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TITLE: THE LOS ALAMOS BRIGHT SOURCES: REVIEW OF THE PHYSICS AND THE DIAGNOSTIC TECHNOLOGY

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INVITED PAPER

The Los Alamos Bright Sources: Review of the physics and the diagnostic technology

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ABSTRACT

The investigation of many interesting physical phenomena in nature requires the generation of high-energy-density fields. To produce energy densities exceeding 10^7 J cm^{-3} requires focusing a very powerful, very bright, short pulse laser. This talk will present a review of the physics that will be investigated with one such laser system, will describe the laser used, will describe the laser diagnostics, and will describe the physics diagnostics. The talk will emphasize the areas of research that will help the diagnostics of different aspects of these bright sources, and their interactions, especially the diagnostics of hot small volumes in picosecond time scales.

2. THE LASER SYSTEMS

2.1 Overview

The Los Alamos Bright Sources (LABS-I and LABS-II)[1,2] are laser facilities that produce well diagnosed sub-picosecond laser pulses using excimer laser technology. Before a recent upgrade, LABS-I operated at the 248 nm KrF wavelength producing 25 mJ pulses at 3 Hz with pulse lengths of 0.7 psec. LABS-I pulses have been focused using f/1.7 optics to an irradiance of 5×10^{17} W/cm^2. After a recent upgrade LABS-I runs at 5 Hz with pulse lengths of .7 psec and energies up to 35 mJ. LABS-II operates at the 308 nm XeCl wavelength producing ~250 mJ pulses at 1 Hz with pulse lengths of 335 fsec focusable, using f/1 optics, to irradiances exceeding 10^{20} W/cm^2.

2.2 LABS-I

The small aperture KrF system (LABS-I) consists of a "front-end" which produces 248 nm seed pulses, followed by two KrF amplifiers. The seed-pulse generation scheme is shown in Figure 1. The output pulse train from a mode-locked Nd:YAG laser is split into two beams. One beam is frequency doubled in KTP and used to synchronously pump a mode-locked dye laser with separate gain and absorber jets. A pulse from the remaining train is selected at a repetition rate of 5 Hz and amplified by a regenerative amplifier up to the 40 mJ level. This 100 ps pulse is frequency doubled in KD*P with 50% conversion efficiency and used to longitudinally pump a three stage dye amplifier seeded by the 650 fsec, 648 nm pulses from the dye laser. The amplified pulse energy is 1.5 mJ and the beam quality is better than two times diffraction-limited. We observe no temporal broadening of the 650 fsec pulses through the amplifier. Advantages of this synchronous amplification scheme include low amplified spontaneous emission (ASE), nearly diffraction-limited amplified beam quality, elimination of timing jitter between the pump pulses and the seed pulses to the amplifier and the availability of the unconverted 100 ps, 1064 nm pulses for mixing purposes. The amplified 648 nm pulses are then frequency doubled in a 2 mm long BBO crystal. The resulting pulses at 324 nm are finally sum-frequency mixed with unconverted 1064 nm pulses from the regenerative amplifier in a second 2 mm BBO crystal to produce 0.1 mJ subpicosecond seed pulses at 248 nm. This scheme, based on synchronous amplification, produces one to two orders of magnitude more energy in the 248 nm subpicosecond seed pulse than previously reported in other systems[2-6].

