UCRL-92248
PREPRINT
CONF-850310--85

Progress in Inertial Fusion at LLNL

Erik Storm

This paper was prepared for submittal to
6th ANS Topical Meeting on Technology of
Fusion Energy, San Francisco, CA
March 3-7, 1985.

April 15, 1985

Lawrence
Livermore
National
Laboratory

UCRL--92248

DE85 010931

PROGRESS IN INERTIAL FUSION AT LLNL*

ERIK STORM
Lawrence Livermore National Laboratory
P. O. Box 5508, L-481
Livermore, California 94550
(415) 422-0400

ABSTRACT

Experiments at LLNL using the 10 TW Novette laser have led to significantly increased understanding of laser/plasma coupling. Tests using 1.06 μm, 0.53 μm and 0.26 μm light have shown increased light absorption, increased efficiency of conversion to x-rays, and decreased production of suprathermal electrons as the wavelength of the incident light decreases. The data indicate that stimulated Raman scattering is the source of the excessive hot electrons and that the effect can be controlled by the proper selection of laser frequency and target material. The control of these effects has led to achievement of higher inertial fusion target compressions and to production of the first laboratory x-ray laser.

INTRODUCTION

The objectives of the LLNL Inertial Fusion Program are to understand, develop, and utilize the science and technology of the Inertial Confinement Fusion (ICF) concept for military applications in the near and long terms and in the long term as a candidate for a civilian power generation technology. Military applications benefits, in the form of weapons physics experiments, are already being realized with the laser facilities constructed for this program. However, the full realization of both the military applications and civilian potential of ICF will be reached with the attainment of well-diagnosed moderate-to-high gain ($\gtrsim$0.1 ton TNT equivalent *yield) thermonuclear performance of ICF* capsules. High gain conditions occur when 2 to 10 mg of DT fuel is compressed to densities exceeding 200 g/cm^3 and when the thermonuclear burn is initiated in a high ($\gtrsim$3 keV) temperature, controlled hot spot. To assemble the fuel in such a state, a precisely time-programmed pressure pulse exceeding 50 Mbar at peak, must be applied over 10 ns duration. Very little preheat of the fuel can be tolerated if efficient implosions are to occur. In order to achieve the $\gtrsim$50 Mbar pressures, the driver intensity must be $\gtrsim 10^{14}$ W/cm^2. Experiments at 2-10 TW on Argus and Shiva designed to achieve high compression and explore the laser plasma interaction conditions required for high gain performance, suffered from the deleterious preheat effects of the fast electrons generated at these intensities with 1.06 μm light. In some experiments, as much as 50% of the incident 1.06 μm laser light appeared as very energetic (10-100 keV) electrons which significantly compromised the quality and usefulness of the experiments. Theoretical work and some small scale experiments on Argus, and at other facilities around the world, indicated that converting the 1.06 μm light to the second (0.53 μm), third (0.35 μm) or fourth (0.26 μm) harmonic would drastically reduce the production of hot (fast) electrons.

LASER/TARGET COUPLING

During the past two years, our 10 TW Novette laser system provided as much frequency converted (0.53 μm) laser energy to targets as the entire 20-beam Shiva laser did at the fundamental frequency (1.06 μm). Utilizing up to 8.5 KJ (in a 1 ns pulse) of 0.53 μm wavelength light from Novette, (see Fig. 1) we studied short wavelength *laser-target interaction phenomena and* verified the positive scaling of this physics under these short wavelength, high energy, large plasma conditions (up to 1000 laser wavelengths in size). With targets irradiated at 0.53 and 0.26 μm, we saw reductions in the hot electron production of two to three orders of magnitude as compared to similar targets irradiated with the same energy at 1.06 μm while absorption and conversion of the incident laser light to soft x-rays

---

*Work performed under the auspices of the U. S. Department of Energy by Lawrence Livermore National Laboratory under contract No. W-7405-eng-48.

