2.B Computerized, Wide-Bandwidth, Multichannel, Soft X-Ray Diode Spectrometer for High-Density-Plasma Diagnosis

The analysis of transient, high-density plasmas such as those produced by high-power lasers and pulsed-power systems often demand a precise, quantitative characterization of the emitted soft x rays. In many cases, such a characterization provides a reliable estimate of the total, radiated x-ray flux, and this has important implications for the radiation and electron thermal transport within the plasma. It critically affects our understanding of the mechanisms responsible for energy absorption, wave propagation, and hydrodynamic instabilities in the plasma. In high-density plasmas these processes occur on a nanosecond time scale. Monitoring the x-ray flux requires a calibrated, broadband, soft x-ray (100- to 2000-eV) spectrometer having a signal bandwidth sufficient to resolve subnanosecond-emission features.

There are, in principle, two architectural approaches to satisfying this requirement for subnanosecond-resolution, broadband, soft x-ray spectrometry on high-density experiments. In many respects they are complementary. The first approach, implemented on several major high-density-plasma facilities, involves using several calibrated x-ray diodes[1] separately filtered for different bands of the soft x-ray region by the incorporation of either K-edge, L-edge, or M-edge filters or specific bandpass x-ray mirrors coated with reflective multilayer structures.[2] The stability of simple metal cathodes used in the x-ray diodes has been studied in detail.[3,4] With a few exceptions, the calibration stability of most metal cathodes has been found to be constant over long time periods (several months) under the typical conditions for these types of experiments, which necessitate frequent vacuum cycling and occasional exposure to oxygen, air, and other elements. With two exceptions,[5,6] the majority of x-ray diodes used in these investigations have response times of several nanoseconds or longer. A spectrometer incorporating diodes having subnanosecond time resolution significantly increases the complexity of the overall system. The diodes themselves must be impedance matched to maintain the signal integrity, and a GHz signal detection system must be used. The fastest commercially available single-pulse oscillographic systems have detection bandwidths of ~1 GHz.[7]

An alternative method of time-resolved, broadband, soft x-ray spectrometry with much greater (≈ 10-ps) temporal resolution is through the incorporation of an x-ray streak camera[8] with an x-ray energy filter system, such as a set of K-edge, L-edge, and M-edge filters[9] or an array of multilayer mirrors,[10] or with a weak x-ray dispersive element such as a freestanding grating.[11,12] The advantage of the latter system is the availability of greater spectral resolution ($\lambda/\Delta\lambda$ up to 100). In addition, systems incorporating streak cameras having soft x-ray photocathodes, usually utilizing thin layers of materials such as Al, Ag, CsI, etc., deposited on 1000-Å plastic foils, and transmissive dispersive optics are difficult to absolutely calibrate, and the calibration stability is less than that of simple metallic x-ray diodes.

Thus, these two approaches are complementary. While a multichannel x-ray diode system provides the greatest calibration stability, a streak camera with dispersive optics[10] has greater spectral and temporal resolution.

At LLE we have recently incorporated both approaches to soft x-ray spectrometry on the OMEGA laser target irradiation facility. A broad array of x-ray diagnostics is now deployed on this facility, including high-resolution x-ray crystal and XUV grating spectroscopy, multichannel hard x-ray (1- to 300-keV) spectrometry, time-resolved x-ray crystal spectroscopy, pinhole camera and microscopic x-ray imaging, and time-resolved streak imaging.

This report describes in detail a multichannel (four-channel), ultrafast (> 1-GHz), soft x-ray diode spectrometer recently deployed jointly by LANL and LLE on the OMEGA target irradiation facility. Signals from these calibrated detectors, which incorporate various thin-film filters to discriminate between different x-ray spectral regions, are recorded on a computerized multichannel digital oscillographic system having an overall bandwidth in excess of 3 GHz.

Multichannel GHz X-Ray Diode Spectrometer

Filtered x-ray photodiode spectrometers have been employed in the ICF community since the early to mid-1970s.[13,14] During this period different photocathode materials were tested, including Si, Al, C, V, Fe, and Cu. In these tests Al showed superior stability and response for channels below 800 eV.[2] The detectors were monitored by standard oscilloscopes.

