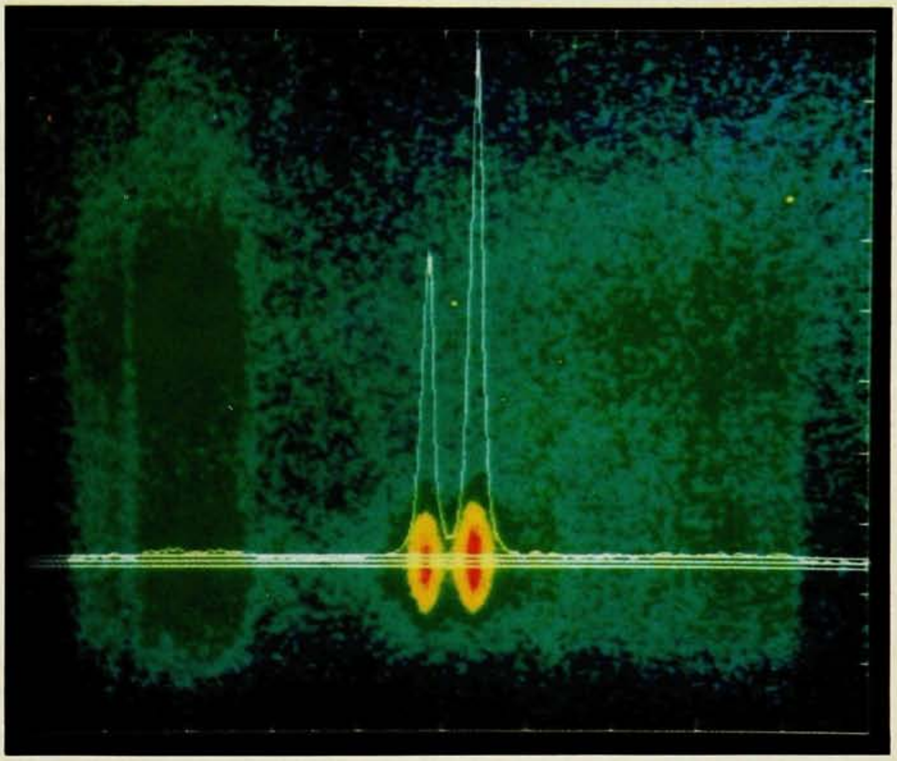
Livermore group reports soft x-ray laser

A group at Lawrence Livermore Laboratory has operated the first soft x-ray laser. As proof, they have extensive diagnostics from more than 100 test shots showing not only that radiation emitted at two wavelengths near 20 nm were up to 700 times more intense than those from spontaneous emission, but also that these lines behaved in other ways characteristic of a laser. Group leader Dennis Matthews, together with Mordecai Rosen, presented[1] Livermore's results at the Boston meeting of the APS Division of Plasma Physics last October. The announcement is a welcome milestone in the quest for an x-ray laser, which has been underway since the first theoretical suggestions of x-ray lasing schemes in the late sixties.[2] Other participants in that search, now more confident of their own eventual success, can be expected to join Livermore in the drive towards greater efficiency, higher power and ever-shorter wavelengths.

Admittedly, the very-short-wavelength region has intrinsic interest as a new frontier, but it has possible practical applications as well—such as x-ray holography of biological structures, x-ray photolithography for integrated circuits and more precise spectroscopy. Furthermore, proponents of strategic defense systems have high hopes for an x-ray laser weapon: According to one report,[3] Livermore has already tested an x-ray laser that is pumped by a nuclear explosion. However, Livermore's weapons program is formally separate from the project Matthews directs.

Also at the Boston meeting, Szymon Suckewer of the Princeton Plasma Physics Laboratory reported enhancements of soft x-ray light by a factor of 100. Since then, he and his colleagues have added an x-ray mirror to their experiment and feel that the results indicate stimulated emission. Both the Livermore and the Princeton experiments are outgrowths of fusion research.