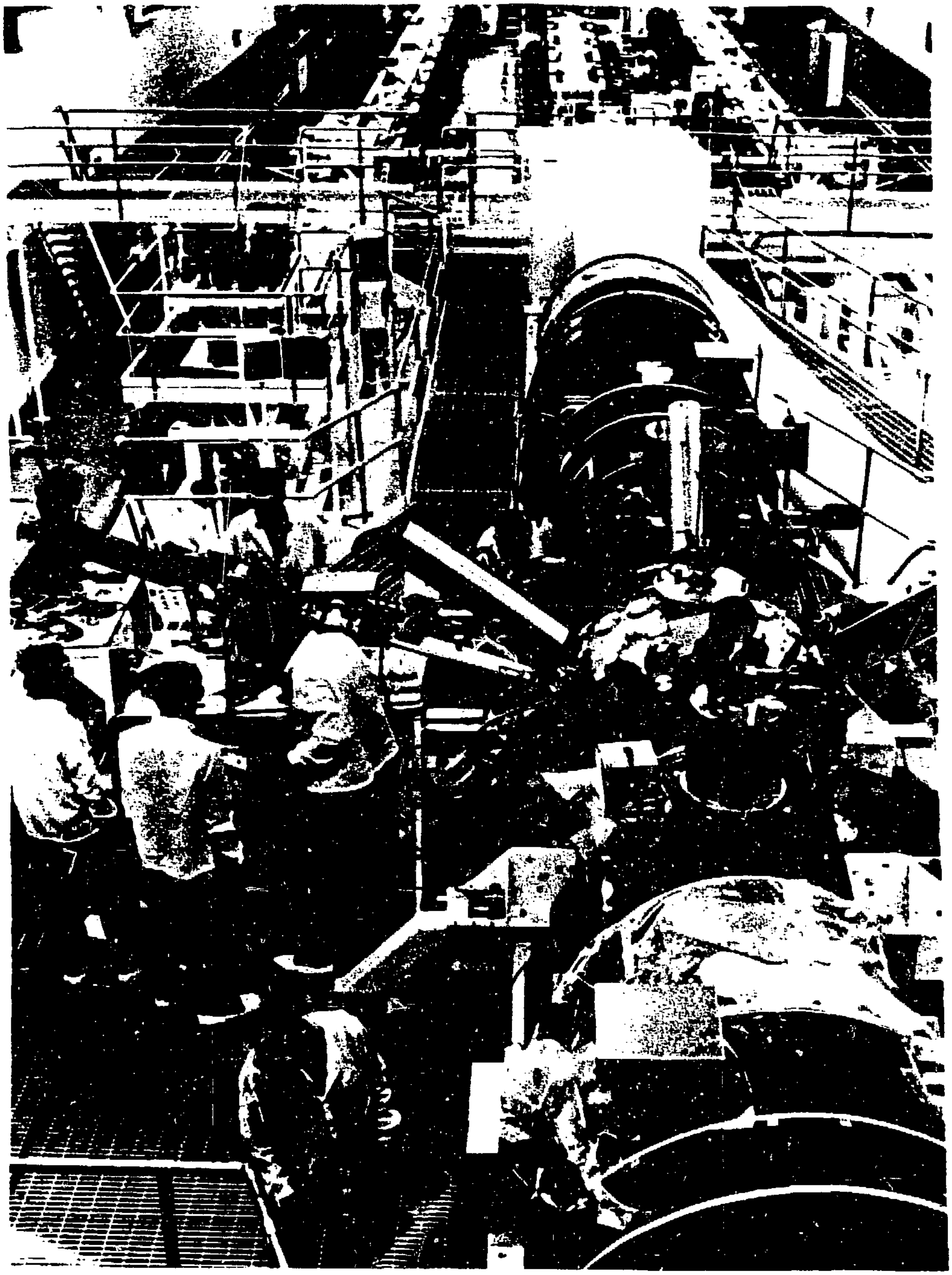


Fig. 1. The two-beam Novette laser performed experiments at 1.06 µm (18 kJ), 0.53 µm (8.5 kJ), and 0.26 µm (1.5 kJ).

increased (see Fig. 2). These experiments, as well as experiments on disks of different <Z>, have identified that Stimulated Raman Scattering (SRS) is the primary mechanism responsible for generating the hot electrons (see Fig. 3). A subset of these experiments also demonstrated that by varying the <Z> of the targets, the laser intensities and the laser wavelength, we could keep the laser plasma interaction conditions below the SRS threshold and hence keep the plasma collisional (see Fig. 4). These experiments and associated modeling indicates that laser plasma coupling in high gain inertial fusion target plasmas, typically 10^4 laser wavelengths in size, will also be collisionally dominated.

