Experimental details of KrF oscillator-amplifier laser configuration

S. S. Harilal, J. Pulsifer and M. S. Tillack

October 24, 2006
Experimental details of KrF Oscillator - Amplifier laser configuration

S. S. Harilal, J. Pulsifier and M. S. Tillack
Center for Energy Research, UC San Diego, CA 92093-0438

Abstract: The experimental details of KrF laser “oscillator – amplifier” configuration used in UCSD mirror damage facility are given. Two commercial KrF lasers are used for running oscillator-amplifier mode of operation. The pulses from Compex KrF excimer laser is sliced using a Pockels cell to FWHM 5ns and passed through the LPX excimer cavity for amplification. The experimental details, gain analysis and other aspects of such system like temporal and spatial profiles, energy stability are discussed. Laser pulse energy of 60 mJ is extracted from the amplifier for an input energy of 0.8mJ with 5 ns pulse with ‘pure’ Gaussian temporal profile.

1. Introduction:
Generating pulses with short duration and high power from excimer lasers have got considerable interest due to its applications in direct drive fusion. There exist some difficulties in obtaining such short pulses from Excimer lasers due to the short excited lifetimes and high gain of excimer media. Nevertheless, some groups achieved this task using different experimental techniques. For example Banic et. al [1] employed fast-discharge KrF oscillator-amplifier system for obtaining 50 mJ pulses with 10 ns FWHM. They were also able to isolate and amplify a single pulse of a mode-locked train and extracted 35 mJ in a 2 ns pulse. Patterson et. al [2]studied Master-Oscillator Power-Amplifier (MOPA) experiment using an electron beam excited KrF oscillator and amplifier operating with various gas mixtures. Kakehata and co-workers [3] investigated gain and saturation of a discharged pumped F2 laser operated at high pressures with an oscillator- amplifier configuration. Cymer (a company based in San Diego) uses dual-chamber approach (MOPA) for obtaining high rep rate (6 kHz), line narrowed ArF laser for lithographic applications. The Nike laser at NRL utilizes a series of discharged pumped and e-beam pumped amplifier stages for obtaining highest energy [4].
2. Present features and specifications of excimer lasers

In this section, the specifications of the 2 excimer lasers currently present in the UCSD Laser Plasma and Laser-Matter Interaction (LPLMI) laboratory is given. Two Lambda Physik KrF lasers available for mirror testing and their maximum energy and rep rate are

a) Compex, 350 mJ, 10 Hz

b) LPX PRO, 700 mJ, 100 Hz.

Typical parameters of Compex and LPX lasers are given in table 1.

<table>
<thead>
<tr>
<th>Specifications</th>
<th>Compex laser</th>
<th>LPX laser</th>
</tr>
</thead>
<tbody>
<tr>
<td>Maximum Pulse Energy</td>
<td>350 mJ</td>
<td>700 mJ</td>
</tr>
<tr>
<td>Max. Rep. Rate</td>
<td>10 Hz</td>
<td>100 Hz</td>
</tr>
<tr>
<td>Polarization</td>
<td>Unpolarized</td>
<td>Unpolarized</td>
</tr>
<tr>
<td>Pulse duration FWHM</td>
<td>25 ns</td>
<td>25 ns</td>
</tr>
<tr>
<td>Discharge voltage range</td>
<td>18.5kV-27kV</td>
<td>16.1-24kV</td>
</tr>
<tr>
<td>Beam dimensions</td>
<td>24 x 6 mm² (VxH)</td>
<td>12 x 23 mm² (VxH)</td>
</tr>
<tr>
<td>Divergence</td>
<td>3x1</td>
<td>1x3</td>
</tr>
<tr>
<td>The standard gas mixture</td>
<td>F₂/He mixture: 60mbar</td>
<td>F₂/He mixture: 80mbar</td>
</tr>
<tr>
<td></td>
<td>Kr: 130 mbar</td>
<td>Kr: 150 mbar</td>
</tr>
<tr>
<td></td>
<td>Ne: 3120 mbar</td>
<td>Ne: 3030 mbar</td>
</tr>
</tbody>
</table>

Table 1. Specifications of Compex and LPX lasers available in the LPLMI lab are given.

