Influence of acoustic waves on TEA CO_2 laser performance

Hubertus von Bergmann[1#], Andrew Forbes[2], Ted Roberts[2] and Lourens Botha[2]

[1]LRI, University of Stellenbosch, Private Bag X1, Matieland 7602, South Africa
[2]CSIR National Laser Centre, PO Box 395, Pretoria 0001, South Africa

ABSTRACT

In this paper we present results on the influence of acoustic waves on the output laser beam from high repetition rate TEA CO_2 lasers. We show that acoustic waves generated inside the cavity lead to deterioration in beam quality, decreased output energy, and an increase in pulse to pulse energy variation. We investigate the impact of gas mix on the acoustic behaviour, and present experimental results on laser performance across a range of gas mixtures. Solutions to the acoustic wave problem are presented together with experimental results. The influence of acoustic damping measures on laser gain are demonstrated showing a significant improvement in gain and output power at high repetition rates. The link between the pre-ionisation method employed and the acoustic wave impact on laser performance is discussed.

Keywords: Acoustic waves, TEA CO_2 lasers, beam quality, energy variation, laser gain

1. INTRODUCTION

Recently there has been renewed interest in CO_2 TEA lasers because of a number of emerging large scale applications, such as extreme UV generation (EUV) for photo-lithography, large scale paint stripping, and non-destructive testing e.g. testing of composite aircraft structures. All of these applications require high output power with large pulse energies, generally at high repetition rates; since they are of industrial nature, long term reliability and cost effectiveness are of overriding importance. However, since the gain medium for these systems is a gas mix, and since a large amount of energy is deposited into the gas in a short time frame, acoustic waves and shock waves are always possible obstacles to stable performance. In particular, since the energy is deposited into the cavity at a distinct repetition rate, resonantly enhanced waves can become a problem in some lasers[1-5].

In this paper we report on acoustic wave experiments on two different laser systems. The first is a high repetition rate system capable of operating at repetition rates of up to 2000 Hz and delivering multi kW laser output, which was originally developed for molecular laser isotope separation. The laser employed a wind tunnel type flow loop with a centrifugal fan driven by a variable frequency drive which provided continuously variable flow speeds up to 90 m/s and provided sufficient clearing ratios for repetition rates in excess of 2000 Hz. The electrode structure consisted of 800 mm long discharge electrodes, separated by 20 mm. The laser employed spark pre-ionisation by two arrays of sparks placed up- and down-stream of the discharge electrodes with a spark separation of 25 mm. Flow profiles, approximating a flow nozzle, provided uniform flow in the electrode region. Arrays of current return feed-throughs were placed up- and down-stream spaced by 50 mm. The total energy supplied to the discharge electrodes was 20 J resulting in a specific energy deposition of 90 to 130 J/l atm, depending on the gas mixture. The system was equipped with a number of diagnostics tools to monitor gas dynamics as well as discharge and laser performance. The gas flow velocity was measured with a Pitot tube, while time resolved pressure measurements were made using fast miniature piezoelectric pressure transducers. Perturbations of the gas density in the inter electrode region were performed using a Schlieren system. Visual observations of the discharge, both in the gas flow direction and in the direction of the optical axis were carried out by CCD video cameras through dedicated observation ports. Recordings were made at 24 frames per second; therefore each video frame was averaged over many discharges. The second system studied is a commercially available TEA CO_2 laser designed by SDI (Pty) Ltd and used extensively for the non-destructive testing of composite materials. The laser is designed for 400 Hz operation with very short time pulses (more than 80% of the energy in the first 100 ns). The

[#] hmvb@sun.ac.za; phone +27 21 8083376; fax +27 21 8083385

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specifications for both lasers require gas mixes that are "rich" in CO_2 (minimum 30%), and consequently experience acoustic problems at lower repetition rates than would be the case with "lean" CO_2 gas mixes. Photographs of the systems are shown in Figure 1.

