# Repetition Rate Scaling up to 100 kHz of a Small-Scale (50 W) Kinetically Enhanced Copper Vapor Laser

Graham D. Marshall and David W. Coutts

***Abstract*—We report on the pulse repetition frequency (PRF) scaling of a small-scale (25 mm bore and 0.61 m long) copper vapor laser (CVL). When operated as an elemental CVL, the laser had a stable output power of 15 W at 15 kHz PRF (0.6% efficiency). After the addition of small quantities of hydrogen and hydrogen chloride to the neon buffer gas, the maximum recorded stable output power increased to 41 W at 25 kHz PRF (1.4% efficiency). This represents a record stable specific output power of 0.14 Wcm$^{-3}$. Pulse repetition frequency scaling of the laser was demonstrated up to 100 kHz where the output power was 9.0 W. By operating the laser at elevated input powers, transient output powers of over 50 W were achieved between PRFs of 25–40 kHz. These results are the highest recorded specific output powers (0.17 Wcm$^{-3}$) for a CVL with this tube diameter.**

***Index Terms*—Gas lasers, halogens, hydrogen, hydrogen compounds, lasers, plasma properties, pulse power systems, thyratrons.**

## I. INTRODUCTION

COPPER vapor lasers (CVLs) are established sources of high average power (tens to hundreds of watts) visible light, their temporal nature being characterized by multikilohertz pulse repetition frequency (PRF) nanosecond-scale pulses. The pulsed nature of CVLs makes them ideally suited to many industrial applications including micromachining [1], high-speed imaging (HSI) [2], and particle imaging velocimetry (PIV) [3]. Previously, the pulse repetition frequency (PRF) of practical high-power elemental CVLs has been limited to a few tens of kilohertz due to the slow relaxation rate of the laser plasma in between pulses. Operation at higher than optimum PRF causes the output power of the laser to fall due to the reduced time for recombination of the plasma during the interpulse or afterglow period. Previously, the only method of PRF scaling elemental CVLs into the 100-kHz region has been to use small diameter discharge volumes where the processes of plasma recombination and metastable relaxation occur principally at the laser tube walls. For example, Soldatov and Fedorov have reported an elemental CVL that produced 32 mW of output power at 235 kHz from an active volume with 8 mm inside diameter (ID) by 360 mm long [4].

Pulse repetition rate scaling of the two other members of the CVL family (CuBr and Cu HyBrID lasers) has also been demonstrated, but only for low power (<12 W) systems. In these lasers, the presence of the hydrogen halide modifies the kinetics by increasing the rates of plasma recombination and metastable relaxation. This has been shown to be responsible for the relatively high specific output powers and efficiency of CuBr and Cu HyBrID lasers (for example, Guyadec *et al.* have reported a Cu HyBrID laser that produced 216 W at 18 kHz with 2.7% efficiency [5]). However, the rapid volumetric recombination also suggests that PRF scaling should also be possible for medium to large bore CuBr and Cu HyBrID lasers. Recently, Little has reported the results of PRF scaling of a small scale (12.5-mm ID by 300-mm-long active volume) Cu HyBrID laser to 50 kHz [6], and Evtushenko *et al.* have reported a small CuBr laser (14-mm ID by 250-mm-long active volume) that operated up to 300 kHz [7]. However, both these lasers produced less than 12 W output power, and the maximum reported PRF for high-power Cu HyBrID and CuBr lasers to date has only been 25 kHz [5].

