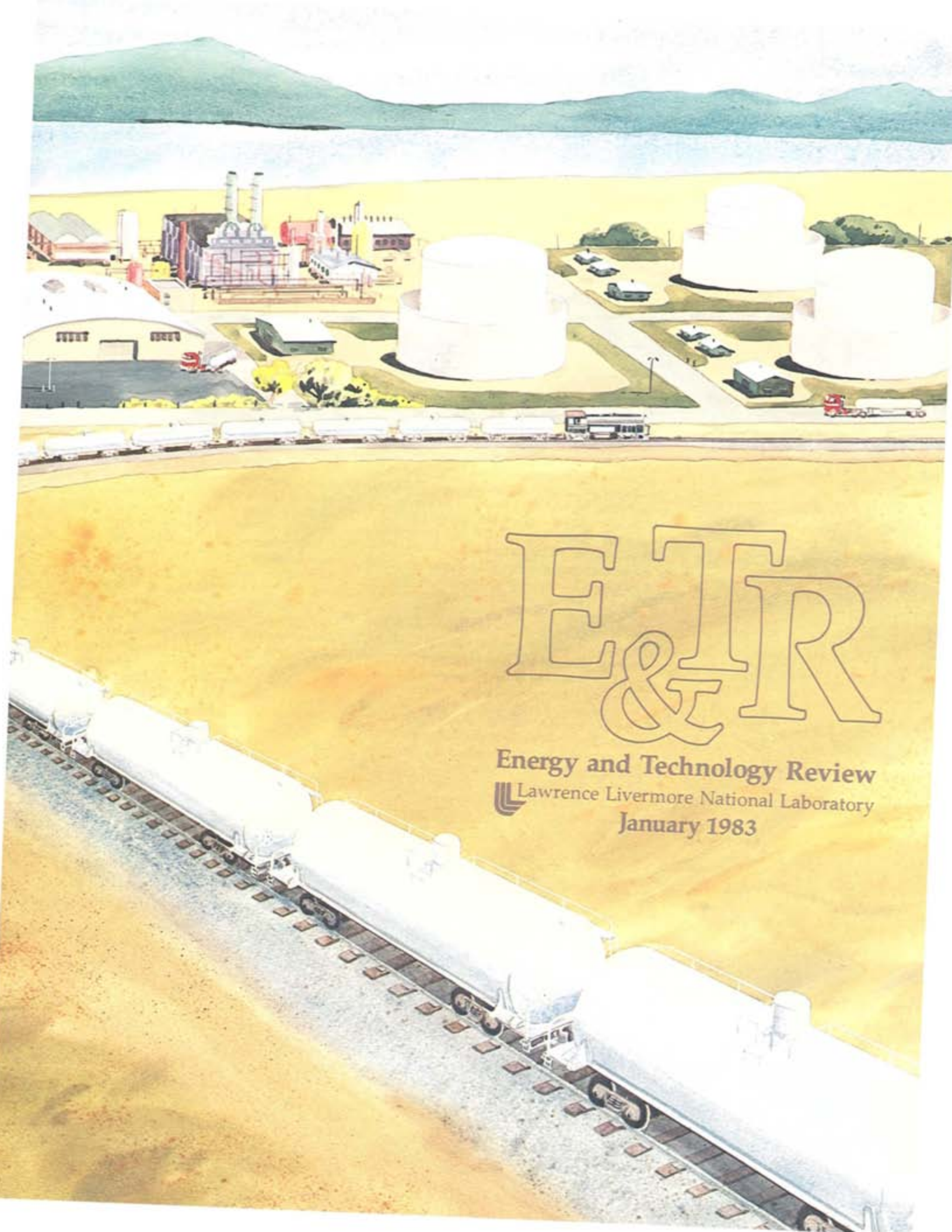

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Energy and Technology Review

Lawrence Livermore National Laboratory

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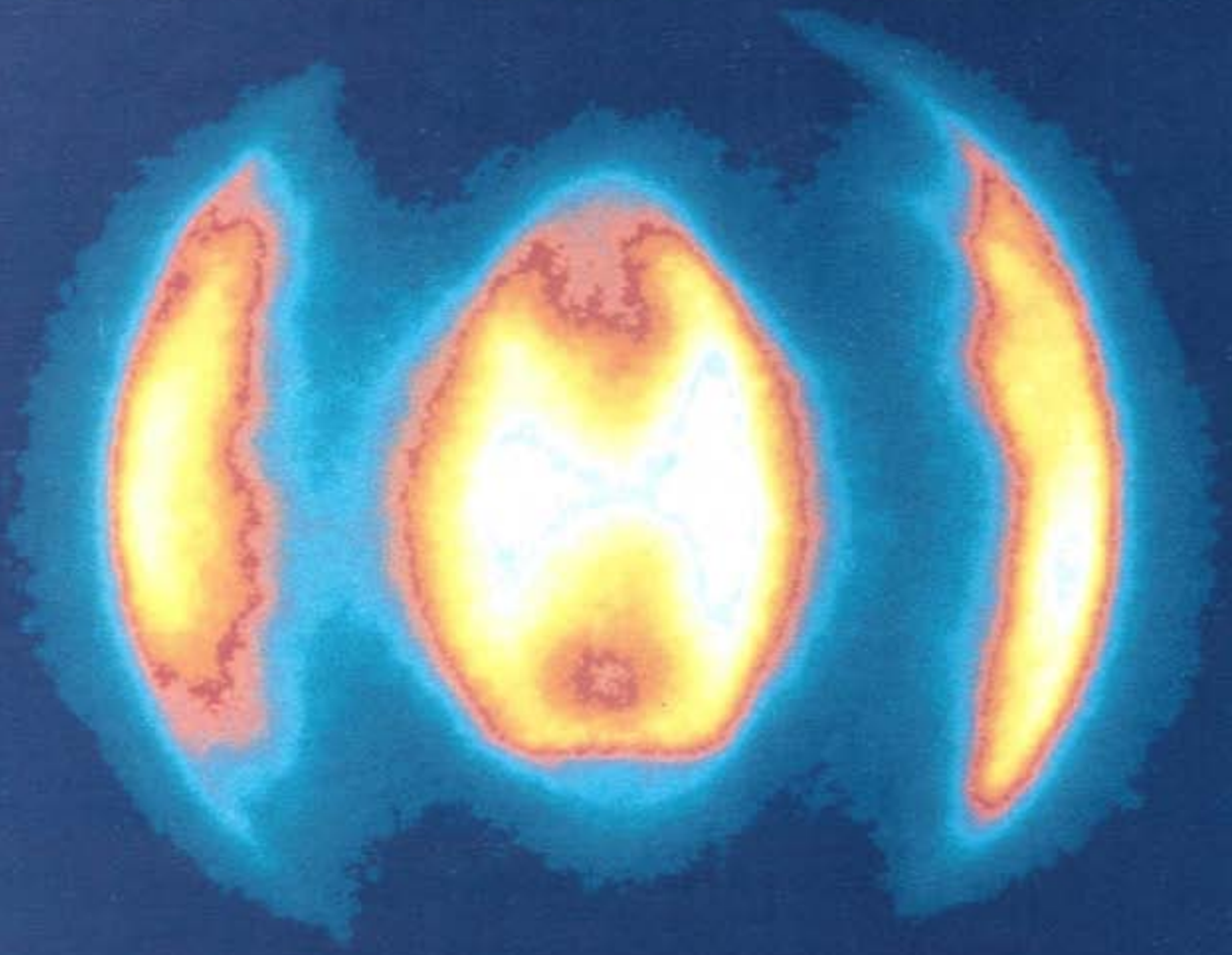
Laser Fusion X-Ray Measurements