There are two laser-driven ICF techniques for generating the required pressures for compression and ignition: "direct drive," in which electrons transport the laser energy to the ablation surface, and "indirect drive," in which x rays transport the energy to the ablation surface. Critical issues that are determining the viability of both approaches are symmetry, stability, fuel preheat, and implosion efficiency. In the direct-drive

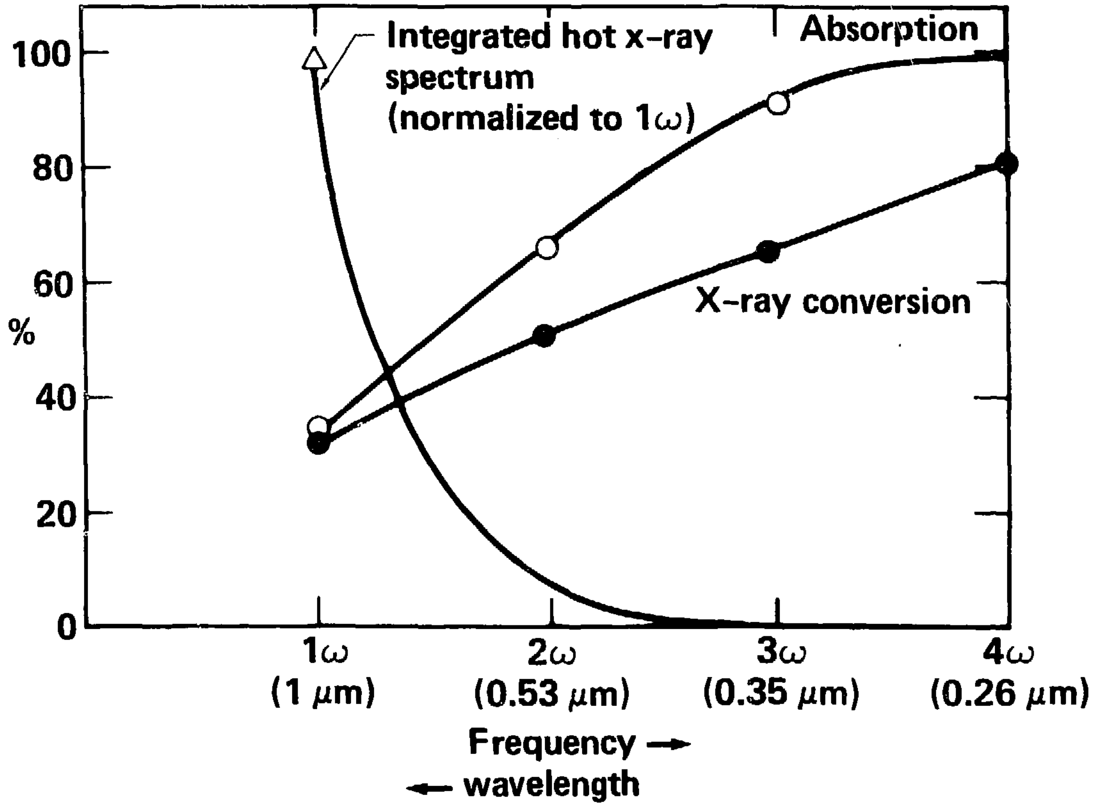


Fig. 2. Absorption and conversion of laser light incident on Au disk targets as a function of frequency. Intensity of incident light is 10^{14}-10^{16} W/cm^2.
Absorption is percent of incident light absorbed. X-ray conversion is percent of absorbed light. The integrated hot x-ray spectrium is a measure of the amount of energy contained in hot (fast) electrons. The curve is normalized to 100% at 1 ω.

approach, the laser driver energy is focused and absorbed at the surface of a spherical ablator surrounding the fuel container. Heating and subsequent mass ablation generates the pressure that drives the implosion. The pressure that can be generated depends strongly on the absorbed laser intensity, with theory and experiment showing,

$$P_{Ablation} \propto I^{0.5-0.6}.$$

In the indirect-drive approach to fusion, which is the principal focus of ICF research at Livermore, the incoming laser light is converted to thermal x rays contained in a high-atomic-number "hohlraum." The soft x rays in the hohlraum drive the target capsule. If submicrometer light is used efficient conversion of laser light into thermal x rays can occur. An advantage of this approach is that it can produce a highly symmetric implosion with a relatively poor laser focal distribution. It also does not require uniformly arrayed laser beams, an advantage for ICF reactor designs.

