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PULSE CHARACTERIZATION FOR THE LONG
PATH LASER AT LLL

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MASTER

PULSE CHARACTERIZATION FOR THE LONG PATH LASER AT LLL^{*}

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Abstract -- Characteristics of the pulse produced by the Laboratory's Long Path Laser are reported. The pulse was studied at the output of the oscillator, the rod-amplifier chain, and the multi-pass disk amplifier. Diagnostic instruments included a Laboratory-built 10-psec resolution streak camera and a high resolution 3.4-m Ebert spectrograph. The oscillator and rod-amplifier chain outputs show strong, regular 26 psec intensity modulation produced by mode beating in the oscillator. The spectrum at each position is a regular series of lines whose wavelength separations correspond to the temporal structure observed with the streak camera. The modulation is smoothed by the disk amplifier and the spectrum is distorted and broadened. Time-resolved spectra were recorded at the output of the rod chain and the disk amplifier. Pronounced spectral differences observed at these two positions correspond to the intensity modulation smoothing observed with the streak camera after nine passes through the disk amplifier.

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1. Introduction

Experimental investigation of laser-produced plasmas in our laboratory has revealed

- production of neutrons and "hard" x rays [1] when pulses longer than 2 nsec are used, and the absence of such signals when even more energetic, shorter pulses were used.
- enhanced light reflection (3 to 4 times) and apparent production of a hard component of the x-ray spectrum from the plasma when the spectrum of the laser was changed only slightly.

To further investigate these features we have studied the details of the pulse produced by the Long Path Laser at LLL. The parameters studied and discussed here are the temporal behavior of the pulse to a resolution of 10 psec and the simultaneous spectral content of the pulse. The former was examined by an ultrafast streak camera and the latter by a 0.06-Å resolution spectrograph.

II. The Long Path Laser System

The Long Path Laser used in these experiments has already been described in [1]. Briefly, it consists of an oscillator, a stretched-out chain of rod amplifiers, a multi-pass disk amplifier, and a target and diagnostic area (Fig. 1). Both rods and disks are made of glass doped with 3 wt% neodymium. All alignment is done with a CW Nd:YAG laser.

The Nd:glass oscillator (Fig. 2) uses 60-cm-radius concave mirrors in a 2-m cavity which is Q-switched by a Pockels cell [2]. A second spark gap triggered Pockels cell in the cavity subsequently dumps the cavity. Two outside Pockels cells then gate the resulting pulse down to a submillijoule

pulse of controllable width (150 to 1.5 ns). A Nd:YAG oscillator that produces nearly transform-limited pulses was also used. Outputs from the oscillators have been used both as single and as double pulses, the latter with variable separation and relative amplitudes (nominally 3 ns apart and of equal amplitude).

The amplifier chain consists of seven 13-mm and three 25-mm diameter rods, each apertured to 3/4 of the diameter. The chain length is 135 m. Hot spots generated in the pulse cross-section are smoothed out by diffraction before the pulse is amplified again. Moreover, amplified spontaneous emission is greatly reduced. Beam expanders are not used because the natural divergence of 200 μ rad will fill the rod cross sections over the length of the chain. This aids in reducing possible damage caused by amplified pulses reflected from the target. In addition, two Faraday rotators are located between the small and large aperture rods to further attenuate reflected pulses. The output energy of the chain can be controlled from 0.5 to 15 J (1.5 ns).