Figure 1: The 2000 Hz laser system is shown on the left, while the commercial system is shown on the right.

Since this work concentrates on the impact of acoustic waves, some of the results are reported without reference to the particular laser system.

2. ACOUSTIC WAVE INFLUENCES

In this section we consider the impact of acoustic waves on the laser output parameters, such as laser beam quality (M^2), output power and energy, output energy variation (jitter) and laser gain. We also consider some factors which impact on the acoustic waves themselves, such as cavity geometry, laser repetition rate, gas mix and the method of transferring energy into the discharge.

2.1 Impact on discharge uniformity

Figure 2 shows the discharge appearance recorded side-on in the flow direction. A section of approximately 300 mm length close to the centre of the main electrodes has been imaged. The dark vertical lines are the up-stream current return feed-throughs and the bright spots at the upper border of the discharge are the pre-ionisation sparks.

At low laser frequencies the discharge has a uniform appearance. With the 36:20:44 gas mix (Figure 2(a)) the discharge becomes non-uniform along the electrode length as the laser repetition rate (frequency) is increased, evident already at a repetition rate of 200 Hz, while further increase leads to distinctive resonant structures with bright regions behind the feed-throughs (designated "type A" structures), which reappear at successively higher frequencies. At higher frequencies other structures appear: e.g. with bright regions behind every second feed-through ("type B") and every third feed-through ("type C") as well as structures displaced by one feed-through separation or with bright regions between feed-throughs. At very high frequencies the glow discharge is concentrated in only a few or even one bright current carrying column eventually leading to discharge arcing. At very high frequencies there are no frequency regimes with uniform discharges in between resonant structures. Viewing the discharge end-on (direction of optical axis) shows contractions of the visible discharge column as well as distinctive sideways shifts at the same frequencies as for resonances along the discharge length. With the more dilute 10:10:80 mix exactly the same resonant behaviour is observed but discharges are generally more benign to disturbances. For example, the first well-defined type A structure appears only at about 820Hz. It has been experimentally determined that the appearances of resonances are largely independent of fan frequency and therefore of gas flow.