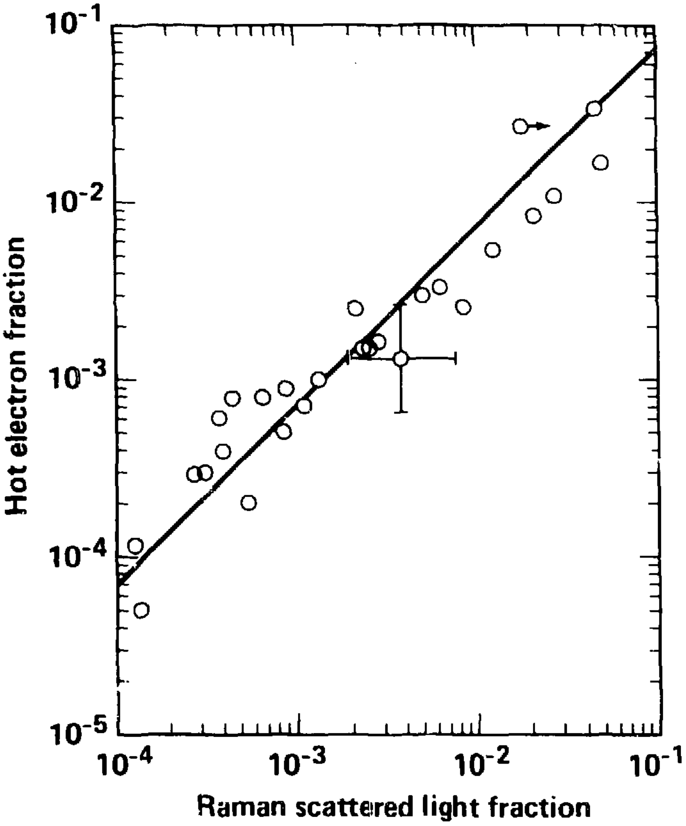


Fig. 3. The fraction of incident energy in hot electrons correlates well with the fraction of incident light that undergoes Raman scattering. The experiments were for 0.5-4.0 kJ, 1 ns pulses of 0.53 μm light incident on Au disk targets at intensities of 10^{14}-2 x 10^{16} W/cm^2.

