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RAPIER: an optical pulse compressor



For further information contact J. J. Ewing (422-6191). Of the lasers operating in the visible-to-ultraviolet spectral range, those based on rare-gas-halide excimers show great promise for scaling up to the average powers and pulse repetition rates required for an inertial confinement fusion reactor. These lasers function efficiently, however, only when they are delivering pulses about 30 times too long for imploding a fusion fuel capsule. To adapt these lasers to the needs of inertial confinement fusion, we must perfect some method of pulse compression to concentrate the energy of long laser pulses into a brief, intense burst. We are constructing RAPIER (an acronym for Raman amplifier pumped by intensified excimer radiation) to study techniques for compressing rare-gas-halide laser pulses efficiently by combining the Raman effect with pulse stacking.

During the past five years our understanding of the physical and technical problems central to inertial confinement fusion has been advanced by a variety of experiments on laser-plasma interaction and laser fusion.1 We now know that a laser driver system for a gigawatt-class fusion power plant, with lasers operating in the 250-to-1000-nm range, must have pulse energies of 0.5 to 5 MJ, pulse durations of 10 to 20 ns, pulse repetition rates of 1 to 10 Hz, and a system efficiency in excess of a few percent.² For best pellet performance, the light should be at shorter wavelengths (ultraviolet).

Of the hundreds of directly excited laser systems now known, only a few, such as the raregas-halide excimer lasers, have the potential to fulfill all these requirements. Rare-gas-halide excimer lasers operate in the ultraviolet range, have high efficiencies, and should be scalable to energies of a few hundred kilojoules per aperture (see Table 1). Their one characteristic drawback is a relatively long pulse duration, which may range from 100 to 1000 ns.³

To adapt one of these otherwise attractive lasers for laser fusion, we need to compress their long pulses efficiently by a factor of about 30. Neither pulse stacking nor Raman compression alone appears able to provide such a large pulse compression at reasonable cost and efficiency. Therefore, we are developing the RAPIER optical pulse compressor testbed (Figs. 1 and 2) to explore the possibility of combining these two approaches to achieve the necessary pulse-compression ratio. This article describes the basic physics and technology issues that we will study with RAPIER as well as the design features of this unique facility.

Pulse compression

Unmodified rare-gas-halide lasers are unsuitable as drivers for fusion because the energy that can be extracted from these media in a single 10- to 20-ns pulse is quite small. The molecules radiate rapidly and are rapidly quenched, yielding excited-state storage times of only about 3 ns. Moreover, nonsaturating losses limit the intensity of the output light. Hence, we must find some means of concentrating the energy of the long pulses into a

Table 1 Krypton-fluoride laser characteristics.	
Efficiency factors	1202.18
Photon energy relative to initial excitation	22%
Extraction in presence of loss	50%
Pulsed power throughput and utilization in gas	70%
Overall	8%
Output intensity, MW/cm ²	10 to 30
Fluence in 10-ns pulse, J/cm ²	0.1 to 0.3
Extractable energy density (long pulses), kJ/m ³	10 to 20
Gain coefficient (small signal), m ⁻¹	2 to 20
Nonsaturating loss coefficient, m ⁻¹	0.2 to 1



Fig. 1 The "front-end" subsystem of the RAPIER pulse compression test bed. The large blue box in the foreground houses a 30-ns discharge-excited krypton-fluoride (KrF) laser that provides coherent narrow-band 248-nm ultraviolet radiation. This laser is potentially scalable to the energies and repetition rates appropriate for inertial confinement fusion but only in pulses about 30 times too long for microsphere implosion. The object of the RAPIER program is to develop pulse compression methods and equipment to concentrate these long pulses into the brief intense bursts needed for inertial confinement fusion. short time. The simplest of these concepts is pure pulse stacking.

Figure 3 is a schematic diagram of a pulse-stacking technique for generating short pulses with a longpulse medium. This approach uses a krypton-fluoride (KrF) amplifier with a timed sequence of short extraction pulses going through it at different angles. We let the different beams spread apart and then reflect them back to the target, adjusting the travel distance of each amplified pulse so that they all strike the target at once. This approach to pulse compression is in principle simple and highly efficient; the only unavoidable losses occur at the surfaces of the mirrors.

However, the net compression achievable by pulse stacking is directly proportional to the number of mirrors and optical alignment systems used. Equipment for very large pulse-stacking compressions may be inordinately expensive. Since an economically feasible excimer laser for power plant applications would have a pulse duration of 300 ns or more, a 10- to 20-ns pure pulse stacker would need to have 15 to 30 beams per aperture and possibly as many as 40 apertures.

The scattering of light by laser windows presents another problem with such a pure pulse stacker. Scattering allows some of the light to fall on the "wrong" pulsestacking mirrors, arriving early and preheating the target. In laser fusion, where the pulse shape must be carefully tailored, all such random effects must be minimized.