The disk amplifier has sixteen disks, 14 cm in diameter and 2.5 cm thick mounted in a row at Brewsters' angle. This geometry produces an elliptical cross-section of ≈ 4 cm². The disks are pumped from both sides by 100 vertically mounted flash lamps with a maximum energy of 360 kJ delivered in 1 ms. The small signal gain of the disk amplifier has been measured to be as high as four to six but is usually between three and four. With a stored energy of over 1000 J, it was deemed practical to make numerous passes through the head so as to extract as much energy as possible. After passing through the amplifier, the pulse travels 55 m through a helium filled pipe. It is then deflected horizontally or vertically one or two beam diameters by a right angle prism, and is finally redirected back to the amplifier by another prism. There is an

array of eight such prisms at each end of the disk amplifier. In this manner, a beam that is almost the same size as the disk aperture can conveniently make one, five, or nine passes through the amplifier, at slightly different angles, before being extracted for use on a target. The net gain per pass is not that quoted above because the natural divergence causes the beam to overfill the disk aperture. Multiple pass gains of fifty for low input and output energies are normally obtained. In traveling as much as one-half mile, the beam becomes quite bright, typically with a beam divergence of 50 μ rad. This performance is possible if the disk head has been allowed to cool as much as 30 min between shots to assure temperature uniformity.

III. Streak Camera

The ultrafast streak camera used for the laser diagnostics reported here was constructed in our laboratory from commercially available components. Figure 3 is a schematic diagram of the camera. The basic design is similar to other reported ultrafast streak cameras [3-5]. A 25- μ m $\times$ 0.95-cm slit is focused ($\sim$ 1:1) by an f/1.1 lens onto the S-1 photocathode of an RCA C7343SAG* gated image tube (P-11 phosphor, fiber optic output). A three-stage, magnetically focused image intensifier, nominal radiant power gain of 10^5 , is optically coupled ($\sim$ 1:1) with an f/2.5 lens to the image tube phosphor. The intensifier screen is photographed (1:0.5) with a standard f/1.3 oscilloscope camera and ASA 3000 Polaroid or Royal-X Pan film.

We trigger and synchronize the camera to the optical event by using direct optically-triggered avalanche transistor circuits [6]. This technique

*Reference to a company or product name does not imply approval or recommendation of the product by the University of California or the U.S. Atomic Energy Commission to the exclusion of others that may be suitable.

provides a sensitive, low jitter (measured to be <100 psec) means of generating the image tube gating and deflection voltages.

The streak speed has been measured by photographing a train of pulses, of known separation, produced by an etalon at the output of a mode-locked Nd-glass oscillator. Image position as a function of time is shown for two different streak speeds in Fig. 4. The faster streak rate, 50 psec/mm at the film plane (about 30 psec/mm on the streak tube phosphor), was used to obtain the data reported in this paper. The limiting spatial resolution of the camera was measured by streaking the elements of a resolution chart illuminated by a 2-ns 1.06- μ m laser pulse. Figure 5a is the photograph obtained and Fig. 5b is the density trace across the streak. The limiting resolution is ~ 0.25 mm. We have photographed a mode-locked Nd-glass oscillator pulse whose width (12 psec) was measured by the two-photon fluorescence technique. Comparison of these data yields an electron transit time dispersion of 7 psec for the camera, in agreement with earlier reported measurement with the same type of streak tube [5]. Overall streak camera time resolution is therefore 10 psec. The characteristics of the camera are summarized in Table I.

IV. Spectroscopy

Two spectrographs were used to study the laser spectrum. A 3.4-m Jarrell-Ash Ebert spectrograph was used at position A (Fig. 1) to observe both the rod amplifier chain spectrum and that of the entire laser. Steak spectra were also taken with this instrument. A 0.9-m spectrograph was used at position B to observe the rod amplifier chain spectra before the radiation passed through the glass disk amplifier. This instrument was constructed here

for spectroscopy of 1.06- μ m lasers. The optical arrangement of this spectrograph is shown in Fig. 6. With these two instruments we can detect changes in the spectrum of the rod amplifier chain output caused by passing the radiation through an active or a passive glass disk amplifier.