The X-Ray Photodiodes

The MINIFLEX detector (originally developed by LANL for use on the eight-beam, HELIOS, high-power, CO_2 laser irradiation facility) is built around four identical soft x-ray photodiodes. It is patterned after the seven-channel MULTIFLEX detector used on HELIOS from 1979 to 1983.[4] The principal components of each diode are shown in Fig. 25.16. Each diode is composed of a 50-mesh/inch anode positioned some 1.25 μm in front of a micropolished (dry-diamond-machined) aluminum cathode with an active area of 1.5 cm^2. Experience demonstrates superior long-term stability of micropolished aluminum photocathodes over rough-finished aluminum photocathodes, with some loss of sensitivity for the micropolished cathodes.[16] These aluminum photocathodes cover a nominal sensitivity range from about 60 eV to over 2 keV.[4]

The photocathode is electrically and mechanically attached to a modified vacuum-feedthrough RF connector. Both are positioned inside a vacuum-compatible cavity that also supports the anode and provides the vacuum interface.

The electrical response characteristics of each diode have been measured using picosecond time-domain reflectometry (using a Tektronix S-52 pulse generator and a Tektronix S-6 sampling module in a Tektronix 7S12 time-domain reflectometer). Each diode displayed a

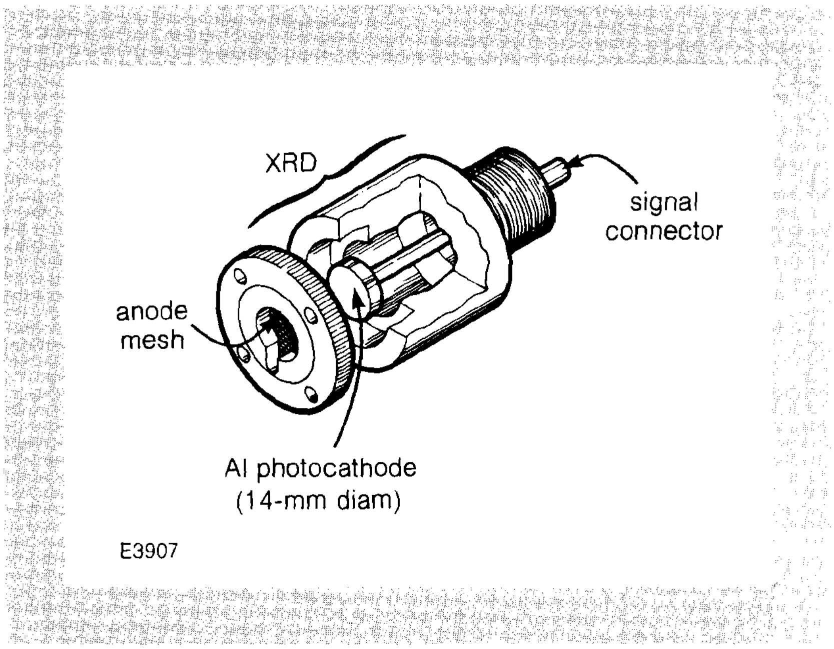


Fig. 25.16
Details of the soft x-ray diode used in the x-ray spectrometer.

nominal response bandwidth of 1.7 GHz. The overall diode sensitivity is dependent on the intrinsic photocathode response, the filter transmission function, and the attenuation of the gold-mesh attenuators. The latter was measured using alpha particles and a surface-barrier spectrometer. *In situ* it was compared with identically filtered but unattenuated channels. The sensitivity of the Al photocathodes was determined from detailed measurements made with dc x-ray sources and calibrated proportional-counter detection.[17] The filter transmission functions were determined from tabulated transmission data and accurate mass and thickness measurements of the individual foils.

The convolution of these three functions then provides an overall sensitivity function for each diode. Typical response functions for a set of four x-ray diode channels used in subkilovolt x-ray emission measurements of laser-produced plasmas are shown in Fig. 25.17.

The X-Ray Diode Detector Assembly

Four x-ray diodes are assembled into an array to form the detector assembly. The x-ray diodes are mounted in a Kel-F[17] plate, which serves as the rear cover for the evacuated, stainless-steel detector housing and provides electrical isolation for the negatively biased diodes. This detector head consists of four individual channels each comprising the x-ray attenuator mesh, the filter stack, a sweeper magnet and collimator tube, and the x-ray diode as shown in Fig. 25.18. Sweeper magnets help inhibit charged particles from entering the diode. In principle, the long time of flight of the charged particles compared to that of the x rays should delay any background. The detector assembly incorporates the four diodes into a single, small-diameter head that attaches to the OMEGA target chamber via a 1.5-m, evacuated flight tube and a gate valve. The flight tube and detector head are evacuated to target-chamber vacuum ($\sim 4\times10^{-6}$ Torr). The gate valve and vacuum interconnects allow intershot modification of filter values of individual channels without perturbation to the rest of the system.