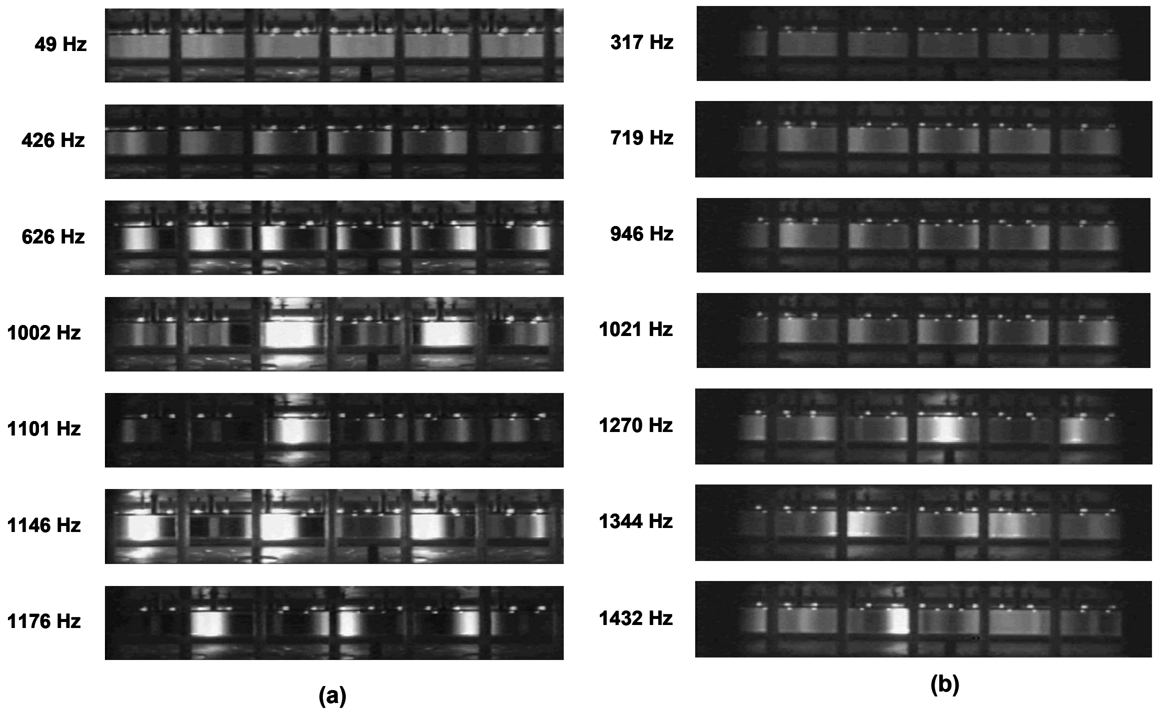

Figure 2: Transverse discharge appearance for various resonant laser frequencies. Gas mixtures: (a) CO_2:N_2:He = 36:20:44, p = 700 mbar and (b) CO_2:N_2:He = 10:10:80, p = 700 mbar

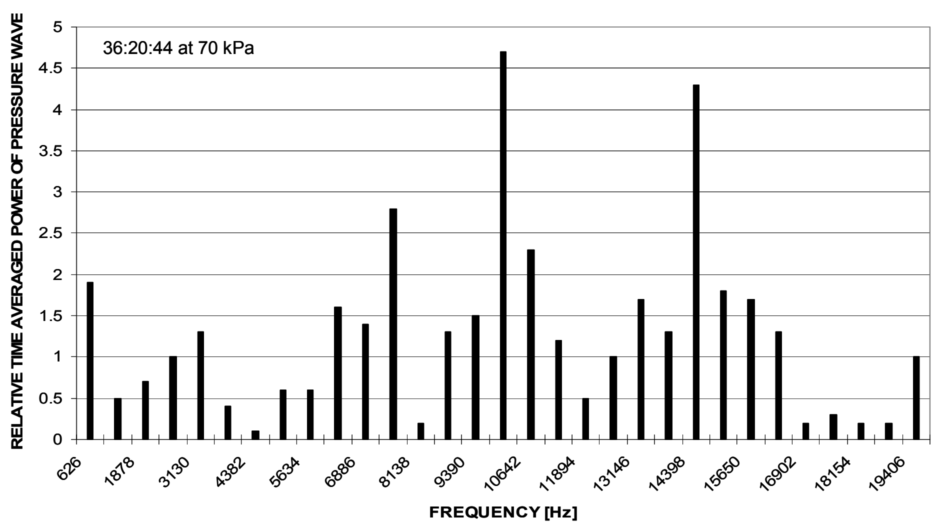

Figure 3: Cavity resonances excited at a laser frequency of 626 Hz by successive harmonics from n =1 to 31

We have analysed the acoustic wave frequency spectrum using a fast piezoelectric pressure transducer and spectrum analyzer. The measured power spectrum for a laser frequency of 626 Hz (visible structure A) is shown in Figure 3. The detector was placed at the laser output window, and is therefore primarily looking at transverse waves (direction of optical axis). The power spectrum consists of a series of Fourier harmonics $f = n \times f_L$ of the pressure perturbation excitation source f_L with an amplitude modulated by the resonant properties of the cavity. The pressure spectrum is, in general, complicated since for a single laser frequency one has a large number of excitation frequencies, while, for an enclosed cavity, there are a large number of resonant frequencies. For small laser frequencies many harmonics can lie within the frequency range of a resonance, whereas for large ones, only one specific harmonic may be capable of exciting the resonance.