We have developed a number of new instruments that greatly improve the energy and time resolution and the energy range over which we can measure x-ray spectra from laser fusion experiments.

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Using an immense laser to implode a tiny precision-fabricated target containing deuterium and tritium is only part of the inertial-confinement fusion (ICF) research picture. A major part is measuring what happened during the implosion (diagnostics) and interpreting the data. The soft, subkilovolt x-ray spectrum emitted from a laser-produced plasma is an important indicator of the plasma temperature. Measuring this spectrum provides us with invaluable and otherwise unobtainable information about plasma conditions in an ICF experiment.

ICF implosion diagnostics are challenging because the signals from them are both weak and brief. Recently, we have developed a number of sophisticated techniques for measuring the spectral distribution of the x rays generated in these microexplosions. Application of these techniques has resulted in several new instruments of greatly improved energy and time resolution and have extended the range of our measurements to x-ray energies as high as 300 keV. Use of these new instruments with the Argus and Shiva lasers has had a major impact on our understanding of the physics of laser-produced plasmas.

The original (and still standard) instruments for measuring high-and low-energy x rays in ICF experiments are the filter fluorescer and the Dante spectrometer (so called because it looks at the Inferno and reports on conditions there).[1] Both of these instruments are based on x-ray filters, each of which transmits a different portion of the x-ray spectrum. The Dante spectrometer (useful only in the low-energy range) contains as many as ten x-ray-sensitive diodes, each covered by a different filter and each sending its signal to a different transient recorder (either an oscilloscope or a digitizer). In the filter fluorescer, the filtered x rays fall on a fluorescer and only the fluorescent x rays reach the photodiode detector.

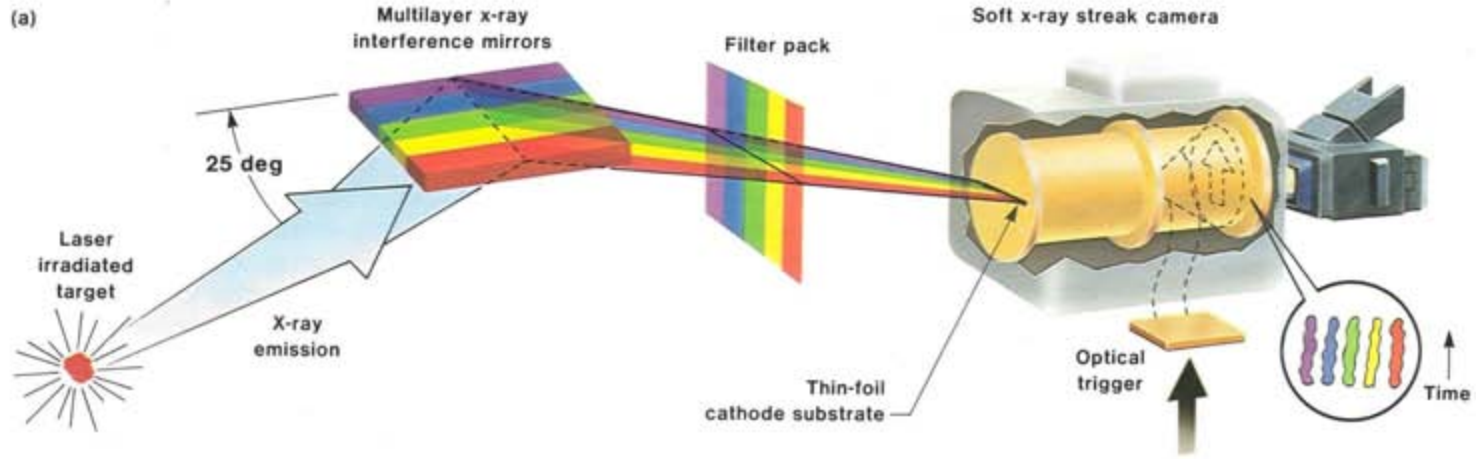
Such measurements yield a low-resolution set of data over a moderate energy band centered at different energy values. The time-resolution is defined by the combined response times of the diodes and the oscilloscopes. Some of the Dante channels are relatively fast (about 150 ps) but most are slow (600 ps). The filter-fluorescer channels are even slower because of the use of highly sensitive but slow detectors.

Most of our new instruments achieve high time-resolution through the use of our LLNL-developed electronic streak camera (see box on p. 16). The electronic streak camera provides a continuous record, analogous to a strip-chart recording, of how some quantity varies with time. Because it combines the detector and display into one instrument, this form of streak camera is capable of extremely fast writing speeds. Its temporal resolution is estimated at 20 ps, almost ten times better than the fastest Dante-spectrometer channels. Table 1 compares the sensitivities and resolutions of the various x-ray spectrometric techniques that are discussed here.

Multilayer-Mirror Streak Camera Spectrometer

The multilayer-mirror x-ray spectrometer, shown in Fig. 1, uses a five-segment interference mirror to select five different narrow spectral bands of the soft x rays from the laser-irradiated target, rejecting the rest.[1] Each segment of the mirror has a vacuum-deposited (sputtered) coating consisting of many alternating layers of high-Z and low-Z material. By choosing appropriate materials and carefully controlling the thickness of each layer, we can make each segment of the mirror preferentially reflect x rays of a different energy onto the slit of the streak camera [i.e., those that satisfy the condition for Bragg interference $\lambda = 2d \sin\theta$, where λ is the wavelength (inversely proportional to energy), d is the layer thickness, and θ is the angle of incidence].

