1.B High-Resolution XUV Spectroscopy Using the OMEGA Laser

Introduction

For the past several years, the National Laser Users Facility (NLUF) has supported a research program in extreme ultraviolet (XUV) spectroscopy in cooperation with the Naval Research Laboratory (NRL) and the NASA Goddard Space Flight Center (GSFC). A 3-m grazing incidence spectrograph, originally built[1] as a rocket flight instrument at GSFC, was installed on the OMEGA target chamber. This instrument has been used to record spectra in the wavelength range 6 Å to 350 Å from a wide variety of targets.

High-resolution XUV spectroscopy is of fundamental interest for several reasons. The measured wavelengths can be used to derive the energy level structures and ionization potentials of highly charged ions. Trends along the isoelectronic sequences indicate the importance of relativistic and quantum electrodynamic (QED) effects, and deviations from expected results point the way toward improvements in the understanding of the atomic physics of highly charged ions. By comparing the experimental results with values calculated by atomic physics computer programs (such as those developed by Cowan, Grant, or Klapisch), the limitations in the present theoretical treatments of highly charged ions can be determined, and improvements can be made that result in more accurate calculated atomic data.

High-resolution XUV spectroscopy also contributes to the understanding of the plasma properties of laser-fusion targets. Different spectral lines are emitted from different plasma regions. The XUV lines are emitted from the hot corona and are characteristic of the electron temperature and density in the ablation plasma. Lines emitted from the central core will be characteristic of the density and temperature in that region. Line profiles and line shifts are powerful measures of the velocity fields in the plasma. Spectral lines from layered targets can be used to infer burn-through and electron energy transport in the corona.

Extreme ultraviolet spectroscopy has recently been used to identify energy levels of importance to x-ray laser systems and to observe population inversions on transitions in highly charged ions in linear laser-produced plasmas. These results represent progress toward the development of a soft x-ray laser with a wavelength below the carbon absorption edge at 43 Å.

XUV Spectroscopy

Figure 29.8 shows a schematic of the apparatus. A cylindrical mirror focuses the radiation from the target onto the entrance slit of the spectrograph. The linear image formed by the mirror is crossed at a small angle with the entrance slit, and this provides spatial resolution of the target in one dimension.[2] Shown in Fig. 29.9 is a typical XUV spectrum from copper-coated targets routinely used for beam pointing and focusing characterization. The 24 OMEGA beams were focused to