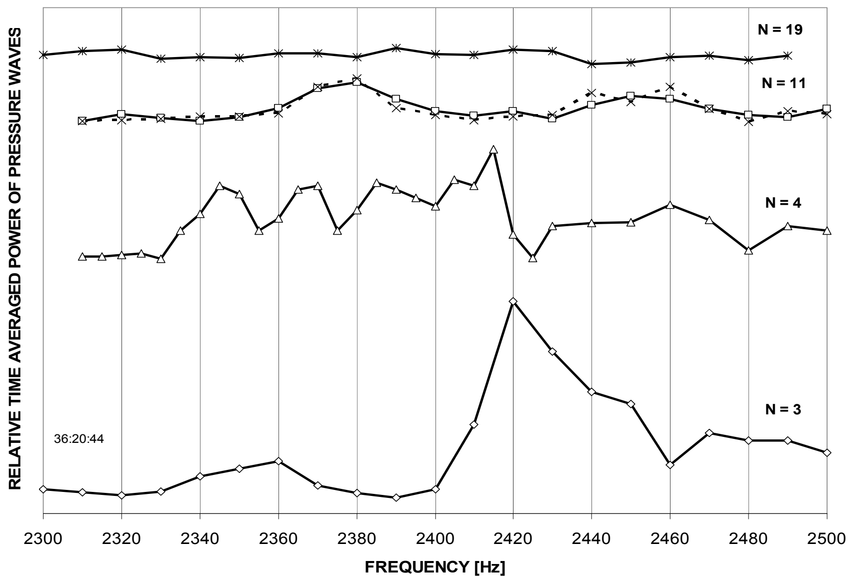

Figure 4: Pressure amplitude scan of the of 2.4 kHz resonance excited by various harmonics of the laser frequency (solid lines for 50 Hz fan drive and dashed 25 Hz)

A specific cavity resonance can be excited by either a high harmonic of a low laser frequency or a low harmonic of a high laser frequency, as can be seen in Figure 4, showing scans of the cavity resonance between 2300 and 2500 Hz excited with the different laser harmonics 19, 11, 4 and 3 (increasing f_L from 2300 Hz/n at the start of the scan, e.g. N=3: 767 Hz, N=19: 121 Hz). Of the four cases shown, only in the case of the 3rd harmonic is a clear visible transverse structure of the discharge evident (type C structure - bright regions every 3 feed-throughs, 15cm).

We have investigated the transverse resonances spatially resolved by moving the pressure monitor along the axis of the electrodes. Clear standing wave structures with pressure perturbation envelope and minima fixed in space could be detected, roughly consistent with the visually observed structure. Looking at the spatial structure of higher frequency resonances one finds that the pressure distribution is not dominated by a single wavelength but there appear standing waves over a wide range of wavelengths. Similar studies were also done by moving the probe in the gas flow direction and observing the longitudinal mode structure. Dominant broad longitudinal cavity resonances around 800 Hz and 2500 Hz similar to those appearing in the transverse pressure studies have been observed.

Normally acoustic resonances in a cylindrical cavity are determined by the boundary conditions at the walls. In the transverse direction the resonant wavelengths would be given by $L = m \times \frac{\lambda_R}{2} = m \times \frac{\upsilon_S}{2 f_R}$, where m is an integer and the f_R therefore are proportional to m: $f_R = m \times \frac{\upsilon_S}{2L} \propto m$. On the other hand if repetitive structures are present in the cavity, the dominant boundary conditions are given by multiple nodes at their separations rather than the boundary conditions being defined by the end walls. For nodes separated by a distance l we have $n \times l = \frac{\lambda_R}{2} = \frac{\upsilon_S}{2 f_R}$, and therefore $1/f_R$ is proportional to m: $f_R^{-1} = n \times \frac{\upsilon_S}{2l} \propto n$.

This can be tested quite easily by looking at the frequencies at which transverse type A structures are observed for both weak and rich gas mixtures. The predicted linear relationship has been confirmed experimentally, and from the slope, which gives the separation of the repetitive structure, one finds good agreement with the physical feed-through separation.

