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Intensification of Rare Gas Halide Lasers

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ABSTRACT

The two techniques of backward-wave Raman pulse compression and pulse stacking are reviewed in the context of using KrF lasers as drivers in inertial confinement fusion. Experimental and theoretical results on Raman pulse compression in methane are presented including data on 70-75% pump energy extraction by the counterpropagating Stokes wave. Results from on-gc pulse stacker/Raman compressor experiments are also described, along with future investigations in this general area.

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I. INTRODUCTION

Fairly well-defined requirements have evolved on advanced laser drivers for inertial confinement fusion.¹ The necessary few Hz repetition rate is most readily achieved by gaseous media, although selected solid-state emitters and excitation scenarios may be important in this context.^{1,2} Other requirements concern wavelength (0.2-2 μm), efficiency (>5%), and scalability to produce multi-megajoule energies in pulse lengths 10-20 ns.³ Use of the efficient rare-gas halide lasers has recently been considered for this application employing the pulse shortening techniques of backward-wave Raman pulse compression⁴ and pulse stacking⁵ to attain the requisite high intensities. Recent reports have shown that the electron-beam-excited KrF laser (248 nm) has an intrinsic operating efficiency about 10%;⁶ other rare

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gas halide emitters, such as XeCl (308 nm) or ArF (193 nm) may also approach this performance level. In this paper we review a series of experiments conducted at our laboratory using the RAPIER (Raman Amplifier Pumped by Intensified Excimer Radiation) facility to evaluate various physics and technology issues relevant to Raman pulse compression and pulse stacking using KrF lasers. RAPIER presently consists of one facility element designated as the Front End, that utilizes discharge-excited KrF lasers, along with another system component denoted as the A-amplifier, which is a dual electron-beam excited KrF gain medium. This presentation is divided into four parts: (i) a summary of backward-wave Raman pulse compression experiments performed with the Front End KrF discharge lasers, (ii) a description of laser/amplifier performance features of the A-amplifier, (iii) on-going pulse stacker/Raman compressor studies using the integrated Front End and A-amplifier facilities, and (iv) future work and outstanding issues in this general area.

II. Backward-Wave Raman Pulse Compression Experiments

Recently, we reported results of high efficiency energy extraction in backward-wave Raman scattering.⁷ In that work, pump depletions of 70-75% were demonstrated for a KrF-laser-driven, methane-gas-filled backward Raman amplifier which were in agreement with predictions of the Frantz-Nodvik saturated-amplifier model. The associated counterpropagating Stokes laser intensity was determined to be ≥ 3.5 times that of the pump; the corresponding pulse compression ratio was ≈ 5 . We now briefly summarize that study.

The investigation employed four UV-preionized KrF discharge media, developed at our laboratory, to produce a nominal 1 J of pump energy at 248 nm in a pulse length of about 35 ns and a linewidth of $0.15 - 0.20 \text{ cm}^{-1}$. A narrow linewidth is necessary to minimize the forward-to-backward Raman gain ratio.⁴ A master oscillator, using three intracavity etalons for line narrowing produced a 20 ns-long, 1 mJ pulse that injection locked a similarly-sized ($1/2 \times 1 \times 100 \text{ cm}^3$) gain medium outfitted with unstable resonator optics to generate a 150 mJ output. A fraction of this energy was used, in turn, to injection-lock a larger KrF discharge volume that also used an unstable optical cavity and that had a gain region of $1 \times 4 \text{ cm}^2$ cross section by 1 m length. Finally, the 35-ns-long injection-locked pulse was amplified by single passage through a second identical amplifier resulting in a total 248 nm line-narrowed pump energy of about 1 J. The KrF discharges were operated at total pressures of 1-1.5 atm using gas mixtures consisting of 0.4% F_2 , 10% Kr, with the balance He. Figure 1 illustrates the allocation of the KrF pump beam to three methane-filled Raman cells serving as (bottom to top) a local oscillator (generating the 268 nm beam by stimulated forward Raman scattering), a backward Raman preamplifier, and a backward Raman amplifier. The three, 3.8 cm diam., stainless-steel cells were capped with 2-cm-thick UV-grade quartz windows and operated at about 380 psi methane pressure. The cell lengths were chosen to give propagation times of 10.3 ns through the oscillator and preamplifier, and 14.0 ns through the amplifier. The solid circles in the backward preamplifier and amplifier of Fig. 1 denote the intersections of the leading edges for the pump and Stokes waves for the 70-75% energy extraction case. For the preamplifier, operated under small-signal Raman gain conditions, the pump delay option allows for passive time tailoring of the transmitted Stokes intensity. Analyses have shown that