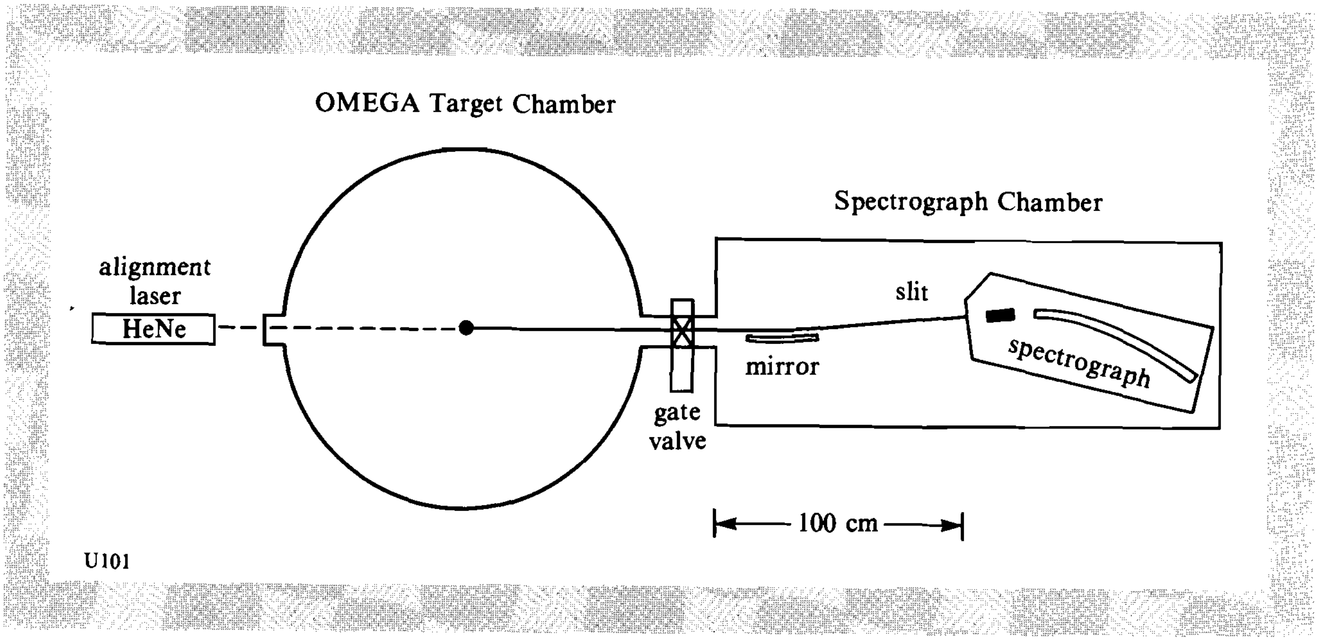

Fig. 29.8
Schematic of the apparatus showing the 3-m grazing incidence spectrograph, the cylindrical mirror, and the OMEGA target chamber.

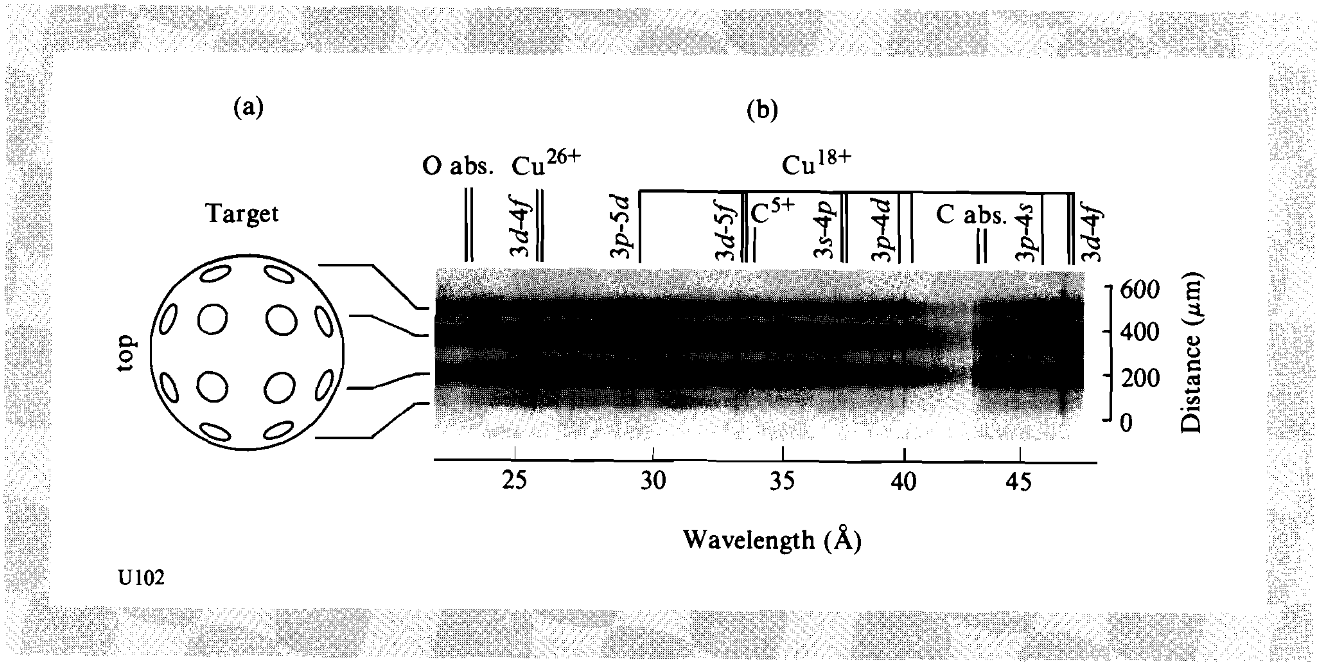

Fig. 29.9
(a) The pattern of laser focal spots on the hemisphere of the target facing the spectrograph. The diameter of each focal spot is 50 μm, and the diameter of the copper-coated target is 600 μm.
(b) The spectrum from 22 Å to 48 Å showing the $3d$-$4f$ transitions in Li-like Cu^{26+} near 25.6 Å, the $n = 3$-4 and $n = 3$-5 transitions in Na-like Cu^{18+}, and the C^{5+} Lyman-α transition at 33.736 Å. The carbon and oxygen inner-shell absorption features are present at 43.5 Å and 23.3 Å, respectively. The distance across the target is indicated by the scale at the right end of the spectrum.