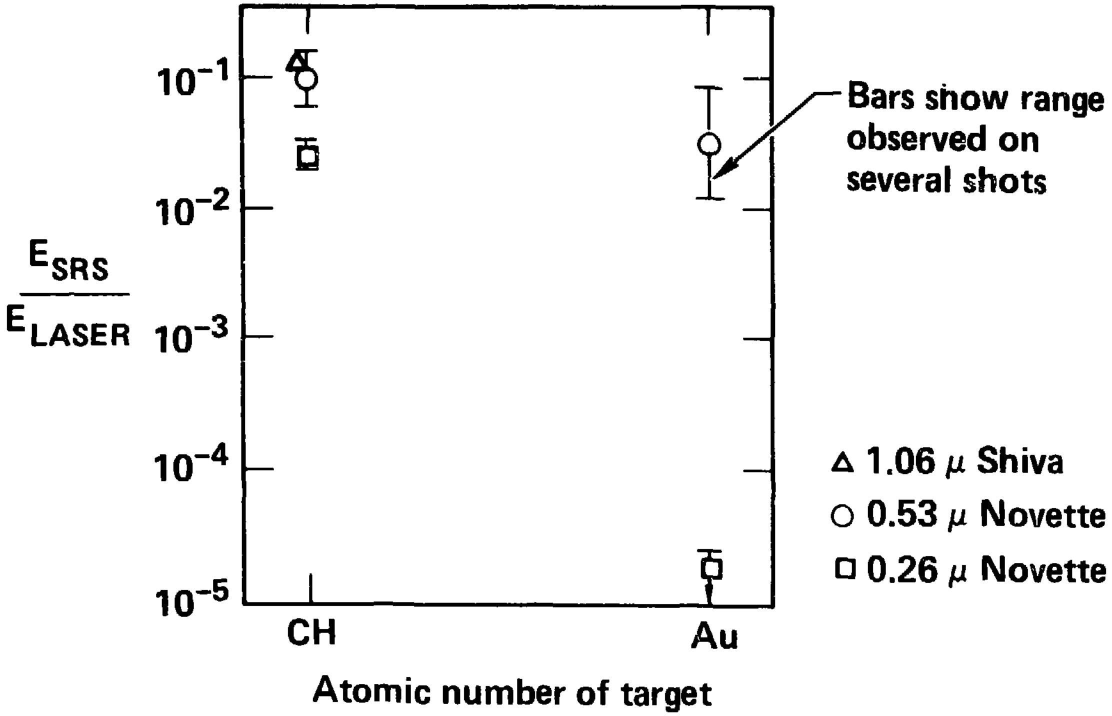


Fig. 4. Fraction of incident laser light undergoing stimulated Raman scattering (SRS) in disk targets of plastic and gold for three light wavelengths.

TARGET COMPRESSION

The laser-plasma coupling achieved on the LLNL Novette Laser, operating at 0.53 μm, represented a significant improvement from that achieved on the earlier LLNL Shiva 1.06 μm laser. We have taken advantage of this improved coupling and significantly reduced fast electron fraction to ablatively implode fusion capsules to substantially higher densities than were possible on Shiva for similar capsule designs. To measure the compression of the imploded target, our colleagues at LLNL measured the areal density (product of density and thickness, $\rho\Delta r$) of the compressed fuel container. The container is referred to as the capsule pusher because of its role in the compression processes. When the target is driven to high density, both the pusher areal density and the fuel density increase significantly. This is in contrast to strongly preheated targets, such as the "exploding pusher" targets first used in ICF demonstrations, in which the pusher areal density remains relatively unchanged. In our high-density implosions, 14 MeV neutrons are produced by the fusion of DT near the time of peak compression of the target. Activation of the pusher material by these neutrons is proportional to the pusher areal density at that time. We infer the fuel density by comparing the measured pusher activation with simple analytical models and with sophisticated hydrodynamic code calculations. As shown in Fig. 5, we measured increases in the pusher areal density over its initial value by factors as great as 70 when using 0.53-μm irradiation. This is a 3- to 4-fold greater compression of the pusher than in similar 1.06-μm experiments on Shiva. Although we do not measure the fuel density directly, these results imply compressed fuel densities in excess of 20 gm/cm^3 (and 10^{10} atm.).