The diffracted x rays, five beams at five different energies travelling side by side, next go to a segmented filter, each section of which is tuned to pass only the particular energy beam of x rays that has been reflected by the



multilayer mirror. The purpose of this filter is to remove from the beam extraneous x rays scattered or reflected from the mirrors.

Each filtered beam then falls on a different part of the streak camera's entrance slit and illuminates a different part of a photocathode. The streak camera electronically sweeps the resulting slit image across a fluorescent screen, producing a visible two-dimensional image of the x-ray intensity at five separate narrow energy bands as a function of time. The visible image is recorded on film or stored electronically in an array of CCDs (charge-coupled devices).

One of the advantages of this multilayer-mirror technique is that it records all five spectral bands simultaneously, on the same instrument. The Dante spectrometer we use for similar measurements requires a separate detector channel for each selected energy segment. Each channel is recorded on one oscilloscope or fast transient digitizer. In addition, each Dante channel is recorded on its own oscilloscope.

The inset in Fig. 1 graphically illustrates the resulting output from the multilayer-mirror spectrometer. Each plane represents the x rays recorded for a single channel, and the height represents the intensity of those x rays as a function of time. The more energetic x rays are in the foreground. By comparing the five bands of data, we find that the hard x rays appear later in time than the softer x rays, rise to lower intensities, and die away more rapidly.