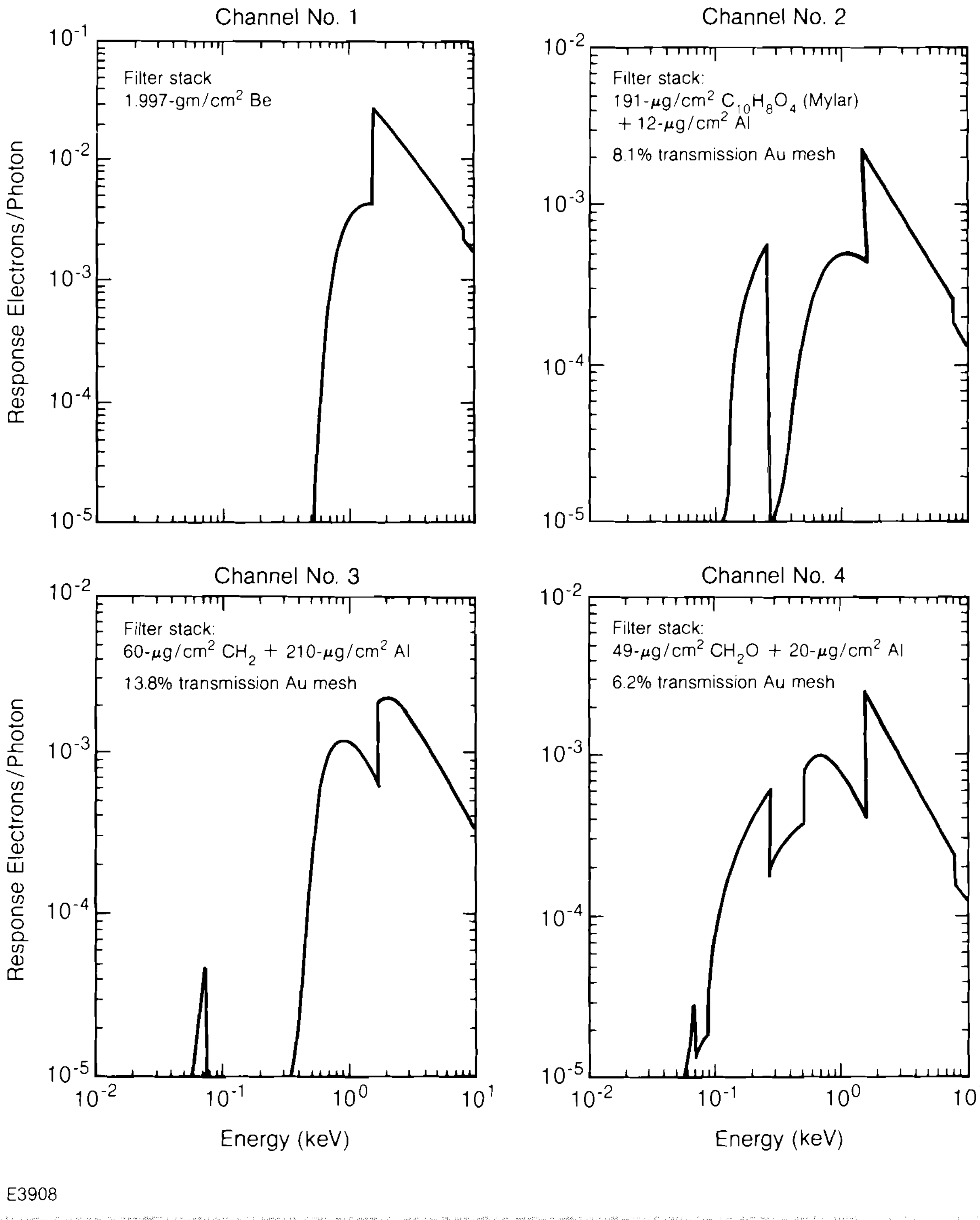


Fig. 25.17
Detailed response curves for the four diodes used in the x-ray spectrometer. These are a convolution of the Al photocathode sensitivity, the filter transmission function, and the attenuation of the anode and the attenuator.