Acoustic wave phenomena have a strong influence on the discharge development. Simple discharge modelling indicates that small pressure perturbations of only 1-2% can introduce changes in the discharge current of up to a factor of in the affected electrode area. Pressure disturbances of up to 4% have been measured in the strongest acoustic resonances which can explain the observed discharge structures and also observed discharge arcing. In addition there is feedback between the spatially non-uniform discharge and the standing acoustic wave, enhancing the effects.

2.2 Impact on gain

Acoustic waves and associated non-uniform discharges have a strong effect on laser performance through the resulting changes in the gain. The output of the high repetition rate laser measured in the original state without any acoustic wave damping measures is shown in Figure 5 versus repetition rate (traces 3 and 4). The output is relatively flat with comparatively small fluctuations for the weak gas mixture 10:10:80. The strong 30:15:55 mixture, however, shows strong resonant behaviour with the output dropping to one third at 1100 Hz. The position of the resonances is very reproducible as can be seen by repeated scans. Together with reduced pulse energy at these resonances, one also observes a dramatic increase in pulse-to-pulse energy jitter.

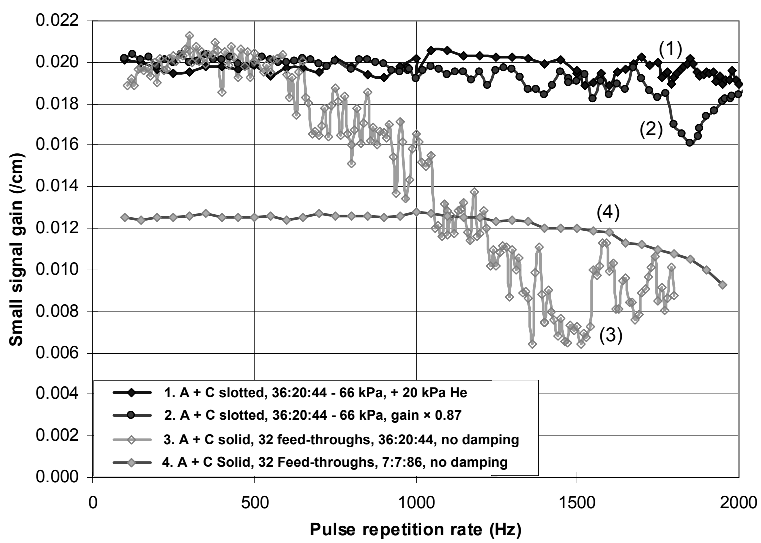

Figure 5: Influence of acoustic waves on laser gain.

2.3 Impact on laser beam quality

Similar resonant behaviour can be seen in the beam quality of the laser, as defined by the M^2 parameter. The measurements shown in Figure 6 were performed on a high repetition rate oscillator of similar design as the high repetition rate laser, but with reduced excitation energy. Because both the beam quality and laser output power decrease at the acoustic resonances, the overall laser brightness is severely affected by acoustic waves.

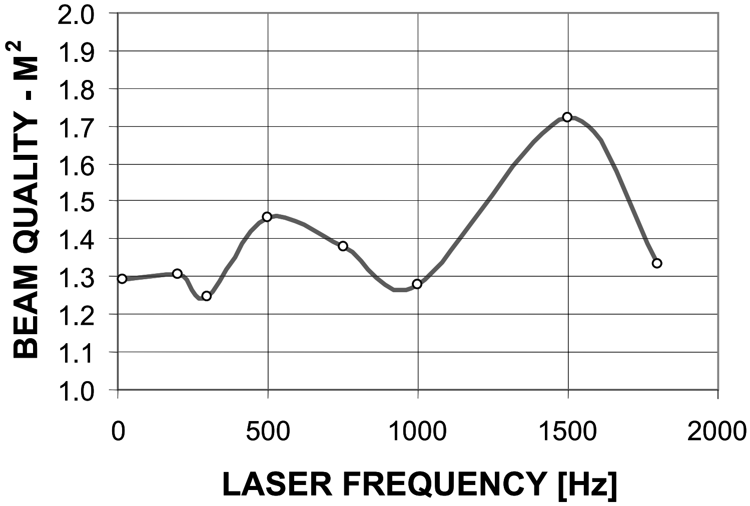

Figure 6: Beam quality factor M^2 of oscillator versus frequency.