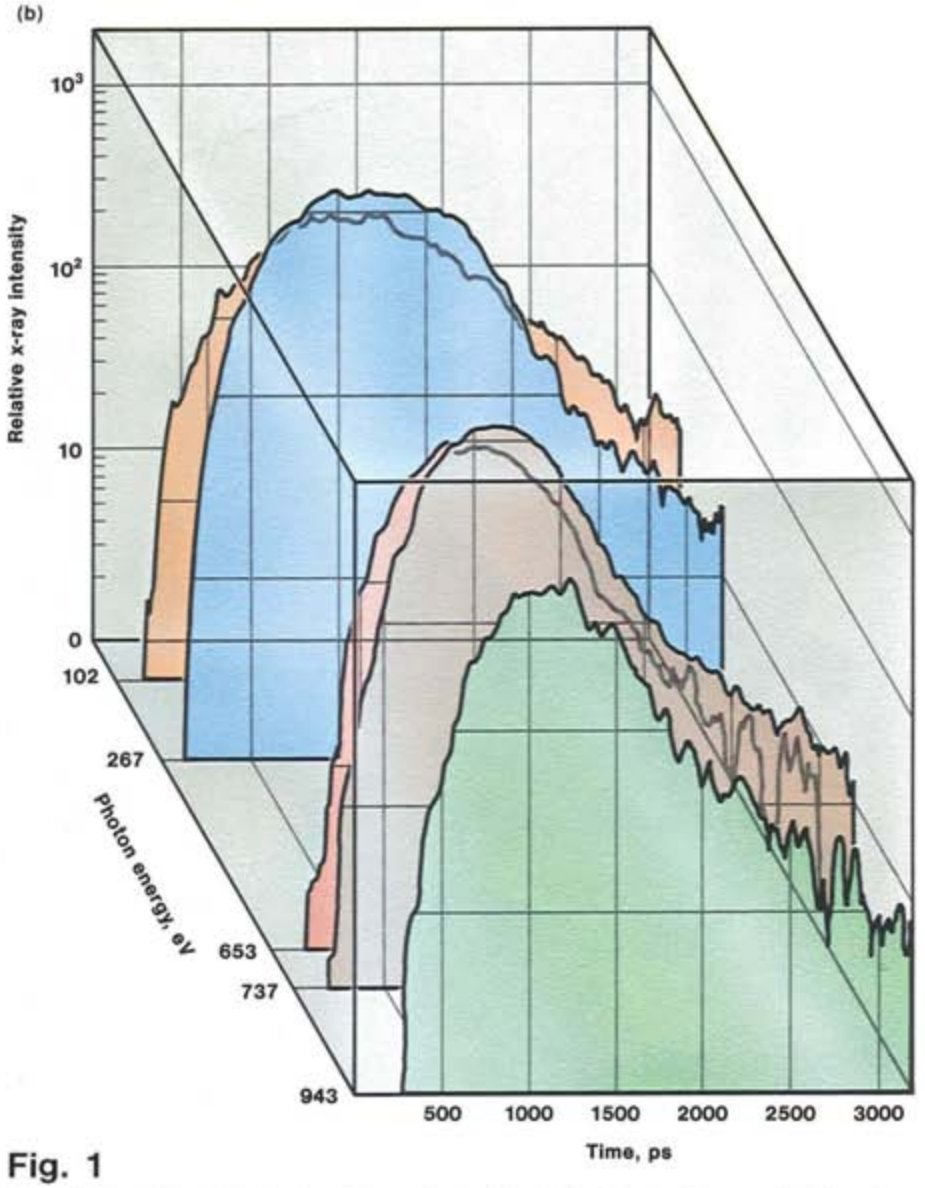


Fig. 1

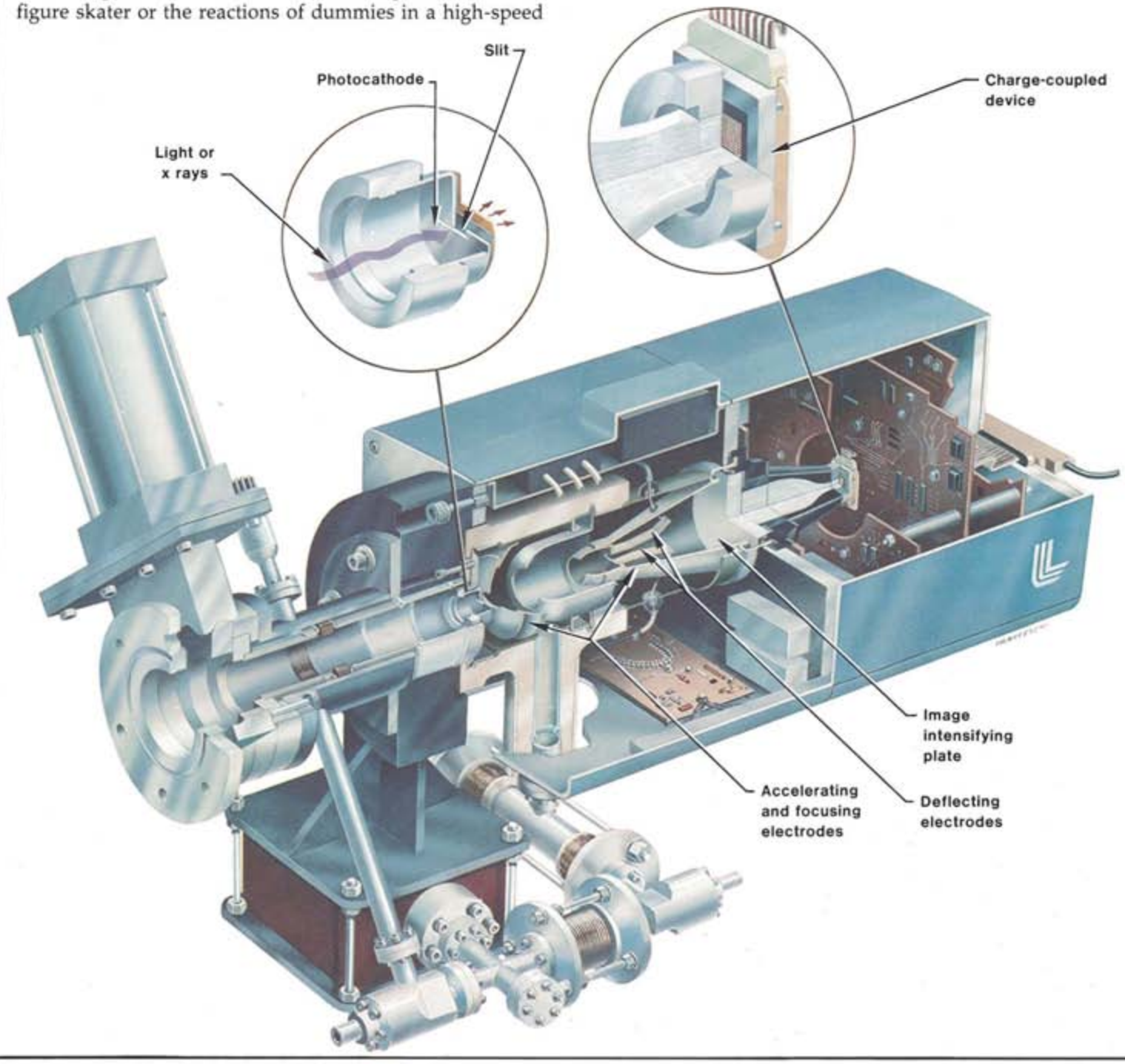
(a) Multilayer-mirror streaked spectrograph capable of simultaneously recording five channels of information on soft x-ray intensities in ICF experiments. (b) Three-dimensional graph of resulting output (intensity vs time as a function of energy).

High-Speed Cameras and Techniques

High-speed cameras originally were just motion picture cameras modified to run at high speed. Such framing cameras, which record motion with a series of still photographs, have advanced to the point of expanding into a viewing segment of tens of minutes events that unfolded in a very few seconds. Although the viewer perceives what looks like a smooth and continuous motion, the record is actually discontinuous, omitting the information between the frames.

Framing cameras are ideal for recording the actions of a figure skater or the reactions of dummies in a high-speed automobile collision. For some subjects, such as an exploding system, however, what we really want is a continuous record of a change in shape or in light intensity. For such subjects, a streak camera provides the required continuous record.

A streak camera sacrifices the overall view of a subject to obtain more detail in a restricted view. A conventional (optical) streak camera focuses an image of the subject on an opaque plate with a slit in it. Another lens projects an image of the slit (and the thin slice of the subject's image



that passes through it) onto one edge of a photographic film. A spinning mirror, synchronized with the action we want to record, sweeps the slit image at high speed across the film, producing a streaked image that records variations in the dimensions and intensity of the thin slice of the subject.

The electronic streak camera carries this concept one step further (see figure). In this case, light (or x rays) enter the streak camera through a slit and impinge immediately on a photocathode, thus producing photoelectrons. The electrons are accelerated by high voltage, focused, and swept across a phosphor where they are converted to light. This light is then recorded on film or a charge-coupled device. The energy spread in the electrons at the photocathode ultimately determines the time resolution of the instrument because electrons of different energies are swept at different rates. Here, we are not using the streak camera to take pictures of an event; rather, we use each point on the streak camera's entrance slit as a separate energy information channel.

An oscilloscope also operates without moving parts, so in principle it could be made as fast as the streak camera. None are, however, partly for economic reasons but mainly because they are designed to be used with auxilliary equipment that limits their time resolution. The Dante spectrometer is slower than the streak camera, not only because its oscilloscope and detector are slow, but also because they are separate. The necessary connecting cable introduces inductance and capacitance into the circuit, lengthening the time it takes for abruptly rising signals to build up on the oscilloscope.

The electronic streak camera is free of these limitations. Since it has never been limited by the capabilities of auxiliary equipment, its sweep is three to four times faster than that of the best available oscilloscope. Furthermore, combining the detector and sweep into one instrument eliminates the x-ray to electronic converter and the connecting cable and its effects.

Reflector-Filter Streak Camera Spectrometer

The reflector-filter spectrometer[2] instrument differs from the multilayer-mirror instrument mainly in the use of highly polished surfaces (grazing incidence x-ray mirrors) in place of multilayers for energy discrimination (Fig. 2). Below the so-called critical energy (determined by the reflection angle and the mirror's atomic number), the mirror surface reflects x rays; higher energy x rays are absorbed. The reflected beam then goes to a filter that absorbs unwanted low-energy x rays, letting through a broad slice of the energy spectrum. The three x-ray beams so defined then go to the streak-camera slit where they are resolved in time and then recorded as a two-dimensional, intensity-modulated image.

The main spectral definition for this spectrometer is provided by the filter, with the mirrors serving primarily to cut off the higher photon energies. This instrument has broader energy resolution than the multilayer interference spectrometer (Table 1), but the x-ray streak camera provides the same excellent time resolution on both. The three energy channels shown in Fig. 2 can be expanded to six by splitting each beam and adding another set of filters.