The characteristics of the two spectrographs are given in Table II. Because of the energy variation delivered to the 3.4-m spectrograph (0.1 to 100 J) we used a series of mirrors and beam splitters to direct radiation less than 100 mJ to the slit. A condensing telescope (5 to 1) was used at times with the 3.4-m instrument to increase the energy at the slit. In all cases, slit diffraction was used to fill the optics of the spectrographs. Both instruments had Number 87 Kodak Wratten Filters at the slit to block radiation below 7400 Å. A CW:Nd YAG laser ($\lambda = 1.06415 \mu\text{m}$) was used as a reference line from which wavelengths could be determined. The dispersions were calculated from ultraviolet and visible lines in mercury or the 1.08- μ m lines from a HeNe laser.

A. Time-Integrated Spectroscopy Instrumentation

Eastman Kodak I-Z spectroscopic plates were used to record time-integrated single-pulse spectra from both instruments. The plates were hypersensitized before each day's use and developed at the end of the day. The reciprocity characteristics of the plates from millisecond to nanosecond exposures are not known, so energy measurements were not made from the film. Linewidths and positions of the spectra were obtained from densitometer traces produced by an Ansco Model 4 automatic recording microdensitometer.

B. Time-Resolved Spectroscopy Instrumentation

The 3.4-m spectrograph was used to obtain ultrafast time-resolved spectra by placing the horizontal slit of the 10-psec streak camera in the position normally occupied by a spectroscopic plate. Since the streak camera slit was 9.5 mm long and the spectrograph was used in first order, 46.3 Å wide spectra could be observed for each laser shot. To observe different areas of the spectrum, the grating was rotated.

V. Measurements and Results

A. Streak Camera Data

The ultrafast streak camera was used to photograph the intensity profile of the pulse at three positions in the laser: at the oscillator, at the output of the rod amplifier chain, and at the output after nine passes through the disk amplifier. The measurements at the last two positions were made with the camera set up at the end of the disk amplifier (A in Fig. 1). To measure the pulse from the rod chain, the first turning prism was removed from the disk system so that the beam made one pass through the unpumped disk head to reach the camera (or the spectrograph). Figure 7 is a scope trace of a fast photodiode signal of the 2-ns oscillator pulse. Figures 8, 9, 10 are the streak camera photographs of the pulse at the three positions in the laser. The oscillator and rod amplifier chain output pulses (Figs. 8 and 9) are nearly indistinguishable. They are characterized by regular deep 28-psec intensity modulation throughout the 2 ns pulse envelope. A weaker, approximately 250-psec modulation is also evident. After nine passes through the disk amplifier, however, the intensity modulation has been smoothed out except in the low intensity leading and tailing portions of the pulse (Figs. 10 a, b, c).

B. Time-Integrated Spectra

Figure 11 shows the spectral output of the glass rod amplifier chain recorded by the 3.4-m spectrograph through a passive disk amplifier. Energies of 0.1 to 1.2 J were produced by the laser. An enlargement of the spectrum (Fig. 11b) reveals line structure within the "lines" seen in Fig. 11a. Changes in the relative intensities of the individual lines were noted from pulse to pulse while the line and group separations remained fixed. The observable width of the spectrum varied with laser energy as one would expect from changes in the laser intensity alone.

The spectra of Fig. 12 are of the Long Path Laser output from the active nine pass disk amplifier. Energies in these pulses ranged from 30 to 60 J. Both the group and line structures seen in the glass rod amplifier chain spectra are clearly visible in Fig. 12a. New structure between the groups and in the wings of the spectrum (Fig. 12b) is observed in addition to considerable broadening. Some of the new structure between the groups of the glass rod spectrum has spacing equal to that of the lines in the groups. The new wing structure does not appear to be regular. Apparent curvature of the lines results from unequal intensity of some lines along the length of the slit (4 mm). We do not know the cause of this spatial variation of line intensity. Table III summarizes the spectral data for the Long Path Laser. Because strong exposures on photographic plates affected adjacent exposures, a full width at half maximum (FWHM) intensity measurement could not be made from the present data. For that reason, the width of the spectrum containing 99% of the photographic density was measured as an indication of spectral width. Given error bounds are errors of the mean obtained by dividing the standard deviation by the square root of the number of data points.