Recently, Withford *et al.* recognized that the addition of small quantities of hydrogen halide to the buffer gas of an elemental CVL would provide similar benefits; thus they developed a new class of CVL: the kinetically enhanced CVL (KE-CVL). They have now reported substantial benefits of adding small quantities of hydrogen and hydrogen chloride to the buffer gas of an elemental CVL [8]. The gas additives increase the plasma relaxation rates during the afterglow period, giving lower prepulse electron densities and higher prepulse copper ground state densities. The changes in the kinetics of the laser increase the output power and efficiency of the laser and also improve the beam quality. For example, Withford *et al.* [9] reported a factor of two increase in output power by kinetically enhancing a 25-W CVL with active volume 25 mm ID by 1.0 m long. Another consequence of the kinetic enhancement is an increase of the optimum repetition frequency (e.g., from 12 to 30 kHz). Previous work on KE-CVLs has only extended to repetition frequencies of 27 kHz [9]. In this paper, we report the studies of a small scale (≈40 W) kinetically enhanced CVL, which was operated at frequencies of up to 100 kHz and produced the highest output powers for any CVL device in the 40–100 kHz range.

## II. EXPERIMENTAL

### A. The Laser Head

The laser used in this study was a small-scale device with a 25-mm-diameter by 61-cm-long active region, giving an active

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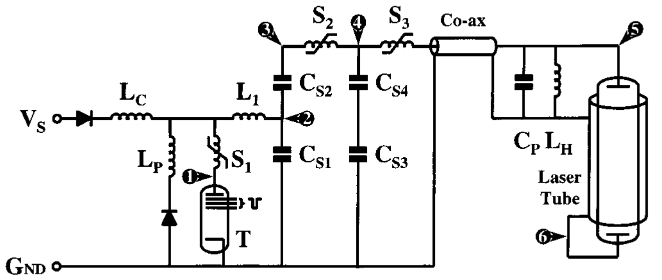

Fig. 1. Magnetic pulse compression circuit used to drive the laser in this study. Diagnosis points: 1) thyratron anode voltage; 2) midplate voltage; 3) top-plate 1 voltage; 4) top-plate 2 voltage; 5) laser head voltage; 6) tube current.

volume of 300 cm$^3$. The plasma tube was made from high-purity alumina ceramic and was surrounded by a fibrous alumina insulator (Rath-type KVS1800/400). This assembly was then jacketed by a 70-mm ID silica vacuum envelope and O-ring sealed to water-cooled brass end pieces. The end pieces also carried the cold slotted copper electrodes and window flanges. Tilted Infrasil single-sided antireflection coated windows were used on the laser. Surrounding the silica and attached to the anode brass end piece was a water-cooled copper tube that served as a heat shield and as a low inductance current return. The laser was typically loaded with 12 1-g pieces of high-purity copper placed at regular intervals inside the ceramic plasma tube. The laser could be operated for periods of 100–200 h before the copper load needed replenishing.

### B. The Excitation Circuit

To generate the high-PRF high-voltage excitation pulses for the laser head, the thyratron (EEV CX1835) switched LC inversion circuit incorporating two stages of magnetic pulse compression (MPC) shown in Fig. 1 was used. To diagnose circuit performance, voltage and current traces were taken from key points. The voltage points were monitored through high-voltage probes (Tektronix model P6014), and the current points were monitored using fast current transformers (Pearson model 410). All waveforms were stored on a 500-MHz digital storage oscilloscope (Tektronix model 2440). The saturable inductors were wound on solid ring ferrite cores and the ratio of turns between $S_2$ and $S_3$ was 1 : 2.5. To operate the laser across the range of pulse repetition frequencies from 10 to 100 kHz, two different capacitor sets were used in the excitation circuit. For lower operating frequencies (10–40 kHz), the "slow circuit" configuration was used. This operated with 1.0-nF storage capacitors. For high-PRF operation (above 40 kHz), the "fast circuit" using 0.56-nF storage capacitors was used. The full charging time for the slow and fast circuits was 30 and 20 $\mu$s, respectively. The peaking capacitor attached to the laser head was a quarter of the storage capacitor value for both circuits. Current and voltage traces for the fast circuit operating at 50 kHz are shown in Fig. 2. After the thyratron switches, the charge on $C_{S1}$ is inverted in a time of 180 ns giving a peak thyratron current of $\approx$100 A and a first-stage peak voltage of 17 kV. This voltage pulse is then compressed by the two MPC stages to produce a laser head voltage of 13 kV with 40-ns full-width half-maximum (FWHM) duration and a peak tube current of 150 A.