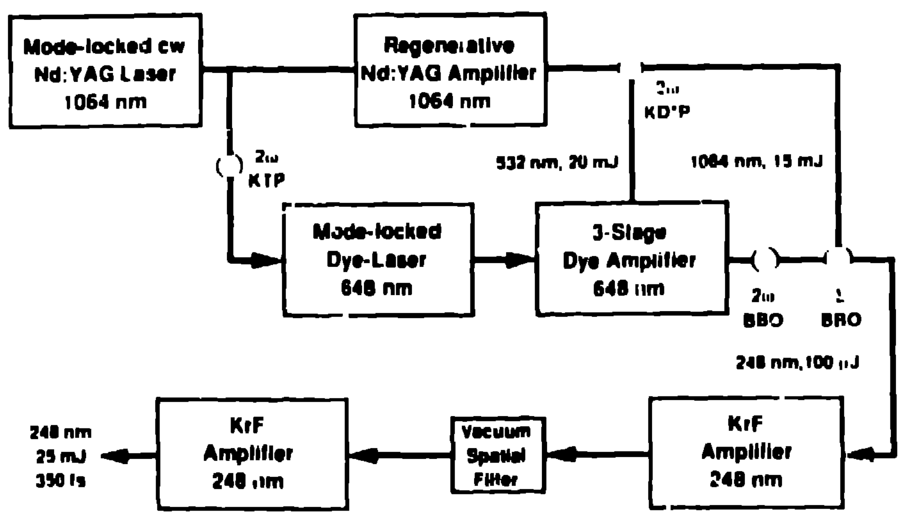

Fig. 1. Seed pulse generation scheme for our high-brightness KrF laser system.

These pulses are then amplified by two Lambda Physik EMG 200 Series KrF amplifiers, separated by a vacuum spatial filter to suppress ASE and to improve beam quality. The output beam diameter is 25 mm and the final output energy is 25 mJ with < 0.5 mJ ASE. The pulsewidth, measured using two-photon ionization in NO, is 700 fsec.

2.3 LABS-II

The large aperture XeCl system is sketched in Figure 2. Pulses of 175 fsec duration at 616 nm are initially generated in a linear cavity, dispersion compensated dye laser (Kiton Red DODCI) that is synchronously pumped by the frequency doubled output of a cw mode locked Nd:YAG laser. A synchronous amplification scheme, similar to that described for the KrF system, is used to amplify these pulses to the 0.20 mJ level. The amplified 616 nm pulses are then frequency doubled in a BBO crystal. Preamplification of these 0.030 mJ pulses to the 3 mJ level is accomplished with a single small aperture XeCl discharge laser. The pulsewidth at this stage is 240 fsec. The beam is then expanded in a vacuum spatial filter before entering the final amplifier.

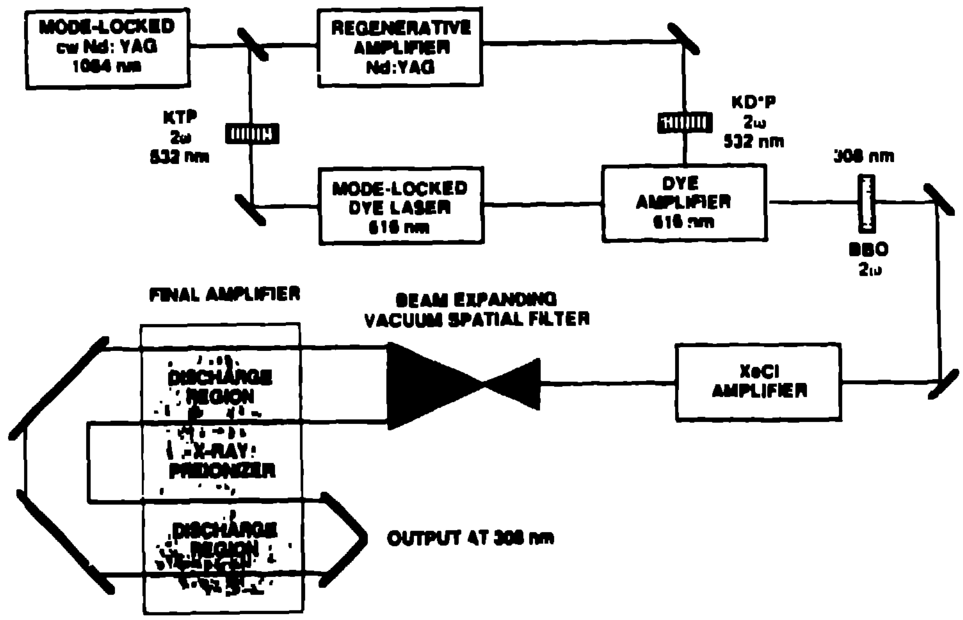

Fig. 2. Large-aperture, high-brightness XeCl laser system.