Both LPX and Compex lasers provide 25 ns (FWHM) pulses and the temporal pulses have a tri-fold profile. Typical profile of Compex recorded with 2 ns rise time photodiode is given in figure 1. The spatial profiles showed large anomalies for both the lasers. We also noticed the spatial profiles of these lasers change drastically with aging of gases.
3. Pulse slicing using Pockels cell:

A Pockels cell is used for slicing a portion of laser Compex pulse.

Pockels cell specifications:

FastPulse Tech. Model 5046E

Crystal material: DKDP (KD$_2$PO$_4$; >95% D$_2$)

Aperture: 16 mm

The 5046E Pulse Extraction System incorporates a Pockels cell light modulator and a high voltage electronic switching driver to produce nanosecond transition optical gating. The Pockels cell mounted in a two axis gimbals to provide pitch and azimuth adjustment for optical system alignment. A cube polarized is used with the system to act as an output analyzer. When subjected to an electric field, the Pockels cell crystal induces a phase shift (retardation) between the o and e- light rays traveling through the cell. The estimated half wave retardation voltage is ~ 1.5kV. The optical axis of the Pockels cell crystal is set in such a way that the input should be p-polarized light and the plane of polarization must be aligned to the axis of the crystal to an angular tolerance of less than 1 degree. To achieve this, the pitch and azimuth micrometers should be tuned.
carefully to obtain the best contrast ratio. Also insure that the laser beam is passing thorough the center of the Pockels cell aperture. This can be done by checking the reflected images from the Pockels cell. The null transmission level is critical in obtaining highest possible extinction ratio. A SRS timing generator (SRS 535) is used for triggering the Pockels cell and the Compex laser. The final timing adjustment of the width of the pulse and time of the slicing can be done at Pockels cell voltage controller. Typical sliced pulse of Compex laser pulse along with original Compex pulse is given in figure 2.

![Figure 2. The Compex laser pulse and sliced pulse using Pockels cell.](image)

Even though the have wave retardation voltage is 1.5 kV, the Pockels cell voltage is found to have significant effect on the ON and OFF rising time of the Pockels cell gate. For example typical sliced profiles obtained from Compex pulse with various Pockels cell voltages are given in figure 3. By varying the gate delay and width of the Pockels cell applied voltage, one can slice various parts of the Compex pulse temporal profile as shown in figure 4.
Figure 3: The Pockels cell sliced profiles of Compex laser with various Pockels cell voltages. The rise time (ON) and fall time (OFF) are found to depend strongly on the applied voltages.

Figure 4: Various parts of the Compex beam can be selected by delaying the Pockels cell applied voltages. The above figure showed profiles of sliced signals at 3 peaks of Compex profile.
The maximum energy available from the Compex laser is 350 mJ. For obtaining maximum energy, the applied discharge voltage should be the highest (27kV). Since the Compex beam is unpolarized, a cube polarizer is utilized for polarizing the beam and p-polarized light is used for slicing with Pockels cell. Moreover, the aperture of the PC is only 16 mm in diameter and it is not advisable to pass a laser beam very close to the edges of the PC crystal. Hence the 24 x 6 mm$^2$ beam from Compex is passed through an aperture to make the beam size 12 x 6 mm$^2$ and hence another 30% of laser energy is lost. The slicing of the pulse reduces the available energy again to less than 1/3. We also noticed that the transmission of crystal used in the Pockels cell is found to be only ~30% at 248 nm. Hence the laser energy available for mirror damage testing facility after the polarization optics and pulse slicing is very limited. For example with an input Compex energy of 200 mJ, the available energy after pulse slicing is less than 2 mJ. An oscillator-amplifier configuration is necessary for obtaining high energy for mirror damage facility.