Evidence for soft-x-ray lasing from Livermore experiments with a selenium foil. The lasing lines appear in this computer-enhanced false-color photograph of data from a transmission grating spectrograph. In the plot, wavelength is on the horizontal axis and time on the vertical axis. Color indicates the intensity of each point, with red denoting the most intense. The superimposed white curve is the intensity versus wavelength, with the two peaks appearing at 20.6 and 20.9 nm.

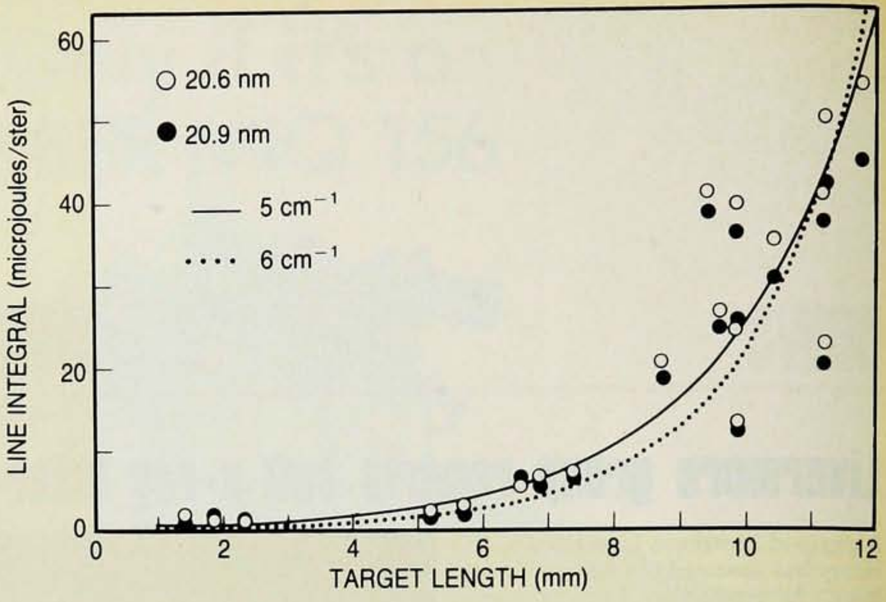
Livermore's experiment. One of the greatest challenges in producing an x-ray laser is to deliver a high enough power density to create a large population inversion within the plasma lifetime. Livermore pumped its soft x-ray laser with 450-psec pulses from the two-beam Novette 532-nm laser, in which each beam has a typical power density of 5×10^{13} W/cm^2. This light vaporized a target of high-Z material (most of their experiments used selenium), creating a plasma of ions with electronic structure similar to that of neon. Collisions with electrons within the plasma then created excited states of these neon-like ions, with a predicted population inversion between the $2p^5 3p$ and the $2p^5 3s$ levels. Transitions between the $J = 2$ and $J = 1$ states of these levels produced amplified radiation at 20.63 and 20.96 nm. Surprisingly, there was no amplification of the $J = 0$ to $J = 1$ line at 18.3 nm, where theoretical calculations had predicted the greatest gain. That one humbling aspect of the experiment is prompting some evaluation of the atomic models currently used in support of such laser work, as well as motivating further research in the lab.

In previous experiments, the Livermore group attributed the absence of any amplification to a steep density gradient by which the x rays were refracted out of the high-gain region. Rosen, Peter Hagelstein and others from Livermore collaborated with KMS Fusion Inc to model the hydrodynamics involved and, hence, to design an exploding foil target that would create a flat electron density. The optimum target design was a 75-nm layer of selenium vapor deposited on one side of a plastic substrate that is 150 nm thick. The foils were less than 0.1 cm wide by 1.1 cm long.

Laser diagnostics. The diagnostic instruments were critical to the success of the experiment, for several previous reports of significant amplification in the soft x-ray region have been either inconclusive or unsubstantiated. The Livermore experiment had two independent spectrographs viewing the axial direction and one measuring emissions at 77° from that axis. The time-resolved spectrum from one of these instruments showed that the two lines near 20 nm were both brighter and had shorter time duration than nearby spontaneous emissions. (See the figure on page 17.) The output pulse length grew shorter as the amplification increased. The off-axis spectrograph verified that the x-ray emissions were anisotropic, with the 20-nm lines not seen off axis at all.