Another optical pulse compression technique, outlined in Fig. 4, is backward-wave-stimulated Raman scattering.^{4,5} This approach uses a tank of a Raman-active medium (such as methane), an efficient ultraviolet light pump (such as a KrF



Fig. 2 The "A" amplifier in the RAPIER experimental area. The long blue cylinders are part of the equipment for injecting 100-A/cm² pulses of 300-keV electrons into the KrF amplifier volume (inside the lead-lined box between the cylinders). The large transparent box in the foreground protects various pieces of diagnostic equipment. The "front-end" room is beyond the door shown at top left.

laser), and a short-pulse laser (the Stokes or extractor laser) operating at a slightly longer wavelength than the pump pulse. The frequency of the Stokes laser is such that the energy difference between the Stokes and pump photons is exactly the same as the energy difference between two appropriate states in the Raman-active medium (for example, the energy required to raise the methane molecule from the ground state to the first vibrational level with no change in rotational quantum numbers). The quantum efficiency for Raman conversion is quite high for ultraviolet lasers because the energy of the vibrational level is low compared to that of the pump photons. For



scattering of 248-nm KrF radiation in methane, the Stokes wavelength is 268 nm.

To use Raman scattering for pulse compression, we must make the methane tank half as long as the pump pulse, or 15 m for every 100 ns. We time the Stokes pulse to enter the exit window of the methane tank just as the pump pulse reaches it from the other end. The Stokes pulse extracts energy from the pump beam by the Raman process and emerges from the far side just as the last of the pump pulse enters. In the meantime the short Stokes pulse grows in amplitude (but not in duration) all the way.

The efficiency of this energy transfer from the pump pulse to the Stokes pulse is influenced by many factors, including:

 The Raman compression ratio (the ratio between the lengths of the pump and Stokes pulses).

• The asymmetry in the gain coefficients for Raman scattering in the forward and backward directions.

• The line width of the pump radiation relative to the scattering molecule's linewidth.

 The gain coefficient of the Raman medium, which is a function of gas pressure and pumpbeam intensity.

 The input Stokes pulse intensity and pulse shape.

 The parasitic gain that may be present in the medium before significant conversion occurs.

Extensive computer modeling of these processes indicates that the most serious limitation on the extraction efficiency is the spontaneous generation of a "second Stokes" wave by Raman scattering of the Stokes pulse itself in the

Raman-active medium. This second Stokes pulse is detrimental because its radiation will probably not be close enough to being parallel for efficient focusing on the target.

It should be possible, however, to operate a backward-wave Raman amplifier conservatively and avoid significant conversion into second Stokes radiation. Figure 5 shows the conversion efficiency that can be achieved in such circumstances, i.e., conversion efficiencies of about 50 to 70% for Raman compression ratios on the order of 8 to 12. This corresponds to a ratio of the output Stokes intensity to the input pump beam of about 6. Hence, for reasonable overall pump and converter efficiencies, pure Raman compression is also inadequate for the factor-of-30 pulse compressions needed for laser fusion.

Since neither approach alone can give the compression ratios reguired, we have been investigating hybrid systems that combine the two.6 A hybrid compression scheme gives us greater net compression at a higher efficiency than

FIC 0 sion by backward Raman scattering. In this system a long pump pulse of KrF radiation travels through a chamber filled with methane gas, exciting the molecules of methane. The Stokes pulse, entering from the other end of the scattering chamber just as the pump pulse is about to emerge, extracts energy from the light beam of the pump and grows in intensity (but not in length) as it traverses the scattering chamber. With proper design. backward Raman scattering can concentrate most of the energy of the original long pulse into a much shorter pulse.





does a pure Raman scheme and requires far fewer optical components than does a pure pulse stacker. It also may be much less expensive than a comparable pure stacker, and it is much more flexible in terms of the final pulse width provided.

Figure 6 is a schematic diagram of one such hybrid, called a stacker-compressor-stacker. Here, the pump amplifier is extracted by three fairly long pulses traveling on three different beam paths. The optical delay introduced by the reflected beam paths brings these three pulses into coincidence in the Raman cell. Two short Stokes pulses, also on different beam paths, supply another factor-of-two compression when they are stacked on the target. Hence, the Raman amplifier needs to supply a compression factor of only 5 for a total system compression of 30.

The RAPIER program

About two years ago we began to study the basic physical properties associated with backward-wave Raman scattering of narrow-band 248-nm (KrF) radiation in



Fig. 6 A hybrid pulse-compression scheme using both Raman scattering and pulse stacking. Three 100-ns extraction pulses divide the 300-ns excitation pulse in the KrF amplifier into three 100-ns bursts. After traversing the various paths to the Raman cell, these pulses become coincident. A pair of 10-ns pulses, separated in time by 50 ns and traveling separate paths, extract energy from the first and second halves of the 100-ns pulse in the Raman cell. Further optical delay brings these amplified 10-ns pulses into coincidence on the target. The overall compression ratio of 30 is achieved without straining the capabilities of either pulse stacking or Raman scattering. high-pressure methane. For this study we used small, 100-mJ, discharge-excited KrF lasers.⁴ The second phase of this effort, the RAPIER program, seeks to expand the research capability to successively higher energy levels, nominally 1, 25, and 200 J. The RAPIER program also will develop the relevant technology base for building more powerful pulse compressors using both Ramancompression and pulse-stacking schemes.