### C. Gas Handling

To deliver the gas mixes to the laser during experiments, a mixing manifold capable of metering flow rates down to 1 cc/min was used. To introduce hydrogen and hydrogen chloride into the laser, a 10% hydrogen in neon mixture was diluted into high purity (99.99%) neon. This gas was then passed through an oven (attached to the anode end of the laser head) containing zirconium chloride powder, which is reduced to form zirconium metal and hydrogen chloride [8]. The concentration of hydrogen chloride was controlled by changing the temperature of the oven (up to 100 °C). The optimum gas pressure for kinetically enhanced operation was found to be 35–40 mbar for all pulse repetition frequencies and resonator configurations.

Because of the reactive nature of HCl, it was necessary to initially passivate the inside of the laser tube; otherwise, HCl added during normal operation would be quickly absorbed by the porous alumina surfaces and removed from the discharge volume. To passivate the laser tube, it was filled with 50 mbar of pure HCl when warm ($\approx$600 °C) and left for 50 h. During passivation, the pressure of the HCl dropped indicating that HCl was being continually absorbed. During warmup, neon and hydrogen mix buffer gas was flowed at a typical rate of 5–40 cc/min. Once the laser was up to temperature and a gas mix giving maximum recorded output power was obtained, the laser was sealed off. Several hours of operation were routinely achieved with a static gas fill. After this period, the output power would drop slowly and the gas mix had to be renewed.

### D. Resonators

Two different resonator configurations were used with the laser. The majority of the work was carried out using a plane–plane resonator. A broad-band multilayer dielectric mirror was used as the high reflector, and an uncoated flat was used as the output coupler giving approximately 8% reflectance. For high-beam-quality work, a confocal negative branch on-axis unstable resonator with magnification $M = 43$ was used (the radii of curvature of the mirrors was 3.2 and 0.075 m). The laser was arranged so that both resonator configurations could be quickly interchanged without turning the laser off. This allowed comparison of the raw power (plane–plane resonator) and high beam quality (unstable resonator) capabilities of the laser.

### E. Pulse Shapes

During experiments, the laser beam was directed onto a thermal power meter, and the diffuse scattered light from the power meter was viewed by a fast photodiode (Thorlabs DET200) to record laser pulse shapes. When using an unstable resonator, the output beam was spatially filtered to remove the divergent amplified spontaneous emission component of the beam, thus enabling the pulse shape of just the high-beam-quality component to be recorded. A comparison between the laser pulse shapes at different PRFs for fixed input electrical pulse energy and wall temperature was also made. Using the slow excitation circuit and a fixed supply voltage (selected for steady-state operation at either 20 or 40 kHz), pulse shapes