4. Oscillator – amplifier configuration:
An oscillator-amplifier mode of operation is useful for obtaining high energy, short pulses from KrF Laser. To begin with, we made gain and saturation intensity measurements of KrF oscillator – amplifier without pulse slicing. The schematic experimental configuration is given in figure 5. The amplification of the laser pulse occurred in the 90 cm long discharge region of the LPX excimer laser with the mirrors removed to eliminate the feedback. However, even with complete absence of optical feedback, the gain was sufficiently high that considerable energy of amplified spontaneous emission (ASE) was emitted from each end of the amplifier. The ASE is also found to be strongly depended on the discharge voltage. (for example, the ASE energy at the front-end of the LPX was 10mJ, 42 mJ and 65 mJ for 16.5, 17.5, 18.5 kV LPX discharge voltages respectively). The timing of Compex and LPX lasers are controlled using SRS DG535 timing generator (50ps jitter). The arrival time of the laser pulse with respect to external trigger for both LPX and Compex laser are found to vary with discharge voltage. We also noticed the timing jitter of the laser pulse is also depended strongly on discharge voltage. Typical estimated jitter of the Compex pulse for
various discharge voltages are given in figure 6. The jitter of the Compex laser depends on several factors. Jitter is found to be highest just after a new gas fill.

Figure 5: Schematic diagram of Oscillator – amplifier system. (BD: beam dump; WP: wave plate)

Figure 6. The estimated jitter in the Compex pulse for various discharge voltages.
For extracting maximum energy from the LPX amplifier, the input trigger timing of the LPX should be changed for different LPX discharge voltages. For example, typical variation of the amplified laser energy with respect to input trigger time after passing the Compex beam through the LPX cavity is given in figure 7. All these measurements were done with a Compex discharge voltage of 20.5 kV. Please also note that the delay time between the oscillator and amplifier changes with various experimental parameters like the optical delay, cable lengths, the Compex and LPX discharge voltages etc. The fractional energy content of ASE coming from the LPX after amplification strongly depends on the delay between the Compex and LPX and ASE reaches its minimum when the delay corresponds to optimal efficiency (at the peaks the curves in figure 6).

Figure 7: The change in output laser energy with delay time between the Compex “Oscillator” and LPX “amplifier” for various LPX voltages. A Compex discharge voltage of 20.5 kV is used for these measurements.

The dependence of output energy on input energy for FWHM 25 ns pulses for various LPX discharge voltages is given in figure 87. The Compex discharge voltage used for this measurements in 20.5 kV. An aperture is used in front of LPX for slicing the Compex pulse (originally 24 x 6 mm²) to 12 x 6 mm². The estimated gain from the
lowest energies and it quickly saturates at highest input energy. Typical cross-sections for these excimer media are very large, in the range of $10^{-16}$ cm$^2$, implying the $F_{\text{sat}}$ of only a few mJ/cm$^2$ where $F_{\text{sat}}$ is the saturation fluence of the material and it represents the
maximum energy per unit area extracted from an amplifier. The gain curve obtained with various LPX voltages for a fixed input laser energy of 5 mJ is given in figure 10. It shows more than 400 mJ of polarized KrF laser beam can be obtained with oscillator–amplifier configuration. Our studies also indicated that we can obtain higher gain with expanded input laser beam that fills the LPX amplifier cavity. With the use an expanded beam, a considerable reduction in amplified spontaneous emission (ASE) from the amplifier was observed.

Figure 10: The gain analysis with various LPX discharge voltages. The input laser energy was fixed at 5 mJ.

5. Oscillator – Amplifier Configuration with Pockels cell

Schematic of the Oscillator – amplifier experimental scheme including Pockels cell is given in figure 11. The Pockels cell is inserted in the frond-end of the LPX amplifier. Trigger pulses from the timing generator were used for timing the Compex oscillator, LPX amplifier and Pockels cell. An aperture is placed in front of the Pockels cell to slice the pulse spatially. Using this aperture, the height of the Compex beam is restricted to ~12 mm. A combination of cylindrical concave and convex lens is used for expanding the beam horizontally before the LPX amplification. The size of the expanded beam was set at ~12 x 20 mm². We also utilized a combination of spherical plano-concave lens (f = -50 cm) and a plano-convex lens (f=100 cm) for expanding the Compex beam.
In principle maximum output can be drained from the amplifier if the input beam size is more or less the size of the LPX cavity dimensions (12mm x 23 mm). Because of the gain saturation, an input energy of ~ 1 mJ is enough for extracting most of the energy from LPX discharge. LPX will automatically shut off if the light level is low in the energy monitor. One can disable the energy monitor by pressing F2+4711. The lifetime of LPX amplifier ASE is found to be 13 ns FWHM (figure 13). The amplifier discharge time is longer than the total duration of the Compex sliced pulse (~ 5 ns FWHM) to allow for finite turn-on time and jitter. In order to get maximum amplified energy, the sliced Compex pulse should encounter LPX ASE. Since the sliced Compex pulse FWHM width is ~ 4-5 ns, there is a probability that the remaining part of the ASE can interact with leaked photons from the Pockels cell and distort the amplified temporal profile. This can
be controlled by changing the delay of the LPX amplifier with respect the arrival of sliced Compex pulse.