a Stokes pulse with a slow rise time is desired for passage through the saturated amplifier in order to stay below the second Stokes generation limit and thereby maximize the energy extraction from the pump beam.^{4,8} The two pump delay mirrors for the saturated amplifier merely allow for fine-tuning the synchronization of pump and Stokes pulses. As shown in Fig. 1, mirrors with partially transmitting dielectric coatings permitted viewing the four input-output beams for the backward amplifier. Temporal records were made of these beams using photodiodes, equipped with apertures a few mm in diameter that were positioned to correspond with spatially smooth sections of the pump beam. Pump beam depletions, and therefore, energy extraction efficiencies were determined from the photodiode data along with pulse compression ratios and intensity enhancements.⁷ Additionally, for the high saturation conditions, calibrated surface calorimeters ($\pm 10\%$ accuracy) were used to insure that the energy from the depleted pump beam was in fact transferred to the back-traveling first Stokes wave.

The results from the saturation experiments with the backward Raman amplifier are shown in Fig. 2 (as boxes), along with the predictions of a computerized Frantz-Nodvik model⁸ (solid lines) for the three indicated temporal profiles of the incident Stokes pulse and for a backward Raman gain $\approx e^5$. The plot shows the photon extraction efficiency for the Raman amplifier as a function of the parameter $R\kappa/G_f$ at the generation limit of the second Stokes wave; where R is the forward-to-backward Raman gain ratio, κ the ratio of pump pulse length to exiting Stokes pulse width, and G_f the second Stokes gain. The corresponding energy extraction efficiency is lower by a factor $248/268 = 0.93$. The R value, which is determined mainly by the scatterer and pump line widths, was in the range 1.5 - 1.7; G_f is set equal to 20, corresponding to a nominal superfluorescence limit above which the

second Stokes component is readily produced.⁴ The lower portion of Fig. 2 shows the varied value for κ at fixed R and G_F , along with the associated laser intensity enhancement factor H . Note that in this investigation, we substantially shortened a relatively long Stokes oscillator pulse (≈ 35 ns) by the combined effects of: (i) low trailing-edge Raman gain in the relatively short methane amplifiers, and (ii) gain steepening in the saturated amplifier. For the study, we merely required that the resultant Stokes pulse width be less than the saturated amplifier length. For this condition, the behavior of the trailing part of the Stokes pulse is not critical in evaluating the Raman pulse compression technique. For the three data points in Fig. 2, the resultant Stokes pulse lengths have the following approximate values: (i) 70 - 75% extraction - 7 ns, (ii) 50% extraction - 3.5 ns, and (iii) 30% extraction - 1.4 ns. The data at the 30% and 50% extraction efficiency levels are in good agreement with estimates that consider a positively-skewed Gaussian Stokes pulse, whereas the 70-75% efficiency case is somewhat less than the predictions that utilized the more appropriate, negatively-skewed Gaussian pulse shape. Most probably, the latter discrepancy is due to the non-plane-wave nature of the pulses used in the experiment (but assumed in the analysis), the lack of exact alignment between the Stokes and pump beams in the saturated amplifier, and the limitations of the modeling due to the finite amplifier cell length.