But the most convincing evidence of laser action stemmed from the Livermore group's ability to vary the length of the target region up to 2.2 cm by adjusting the focal-spot size, by placing both laser beams side by side and by aligning two target foils end-to-end. In this way they determined that the energy appearing at the lasing wavelengths varied in a highly nonlinear way with the length of the foil. In the figure on this page, the data come from the grazing-incidence spectrograph, whose detector is gated in time to exclude background emissions occurring late in the experiment.) Theoretically, the intensity of a laser varies almost exponentially with the length of the gain medium; the constant in the exponent's argument is called the gain coefficient. Matthews and his colleagues concluded that the gain coefficient for each selenium line was (5.5 ± 1.0) cm^{-1}. Michael Kay (Rutherford Lab) told us he feels that for a "true" laser, the product of the gain coefficient and length should exceed 10 rather than the 5.5 measured by the Livermore group. "It should be possible," Key said, "to produce a proper laser device since very high gain is seen without any doubt."

The Livermore group also experimented with a higher-*Z* (and hence lower wavelength) material—yttrium—and measured amplification of emissions at 15.49 and 15.72 nm.



Nearly exponential growth of intensity of emitted radiation was a key indication of lasing in the Livermore experiment. Curves corresponding to gain coefficients of 5 and 6 cm are superposed on data points from lasing lines at both 20.6 and 20.9 nm. Additional measurements out to 2.4 cm indicated continuation of this exponential growth. (From reference 2.)

Before publicly announcing their results, Livermore's director, Roger Batzel, invited a panel of laser specialists to review the data. Among those who examined the data were Charles Rhodes (University of Illinois, Chicago), William Silfvast (Bell Labs) and Ray Elton (Naval Research Laboratory), all of whom were favorably impressed. Silfvast commented to us that he found the crucial features of the demonstration to be both the instrumentation to detect the laser radiation and the creation of a long enough plasma region to give convincing growth.

The Novette laser is now shut down, to be replaced with the larger Nova facility, which should be operating this month. For six months starting around June, Matthews's group will have two of the laser beams from that facility devoted to the soft-x-ray experiments. The first objective in that work will be to try to achieve saturation in the laser. Matthews estimates that they might be able to increase the peak power by orders of magnitude with a new cylindrical lens designed to increase the length of the focal region up to 3 cm.

The Livermore team will also try to improve the efficiency of the scheme, partly by using x-ray mirrors developed by Troy Barbee (Stanford) to make a double pass through the lasing medium. These mirrors consist[4] of alternate layers of high-density and low-density material—molybdenum and silicon in this case. The thickness of the layers is tailored so that x rays reflected off the successive molybdenum layers will interfere constructively. Barbee told us that measured overall reflectivities at normal incidence range from 50% to 60% for wavelengths from 16 nm to 22.8 nm. He is working on mirrors for x rays as short as 3 nm, although the reflectivity of these is so far barely 10%. Still shorter wavelengths will have to be reflected by crystals.

Matthews commented that his group will move towards shorter-wavelength lasers. The lowest they can anticipate with their collisional-excitation approach is about 10 nm, using molybdenum as a target. They are working on other laser schemes that might take them to 5 nm.

A published report indicates[3] that the nuclear-pumped x-ray laser operates at 1.4 nm. That report described one possible option for a weapon based on such a laser as consisting of a ring of about 50 dense metal lasing rods arranged around a low-yield nuclear warhead.