The 10x10 cm^2 aperture final amplifier consists of two independently pumped discharge gain regions, each sharing a common 135 keV x-ray preionizer. The output energy from this amplifier is 250 mJ in the 335 fsec pulse. The wavefront distortion at 632.8 nm is less than one-twentieth of a wave over 80% of the aperture.

3. DIAGNOSTICS OF THE LASER BEAMS

The diagnostics requirement of the bright source laser beams are unique due to their short pulse length and low repetition rate. Typical short pulse length lasers run at few tens of MHz where autocorrelation and sampling techniques are feasible. Such techniques are applied to diagnose the front end pulses of our laser systems. However, at the output of the amplifiers, new sampling techniques must be used to measure the laser pulse length, laser irradiance and phase front distortions. Since these lasers are typically used at their best focus, one must decide the validity and usefulness of measuring these properties before focus. Propagation in air will cause distortion and phase front modulation due to instabilities at the high irradiance of the unfocused beam.

Let us take as an example the focusability of the laser beam. One may use a shearing interferometer to measure the incident irradiance and phase distributions of the beam (see figure 3), then using the measured properties of the focusing elements calculate the irradiance distribution at focus. However such measurements are fraught with difficulties. The laser pulse lengths used are shorter than 700 fsec. Thus path lengths in the interferometer must be less than 210 micrometers for interference to occur.[8] The fringes in Figure 3 were taken with a wedged air-spaced interferometer of average separation 50 micrometers. Two feature are of interest: first, the wave front distortion across the beam is less than λ/5 while, second, the intensity distribution is not uniform. The laser beam when focused by an f/6.2 on-axis parabolic reflector and observed with an numerical aperture 0.4 transmitting microscope shows a reasonable spot (see Figure 4). The first zero of the diffraction pattern occurs at a diameter of ~10 μm. The far field pattern from a uniformly illuminated diffraction limited optic of the same numerical aperture has a diameter 9.5 μm. The figure is overexposed in order to show the intensity in the outer diffraction rings. The phase distortion causes a nonsymmetric modulation of the ring intensity distribution.

Fig. 3. Shear interferogram of the output beam of our early LABS-I KrF beam. The laser pulse length was 0.7 ps, the beam diameter was 2.5 cm, and the energy was 25 mJ.

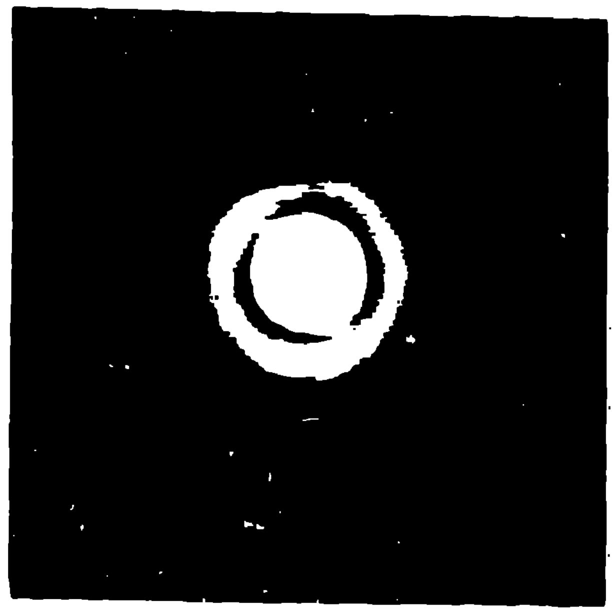

Fig. 4. A microscope photograph of the interference pattern at the focus of the f/2.7 parabolic mirror. The first zero has a diameter of 10 μm.