50-μm spots in a spherically symmetric pattern, and the rows of focal spots were resolved in the XUV spectrum. Highly charged ions were abundant in the hot plasma, and spectral lines from these ions appear bright on the photographic plate in the laser focal regions. Transitions in Li-like through F-like copper were identified in the spectrum.[3,4] Such a hot copper plasma had never before been observed in the XUV region, and all of the Li-like Cu^{26+} transitions and many of the other copper transitions represent new identifications. This illustrates the uniqueness of the OMEGA facility for high-resolution XUV spectroscopy. No other laboratory presently has a high-resolution XUV spectrograph recording data from targets irradiated by such an intense laser.

The spectroscopy work supported by NLUF has resulted in 15 papers during 1985-86.[2-16] This work is summarized in Table 29.I. Elements from silicon [atomic number (Z) = 14] to uranium (Z = 92) have been studied. Transitions in the isoelectric sequences HI through NaI were identified in the elements $Z \leq 50$. For the heavier elements

Table 29.I
Table of elements and ionization stages that have been studied. The numbers refer to the references.

Element	Atomic Number	Isoelectronic Sequence													
		H	He	Li	Be	B	C	N	O	F	Na	Fe	Co	Cu	Zn
Si	14	8	8	8	8										
Cu	29			3	3	4	4	4	4	9					
Zn	30						9	9	9	9					
Ga	31						9	9	9	9					
Ge	32						9	9	9	9					
As	33								10	10					
Se	34								10	10	11				
Br	35					12	12	12	10	10	12				
Rb	37								10	10					
Y	39								13						
Zr	40								13	14					
Nb	41								13	14					
Mo	42									14					
Ru	44									14	15				
Rh	45									14	15				
Ag	47									14	15				
Cd	48									14	15				
Sn	50									14	15				
Sm	62											16	16		
Eu	63											16	16		
Gd	64											16	16		
Au	79											5	5	5	5
Pb	82											5	5	5	5
Bi	83											5	5	5	5
Th	90													5	5
U	92												5	5	5

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$Z \geq 62$, transitions in the FeI through ZnI isoelectronic sequences have been identified. Since the relativistic and QED contributions to the transition energies grow rapidly with increasing Z, the heavier elements are of particular interest for the study of these effects. The importance of QED effects in the CuI sequence is illustrated in Fig. 29.10. The inclusion of QED terms of order Z^4 in the calculated wavelengths improves the agreement with the observed wavelengths, but the growing discrepancies at high Z indicate that terms of higher order in Z should be included in the calculation.[5]