2.4 Influence of pre-ionisation on acoustic waves

A surprising result was the impact of the chosen energy transfer circuit on the acoustic amplitudes, suggesting that how energy is deposited into the laser (other than via the repetition rate parameter) is just as important as the cavity geometry (acoustic resonances) when determining acoustic disturbances.

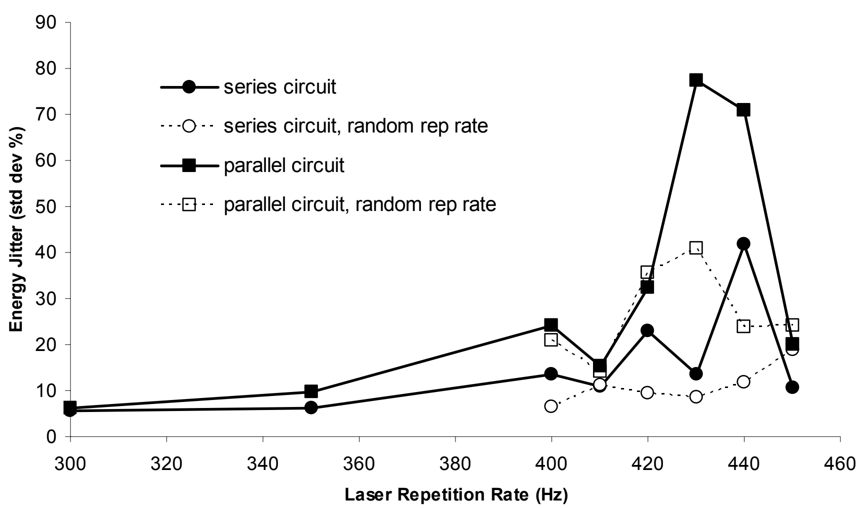

Figure 7: The parallel circuit shows much higher sensitivity to the acoustic waves.

Figure 7 shows data for a pre-ionisation circuit where all the energy passes through the pre-ionisation sparks prior to the discharge (series circuit), and for a circuit where the pre-ionisation is in parallel to the discharge in the circuit (i.e., only some of the energy passes through the pre-ionisation), henceforth referred to as the parallel circuit. In the case of the parallel circuit, the acoustic amplitudes are far more pronounced. Further tests confirmed that these effects are only due to acoustic waves, and not some other form of jitter from the electrical system. This is also borne out by comparing the impact of various acoustic damping solutions while keeping everything else constant – the parallel circuit returns to "normal" behaviour with very little energy jitter as a function of repetition rate. Clearly there is some mechanism coupling the pre-ionisation to the acoustic waves. One possibility is simply that discharge disturbances become more manifest under weak pre-ionisation conditions, and that the parallel circuit provides an overall weaker pre-ionisation. Another possibility is that the regularly spaced pre-ionisation structure, which acts as a source term for small amplitude waves through the spark mechanism, is resonantly enhancing the acoustic waves. At the moment the exact mechanism is not well understood and requires further study.

3. ACOUSTIC WAVE DAMPING SOLUTIONS

It is possible to damp the acoustic waves inside the laser cavity to an extent that their influence on the laser output parameters is reduced, or in some cases, eliminated entirely. The trivial case is to simply choose an operating regime where no acoustic problems manifest themselves (such as a very low repetition rates). In this section we present solutions for reducing the influence of acoustic waves at operating regimes where their influence would usually be severe.