Figure 2 also shows a streaked record from this spectrometer, using x-ray filters of carbon, vanadium, and iron, measuring the radiation from an experimental laser-irradiated target. The indicated energy ranges are from 510 to 710 eV for the iron filter, 280 to 510 eV for the vanadium filter, and 160 to 280 eV for the carbon filter. Computer processing has color-coded the intensity contours of the image to make it easier to see the intensity variations. The time variation of the x-ray intensity in the three channels is also shown graphically.

Transmission-Grating Streak-Camera Spectrometer

Our new transmission-grating spectrometer[3] differs from the two instruments described above and from the

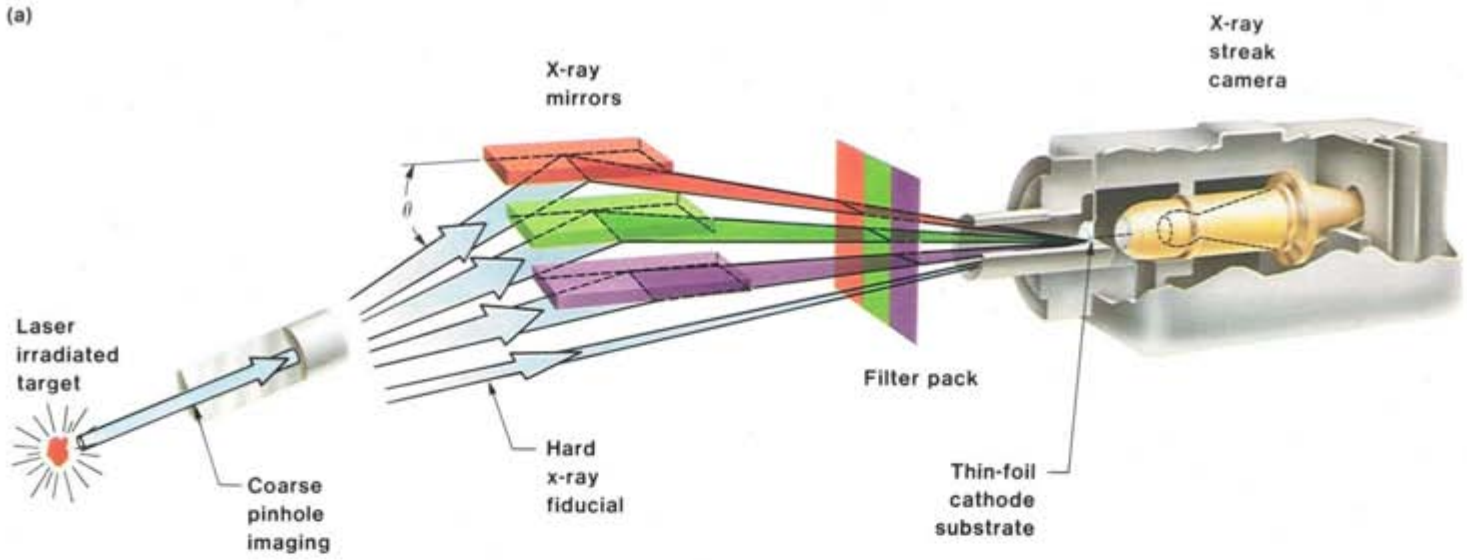
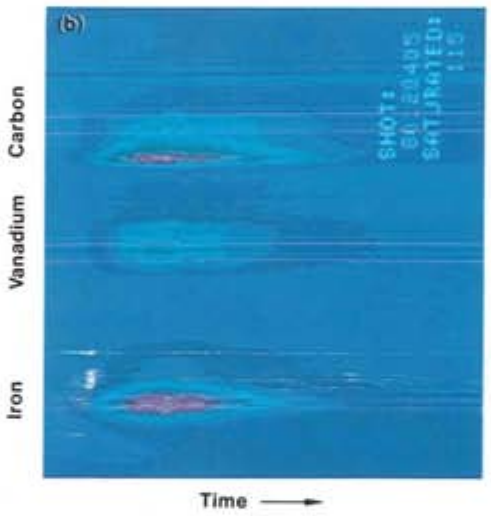


Fig. 2

(a) The three-channel reflector-filter streak-camera spectrometer for measuring soft x-rays, as mounted on Shiva. (b) Computer-enhanced color and (c) microdensitometer traces of reflector-filter spectrometer data.



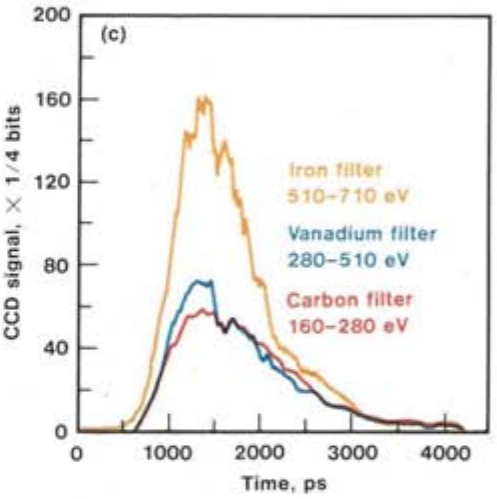


Table 1 Resolution and range parameters for various x-ray detection systems.

System	Resolution: Energy, E/ΔE	Resolution: Time, ps	Energy range, keV	Channels
Low energy				
Dante	2.0–4.5	150	0.01–2.0	10
Multilayer-mirror streak	30–100	20	0.1–1.0	5
Reflector-filter streak	3–10	20	0.2–0.7	3–6
Transmission-grating streak	4–125	20	0.1–1.5	Continuous
High energy				
Filter fluorescer	3–9	500–3000	1.5–100	10
Optical streak	about 1	10	above 25	1
Hyper filter fluorescer	1	—	150–300	4

Dante spectrometer in that it produces a continuous record of the x-ray spectrum over a broad range instead of a series of discrete moderate or narrow slices (Fig. 3). This is useful in cases involving line radiation, which may occur at some energy between those selected by the mirrors or filters and thereby be overlooked in our measurements.

The geometry for this instrument is shown in Fig. 4. A free-standing linear array of gold slats (arranged like the slats in a Venetian blind) about 0.5 μm wide and spaced 0.3 μm between centers functions like a diffraction grating in an optical spectrometer.[4] It disperses the x-rays from the experiment into an energy spectrum along the slit of an x-ray streak camera. With this instrument, we made the first time-resolved *continuous* low-energy (100 eV to 1.5 keV) x-ray spectrum measurement from a laser irradiated target, as opposed to constructing the spectrum from discrete Dante measurements.