III. Dual Electron Beam KrF Amplifier

KrF discharge lasers are limited in size to relatively small apertures (few cm^2) and energy outputs of a few J. The application of rare gas halide lasers for inertial confinement fusion therefore requires use of efficient and

scalable electron-beam-excited media. The RAPIER A-amplifier is a representative step in that technological direction. The amplifier, developed at our laboratory^{9,10} and shown in Fig. 3 has a gain volume $10 \times 10 \times 50 \text{ cm}^3$ which is excited by two opposed electron beams with nominal characteristics: 300 keV-voltage, 100 A/cm^2 -current density, and 60 ns-pulse duration. The 5-liter active volume can be pressurized to 2 atm and consists of a gas composition 0.3% F_2 , 6% Kr, with the balance Ar. Referring to Fig. 3, the high voltage is applied by water-dielectric Blumlein lines which are pulsed charged by storage Marx banks (not shown). The electron beams irradiate an area 10 cm high by 50 cm long and enter the laser mixture through opposing metal foil walls. The foils, either 0.5 mil Inconel X-750 or Havar, are supported on a 90% open area hibachi foil support constructed from a non-magnetic stainless steel. The diode is evacuated to $<2 \times 10^{-5}$ Torr. The electrical pulse is delivered to the diode by a positively-charged triaxial Blumlein. The two nested co-axial pulse forming lines are charged in series, the outer one through a metal rod (labeled "HV input") penetrating to the middle cylinder from the rear and the inner one through a charging inductor located at the front of the Blumlein. Bubble-free, deionized water is used as the dielectric material in the Blumlein and is circulated from a reservoir where the water is deionized and filtered so that the resistivity is $>10 \text{ M}\Omega\text{-cm}$. The output impedance of the line is 5Ω which matches the nominal impedance of the diode.

When operated as an oscillator using a stable resonator cavity, the A-amplifier produces an output of 35 J at 248 nm. A comparable output energy, at an intrinsic medium efficiency of 9%, is obtained when the A-amplifier is injection locked by a line-narrowed discharge laser which delivers its energy through a partially-transmitting cavity mirror that serves

as one-half of an unstable laser resonator.¹⁰ Our studies have shown that the line-narrowed injecting beam need be only about 1 part in 10^4 as energetic as the total available device energy to produce a resultant line-narrowed output, i.e. the injected power must be greater than the corresponding spontaneous emission radiated into the appropriate solid angle. Subsequently, stacker operation of the A-amplifier was demonstrated by passing a sequency of three, discharge-laser-generated input beams of 20-ns duration. The measurements showed that the divergence of the transmitted beams was $\approx 100 \mu\text{rad}$, and that the amplifier output exactly reproduced the characteristics of the input beam and the optical system. Such favorable performance by the A-amplifier led us to link up the Front End and A-amplifier to investigate combined pulse stacker Raman compressor performance. The larger-scale backward Raman amplifier experiments will be undertaken at lower methane densities and larger Fresnel numbers. Operation under the latter condition will more critically test propagation behavior for large apertures, where diffraction and interference effects are more representative of sizable, fusion drivers. Furthermore, with such large aperture Raman amplifiers, a more detailed study can be made of the pump beam spatial averaging property inherent in the backward Raman scattering technique.⁴ This feature may significantly relax constraints on the quality of optics that handle the KrF beams in any target-irradiation installation.