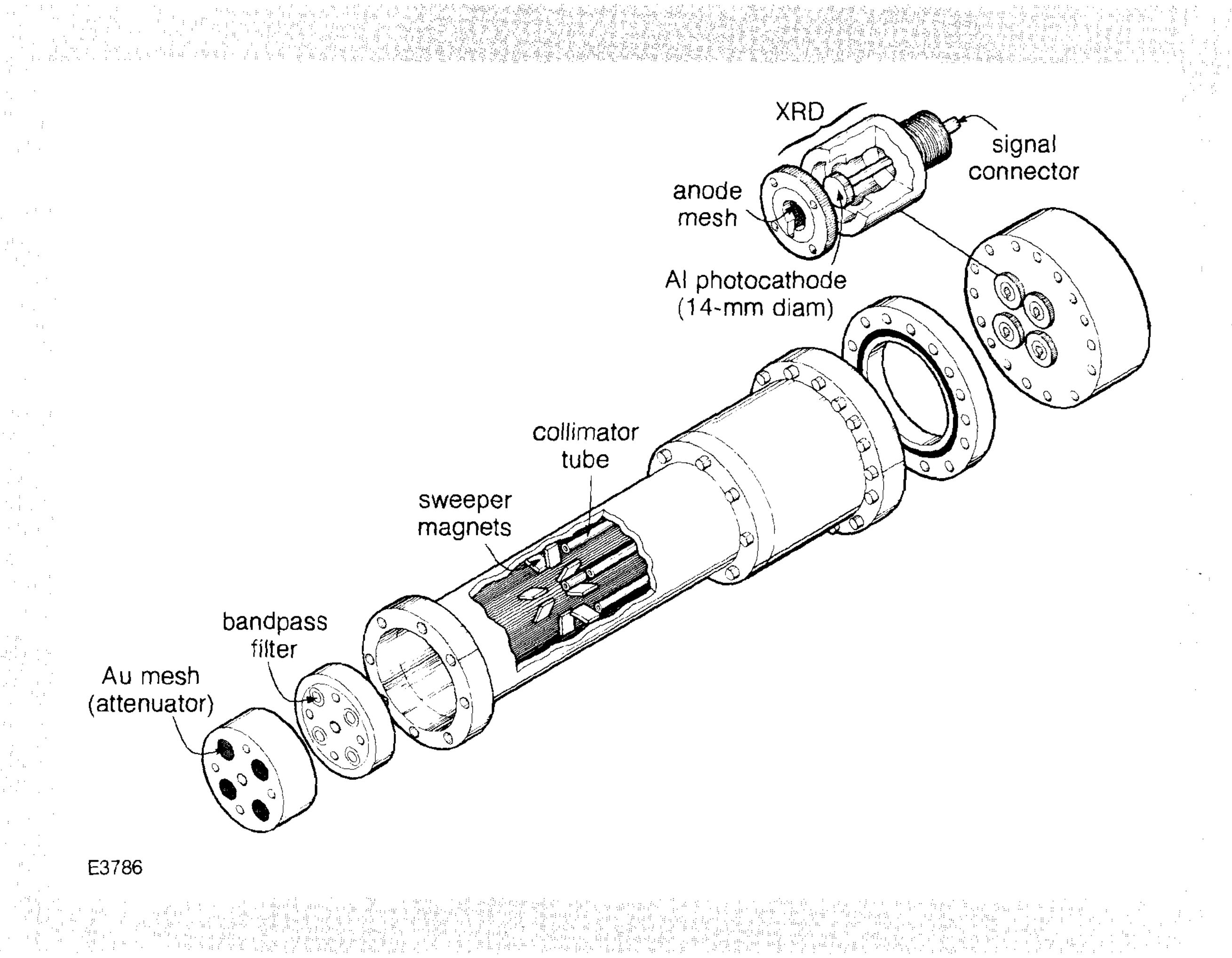


Fig. 25.18
Configuration of the four-detector array in the soft x-ray spectrometer housing.

Signal Recovery

The signal acquisition system used with this x-ray diode spectrometer is based on four Lockheed-modified Tektronix LM7912A transient digitizers. These digital oscilloscopes have been modified[17] to exploit the generic bandwidth of their type 7910 cathode ray tubes. This modification resulted in the designation change from Tektronix R7912 to Lockheed/Tektronix LM7912A. The LM7912A transient digitizer has a bandwidth of 3.5 GHz at the −3dB point, less than 5% undershoot and overshoot, with a 12-bit output (2 mV/bit). It operates under CAMAC control via the Tektronix 7912DPO bus interface. The signal from each x-ray diode is fed via 3 m of RG-214 coaxial cable to a high-speed biasing capacitor, which is connected through 1 m of 50-ohm, semirigid coaxial cable to each of the digital oscilloscopes (see Fig. 25.19). High-bandwidth signal attenuators are optionally inserted into the semirigid leg of the system, as each LM7912A offers only fixed vertical amplification. The LM7912As and their CAMAC crate and controller, as well as timing-control hardware and an on-board calibration pulser, are positioned some 3 m from target center inside an EMI-shielded rack.