The other parameter required to determine the irradiance is the pulse length. The pulse length is too short to measure using fast photodiodes, and is almost too short for streak cameras. The fastest streak camera we have has a temporal resolution of 1.5 psec. The resolution of the streak camera was determined using the red beam from the mode locked front end of LABS-I. Using standard autocorrelation techniques the pulse width at 648 nm was 650 fsec FWHM. When the UV beam at 248 nm was used, the streak camera measurement yielded a deconvolved single shot pulse length of 1.1 psec. Another method of measuring the shorter of the pulse length and the coherence time was developed in References 8 and 9. The method uses diffraction from two objects placed in the beam and works best at pulse lengths shorter than the separation between the sampling objects. In Figure 3 each fringe corresponds to a time difference of 4×10^{-16} sec, thus the figure sampling time was 10^{-15} seconds. By increasing the fringe density one should be able to increase the window to few picoseconds. Figure 5, generated by interference from two slits,[9] shows a time of 1.1 psec as well

Another optical method for measuring the single shot pulse length of visible light is the measurement of the wavelength spectrum of the pulse. Using the complementarity of time and frequency, the spatial spectrum can be obtained by Fourier transforming the frequency spectrum. For bandwidth limited pulses the uncertainty principle gives a special relationship relating the spectral and temporal widths $\Delta_\nu \Delta_t = \pi$. A 600 fsec FWHM bandwidth-limited pulse has a spectral width FWHM of 4.4 angstroms at 5000 angstroms, a width that is quite easily resolved in most spectrometers. Other techniques for measuring the laser pulse width are two-photon ionization[10] of, and two photon fluorescence[11] from, a suitable gas using counter propagating laser beams. The products from the interaction volume are imaged and each point in the spatial image is correlated with a point in time. Both of these techniques require a mJ energy to work, but they can produce sub-picosecond resolutions.

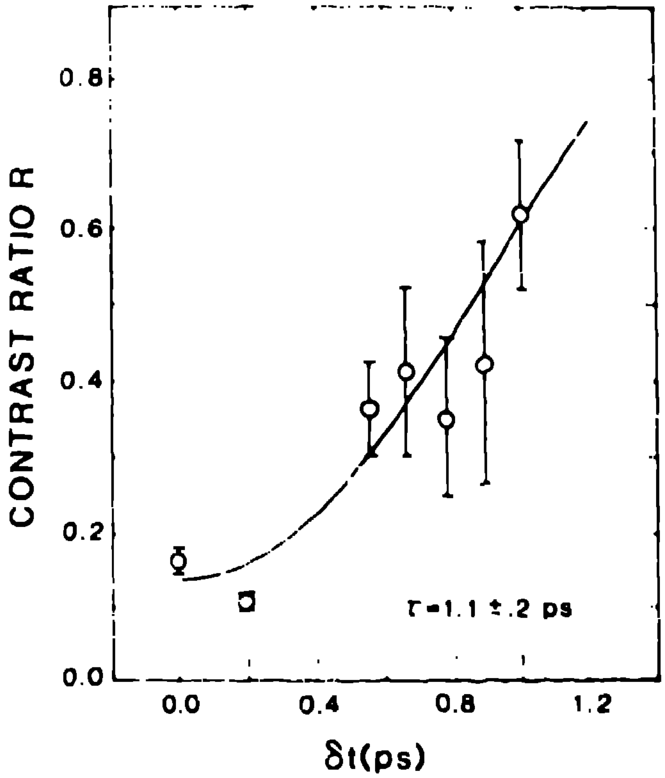

Fig. 5. A weighted least square fit of the contrast ratio of the interference pattern as a function of the delay between the two slits for our KrF laser system.