IV. Combined Pulse Stacking/Raman Compression Experiments

Figure 4 gives the layout for our on-going stacker/compressor study. KrF laser beams at 248 nm are shown as solid lines; 268-nm first Stokes beams are represented as broken lines. The current experimental arrangement in the

Front End features two KrF discharge lasers that are upgraded versions of those described in Section II. The basic design difference involves a reduction in inductance that leads to shorter pulse lengths (20 vs 35 ns) at roughly the same 1 J output per device. Each of these injection-locked lasers is equipped with unstable resonator optics and two intra-cavity, pick-off mirrors thereby generating a total of four KrF laser beams. As seen in Fig. 4, three beams are directed from the Front End to the A-amplifier facility: one 248 nm pulse to laser trigger two spark gaps on the A-amplifier Blumleins (an upgrading of the electrical-pulse-trigger approach shown in Fig. 3), a second 248 nm beam that is used to triple stack the A-amplifier using partially-transmitting optics and appropriate delay lengths, and one 268 nm beam serving as the input for the indicated methane cell. Note that the optical delay for the 268 nm pulse is necessary to properly synchronize arrival times for the pump and Stokes beams at the methane cell. Using novel pulse-charging techniques and the laser-triggered spark gaps, we have achieved a relative jitter among the Front End discharge lasers and the A-amplifier of ≤ 1 ns. In order to overlap the beams over the entire methane cell length of 3 m, a pair of parallel glass plates are positioned inside the Raman cell. The reflectivity of plain glass at grazing incidence is sufficiently high so that less than 10% of the pump energy is lost due to use of the light guide. The effective gain aperture in the Raman amplifier is about 20 cm^2 . Initial experiments at 200 psi methane pressure have measured the small-signal Raman gain as a function of pump energy with the results in good agreement with theory. Preliminary studies have also shown that the amplified Stokes beam exiting the large methane cell preserves the spatial characteristic of the input Stokes intensity, thereby verifying the averaging property of backward Raman scattering using a "scrambled" pump. Several

experiments have demonstrated amplification of a Stokes wave of low divergence by a highly divergent pump.¹¹ Current investigations are concentrating on Raman amplifier performance for conditions of maximum intensity enhancement and maximum energy extraction by the input Stokes beam, similar in scope to the results of Fig. 2, but for significantly greater aperture size and total pump energy. These studies will be described in future publications.

V. Future Work on Intensification of Rare Gas Halide Lasers

Here we briefly indicate various current and future investigations on the intensification of rare gas halide lasers for possible use in inertial confinement fusion.

Near-term work with the RAPIER facility will involve the use of Pockels cells to: (1) increase the number of sequenced beams passing through the A-amplifier from the present three to at least five by "slicing" out an appropriate portion from the 20 ns-long KrF pulse delivered by the Front End, and (2) temporally shape the Stokes beam input to the large methane cell so that a slowly-rising pulse is created to optimize the energy extraction from the pump beam at the second Stokes limit.^{7,8} Development of a RAPIER B-amplifier at our laboratory is scheduled for completion during the next year. This device will have an active gain volume approximately $30 \times 30 \times 1200 \text{ cm}^3$ and generate a few hundred J of KrF energy for durations nominally about 150 ns. The B-amplifier will produce a total of six electron beams using Blumlein pulse forming lines that are about the same diameter as the A-amplifier lines but three times as long. They will be upgraded to operate at 450 kV.

Regarding pulse stacking, and depending on the success of future research and development, alternate gain media may supercede KrF for the fusion application with the excimer candidates XeCl and ArF serving as possible examples. An outstanding issue for Raman compressors is the suppression of second Stokes generation which, if possible, would permit for high energy extraction efficiencies from the pump beam at significantly higher pulse compression ratios. Among the several approaches possible,⁴ we indicate the two appealing options of (i) selective molecular absorbers, and (ii) near-resonant atomic Raman scatters. The first option uses molecules added to the Raman medium that selectively absorb at the 292-nm wavelength of the second Stokes component but not at the 248-nm pump or 268-nm first Stokes wavelengths for the KrF/CH₄ combination. Molecules that readily saturate at 248 and 268 nm are also possibilities providing that the absorption at 292 nm is great enough to suppress the buildup of the second Stokes wave from spontaneous emission. Several promising candidates have been identified, but the resolution of pertinent spectra is not great enough in the UV to fully ascertain their potential effectiveness. Furthermore, any molecule with satisfactory absorption properties may be dissociated by multiphoton absorptions at the pump and first Stokes wavelengths for which the intensities may range to $\lesssim 200 \text{ MW/cm}^2$. Obviously, any prospective absorber must be able to withstand such intense irradiation. The second option uses atomic Raman pulse compressors that offer the attraction of large first Stokes cross sections when operated near an atomic resonance with correspondingly low cross section for the second (non-resonant) Stokes wave. Recent work by Djieu¹² demonstrated backward wave Raman pulse compression at 458 nm in Pb vapor when excited by the XeCl laser at 308 nm. In that work, a compression factor > 6.7 was observed with a photon efficiency of 42%. A practical difficulty with