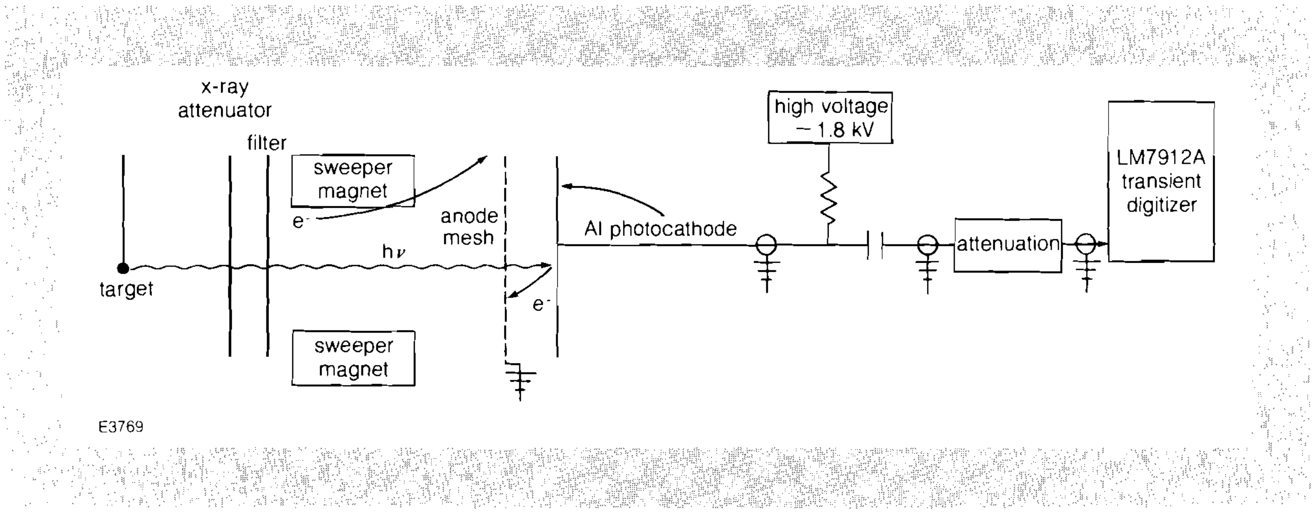


Fig. 25.19
Schematic of the signal acquisition details of each soft x-ray diode.

In order to calibrate the bandwidth response of the system, we substituted a Tektronix S-52 70-ps rise-time pulser in place of the x-ray diode in each acquisition arm. We then acquired traces of this fast-rise pulse using the acquisition system in standard calibration mode (i.e., normal acquisition sequence, with a generated trigger and signal). As shown in Fig. 25.20, the measured 10%–90% rise time of this 200-mV, 70-ps rise-time input pulse was observed as a 200-mV, 130-ps rise-time pulse. Thus, we determined that each acquisition arm performs at a nominal 2.7-GHz bandwidth response at the −3dB point.

