

Like many things in physics, refractive index isn't as simple as we learned in high school. In addition to the familiar constant is a term that depends on intensity: $n = n_0 + n_2 I$.

This intensity dependence, known as the optical Kerr effect, underlies the phenomenon of self-focusing. If a beam of light is brighter in the center than at the edges—as most are—the center will encounter a bigger refractive index and slow down. Wavefronts that start out planar will therefore collapse about the center. A tighter beam results.

For air, n_2 is so tiny that the power must exceed several gigawatts for self-focusing to kick in. Only strongly focused or ultrashort-pulse lasers can provide such prodigious power. (For more on powerful ultrashort lasers, see the article by Gérard Mourou, Christopher Barty, and Michael Perry, PHYSICS TODAY, January 1998, page 22.)

In 1994, soon after ultrashort lasers came on line, Mourou and his group at the University of Michigan fired 10-GW, 200-fs pulses across their lab through air. Their goal was to mimic a pulsed microwave radar with light. Along with the expected self-focusing, they discovered something else.[1] To their surprise, the narrowed pulses, which they termed filaments, acted as their own waveguides, retaining their width and propagating across the lab for tens of meters.

In this and other experiments, it became apparent that plasma formation plays a key role in the filament propagation. Self-focusing increases the intensity, which leads to greater self-focusing, which further increases the intensity. What halts this runaway process is ionization.

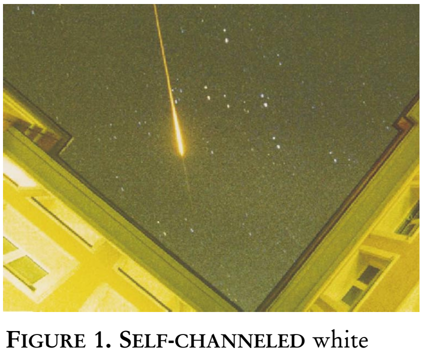

FIGURE 1. SELF-CHANNELED white light pulse pushes through the atmosphere above a courtyard at the Friedrich Schiller University in Jena, Germany. The beam was launched from the courtyard. (Courtesy of Ludger Wöste.)

When self-focusing pushes I above 10^{14} W cm^{-2}, multiphoton ionization creates a plasma, whose refractive index, being less than air's, causes the beam to defocus. Without self-focusing to boost it, I drops below the ionization threshold. The Kerr effect switches back on, and self-focusing resumes. The filaments' propagation depends, therefore, on a quasi-dynamic equilibrium between Kerr focusing and plasma defocusing.

At high intensities, slight irregularities in the beam profile act as seeds for the filaments, which travel together in parallel. This phenomenon, known as modulation instability, causes each stable filament in a 100-fs beam to draw roughly one millijoule of energy from the initial pulse. In a sense, the filaments are quantized.

Now, a more detailed view of filament propagation has been obtained, thanks to experiments at the Ecole Nationale Supérieure de Techniques Avancées (ENSTA) and the Ecole Polytechnique in Palaiseau, France. Stelios Tzortzakis, his thesis adviser André Mysyrowicz, and their colleagues

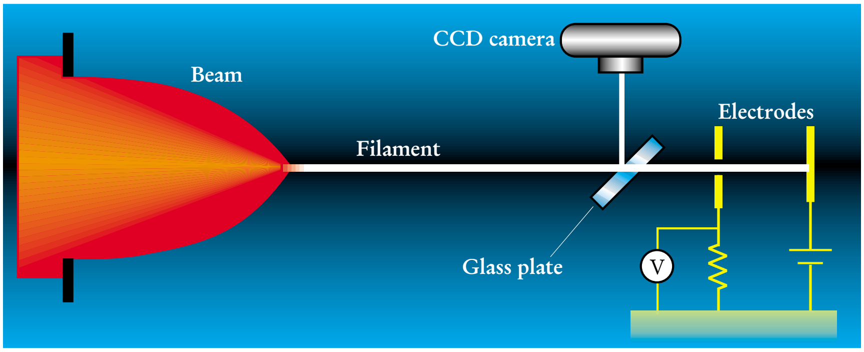

FIGURE 2. EXPERIMENTAL SETUP. Infrared laser light is focused to the point where the intensity initiates self-focusing and a white-light filament results. The shape of the optical filaments is measured by a charge-coupled device camera. A voltmeter connected to a simple DC circuit measures the conducting plasma column when the column completes the circuit between the electrodes. (Adapted from ref. 4.)

Michel Franco and Bernard Prade have followed the self-focusing process as it happens. Their experiments reveal that filaments propagate by carefully husbanding their energy through merging.[2] If a beam breaks into two filaments, those two filaments will combine before the intensity of either drops below the threshold for self-focusing.

The ability of self-focused filaments to propagate without the usual broadening due to diffraction makes them attractive for applications. Already, as figure 1 shows, filaments have been fired through the atmosphere. A Franco–German team is using the filaments to remotely sense atmospheric pollutants. And more speculative applications such as lightning channeling and cloud seeding are under investigation.

Feverous pulses

Measuring powerful femtosecond light pulses is difficult because of the high intensities and ultrashort timescales, but it's straightforward in principle. Figure 2 shows the setup used by the ENSTA investigators.[4] The laser, a 1-kHz Ti:sapphire oscillator amplifier system, emits pulses that last 50 fs and have a wavelength of 810 nm. How the pulses change shape with time and distance is measured by a charge-coupled device camera, which records a small fraction of the beam that bounces off a reflective glass plate. The plasma's conductance—a main ingredient in models—is measured by a resistive circuit that shorts when the plasma spans the two electrodes.