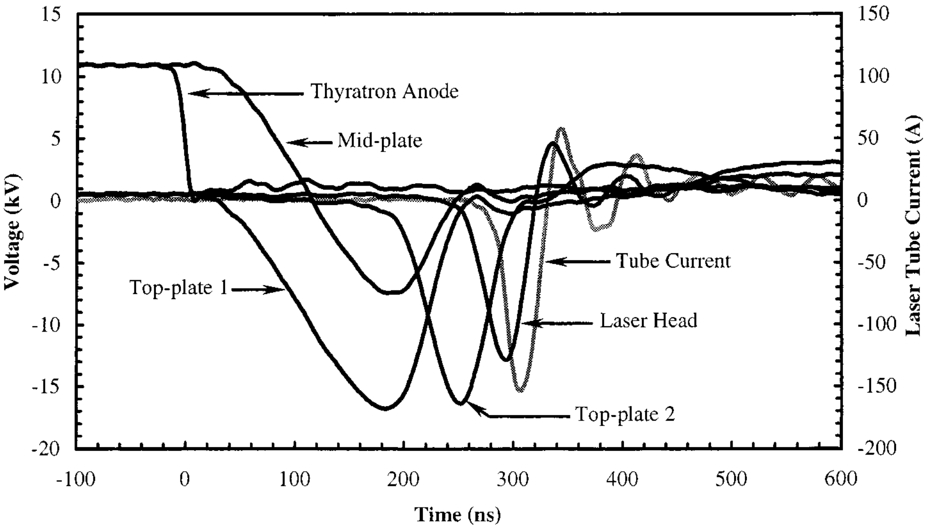

Fig. 2. Voltage and current traces taken from points around the circuit shown in Fig. 1 for the KE-CVL operating at 50 kHz with 0.56-nF capacitor set.

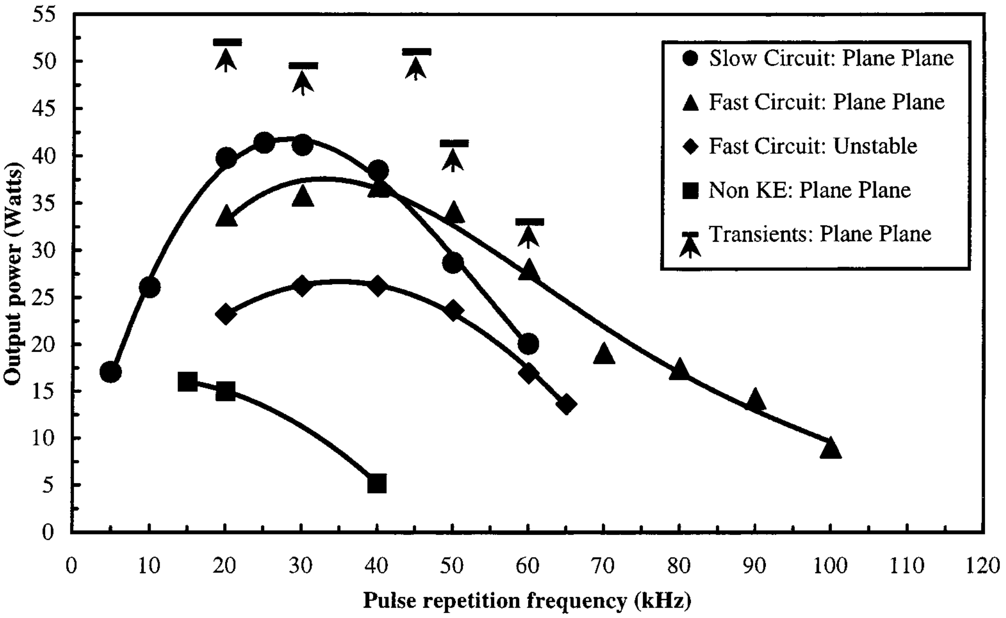

Fig. 3. Variation of output powers with pulse repetition frequency for different power-supply and resonator configurations.

were recorded while momentarily varying the pulse repetition frequency from the steady-state value.

## III. Results

Average output powers at different operating frequencies under different resonator and power-supply configurations are shown in Fig. 3. Unless otherwise indicated, all the values plotted in Fig. 3 represent stable operation of the laser where the input power at each PRF was 3.0 kW, and sustained output without overheating the laser was achieved.

As a conventional CVL (before the addition of any HCl and with trace quantities of hydrogen present), the laser typically gave 15 W of stable output power at an optimum PRF of 15 kHz from 2.4 kW of input power (using a plane–plane resonator). The nonkinetically enhanced output power was reduced to just 5 W at 40 kHz. For KE operation, an insulation layer outside of the silica envelope was removed to allow higher input powers. With the removal of this insulation, the elemental CVL output power was reduced slightly to 12 W at 15 kHz PRF and the input power increased to 3.0 kW.