The resulting streak-camera record (Fig. 4 inset) yields direct experimental observation of prominent line radiation and absorption bands. The first bright band is made by undispersed x rays that came straight through the gold transmission grating. Next comes a broad band of high-energy (0.7- to 1.1-keV) x rays, actually unresolved line radiation from recombinations involving N-shell electrons in gold ions in the plasma. The darker band following is an artifact of the instrument, caused by

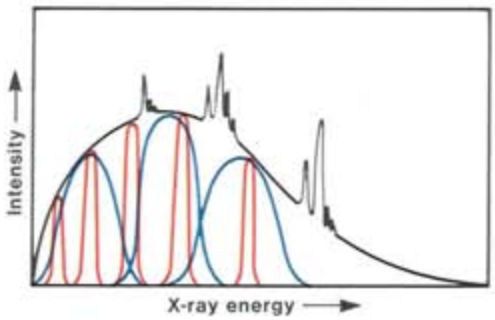


Fig. 3

A hypothetical x-ray spectrum and typical response curves for the multilayer-mirror spectrometer (red), the reflector-filter spectrometer (blue), and the grating spectrometer (black).

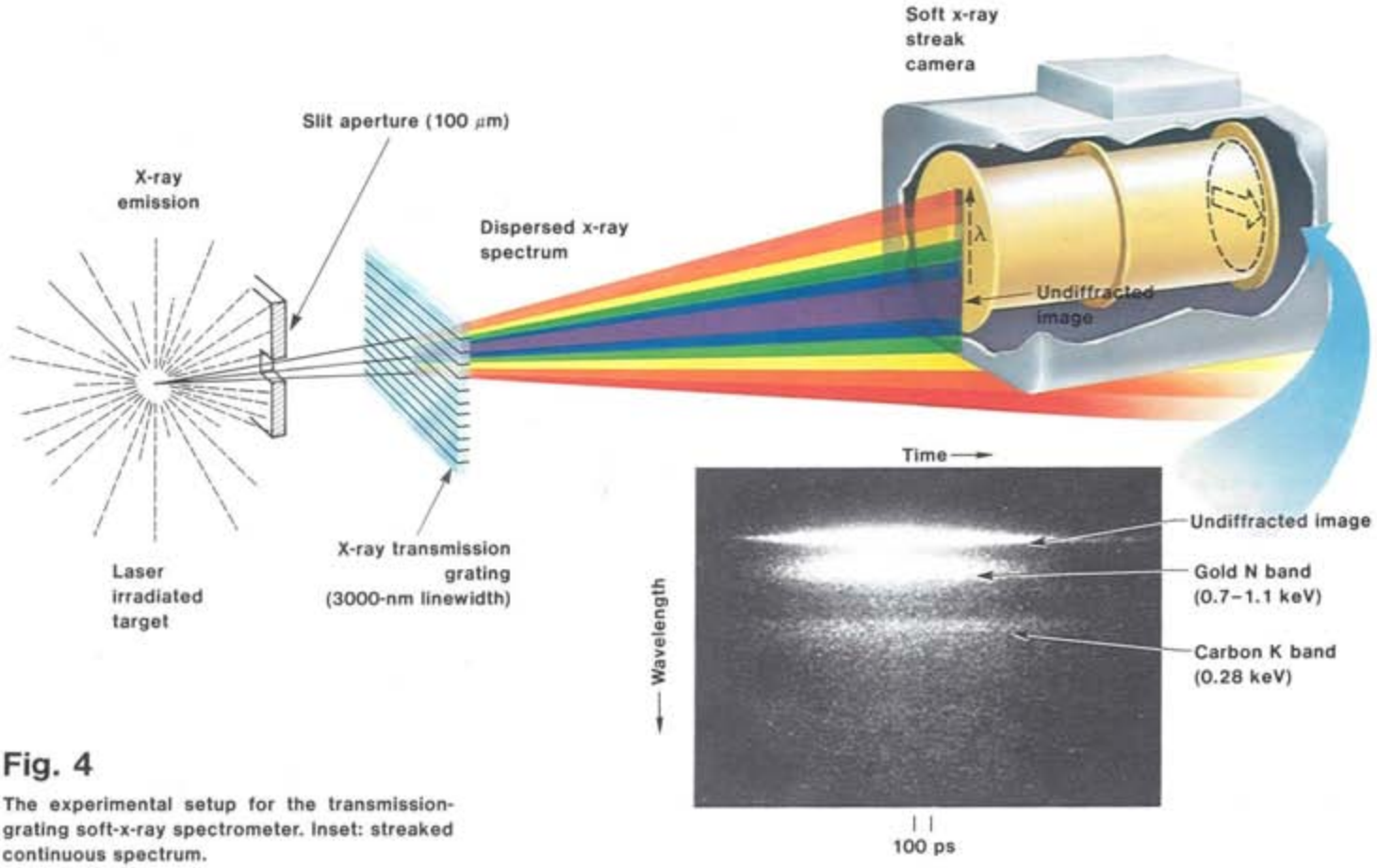


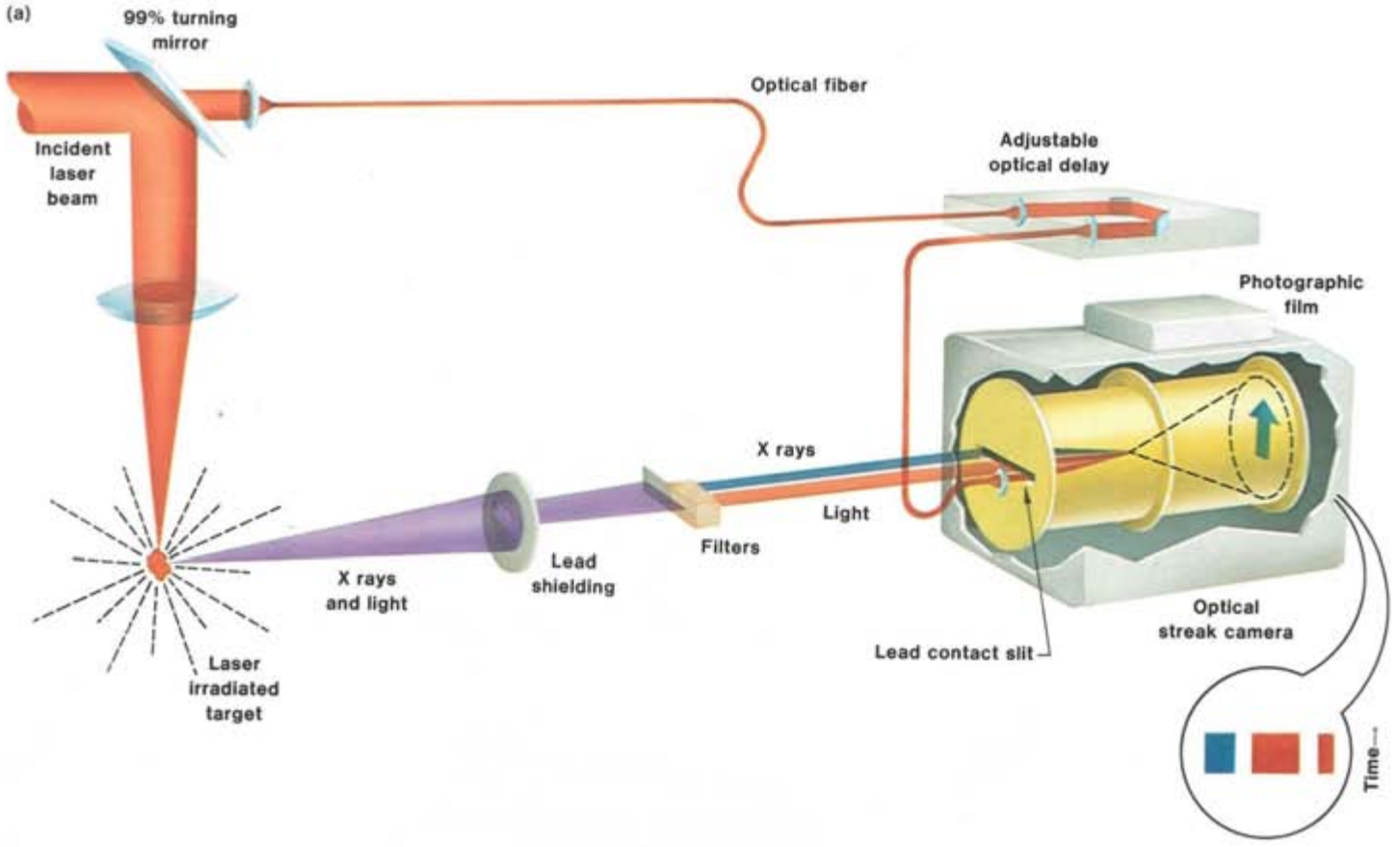
Fig. 4

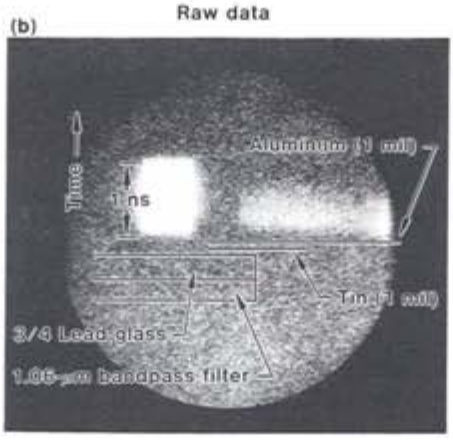
The experimental setup for the transmission-grating soft-x-ray spectrometer. Inset: streaked continuous spectrum.

absorption of x rays in the streak-camera entrance window. The bright band after that is part of the continuous low-energy x-ray spectrum, illustrating the sharpness of the window's K-edge cutoff at 0.28 keV.

Optical Streak Camera X-Ray Spectrometer

The three spectrometers discussed above perform best in the low-energy range (0.01 to 2 keV) and discriminate against the high-energy x rays (2 to 300 keV). These high-energy x rays are important, however, because they serve as a measure of the suprathermal (high-energy) electrons. It is one of our goals to suppress these electrons because they can preheat the fuel in a laser fusion target, stiffening it against compression and thereby interfering with the implosion.





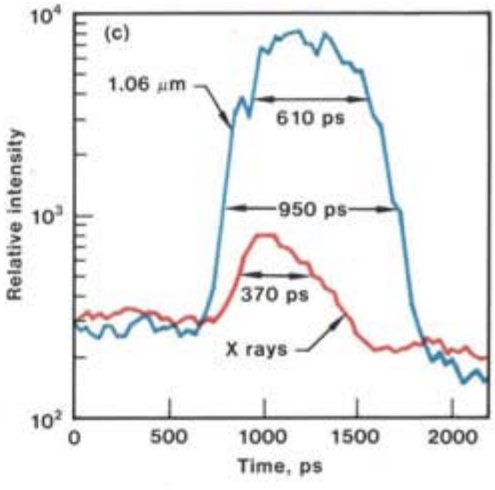


Fig. 5