4. DIAGNOSTICS OF THE EXPERIMENTS

4.1 Overview

The bright sources are used to perform a variety of experiments. We concentrate, however, on the fundamentals of the interaction of the intense laser fields with free atoms and the mechanisms for absorption with solids. A main goal for the use of these "table top" lasers is to find a method to meet the stringent requirements for pumping an x ray laser. Our first studies, using the KrF laser, indicate that we can ionize a free atom to a highly charged state (e.g., Ne^{11+}), however, no simultaneous inner shell radiation was found. When irradiating a solid target, highly charged ions (e.g., Al^{+12}) are found, but now kilovolt radiation is produced in copious amounts. The diagnostics required to investigate the laser and the plasma properties produced by Bright Source I are formidable. Many of the processes have time scales much faster than can be resolved by available diagnostics equipment. With LABS-II, the diagnostic requirements will be even more severe. Techniques for single shot parameter measurements will have to be developed. While progress has been made in the visible region of the spectrum, similar efforts need to be made in the detection of and the characterization of subpicosecond x-ray pulses.

The various experiments require diagnostics on different time scales. We will discuss in what follows two experiments that require fast diagnostics, which shed light on the x-ray generation process.

4.2 Interaction with solid density Aluminum

One of the most interesting uses of the laser is to study the interaction of the high-irradiance pulses with a solid target. Investigation of the target state during the irradiance, and the absorption and conversion of the absorbed energy is of interest. In contrast with earlier work using fusion lasers, hot states of matter can be achieved with moderate energy,[12] provided the laser energy can be focused to small volumes in short time scales. Aluminum, for example, can be heated to an electron temperature greater than 500 eV in less than a picosecond. The resultant x-ray emission is efficient as well as fast. Conversion efficiency to x-ray radiation above 1 keV depends on target material but can exceed ~1%. Figure 6 shows a typical x-ray temporal history using an x-ray streak camera. The x-ray streak camera has a CsI photocathode and has a 20 psec instrument function. It is seen that the x-rays last for a time limited by the streak camera temporal resolution. The deconvolved spectrum, assuming gaussian response is less than 10 psec. However, examination of the rise time of the x-ray signal in the beryllium channel yields a 2 psec risetime. The channel transmits light in the soft x-ray region where the signal is expected to be longest. The streak record thus sets an upper limit on the x-ray radiation time, a period between 2 and 10 picoseconds. The x-rays are generated in a line spectrum. Most of the emitted x-rays result from the Helium-like resonance line at 1.59 keV (7.75 angstrom). The conversion efficiency to x-rays in that single line is 0.5% of the laser energy. The brightness of the x-ray line can be estimated by measuring the emission spot size. The x-ray emission was imaged using an x-ray pinhole camera with a 3 micrometer pinhole and a magnification of 15. The image diameter was less than 6 micrometer limited by the resolution of the pinhole camera. Combining these measurements gives a radiance of 10^{14} W/cm^2, one of the brightest x-ray sources made in the laboratory.

This emission is well suited to pumping of inner-shell x-ray lasers.[13] These lasers have upper state lifetime of few femtoseconds and require enormous pumping powers. Using LABS-II, an order of magnitude increase in the pumping power will be feasible. In order to use those x-rays efficiently we will have to diagnose the temporal evolution of the x-ray spectrum in more detail. For inner-shell lasers, travelling wave pumping is required to overcome laser lethargy and the finite lifetime of the upper laser level. A spatio-temporal history of the x-ray emission from a moving focus is required in order to couple the x-rays to the lasant material efficiently