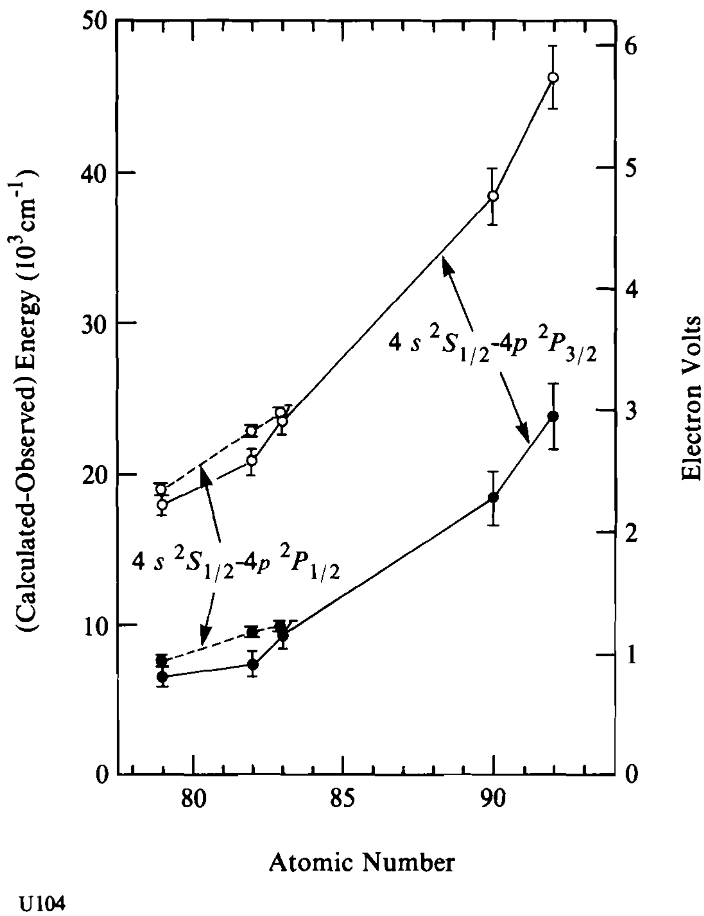


Fig. 29.10
Comparison of the observed energies of the $4s$-$4p$ transitions of Cu-like ions with the energies calculated by using Grant's program without QED contributions (open circles) and with QED contributions (solid circles).