(a) Experimental setup for the optical/x-ray streak camera, showing the system for introducing a fiducial marker (the optical fiber and related components at the top of the figure). (b) Streaked image from experiment; (c) resulting microdensitometer trace.

Among clues to the nature of these high-energy electrons (and to possible methods of eliminating them or preventing their formation) are the shape of their energy spectrum and the time history of their appearance during the laser heating. It is also important to measure their absolute intensity. We have made major advances in techniques for measuring these quantities.

Our original instrument for measuring high-energy x rays is the filter-fluorescer spectrometer, which is effective to about 100 keV. This technique is similar in principle to the simpler x-ray filter-detector spectrometer (Dante), but it is effective in a much higher energy range. However, the time resolution for the filter-fluorescer spectrometer is limited by the time response of its detectors. The fastest of these, a fluor-microchannel plate combination, has a time resolution of 500 ps; most of the other channels record at 3000 ps.

Our new high-energy x-ray spectrometer uses an optical streak camera as a combination detector-recorder. It responds to optical light and to x rays energetic enough to penetrate its thick entrance window. Its time resolution is 10 ps. By simultaneously measuring the scattered laser light and high-energy x rays, we determine when the hot electrons were produced with respect to when the laser light was being absorbed.

We interpose a compound filter that transmits x rays only on one side (left, Fig. 5) and light only on the other (right, Fig. 5). X rays pass readily through thin aluminum foil, which is totally opaque to visible and infrared light. A layer of lead glass about 2 cm thick, however, can stop x rays and yet be transparent to infrared (1.06-μm) light from the laser.