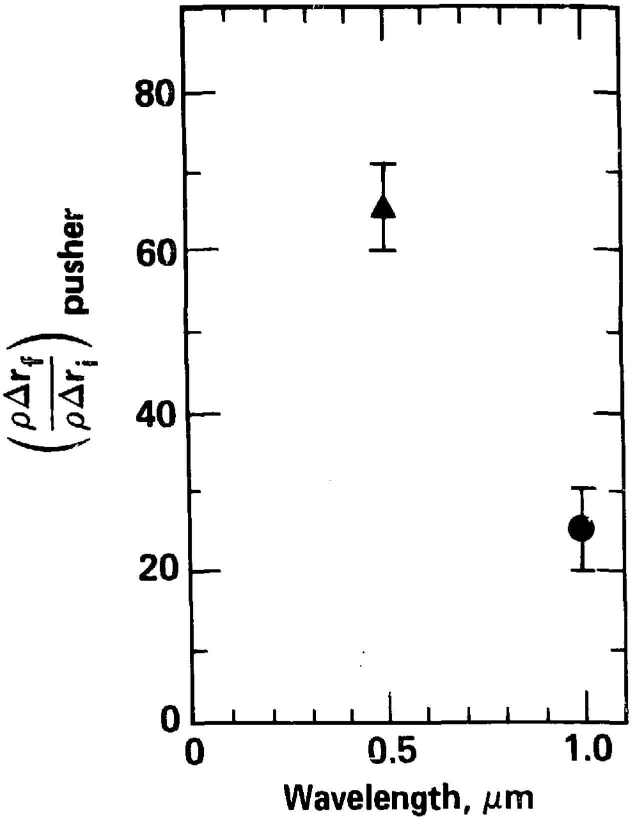
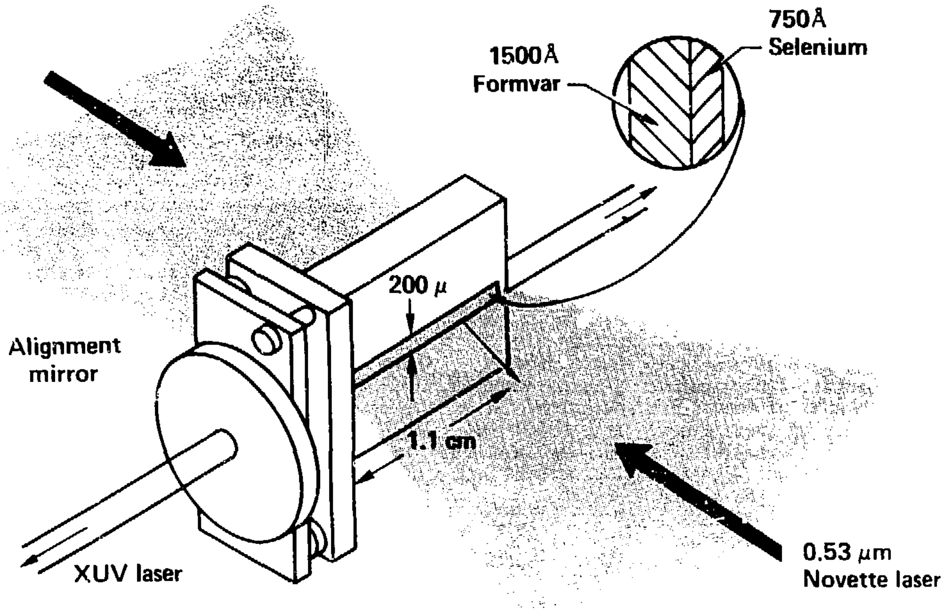


Fig. 5. Compression of the fuel pusher for light at 0.53 and 1.06 μm.

The Novette plasma coupling data and these compression results lead us to expect that by using temporally shaped 30 to 50 kJ of 0.35 μm light from Nova, we can ultimately compress DT fuel to the 200 g/cm^3 densities required for high gain target performance. Although we do not expect to observe high gain in Nova experiments (because the ρΔr of the targets will be too small to sustain propagating thermonuclear burn), obtaining the compressions needed in the Nova scaled targets will give us confidence in predicting the driver energy necessary (currently estimated at 1-10MJ) to obtain high gain. One of the more significant implications of the Novette experiments is that 0.3 μm to 0.5 μm may be a short enough wavelength for high gain target performance. We plan to resolve these issues with our recently completed 100 TW Nova laser system.

X-RAY LASERS

The elimination of the fast electron problem also allowed us to observe stimulated emission in the soft x-ray region. The experiments utilized a 2 TW, 450 ps pulse from the Novette laser to irradiate thin-foil selenium targets up to 2.2 cm long at a power density of 5 x 10^{13} W/cm^2 with 0.53-μm light (see Fig. 6). The capability to irradiate candidate x-ray laser targets over longer dimensions (>1 cm) and to couple the laser light to higher density plasmas than used in previous experiments was crucial in obtaining sufficient single-pass gain to make this unambiguous observation. Other important advances leading to these observations were in the areas of x-ray diagnostics, target fabrication, and modeling.



Design produces:

- : Nearly uniform N_e, T_e plasma
- : Dimension 0.015 × 0.015 × 1.1 cm
- : For a time period ~ 200 psec

Fig. 6. To produce losing at XUV wavelengths, selenium foils 750 Å thick are illuminated by opposing 0.53 μm line forcused beams. A "rod" of neon like Se^{+24} plasma 1 cm long and 150 μm in diameter is produced. Soft x-ray beams (59 and 60 eV) are produced by amplified spontaneous emission (ASE).