this general approach is that many of the identified Raman scatterers require high temperatures ($\geq 1200^{\circ}\text{C}$) to generate a suitable number density. A physical limitation may be imposed by absorption in the wings of the collision-broadened resonant transition that can lead to superfluorescent loss involving intermediate levels. Additionally, any atomic Raman scatterer must not be limited by multiphoton ionization processes and the consequent intensity loss by either the pump or Raman beams. Other combinations of pump/atomic Raman scatterer are under evaluation for this application. (In a related context, UV beam propagation through the few Torr ambient pressure of Li vapor in a practical fusion reactor chamber must also be assessed.) It is necessary to underscore that approaches (i) and (ii) represent desirable but not necessary options in the use of Raman pulse compressors for fusion, i.e., operation at the second Stokes limit with efficiencies of 70-75% and pulse compressions ≈ 5 (see Fig. 2) is acceptable. In addition to relaxing constraints on KrF beam-handling optics, as noted previously, placement of a Raman compressor at the recombined output of a stacked amplifier can greatly reduce fusion target preheat since the Stokes intensity is counterpropagating with respect to the pump. By contrast, a straight stacker target irradiation scenario greatly restricts the amount of "spill over" that a particular stacked beam can deliver to a "wrong" recombining mirror at the amplifier exit.

The ultimate utility of short wavelength lasers for fusion depends, in part, on near-term studies using drivers at $10\text{ }\mu\text{m}$ (CO_2), $1\text{ }\mu\text{m}$ (Nd-glass), and harmonics of $1\text{ }\mu\text{m}$ (0.532, 0.355, and $0.256\text{ }\mu\text{m}$) that will evaluate the wavelength dependence of target coupling. Initial experiments using harmonics of Nd-glass lasers have shown increased laser absorption and decreased hot

electron generation¹³ (which thwarts target compression). Continuing investigations at higher intensities will place the wavelength-scaling issue in better perspective.

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Figure Captions

- Figure 1. Diagram of the experimental arrangement used in the study of backward-ve Raman pulse compression. The total KrF pump laser intensity (solid line) is divided and directed to three methane-filled Raman cells which serve (bottom to top) as the Stokes oscillator (using stimulated forward Raman scattering to generate the 268-nm pulse depicted as a broken line); backward Raman preamplifier and backward Raman amplifier. Omitted for clarity are various focusing lenses and collimating telescopes.
- Figure 2. Photon extraction efficiency for a backward Raman methane amplifier as a function of the parameter R_K/G_F (see text) at the generation limit for the second Stokes wave. Computations for three different input Stokes temporal pulse shapes are shown (solid lines) along with the experimental results and their associated uncertainties (boxes).
- Figure 3. Illustration of one side of the A-amplifier showing the laser cell, diode, and pulse-forming line.
- Figure 4. RAPIER system layout that integrates the Front End and A-amplifier facilities for on-going pulse stacker/Raman compressor experiments.

Fig. 1

$$\kappa = \frac{\tau_{\text{pump}}}{\tau_{\text{Stokes}}} : \approx 5 \approx 10 \quad \approx 25$$

$$H = \frac{I_{\text{Stokes}}}{I_{\text{pump}}} : \approx 4 \approx 5 \quad \approx 8$$

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Fig. 2

Fig. 1