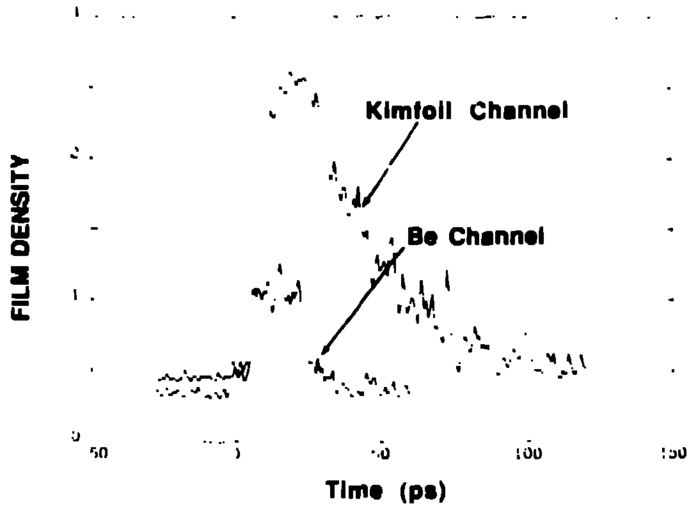

Fig. 6. Densitometered streak camera record of the 25 μm Be and the 270 gm cm^{-2} aluminized Kimfoil filtered channels. The Be channel responds to x-rays above a kilovolt energy. The Kimfoil responds between 200-284 eV x-ray radiation. The instrument broadening corresponds to about 20 psec.

4.3 Single atom x-ray generation

Another use of the laser is to generate x-rays and harmonics during the interaction of the laser with single atoms in the non-collisional regime. It was demonstrated in our laboratory that a single xenon atom can absorb a few hundred photons during a laser pulse. This multiphoton ionization absorption generated eleven times ionized Xenon.[14] One expects that characteristic inner shell radiation might be produced as well. The mechanism thus would have been an attractive method to achieve inner shell lasing at x-ray energies. An experiment was set up to look for these prompt x-rays from Xenon. The inner-shell radiation has a characteristic time of few tens of femtoseconds. While x-ray radiation was observed, none of the observed photons was prompt.[15] Temporal resolution played a significant part of the search for these prompt x-rays. In this particular experiment single photon counting techniques were used. However, careful attention to the details of establishing zero time fiducial (by using the results of the solid experiments for prompt x-ray generation), allowed us to discriminate against late photons, as shown in Figure 7. An upper limit was set on the probability of x-ray generation from Xenon, 5x10^{-5} per atom per laser shot. This study eliminated the possibility of using this scheme as a method for x-ray lasing, at least at irradiances less than 10^{17} W/cm^{2}.

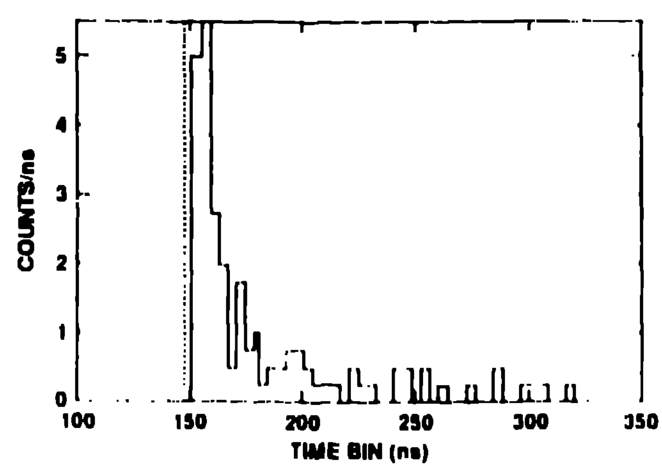

Fig. 7. A time of arrival histogram for x rays between 100-120 eV. The dashed line is the zero-tim fiducial where inner-shell radiation wou. ve occurred.

5. SUMMARY

We have discussed some of the diagnostics used on the Los Alamos Bright Source. Two sets of diagnostics are discussed. The first, to measure the quantities that characterize the laser irradiance on target. Due to the small size of the focal spot, less than 5 micrometer diameter, larger spatial resolution with reasonable dynamic range is required in order to characterize the focal volume in-situ. Due to the shortness of the laser pulse, newer pulse length diagnostics are required. The second set of diagnostics are used to quantify the interaction physics at high irradiation density and at x-ray wavelengths. The plasmas produced are hot, short lived, and of micron size dimensions. Many opportunities exist for inventing new techniques to diagnose those plasmas on a single shot basis.

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