The technique used in these experiments for producing soft x-ray gain is the electron collisional excitation of neon-like ions. It has long been recognized that the large difference in the radiative decay rates of the $2p^53p$ and $2p^53s$ states in neon-like ions can lead to population inversion between these states in an optically thin plasma. With a sufficiently high pumping rate, calculations based on isoelectronic scaling of the neon-like configuration in higher-Z ions showed that gain at XUV and soft x-ray wavelengths was possible. The required pumping rates at sufficient electron density and over a sufficient length of active ions was achieved by bringing the two opposing Novette laser beams to a common line focus with a combination of cylindrical and spherical lenses. Uniform neon-like plasmas with the proper density conditions were generated using a so-called "exploding-foil" target. These targets, originally designed for the plasma physics studies mentioned earlier, are composed of thin foils of selenium (750 Å) on a thin Formvar backing (1500 Å) with a density-thickness product of about 4×10^{-5} g/cm^2. The foils explode because of the rapid heating and ablation of the entire target volume. Using a 20 ps time resolution holographic interferometer, scientists at KMS Fusion confirmed the expected density profile of the expanding thin-foil selenium plasmas. They demonstrated a transverse density scalelength

$$\left(\frac{1}{n}\frac{dn}{dx}\right)$$

of 100 μm at $n_e \approx 3 \times 10^{20}$ cm^{-3}, which was uniform enough to prevent refraction of 200-Å photons from the laser channel, 1 cm long and approximately 100 μm wide.

Large amplification of the neon-like $3p^53p$ - $3p^53s$ transitions in selenium (Se^{+24}) can be readily seen in Fig. 7(a), which shows the x-ray spectrum under typical gain conditions. The spectrometer that recorded this data observed the x-ray intensity along the plasma axis. The lines at 206 and 209 Å dominate the spectrum. The spectrum in Fig. 7(b) was recorded on the same shot as Fig. 7(a) with an instrument looking transverse to the plasma axis, but recording the total radiating plasma volume. The lines at 206 and 209 Å were not observed, presumably because they were not amplified in the short transverse direction. The time-resolved measurements shown in Fig. 7 were made with an absolutely calibrated spectrometer. They indicate a lower bound of 35 to 50 keV for the equivalent brightness temperature of these lines. This brightness temperature is consistent with x-ray gain and is not consistent with thermal processes associated with the plasma electron temperature of less than 1 keV or with the intensity of nearby lines, which are not amplified but have equivalent temperatures of about 0.1 keV. A small-signal gain coefficient of about 6 cm^{-1} was inferred for both lines by means of experiments in which the plasma length was varied from 0.1 to 1.2 cm (Fig. 8). Similar experiments with 29-times ionized yttrium produced equivalent brightness temperatures of about 10 keV at 154 Å, demonstrating isoelectronic scaling of the neon-like transitions to shorter wavelengths.

The peak output spectral brightness from this laser system is $6(10^{10})$ W $cm^{-2}Å^{-1}sr^{-1}$, which was obtained from a 2.2-cm-long plasma irradiated by laterally displacing two opposed 1.1 cm x 0.01 cm focused Novette beams to excite a 2.2-cm-long active region. The peak brightnesses from these small x-ray sources are 10^{10} to 10^{11} times greater than today's most powerful x-ray generators and synchroton sources. They are, of course, presently one-shot, short-pulse devices that need a great deal more effort before they become useful laboratory x-ray sources.

CONCLUSIONS

Experiments using the harmonically converted Nd:glass laser Novette at 0.53 and 0.26 µm demonstrated satisfactory coupling of laser light to fusion and x-ray laser targets. The coupling of short-wavelength laser light to these plasmas is now well understood and is primarily collisional in nature, in contrast to previous experiments at 1.06 µm and 10 µm where the coupling was collective. The coupling improvements led directly to the demonstration of higher-density, ablative implosions of DT fusion fuel and to the first unambiguous observation of amplified spontaneous emission in the soft x-ray region. The Nova laser, providing 30-