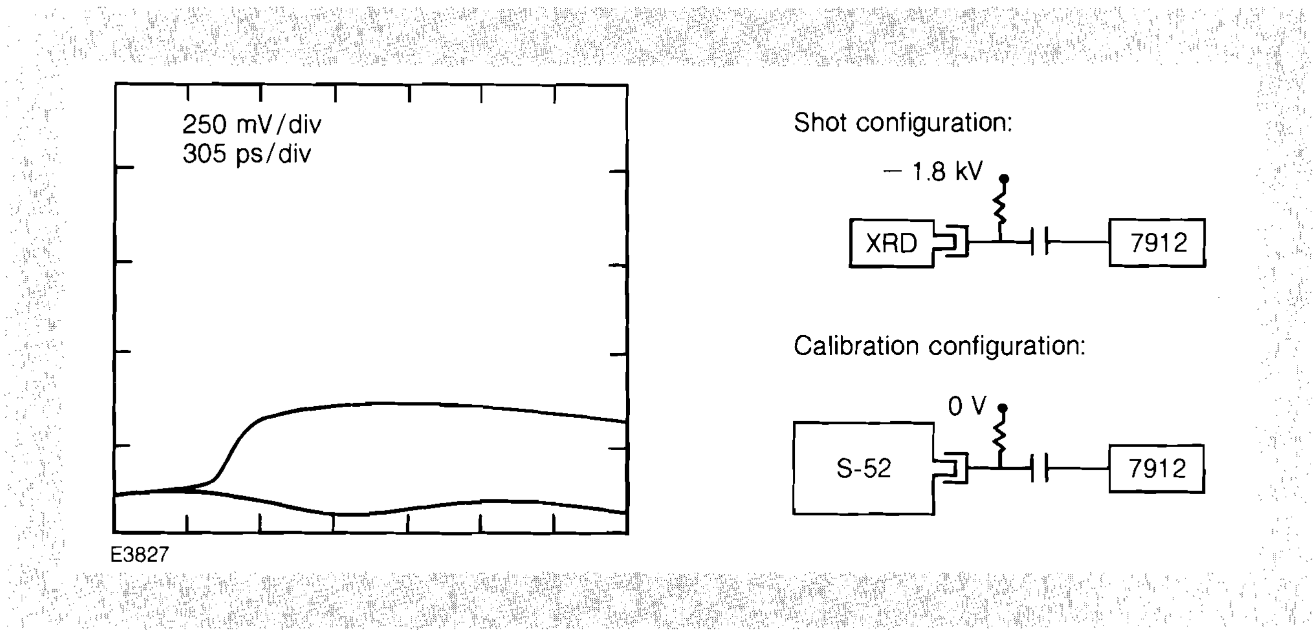
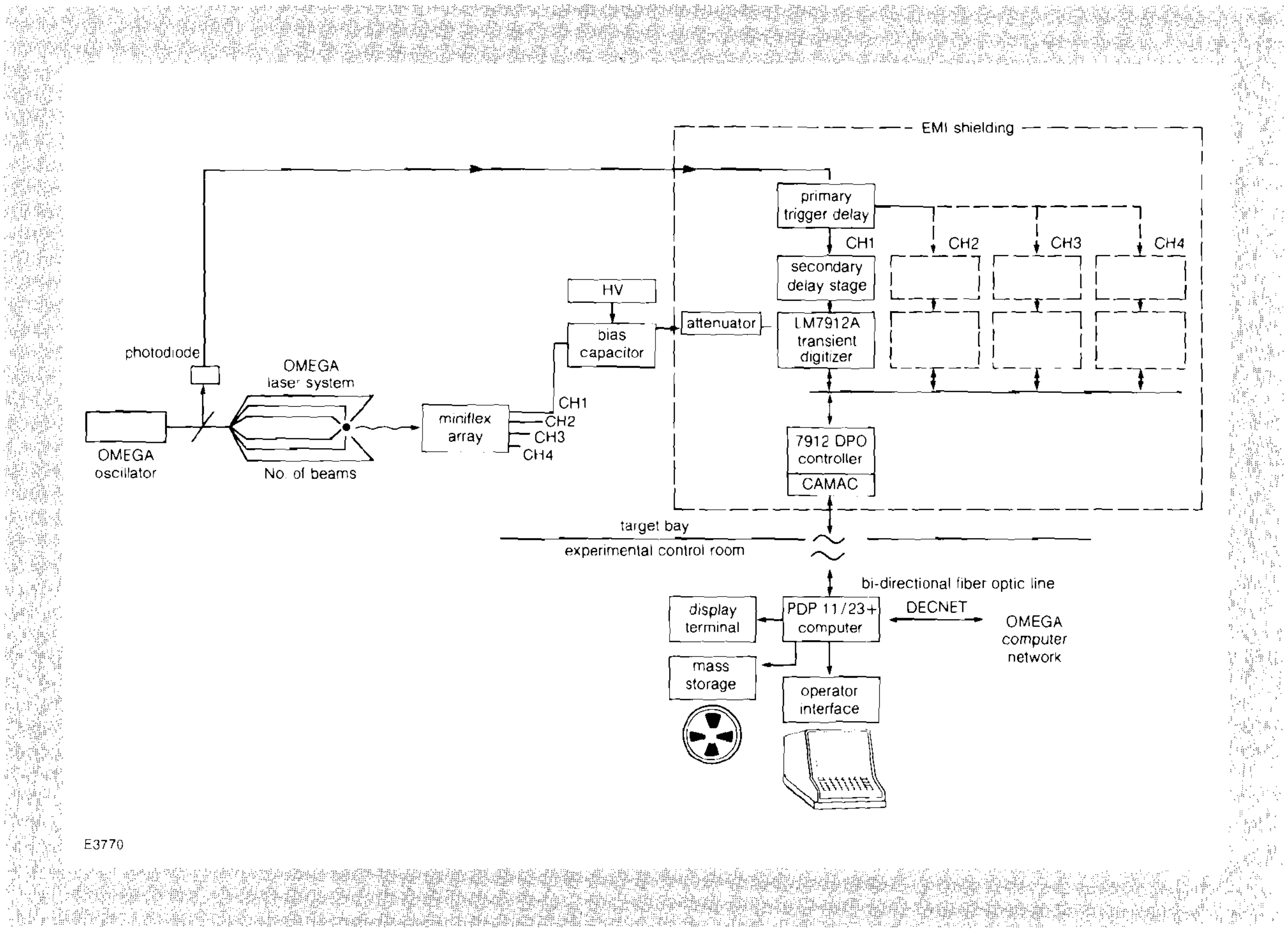