The RAPIER system will be used to extend Raman-compression and saturated-extraction measurements, develop the technologies associated with hybrid schemes, and improve our understanding of the scaling limitations of the pump lasers in the e-beam energydeposition regimes of interest for laser fusion applications. A major objective is the demonstration of efficient hybrid pulse compression by factors of 30.

In line with these goals, we have chosen for RAPIER an operating pump-pulse length of 50 ns, with anticipated pulse durations after compression of 1 to 2 ns. This pulse length is less than that projected for use in a fusion power reactor, but it is about the length appropriate for the near-term target irradiation studies now being performed on Argus at 1.06- μ m wavelength. Scaling of the technology to longer pulse lengths and higher energies will primarily require us to build a larger pulse compressor.

The RAPIER system consists of two main subsystems: the front end containing a narrow-band KrF laser and a Stokes master oscillator laser; and the "A" amplifier, a larger KrF laser for amplifying the pulse from the front-end KrF laser (Fig. 7). Both subsystems have associated Raman oscillatoramplifiers for performing Raman physics experiments at successively greater energies. These two subsystems are currently being operated separately. When we have determined their best operating conditions, we will link them together for experiments as a hybrid Raman compressor-pulse stacker.

The two KrF lasers in RAPIER illustrate the two competing methods—electric discharges and relativistic electron beams—of exciting an excimer laser. Electricdischarge excitation is simple and relatively inexpensive, but it works well only in relatively small volumes. Electron-beam excitation uses high-current pulses of energetic electrons to ionize the laser medium. It requires somewhat more complex equipment than does discharge excitation, but it is more readily scaled to large volumes.

We use fast-pulse electric discharges to excite the front-end KrF laser, which produces 1 J of



Fig. 7 Schematic layout of the RAPIER experimental facility for developing pulsecompression techniques and equipment. The front-end room contains the narrow-band KrF laser, the Stokes master oscillator, and amplifiers. We compensate for the extra length of the path from the Stokes master oscillator through the multibeam generator to the Raman cell by inserting an optical delay line in the KrF beam path. The radiation from the "A" amplifier alone is centered on 248 nm but has a broad bandwidth. Radiation from the front-end laser locks the "A" amplifier onto the desired narrow band. high-beam-quality, 248-nm radiation with a linewidth of about 0.2 cm⁻¹. The "A" amplifier has a 5-litre laser volume, excited by two opposed 300-keV, 100-A/cm² electron beams (Fig. 2). Broadband outputs of more than 35 J and narrow-band outputs of more than 20 J have been achieved. To our knowledge, the use of opposed electron beams in the "A" amplifier is unique to RAPIER and should result in a more uniform excitation of the KrF medium than would occur if only one beam were used.

With the 1-J output of the frontend KrF laser, we have been conducting pure Raman compression experiments, determining precise values for compression parameters, investigating limitations imposed by generation of the "second Stokes" wave, and evaluating second Stokes suppression techniques.

Once we mate the front-end laser and "A" amplifier, we expect to have an output energy of 25 J in a 50-ns pulse at the KrF wavelength of 248 nm. We estimate that the stacked Stokes output at 268 nm will be 10 J in 1 ns. With this system we will be able to investigate KrF amplifier performance under e-beam excitation and to determine KrF amplifier operating parameters. Furthermore, we can then experiment with axial parasitic control of the KrF amplifier, assess e-beam diode and switch performance, and perform hybrid pulse-compression experiments.

We are also designing a second, much larger e-beam-excited amplifier to follow the "A" amplifier for experiments at higher energies. Adding this "B" amplifier will give us a KrF output of 200 J in a 50-ns pulse at 248 nm and permit Raman compression experiments at higher intensity levels. This additional energy will also enable us to experiment with transverse parasitic control of the KrF amplifier, assess ways to control the time jitter among multiple e-beam modules, investigate ways to control beam pinch, optimize the optical design, and assess optical damage effects.

Summary

By combining two existing pulse compression schemes-pulse stacking and Raman scattering-we plan to develop the means for adapting KrF lasers to inertial confinement fusion. We have constructed a testbed consisting of discharge-excited KrF lasers capable of supplying 1-J, 50-ns pulses of ultraviolet (248-nm) radiation, a Stokes-laser oscillator-amplifier chain operating at 268 nm, and an e-beam-excited KrF amplifier to boost the energy of the pulses coming from the first two lasers by a factor of ten or more. Using information from the "A" amplifier system, we are also designing a much larger secondstage amplifier to increase the output power another factor of eight to ten.

The RAPIER system is a laser research and development testbed, not a prototype laser driver for inertial confinement fusion. However, its pulse lengths (50 ns in, 1 to 2 ns out) may make it suitable for target studies in the ultraviolet. Moreover, our experience with this testbed will provide valuable insights into the problems inherent in high-power hybrid pulse stackers–Raman compressors for use in very large lasers for power plant applications.

Key words: electron-beam excitation; excimer lasers; excimers; inertial-confinement fusion (ICF); krypton-fluoride lasers; pulse stacking; Raman scattering.

Notes and references

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