Figure 5 outlines the experimental setup. X rays and scattered 1.06-μm light from the target pass through the filter and are measured. We also bring in 1.06-μm light by a separate channel to serve as an optical fiducial to mark the instant when the incident laser light strikes the target.

As mentioned above, the optical streak camera responds to x rays only if they are energetic enough to pass through its entrance window. We are having a special thin-window streak camera made, using a mica window, to incorporate several lower energy channels into the same instrument.

Figure 5 also shows the streaked image from such an experiment and the resulting microdensitometer trace indicating the variations of intensity with time of incident laser light (1.06-μm wavelength) and x rays above 25 keV. The x rays occur early in the laser light pulse and die away while the laser is still delivering energy at nearly peak intensity. These results depend on the target used, and their full significance is still under investigation.

Hyper Filter Fluorescer Spectrometer

The standard filter fluorescer technique was developed in the Nuclear Test Program for Nevada applications.[5] It uses elemental materials in combination so that their x-ray edges define the spectral slice seen by each channel in the spectrometer (Fig. 6). The filter passes x rays of low energy and cuts off those above a certain value (different for each material). The fluorescer responds to x rays above a certain minimum energy by emitting x rays of a characteristic energy. If we choose a pair of materials such that the filter's cutoff is just above the fluorescer's threshold, the response of a detector shielded from all direct radiation and seeing only the x rays from the fluorescer will be proportional to the intensity of x rays in a narrow slice of the original x-ray spectrum.

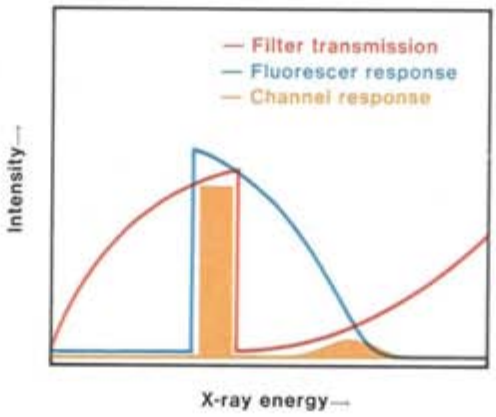


Fig. 6

Filter-fluorescer operation. The brown area indicates the detector response, which is proportional to the product of the filter transmission (blue) and the fluorescer response (red).

This scheme suffers from a few drawbacks and limitations. Neither the filter nor the fluorescer behaves exactly according to the above description, so that the detector also sees a contribution from the small high-energy bump (due to a higher energy x-ray edge) in the response curve (Fig. 6). Various methods have been developed to suppress this bump, confining the instrument's response more nearly to the desired narrow spectral slice.

Another limitation has to do with the available materials. The K-edge cutoff of uranium, the highest of any practical filter material, is about 120 keV. Making a filter-fluorescer responsive to energies above 120 keV required a rethinking of the entire detection scheme.

What we did, in essence, was to choose a set of "incompatible" filter-fluorescer pairs. We kept the experimental geometry the same, but used a fluorescer whose threshold was above the filter's cutoff energy. This eliminated the usual spectral slice, leaving only the high-energy bump.

Stated thus, this seems like a trivial accomplishment, but the result is not. The standard scheme for measuring these x rays above the range of the normal filter fluorescer was to use a thick lead filter on a Dante-style filter-detector instrument. This effectively removed all x rays below a certain energy, but it registered all the rest, no matter how high their energy. Our new filter-fluorescer technique registers mainly those x rays within a given energy range, discriminating against those both below and above, and giving much better spectral definition to the measurements.

We used this technique at the Shiva laser facility to produce the spectrum shown in Fig. 7; our highest energy point is well above 300 keV.

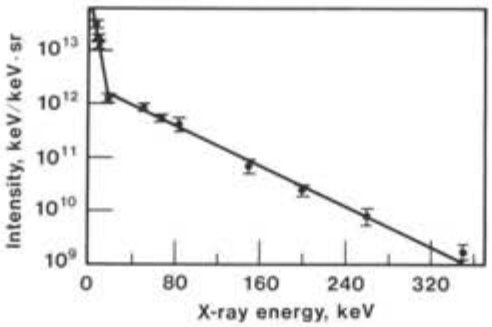


Fig. 7

Composite high-energy x-ray spectrum obtained with the filter fluorescer x-ray spectrometer (up to about 100 keV) and the hyper filter fluorescer spectrometer (out to more than 300 keV).

Conclusion

We have developed an array of spectrometers of various sensitivities and temporal resolutions. These advances expand the range of phenomena we can investigate, both in energy and in time. Together with our already extensive instrumentation, they give us the capability to provide timely and accurate data in the rapidly evolving fields of plasma physics and inertial confinement fusion.

We have already acquired a great deal of experience with Dante and filter fluorescer spectrometers and have ben able to perform absolute calibrations that enable us to make quantitative measurements. So far, however, none of our new instruments has been calibrated absolutely, and this produces only relative measurements; we still need to supplement their output with simultaneous Dante and filter fluorescer measurements. Only when we devise absolute calibrations for these new instruments, or do enough cross comparisons, will it become possible to lessen our reliance on the Dante and filter fluorescer spectrometers.

Key Words: Dante; diagnostics—ICF; inertial confinement fusion (ICF); laser fusion—experiments; streak camera; x-ray spectroscopy.

Notes and References

1. G. Stradling, *Multilayer X-Ray Interface Mirrors for an Improved SXRSC Spectrometer*, Lawrence Livermore National Laboratory, Rept. UCRL-50021-80 (1980).
2. R. Kauffman, G. L. Stradling, E. L. Pierce, and H. Medecki, *Quantitative Measurements Using Soft X-Ray Streak Cameras*, Lawrence Livermore National Laboratory, Rept. UCRL-85977 (1981).
3. N. M. Ceglio, R. L. Kauffman, A. M. Hawryluk, and H. Medecki, *A Time-Resolved X-Ray Transmission Grating Spectrometer for Investigation of Laser Produced Plasmas*, Lawrence Livermore National Laboratory, Rept. UCRL-87800 (1982); this instrument was used in the experiment described on p. 23 of this issue of *Energy and Technology Review*.
4. A. M. Hawryluk *et al.*, *J. Vac. Sci. Tech.* **19**, 897 (1981).
5. The technique of x-ray spectral analysis using K-edge filters and fluorescers has been developed during the last three decades at LLNL and Los Alamos. See C. L. Wang, *Rev. Sci. Instrum.* **52** (9), 1317 (1981).