With kinetic enhancement, a maximum stable output power of 41.3 W was recorded at a PRF of 25 kHz. The input power of the laser under these conditions was 3.0 kW, giving the device a wall plug efficiency of 1.4% and a stable specific output power of 0.14 $\mathrm{Wcm}^{-3}$. Transient output powers of over 50 W were achieved at pulse repetition frequencies of 20–45 kHz by operating the laser at elevated input powers (up to 6 kW) for short periods. These results correspond to specific output powers of 0.17 $\mathrm{Wcm}^{-3}$ and are 1.7 times higher than results previously reported for a KE-CVL of the same tube diameter and over three times higher than the specific output power of the laser when operated as an elemental CVL.

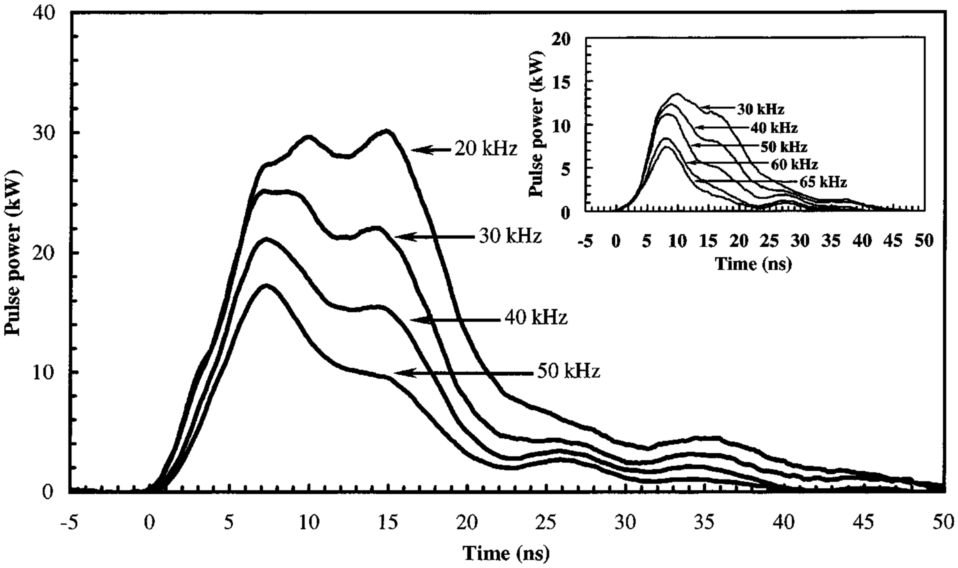

Fig. 4. Plane–plane resonator optical pulse shapes at different pulse repetition frequencies using 0.56-nF capacitor set (inset: unstable resonator optical pulse shapes at different pulse repetition frequencies using 0.56-nF capacitor set).