The Princeton group uses[5] a recombination lasing scheme. The technique is to use incoming laser light to vaporize a target of low atomic number, such as carbon, stripping the atoms completely of electrons in the process. While confined in a magnetic field, the resulting plasma is cooled radiatively as electrons repopulate the higher states. (Suckewer noted that the radiative cooling—as opposed to adiabatic cooling—helps to ensure a uniform plasma density and provides faster cooling.) The resulting hydrogen-like ions are expected to have a population inversion between the levels with principal quantum numbers $n = 3$ and $n = 2$. Transitions between these levels in carbon ions produce radiation whose wavelength is 18.2 nm. A similar method creates lithium-like ions.

In recombination schemes the electron temperatures and densities required for lasing are lower for the same wavelength region than those in the collisional-excitation method used at Livermore. These schemes are thus more adaptable to much smaller-scale facilities. Furthermore, the wavelengths at which lasing is predicted to occur decreases more rapidly as the atomic number of the target material increases.

In the Princeton experiment a 10–20-GW carbon dioxide laser is focused[5] onto a 200- to 400-micron-diameter spot size to produce energy densities on the order of 10^{13} W/cm^2. Suckewer and his colleagues measured the enhancement of the axial emission at 18.2 nm by comparing its intensity to that in the transverse direction. They also compared the ratio of axial to transverse intensities of this line with that of a nonlasing line. Using a solid carbon target, they obtained a product of gain coefficient and length equal to 6.5.

The geometry of the Princeton experiment prevents one from varying the length of the plasma to observe the growth in gain with length. Since the Boston meeting, the Princeton group has acquired from Barbee a spherical x-ray mirror with a radius of curvature of 2 m, to increase effectively the length of the target region. Although the Princeton workers feel they have not yet optimized the mirror arrangement, they observe that their enhancement is 2.0 times greater with the mirror in place, consistent with what they expect for stimulated emission with a mirror of the given reflectivity and small angle of acceptance. They plan further experiments with different targets, with an x-ray mirror of shorter radius, with lithium-like neon ions and with schemes to go to shorter wavelengths.

The x-ray laser schemes described so far have been pursued by others as well. In 1975 Elton suggested[6] a collisional excitation scheme for vacuum ultraviolet light. Later, A. Zherikin, K. Koshelev and V. S. Letokhov (Institute for Spectroscopy, Moscow) described[7] methods of obtaining population inversion between the 3p and 3s levels in neon-like ions. About the same time, A. V. Vinogradov, I. Sobelman and E. Yukov of the Lebedev Physics Institute in Moscow were very active in investigating[8] several x-ray lasing schemes, including collisional excitation. More recently, Elton's colleagues at NRL, some in collaboration with Suckewer and Anand Bhattia (NASA Goddard), and, independently, Hagelstein from Livermore, have extended[9] this work with calculations of the shorter wavelengths expected from neon-like systems at higher atomic numbers. In 1977 a team headed by A. Ilyukhin claimed[10] to have achieved a laser cavity at 60 nm. According to Elton, their claim was never substantiated and the Russians have not published any results on this device since then.

Several experiments in Europe are based on the recombination scheme. Geoffrey Pert and his colleagues at the University of Hull (England) have a setup similar to that of the Princeton group, but with a thin carbon fiber as the target. They reported gain in 1980 and claimed[11] to have measured a gain–length product of approximately 5 on the 18.2-nm line. For the past two years, Pert and his colleagues have been collaborating with Michael Key and others at Rutherford. They are currently planning experiments on a larger scale similar to the Livermore work. At the University of Paris Sud, Orsay, a team led by Pierre Jaeglé is experimenting[12] with a recombination scheme involving lithium-like aluminum, with radiant emission at around 10.5 nm, from which they have reported small gains on the order of one.