Figure 3 encapsulates the main finding of the ENSTA team. There we see that when the power is high enough to form filaments, those filaments, after propagating a few meters, fuse to form a single filament, which continues to propagate.

To model the formation and merging of filaments, the ENSTA team enlisted the help of Luc Bergé and Arnaud Couairon, two theorists from the French Atomic Energy Commissariat at Bruyères-le-Châtel. Bergé and Couairon's numerical model confirmed the basic picture and predicted the size, shape, and duration of the filaments, as well as the plasma properties and the criteria for whether filaments merge.

Bergé and Couairon's model followed an approach devised two years ago by the University of Arizona's Michal Mlejnek, Miroslav Kolesik, Jerry Moloney, and Ewan Wright.[3] (Mlejnek now works for Corning Inc.) As their starting point, the Arizona group used the nonlinear Schrödinger (NLS) equation. "The NLS is a natural," explains Moloney. "It describes weakly nonlinear dispersive behavior in any physical system—optical propagation, water waves, or plasma instabilities in Langmuir turbulence."

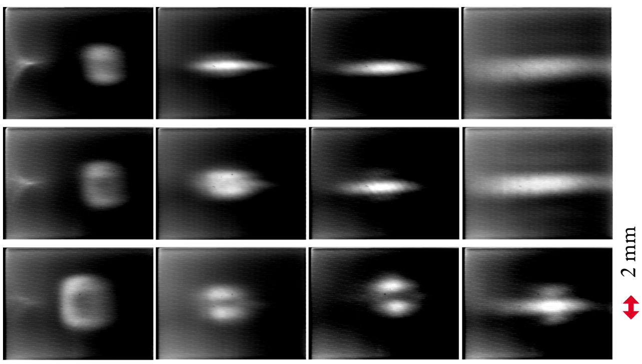

FIGURE 3. THE SHAPE of a self-focused filament changes as the filament propagates in a way that depends on its energy. The columns, from left to right, show CCD photographs of the pulses at propagation distances of 2.5, 4.5, 6.5, and 8.5 m. The pulse in the top row has an initial energy E_{in} of 1 mJ; in the middle row, E_{in} = 2.5 mJ; in the bottom row, E_{in} = 5 mJ. All the pulses originally lasted 50 fs. (Adapted from ref. 2.)

Like the self-focusing itself, solutions to the NLS evolve toward a singularity unless something steps in to avert that fate. In the Arizona model, multiphoton ionization, as embodied in a plasma model, plays the role of moderator.

Averting the singularity is more than a matter of mathematical neatness. Multiphoton ionization costs less energy than the processes that would occur if self-focusing proceeded further. Filaments are able to propagate because multiphoton ionization causes diffraction that temporarily spreads the filaments' energy but doesn't absorb much of it.

Foreshadowing Tzortzakis's experiments, the Arizona model produced filaments that propagated, merged, and then continued to propagate. Unlike the ENSTA experiments, the Arizona model wasn't constrained by the output power of real lasers and could produce up to 30 filaments. The laser that Tzortzakis used could produce two.

But in a new set of experiments with a more powerful laser, Tzortzakis hopes to test a key prediction of the Arizona model: that a beam of, say, 10 filaments would merge, then, having lost some energy because of ionization, would break up again into a smaller number of filaments, say, 8, that would merge and break up yet again.

Photon torpedoes

Although the self-guided filaments are intense, they contain just a few millijoules of energy—far too low for use as Star Trek phasers, let alone photon torpedoes. But they are potentially useful even so.

Under the extreme conditions of filament formation, nonlinear effects convert the initially monochromatic light to a continuum that stretches from 300 nm in the ultraviolet to 4.5 μm in the infrared. Couple this property with the filaments' ability to travel undispersed over long distances, and one has the potential to do remote spectroscopy of atmospheric pollutants.

Laser pulses are already used to map pollutants in the atmosphere. The technique, known as lidar, involves launching two laser beams into the atmosphere. One beam is tuned to an absorption band of the pollutant of interest; the other acts as a reference. The two beams—one diminished by absorption, the other not—scatter off nitrogen and oxygen molecules or dust particles in the atmosphere. A detector on the ground measures the backscattered fraction of each beam.

This, the traditional form of lidar, suffers from three drawbacks that don't beset self-focused filaments.

▷ Traditional lidar can measure only one pollutant at a time. That's not a problem for the filaments, whose broad continuum encompasses multiple absorption bands.

▷ Most interesting species have absorption bands in the infrared, but the backscattered signal is weak in that waveband. The filaments don't rely on backscattered light at all. Rather, they generate their own infrared emission, which, thanks to a back-reflection process induced by the plasma, is preferentially directed backward to the ground.

▷ Monochromatic sources are insensitive to the form the species takes: they can't, for instance, measure the size of aerosols. The filaments, being broadband sources, lack this limitation because the spectrum of scattered light depends on the size of the scattering particles.

In addition to these advantages, self-focused filaments share one of traditional lidar's useful properties: the ability to exploit the delay time of reflected pulses to yield distance information.

Exploiting self-focused filaments for detecting pollutants is one of the aims of Teramobile, a mobile terawatt laser.[5] The nine-ton facility, which fits in a standard cargo container, is a joint project of two French and two German research groups: Mysyrowicz's at ENSTA, Jean-Pierre Wolf's at Claude Bernard University in Lyons, Roland Sauerbrey's at Friedrich Schiller University in Jena, and Ludger Wöste's at Berlin's Free University.

In its four-month life, Teramobile has already detected water and methane in the atmosphere. "Now we want to attack the real pollutants," says Wöste. Those experiments begin this month in Jena.

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