Fig. 25.20
To measure bandwidth response of the acquisition arm, the x-ray diode is replaced by a Tektronix S-52 70-ps, 10-mV pulser. The LM7912A transient digitizer outputs a 130-ps rise-time pulse. This test includes all cables and electrical components for each of the four acquisition arms of the system. As shown, a bandwidth of 2.66 GHz at the −3dB point is confirmed.

Data Recovery

The four LM7912A transient digitizers are all controlled over a Tektronix CP bus, which connects via a Tektronix 7912DPO controller to a fiber-optical-linked CAMAC serial highway. The CAMAC crate and DPO bus are housed along with the LM7912As in the EMI-shielded rack, while the fiber-optic link leads down through the concrete target-bay floor to the OMEGA target diagnostics processor, a DEC PDP 11/23+ operated under RSX-11M. This system is outlined in detail in Fig. 25.21, which shows a schematic of the overall architecture of the transient digitizer acquisition system. The OMEGA target diagnostics processor interconnects into the OMEGA laser system computer network via DECNET. Since many of the OMEGA target diagnostic systems operate under CAMAC, a modular, parameter-driven software scheduling system is used under which individual FORTRAN routines are controlled separately. Modules have been written that initialize and arm the LM7912A transient digitizers, acquire base-line data just prior to each shot, rearm for the event, acquire and archive the shot data, and display and perform preliminary data reduction. These operations are done automatically. Alteration of the vertical amplification of the LM7912A digitizer is facilitated by an attenuation selection. The system may be disabled, when desired, via a menu-driven, parameter-configured operator interface. This interface is common to all of the OMEGA computer-controlled target-diagnostic systems.

Fig. 25.21
Schematic of the signal acquisition and control system of the four-channel, 3-GHz, digital oscilloscope system.



Initial synchronization of the data-acquisition cycle to the timing sequence of the OMEGA shot-diagnostic acquisition system is done through the central computer system, while final synchronization of the data acquisition to the shot is accomplished with a hard-wired timing signal derived from a fast photodiode situated at the front end of the OMEGA laser chain. This photodiode signal is transmitted on a separate HELIAX cable to the EMI-shielded acquisition system and is then run through several delay stages before triggering each separate LM7912A digitizer in synchronism. On the fastest time-base setting used, the acquisition window for each LM7912A digitizer is only 2 ns wide. Synchronization accuracies are better than 100 ps. Synchronization of the triggering of the digitizers is accomplished by substituting a signal from a photodiode mounted on the OMEGA target chamber for each of the x-ray diode signals. The substitute diode samples a lower-power laser pulse propagated from the oscillator through the OMEGA laser system, which serves as a timing mark to synchronize the triggering of the transient digitizers to the laser target interaction. Once each digitizer channel is synchronized to this signal, an offset delay is added to each digitizer trigger-input line to account for the additional x-ray time of flight from the target to the x-ray diode detector array. This system, therefore, ensures minimal (less than 50-ps) triggering jitter in the signal acquisition of the four digitizers.

During each shot cycle, after being automatically armed for a single sweep, the LM7912As are triggered by the photodiode monitoring the laser pulse. The writing beam of the LM7912A encodes the trace on a 512 by 512 diode array in real time. The diode array is then recharged by a reading beam scanning the array over the next 85 ms. These data are stored in on-board memory, and each LM7912A awaits recovery of the data by the controlling software routines. Two files are being written for each OMEGA target shot, one for base-line data and one for event data. Each file carries a system header, followed by four subfiles containing channel data (each from a system parameter file) and that channel's data set. Following the shot, preliminary reduction is performed under full automatic control. Scaling and correction of the data is made for each channel, using previously determined calibration data for that channel. The signal duration (FWHM), peak voltage, and integrated charge are calculated from the digitized signal and base-line record. The base-line and event curves are then displayed on a video screen as a corrected plot with channel parameters and reduced data under the DEC REGIS graphics protocol. A hard copy of the data is created as well. The data files for a particular shot are then transmitted over the OMEGA data network for archiving, along with all other data files for that shot.