3.1 Random repetition rates

Since the acoustic waves inside the laser cavity are a result of acoustic harmonics resonant with the laser cavity dimensions, one way to reduce the influence is to reduce the resonant addition of these waves. Such a solution was implemented via a random repetition rate selection experiment. In this experiment the repetition rate was varied randomly around some chosen operating point. The distribution of repetition rates was such that the mean repetition rate equalled the desired value, so that on average the power output from the laser was not different to the case of running continuously at the chosen repetition rate. The acoustic wave activity was notably reduced under this new operating condition, as shown in Figure 7.

3.2 Slotted electrodes

One method of reducing the amplitude of the various acoustic harmonics is to damp the waves as they propagate back and forth along the various propagation axes. In the case of acoustic waves propagating normal to the electrodes, damping can be introduced by "slotting" the electrodes, thus increasing the losses of the waves. Surprisingly the discharge "glow" does not degrade due to this change in the electrode structure as long as the profile of the electrode is maintained (i.e., an known electrode profile is machined and then slotted) and the slot geometry is judiciously chosen. An example of a slotted electrode is shown in Figure 8.

Figure 8: Both sides of a brass electrode that has been slotted to reduce acoustic wave amplitudes. The electrode is hollowed to allow for a suitable damping material to be inserted.

The decrease in the acoustic wave influence can be seen by comparing the amplifier gain in Figure 5 (traces 1 and 2), where various optimised damping structures have been employed, and the pulse to pulse energy jitter due to the acoustic waves both with and without slotted electrodes in Figure 9.

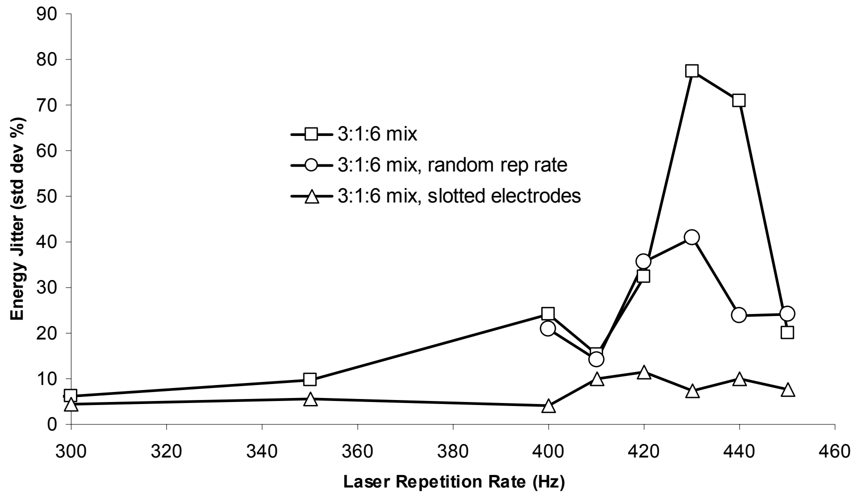

Figure 9: Comparison of acoustic effects with and without damping solutions.

Considering Figure 9 one notes that under normal operating conditions the laser showed acoustic influences at repetition rates above 300 Hz. The random repetition rate solution dramatically reduced the acoustic amplitudes, while the slotted electrode solution almost entirely eliminated acoustic problems to the point that the 3:1:6 mix behaves in a similar fashion to "weak" mixes, such 10:10:80.

4. CONCLUSION

We have presented experimental results on the influence of acoustic waves on the output laser beam from high repetition rate TEA CO_2 lasers. At the laser repetition rates that lead to resonant conditions inside the cavity for the acoustic waves one finds deleterious effects on the laser gain and discharge uniformity, leading to decreased output energy, a worsening of the laser beam quality, and an increase in pulse to pulse energy variation. The implementation of slotted electrodes and/or operating at the laser at random repetition rates was shown to decrease the impact of the acoustic waves.

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