Spectra of the oscillator taken with the 0.9-m spectrograph show that the origin of the spectral lines and groups of lines is in the oscillator. The Pockels cells in the cavity (constructed as shown in the inset in Fig. 2) can act as etalons. The Q-switch Pockels cell was disassembled to obtain the dimensions shown in the figure. The relation for wavelength maxima produced by an etalon is $\delta\lambda = (\lambda^2/2nd \cos\theta)$ where λ is the wavelength, n the index of refraction, d the separation of etalon surfaces, and θ the angle of incidence ($\sim 0^\circ$). Using this relation, we find $\delta\lambda_1 = 1.23 \text{ \AA}$ for an etalon formed by an end window ($1.20 \pm 0.08 \text{ \AA}$ was the observed group separation) and $\delta\lambda_2 = 0.139 \text{ \AA}$ for an etalon formed by the inner surfaces of the windows ($0.142 \pm 0.001 \text{ \AA}$ was observed for the line separations). Line groupings formed by an etalon composed of the inner surfaces of the windows and KD*P crystal ($\delta\lambda = 3.9 \text{ \AA}$) were not observed.

Although the calculated and observed values of wavelength separations are not in exact agreement, we feel that the origin of the spectral lines and groups is in the two cavity Pockels cells. The difference between observed and calculated values are within the errors made if one assumes that both etalons are identical and are placed within the cavity with $\theta = 0$.

C. Time-Resolved Spectra

Figures 13a and 13b show typical time-resolved spectra (streak spectra) taken during the early and late portions of pulses from the rod amplifier chain. One to two J were produced by the laser while streak spectra were taken. The groups of lines were observed with the streak camera-spectrograph combination in first order ($\sim 1 \text{ \AA}$ combined resolution) because the second order grating spectrum was too weak for the streak camera to detect. Note that the

intensity profile is smooth, i.e., the 18-psec and 250-psec structures are not present. Simultaneous time integrated spectra taken by the 0.9-m spectrograph and the corresponding streak spectrum are shown in Fig. 14.

By knowing both the time and frequency (wavelength) character of the pulses from the rod amplifier chain, we can compare the observed wavelengths and pulse modulation periods. Using the expression for the wavelength separation, $\delta\lambda$, produced by an etalon, and identifying λ^2/c with the temporal separation, δt , of the subpulses (modulation), one obtains $\delta\lambda\delta t = \lambda^2/c$ or $\delta\lambda\delta t = 37.5 \text{ psec} - \text{\AA}$ at $1.06 \text{ }\mu\text{m}$. The observed $0.14 \text{ }\text{\AA}$ separation results in $\delta t = 268 \text{ psec}$ while the $1.2 \text{ }\text{\AA}$ spectral separation gives a 31-psec subpulse separation. These values correspond to the periods of the temporal structure obtained from the streak camera. We also note the intensity modulations of the pulse, in time and wavelength, have the same relationship, i.e., $0.14 \text{ }\text{\AA}$ and 268-psec modulation are shallow while $1.2 \text{ }\text{\AA}$ and 31-psec modulations are deep. Thus, the temporal and spectral modulations arise from the oscillator cavity Pockel cells acting as etalons, and correspond to the 3.15-mm and 25.5-mm etalon dimensions shown in the inset of Fig. 2.

A time-resolved spectrum of the Long Path Laser with active nine pass disk amplifier is shown in Fig. 15. The pulse energy was 41 J on this shot. One immediately notices this spectrum is radically different from the rod amplifier chain spectrum.

The detection system is not free of instrumental effects, however. The grating degrades the temporal resolution of the system by time mixing the wavefronts of the pulse. This time mixing of a wavefront has been calculated for the 3.4-m spectrograph to be 317 psec according to the formula $N\lambda/c$, where N is the number of grooves in the grating. The complex character of the

spectrum in Fig. 15 is the result of this instrumental time smearing impressed on the rapidly varying spectral character of the pulse. No other instrumental effects are known that could degrade or confuse the temporal character of the streak spectra obtained by our instruments. Because this instrumental effect was present for all streak spectra measurements and the temporal modulations of the spectral lines appear only in the disk amplifier spectra, we cannot conclude the observed spectra are a result of instrumental effects alone. These results suggest self phase modulation in the disk amplifier associated with the 28-psec pulse structure identified at the input. Note the spectral lines beginning to reappear in the low intensity tail of the pulse (top of the picture in Fig. 15).