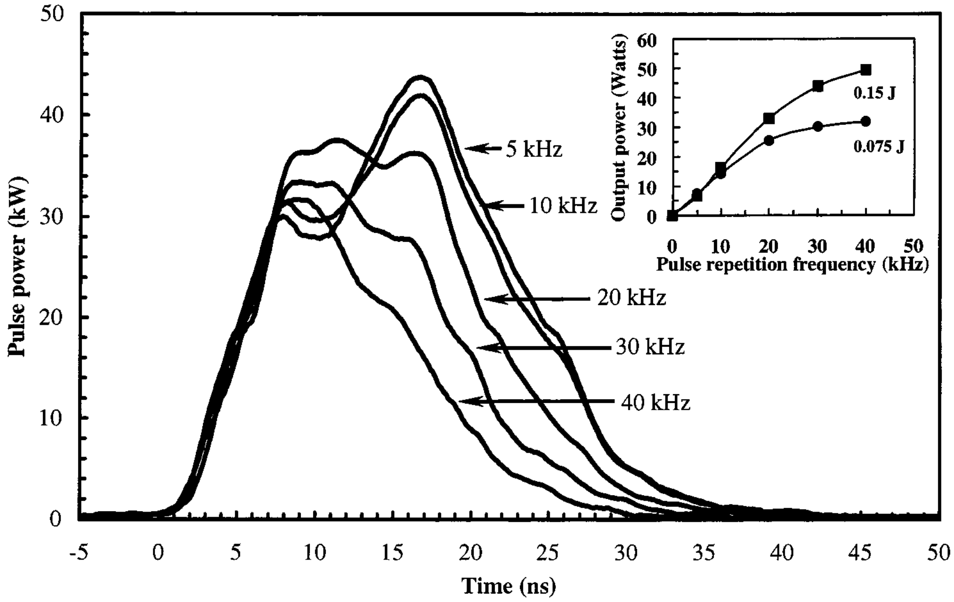

Fig. 5. Plane–plane resonator pulse shapes at fixed input pulse energy (0.075 J, optimized for 40-kHz PRF), tube wall temperatures, and using 0.56-nF capacitor set (inset: variation in laser output power with pulse repetition frequency for fixed input electrical pulse energies of 0.075 and 0.15 J using 0.56-nF capacitor set).

High-power operation up to very high repetition frequencies was achieved. At pulse repetition frequencies up to 80 kHz, the KE-CVL gave output powers in excess of the 15 W (at 15 kHz PRF) maximum ever obtained when operated as a conventional CVL. Even at 100 kHz, 9.0 W of output power was obtained in a beam that remained centrally peaked and showed no signs of becoming annular. Limitations with the excitation circuit unfortunately prevented scaling to higher PRFs.

With an unstable resonator, more than 25 W of high-beam-quality light was available from the laser over the pulse repetition frequency range of 30–40 kHz. This spatially filtered component even up to 60 kHz was in excess of the total plane–plane resonator output power obtained without kinetic enhancement.

The optical pulses at a range of repetition rates using the plane–plane and unstable resonator configurations are shown in Fig. 4. Using the plane–plane resonator, the output pulse durations were typically 20–25 ns at base and up to 17 ns FWHM. These pulse durations are much shorter than those previously reported for KE-CVLs; however, this may be due to the relatively short excitation pulse (<40 ns FWHM) of the present excitation circuit. Using the unstable resonator, up to four round trips of high-beam-quality output were obtained at all pulse repetition frequencies studied. The optical pulse shapes for PRFs from 5 to 40 kHz at constant switched pulse energy (0.06 J) and constant tube wall temperature are plotted in Fig. 5. The peak power contained in the first round-trip output from the laser was relatively constant for pulse repetition frequencies from 5 to 40 kHz. Subsequent round-trip output intensities were reduced at pulse repetition frequencies above 10 kHz. The output power of the laser at fixed electrical pulse energy is shown in the inset of Fig. 5. The output powers were calculated from pulse shapes obtained by momentarily changing the PRF of the laser from a steady-state value at either 20 kHz (33 W obtained, 0.15 J switched pulse energy) or 40 kHz (30 W obtained, 0.075 J switched pulse energy). The output power showed a linear increase with PRF from 0 to 20 kHz and continued to increase up to 40 kHz, where 50 W was obtained at 0.15 J switched energy (6 kW average input power).

## IV. DISCUSSION

### A. Pulse Repetition Frequency Scaling

By kinetically enhancing the laser used in this study, increased output power and extended PRF limits of the laser were obtained. The output power of the laser increased with PRF in an approximately linear fashion up to 20 kHz, with the optimum PRF being between 25–30 kHz. Withford *et al.* have reported similar results [8] for a larger (38 mm bore by 1.5 m long) CVL, which showed a linear increase in output power up to PRFs of 22 kHz where a maximum output power of 150 W was obtained. However, the output powers reported by Withford et al. were not steady-state values and represent operation of the laser in a transient regime where the laser is overheating [10]. Since the laser used by Withford *et al.* has a larger bore diameter than the device used in this study, it is likely that the optimum PRF for the 38-mm device will be lower than the optimum for our 25-mm device of 25–30 kHz.