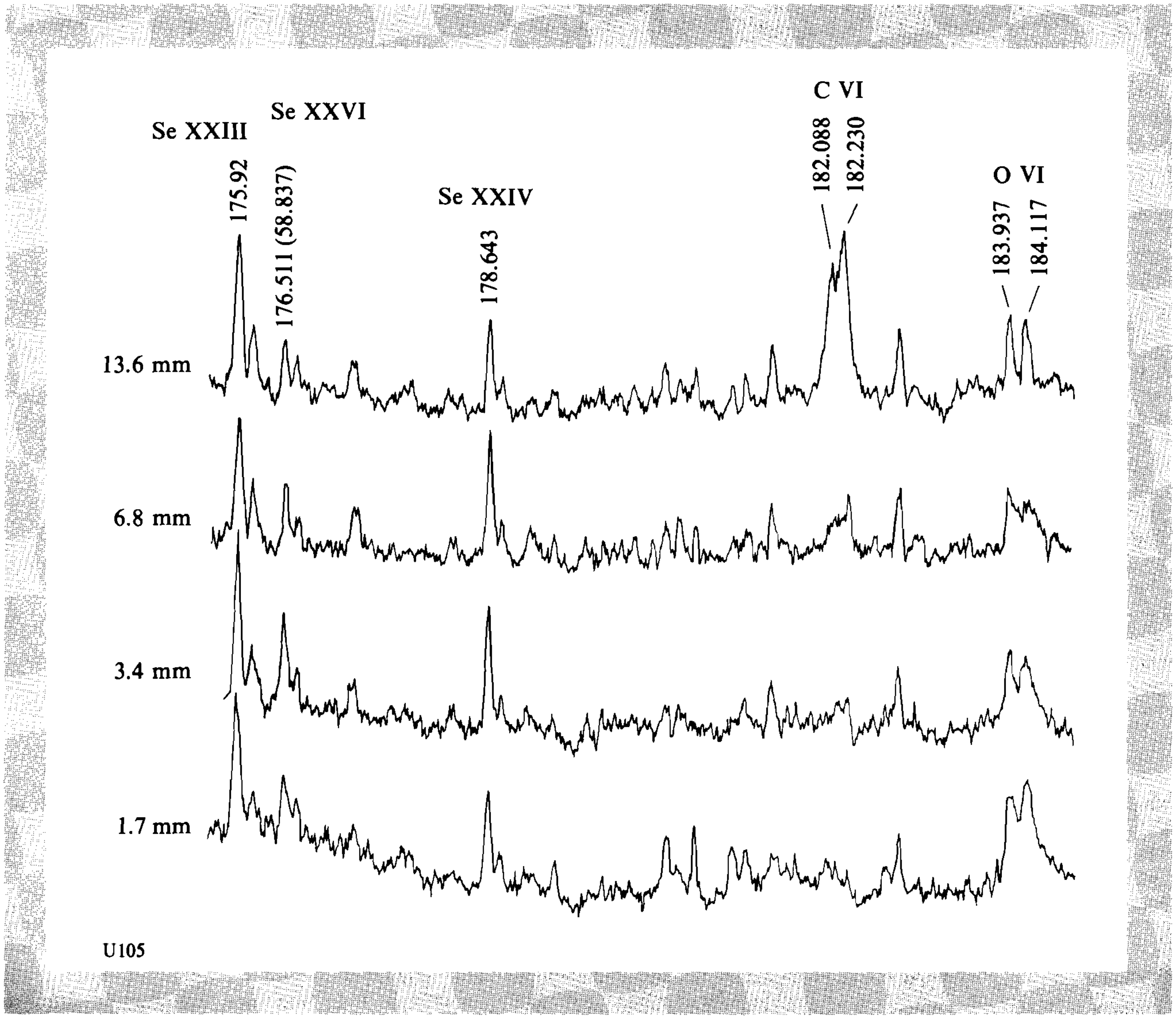
Coronal Physics

The emission of XUV radiation is a function of the electron temperature and density of the corona. Depending primarily on the ionization potentials of the various ionization stages of a given element, different ionization stages are abundant at different electron temperatures. The spectral line intensities in a particular ion may also be sensitive to the electron temperature and density. For example, the ratio of the $3s\ ^2S_{1/2} - 3p\ ^2P_{3/2}$ and $3p\ ^2P_{3/2} - 3d\ ^2D_{5/2}$ transitions in Na-like ions is a strong function of electron density. Based on the measured intensity ratio for these transitions in Mo^{+31}, we determined that the emission occurred in a plasma region with electron density of order 10^{21} cm^{-3}. The electron temperature was determined to be 2 keV to 3 keV.[6] In related experiments on layered targets, the observation of transitions from the underlying layers is characteristic of the burn-through time and electron energy transport in the corona.[17]

X-Ray Laser Research

The verification of population inversion and gain in the XUV and soft x-ray spectral regions has received considerable attention in the past several years. High-resolution spectroscopy is important for the identification of the lasing transitions and for the diagnosis of the gain medium. Following the results from Lawrence Livermore National Laboratory (LLNL)[18] on lasing in Ne-like selenium (Z = 34) at 206 Å and 209 Å, experiments were performed on selenium-coated Formvar at LLE. Up to eight OMEGA beams were focused in a line 100-μm wide and up to 13.6-mm long. Spectroscopic data from the selenium/Formvar plasmas were recorded on a number of shots.

Fig. 29.11
The spectra from selenium/Formvar plasmas of lengths 1.7, 3.4, 6.8, and 13.6 mm. The intensity of the C^{5+} n = 3-2 feature at 182 Å increases dramatically with the length of the plasma. This is consistent with a gain of 3 cm^{-1}.



Although none of the selenium transitions indicated gain, the hydrogenic C^{5+} $n = 3$-2 transitions at 182 Å increased dramatically in intensity when the length of the plasma was increased, as shown in Fig. 29.11.[7] This was consistent with a gain on these transitions of 3 cm^{-1}. Modeling indicates that the mechanism producing the population inversion was radiation cooling of the plasma by the highly charged selenium ions, collisional recombination, and cascading into the C^{5+} $n = 3$ level.[19]

One of the primary motivations in x-ray laser research is to produce coherent radiation at wavelengths below the carbon absorption edge at 43 Å. When a biological specimen is irradiated with such radiation, contrast is enhanced by the increased absorption in the organic material. The $\Delta n = 0$ transitions, such as the $3s-3p$ transitions in Ne-like selenium, scale slowly to lower wavelengths with increasing Z, while the wavelengths of the $\Delta n = 1$ transitions in hydrogenic ions scale rapidly as Z^{-2}. In order to produce gain at wavelengths below 43 Å in laboratory plasmas, it is advantageous to use transitions in hydrogenic ions. The $n = 2$-3 and $n = 2$-4 transitions in H-like and He-like silicon fall in the wavelength range 24 Å-40 Å and are of interest for lasing below the carbon absorption edge. As shown in Fig. 29.12, these transitions were identified for the first time in the XUV spectra from glass microballoons.[8]