There is certainly more than one way to pump a laser, and many other candidates are being studied. The recent success with a collisional excitation scheme does not necessarily indicate the way for future experiments to go; this early in the game it simply speaks to the viability of the x-ray laser concept. —BGL

References

1. D. L. Matthews, P. L. Hagelstein, M. D. Rosen, M. J. Eckart, N. M. Ceglio, A. U. Hazi, H. Medecki, B. J. MacGowan, J. E. Trebes, B. L. Whitten, E. M. Campbell, C. W. Hatcher, A. M. Hawryluk, R. L. Kauffman, L. D. Pleasance, G. Rambach, J. H. Scofield, G. Stone, T. A. Weaver, Phys. Rev. Lett. **54**, 110 (1985).
2. L. I. Gudzenko, L. A. Shelepin, Sov. Phys. Doklady **10**, 147 (1965); M. A. Duguay, P. M. Rentzepis, Appl. Phys. Lett. **10**, 350 (1967).
3. C. Robinson, Aviation Week and Space Technology, 23 February 1981, page 25.
4. T. W. Barbee Jr, S. Mrowka, M. C. Hettrick, "Molybendum–silicon multilayer mirrors for the extreme ultraviolet (EUV)," Appl. Optics, to be published.
5. S. Suckewer, C. Keane, H. Milchberg, C. H. Skinner, D. Voorhees, in *Laser Techniques in the Extreme Ultraviolet*, S. E. Harris, T. B. Lucatorto, eds., AIP Conf. Proc. No. 119, Subseries No. 5 (1984), p. 55.
6. R. C. Elton, Appl. Optics **14**, 97 (1975).
7. P. Hagelstein, Plasma Phys. **25**, 1345 (1983); U. Feldman, A. Bhattia, S. Suckewer, J. Appl. Phys. **54**, 2188 (1983); U. Feldman, J. F. Seely, A. K. Bhattia, J. Appl. Phys. **56**, 2475 (1984); J. P. Apruzese, J. Davis, Phys. Rev., **A28**, 3686 (1983).
8. A. Zherikhin, K. Koshelev, V. Letokhov, Kvant. Elektron. (Moscow) **3**, 152 (1976) [Sov. J. Quantum Electron. **6**, 83 (1976)].
9. A. V. Vinogradov, I. Sobelman, E. Yukov, Kvant. Elektron. **4**, 63 (1977) [Sov. J. Quantum Electron. **7**, 32 (1977)].
10. A. Ilyukhin, G. Peregudov, E. Ragozin, I. Sobelman, V. Chirkov, Pis'ma Zh. Eksp. Teor. Fiz. **25**, 569 (1977) [JETP Lett. **25**, 536 (1977)].
11. D. Jacoby, G. J. Pert, L. D. Shorrock, G. J. Talents, J. Phys. **B15**, 3557 (1982).
12. G. Jamelot, P. Jaeglé, A. Carillon, A. Bideau, C. Moller, H. Guennou, A. Sureau, in *Proc. Int. Conf. Lasers 81*, New Orleans, La., December 1981, p. 178.

Zeta revisited: Have we really seen the Higgs?

Much excitement was generated last summer at the XXII International Conference on High Energy Physics in Leipzig by the Crystal Ball collaboration's report of evidence for a curious new particle, the 8.32-GeV "zeta" boson, that might well have been the long-sought-after Higgs particle. In October (PHYSICS TODAY, page 18) we reported that this hint of the Higgs had set in motion considerable activity among particle theorists, because these data were not entirely consistent with the simplest Higgs particle one might have expected.

It now appears, however, that the experimental signal is going away. At the beginning of November the Crystal Ball group reported at the Santa Fe meeting of the APS Division of Particles and Fields that the partial analysis of their 1984 data sample had failed to confirm the zeta signal discovered in their 1983 data. "The potential physics impact of the zeta is so great," the group declares, "that experimenters bear the burden of proof to show that it reproduces in every valid data set."

The Crystal Ball data were taken at the DORIS e^+e^- storage ring at DESY in Hamburg. At Leipzig, the Columbia–Stony Brook CUSB detector group had reported that their preliminary data, taken at the Cornell CESR e^+e^- ring, gave no indication of a new particle near 8.3 GeV. At the November meeting in Santa Fe, the CUSB group reported that additional data had not revealed a zeta signal. Two other detector groups have also joined the search—ARGUS at DORIS and Cleo at CESR. Both groups reported at the