VI. Conclusion

The results of target interaction and plasma heating experiments with the LLJ Long Path Laser have been reported previously [1,7]. The measurements presented here more thoroughly characterize the laser pulses with which the target experiments were done. This knowledge is vital for an accurate description of the processes involved in the energy transfer to the plasma as well as for an understanding of the operation of the laser itself. The appearance, disappearance, and reappearance of the picosecond time scale intensity modulation during the 2-ns pulse envelope and the large modulated spectrum introduce added complexity to the laser-plasma interaction. Although there are detailed features of the pulse amplification by our disk amplifier which are not yet fully understood, the basic features of the intensity and spectral modulation are clearly displayed by the data presented here.

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TABLE 1
 Characteristics of LLL 10-psec Streak Camera

Parameter	Value	Comment
Voltage on first grid (V)	2500	
Accelerating field (V/cm)	3500	
Sweep speed (10^9 cm/sec)		
Slow sweep	2	On screen of streak tube
Fast sweep	3	On screen of streak tube
Usable sweep length (mm)	40	On screen of streak tube
Spatial resolution (mm)	0.28	On screen of streak tube for fast sweep
Technical resolution ^a (psec)	6	For fast sweep
Electron transit time spread (psec)	7	See text
Slit-width time spread (psec)	1	For fast sweep
Overall camera resolution (psec)	~10	For fast sweep

^aTechnical resolution is the quotient of the spatial resolution and the sweep speed.

TABLE II
Spectrograph Characteristics

	5.4 Meter Short Spectrograph	0.9 Meter LLL Spectrograph	
Grating	596 lines/mm, 1.0 blaze	1200 lines/mm, 1.0 blaze	
Ruled width	152 mm	52 mm	
Focal length	5.355 m	0.937 m	
	<u>First Order</u>	<u>Second Order</u>	<u>First Order</u>
Reciprocal dispersion	4.86 Å/mm	2.17 Å/mm	4.42 Å/mm
Resolution at 1.06 μ	0.14 Å	0.058 Å	0.45 Å
f-number	51.5	54.6	22.8

TABLE III

Long Path Laser Spectral Characteristics

Average	Rod Amplifier	Nine Pass Disk Amplifier
Number of groups	70	115
Number of lines per group	three (ranged from 1 to 6)	3
Total lines	210	345
Group separation	$1.20 \pm 0.08 \text{ \AA}$	$1.20 \pm 0.02 \text{ \AA}$
Line separation	$0.142 \pm 0.001 \text{ \AA}$	$0.136 \pm 0.002 \text{ \AA}$
Line widths	$0.078 \pm 0.002 \text{ \AA}$ (some at resolution limit)	$0.101 \pm 0.003 \text{ \AA}$ (some at resolution limit)
Width of 99% of plate density	$64 \text{ \AA}$	$112 \text{ \AA}$
Ratio of above width to center wavelength	0.006	0.011

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Coleman - Fig. 1

Coleman - Fig. 2

Coleman - Fig. 3

Coleman - Fig. 4

Coleman - Fig. 5a

Coleman - Fig. 5b

Coleman - Fig. 6

Coleman - Fig. 7

Coleman - Fig. 9

T
↑

┌
└

100 psec

100 psec

Coleman - Fig. 10c

10 Å

Coleman - Fig. 11a

10 Å

10 Å

Coleman - Fig. 12a

Coleman - Fig. 12b

46 Å

T
↑

100 psec

46 Å

100 psec

Coleman - Fig. 14

46 Å

T

100 psec