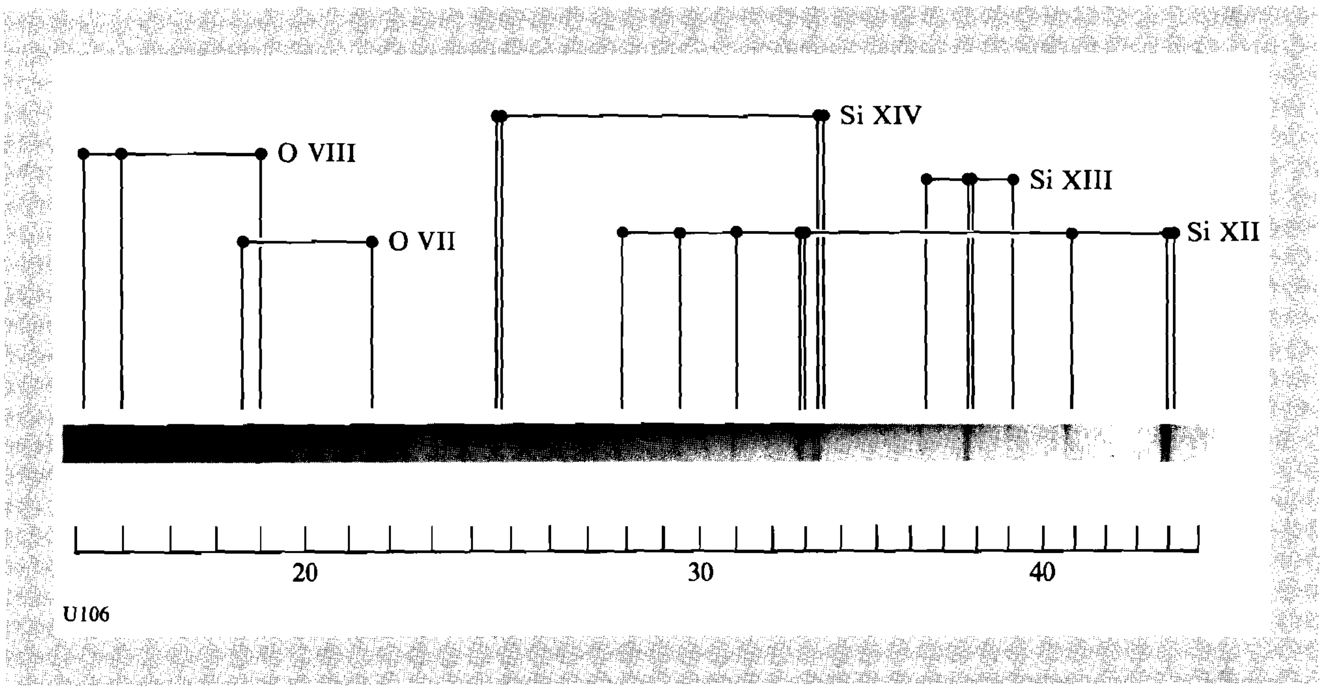


Fig. 29.12
XUV spectrum from a glass microballoon between 15 Å and 45 Å. Transitions in highly ionized silicon and oxygen are indicated.

Ions with one electron outside closed shells have energy-level structures similar to hydrogenic ions, and transitions in Li-like, Na-like, and Cu-like ions also scale rapidly to lower wavelengths with increasing Z. In point-focus experiments performed at LLE, population inversions have been observed on transitions in a number of highly charged "one-electron" ions. For example, population inversion in Li-like Cu^{26+} on the $3d$-$4fd$ transitions at 26 Å was observed in the experiments previously mentioned.[3] Li-like ions have great promise for achieving gain in this interesting wavelength region, and future experiments are planned.

Summary

The XUV spectroscopy research supported by NLUF has been a productive collaboration with the Naval Research Laboratory and the NASA Goddard Space Flight Center. High-resolution spectroscopy has produced understanding of relativistic and QED effects in highly charged ions of elements with a high atomic number. The electron density and temperature of the coronal plasma have been determined. Progress has been made in x-ray laser research with the observation of gain on the C^{5+} 182-Å transitions and the observation of population inversion in Li-like Cu^{26+} at 26 Å.

Plans for the future include the implementation of a normal-incidence XUV spectroheliograph and a 2-m grazing incidence Schwob-Fraenkel spectrograph with a microchannel plate intensifier. The spectroheliograph images the XUV radiation emitted from the coronal plasma of the laser-irradiated target, which is useful for understanding coronal physics. The spectroheliograph has been installed on the OMEGA target chamber, and preliminary data look promising. The design of this instrument is similar to instruments built by NRL and flown on the spacecraft Skylab. These instruments recorded high-quality images of the solar corona that even now represent the best data of this kind on the solar corona.

ACKNOWLEDGMENT

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