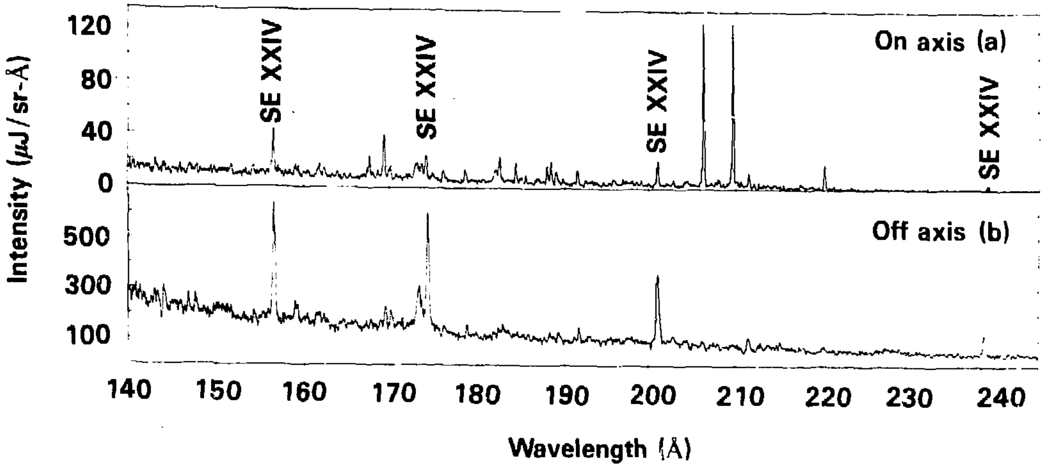


Fig. 7. X-ray spectra on and off the axis of the Se plasma "rod".

to 50-TW output at 0.53 and 0.35 μm, will be used to extend laser-plasma studies to plasmas several times larger than those used on Novette. We expect that these experiments will confirm our theoretical and experimental understanding of the laser-plasma coupling and of the implosion physics of the capsules that will be required for high-gain operation. We also expect to extend x-ray laser performance to shorter wavelengths, higher power, and increased spatial coherence, and to conduct a variety of shock wave, atomic physics, and hydrodynamic experiments that become possible with the development of multi-terawatt, short wavelength lasers.

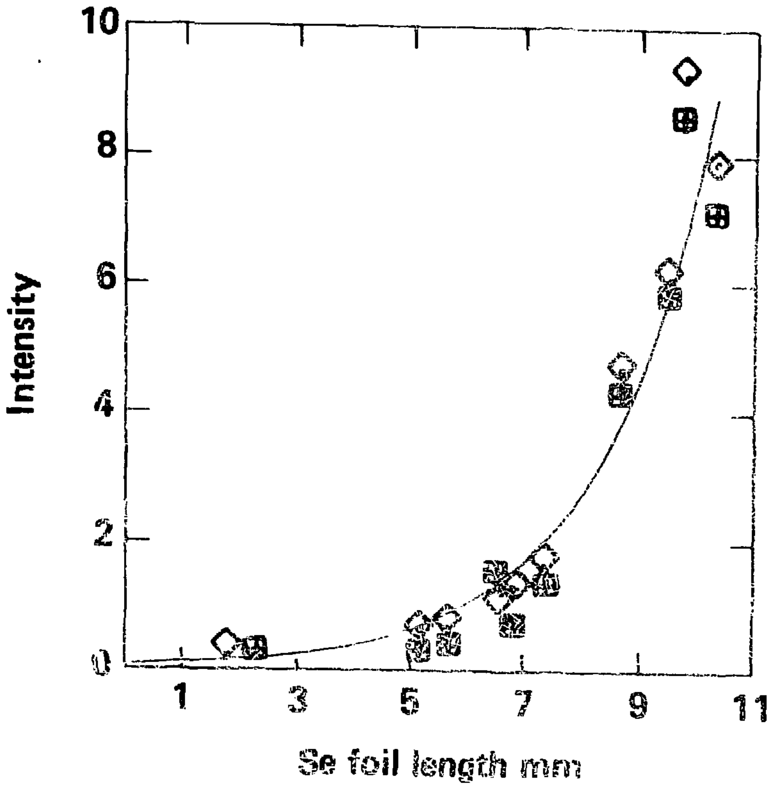


Fig. 8. Intensity of emitted 206Å and 209Å radiation as a function of Se foil length.

DISCLAIMER