Please also note that changing the delay of LPX discharge with respect to arrival of Compex sliced pulse can change the temporal profile as well as amplified energy. The stability of the amplified energy also depended on the sliced pulse shape and laser jitter. For example, figure 13 (a -c) demonstrate the energy stability of the amplified signal with respect to various delays between the LPX and Compex for the same sliced pulse. All these runs are with a Compex and LPX voltages of 20.5 kV and 17.5 kV respectively. The temporal profiles of amplified laser pulse are also given in the insets of the figures. A pulse energy of 60 mJ is obtained with a clean temporal ‘Gaussian’ profile (figure 13a). By changing the delay between the Compex and LPX more laser pulse energy can be obtained, but with a distorted ‘Gaussian profile’ (figures 13b and c). The distortion of the amplified temporal pulse may be due to incomplete Pockels cell switching (Pockels cell leakage) and ASE from LPX laser. The energy stability of the amplified output also depended on the part of the Compex pulse sliced and pulse width. Energy Stability is better for larger pulse width. More amplified laser energy can be obtained with increased LPX voltage, but with the presence of enhanced ASE. The gain curve obtained with Oscillator-amplifier mode of operation with 5 ns ‘clean’ Gaussian pulse is given in figure 14.

Figure 12: Temporal profile of ASE from LPX.
Figure 13(a): The energy stability and temporal pulse shape of the LPX amplified profile. The FWHM of the pulse is 4.7 ns.

Figure 13(b): The energy stability of the LPX amplified pulse. The temporal profile of the amplified pulse is also given. The experimental parameters are same with figure 12 a, expect the delay between the LPX and Compex.
Figure 13[c]. The energy stability of the LPX amplifier is shown. The amplifier temporal profile is also given.

Figure 14: Gain curve for oscillator-amplifier configuration with sliced pulse (4.5 ns FWHM)
We also noticed better energy stability and temporal pulse stability can be obtained with placing the cube polarizer after the amplifier. The rejected beam from the Pockels cell co-propagates with the target beam through the LPX amplifier and then separated by cube polarizer. The co-propagated pulse preserves the pulse shape and contrast of the laser pulse by maintaining a constant loading of the partially saturated amplifiers. Typical temporal profiles and laser energy recorded with cube in the front-end and after the LPX amplification are given in figure 15. From the figures one can easily notice that the distortion in the temporal profile is minimum when the polarization cube is placed after the LPX amplifier. In strongly saturated amplifiers, it is in general difficult to keep the output pulse widths from broadening. With co-propagation of both the Pockels cell sliced and rejected beam through the amplifier, the broadening of the sliced pulse become minimum.

![Figure 15a: Temporal profiles of Pockels cell sliced pulse and amplified pulse by placing polarizing cube before and after the LPX.](image)

6. Beam smoothing effect with Oscillator-Amplifier configuration:

The spatial profiles of near-field and far-field Compex beam recorded using a Data ray profiler are shown in the figures 16 and 17. The profile shown in figure 16 recorded at a distance ~1.5 m from the laser and the figure 17 corresponds to the profile recorded at a distance ~10 m from the Compex laser. These profiles indicate the Compex laser profile changes with distance. The spatial profile of LPX amplified beam is given in figure 18 shows dramatic improvement in its smoothness.
Figure 16: Compex near-field profile.

Figure 17: Compex beam far-field profile (after flipping and passing through an aperture).
Figure 18: The spatial profile of the amplified beam showing the smoothing.

Summary:

The experimental details of KrF oscillator –amplifier configuration is described in this report. The beam from the Compex KrF laser is sliced using a Pockels cell and passed through the LPX amplifier. 5 ns pulses with a stable energy of 60 mJ are obtained after amplification. More energy can be extracted from the amplifier, but with a distortion in the amplifier temporal profile. The amplified laser pulse also showed dramatic improvement in the spatial profile.