We have demonstrated high transient output powers (over 50 W) at PRFs ranging from 20 to 45 kHz. These results may suggest that the optimum PRF of the laser is greater than 45 kHz. However, at PRFs above 50 kHz, a clear rolloff in the maximum measured transient output power is seen. Thermal redesign of the laser may permit steady-state operation at the 50-W power level. However, it is not clear whether this regime corresponds to unstable thermal runaway conditions where the power coupling into the plasma tube increases with time [10].

### B. Pulse Repetition Frequency Limits

The performance benefits offered by kinetic enhancement result from the increased rate of plasma recombination in the afterglow [11]. The increased rate of recombination mops up electrons in the afterglow and reduces the cumulative effects of radial cataphoresis. Hence the beam profile of the laser remained centrally peaked even at elevated PRFs. This is in contrast to the annular profiles, which develop in elemental CVLs when operated at higher than optimum PRFs. One consequence of the lower electron density in the afterglow is a decrease in the rate of metastable depopulation since superelastic collisions between copper atoms and electrons are responsible for the process. In elemental CVLs, the metastable population proceeds with two decay rates [12]. The first and quickest rate occurs for the first 10 $\mu$s; then a slower rate of decay is observed. For PRFs of 100 kHz and above, the interpulse period is shorter than this initial decay period, giving insufficient time for the metastables to decay. Preliminary radially and temporally resolved investigations of the afterglow metastable population have been made. By operating the KE-CVL at 50 kHz and probing with a second CVL (synchronized at 10 kHz), we have observed strong absorption of the probe light during the first 10 $\mu$s of the afterglow, indicating that large proportion of the copper atoms are in the metastable level. We expect that the growing remnant metastable copper atom density is the likely mechanism for limiting the maximum PRF of a KE-CVL. It may be possible to enhance the output power at high ($>$50 kHz) PRFs with the introduction of a metastable clearing additive such as Cs [13].

### C. The Excitation Circuit

Operation of a thyratron-based exciter circuit at 100 kHz required careful design with respect to both the circuit and its geometry. While the circuit in Fig. 1 represents the circuit initially used for repetition rates of up to 50 kHz, it was found that for operation above this rate, the thyratron reverse voltage protection diode and inductor $(L_P)$ had to be removed. This subjected the thyratron to a greater duration negative voltage when the reflected electrical pulse from the laser head returned to the thyratron. This extra negative bias helped reset the thyratron into its nonconducting state ready for the next pulse. Additionally, the number of turns on the saturable assist $(S_1)$ was reduced to increase the magnitude of the reversal on the thyratron to $\sim$2 kV.

At pulse repetition frequencies of order 100 kHz, the output power of the laser was limited by the low excitation voltages attainable. To provide the minimum head voltages required for efficient operation at such elevated PRFs, lower value capacitors must be used in the exciter circuit. However, any such reduction in capacitance would further shorten the excitation pulse and hence the laser pulse. Alternatively, thermal redesign of the laser head to accommodate higher input powers may enable more efficient operation of the laser at PRFs of order 100 kHz.

## V. CONCLUSION

Repetition rate scaling of a kinetically enhanced CVL has been demonstrated up to 100 kHz. The maximum recorded stable output power of 41 W was obtained at pulse repetition frequencies between 25–30 kHz, and transient output powers of over 50 W were achieved between 20–45 kHz. Using the fast excitation circuit, the high-frequency rolloff in output power only began for PRFs above 50 kHz, and the output powers for PRFs up to 80 kHz were in excess of the maximum obtained at 15 kHz without kinetic enhancement. The maximum recorded specific output power of 0.17 Wcm$^{-3}$ is 70% higher than that previously reported for a 25-mm bore diameter CVL. Efficient generation of high-beam-quality output was demonstrated at PRFs up to 65 kHz. Preliminary experiments indicate that the remnant metastable population limits the maximum repetition rate at which the laser will operate.

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