Soft X-Ray Measurements on Laser-Produced Plasmas

The soft x-ray diode spectrometer has been used in several experimental investigations on the 24-beam UV OMEGA laser system. Here we discuss interpretation of the time- and energy-resolved data acquired during two experimental programs. Both of these experiments used the soft x-ray diode spectrometer in the configuration described earlier. The only variation between them lies with the different electrical attenuation values ahead of the digitizers to accommodate the particular x-ray fluences germane to each experiment.

X-Ray Conversion Studies

The first[18] of these experiments was a joint LLE-LANL investigation of x-ray conversion in plasmas produced from solid, high-Z (Au)-coated targets at intensities in the range of 10^{13} to 10^{15} W/cm^2. The main purpose of this investigation was a comparison of the x-ray emission spectrum and the x-ray conversion efficiency with the respective findings from previous planar target experiments, and with detailed hydrodynamic computer codes.

As shown in Fig. 25.22, the energy resolution of this spectrometer is obtained by using different filter values for the four channels. The CH_2O/Al filter used in Channel 4 provides information across the 150-eV to 1.5-keV range, CH_2/Al in Channel 3 emphasizes the 700-eV region, Mylar/Al in Channel 2 observes 250 eV and 1 keV, and the Be filter in Channel 1 accepts emission above 800 eV.

The signals from the four channels are then iteratively deconvolved with the spectral response of each detector, to determine the spectral characteristics of the emission.

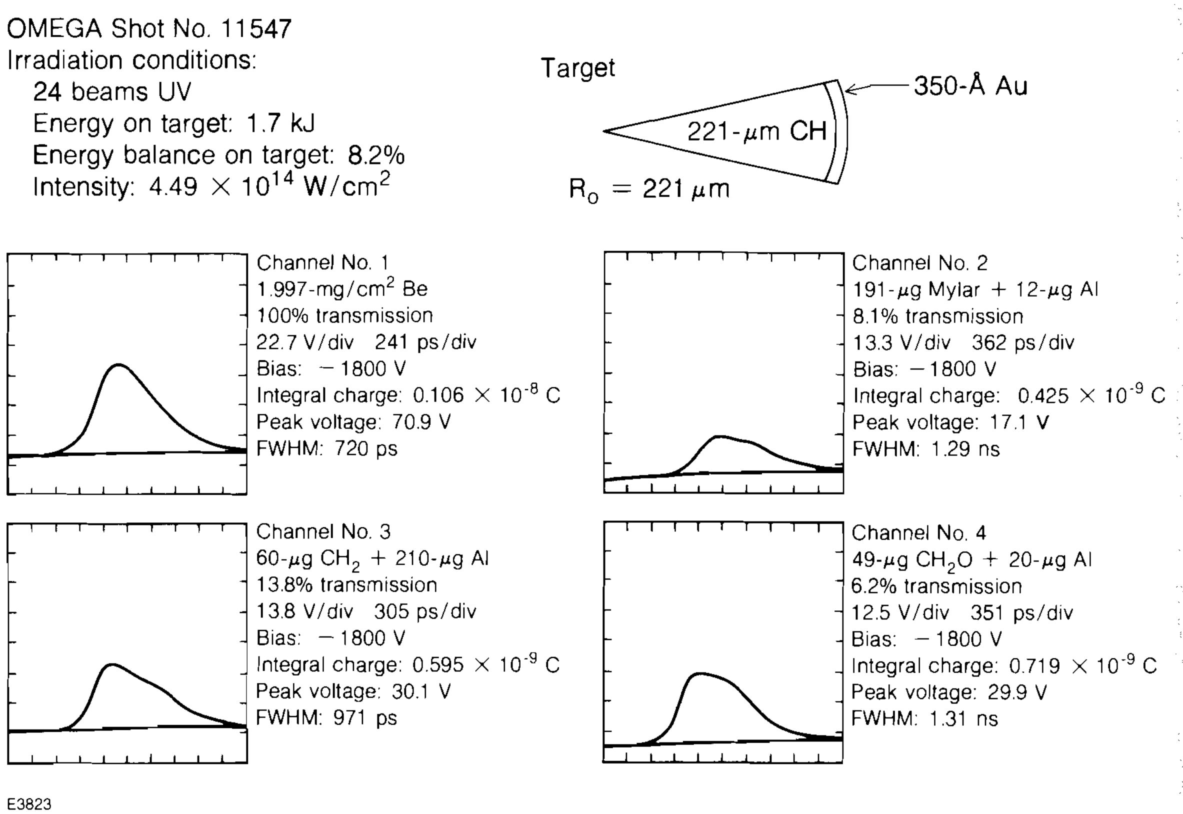


Fig. 25.22
Typical spectrometer data acquired in experiments on high-Z-coated targets.

Although the soft x-ray diode spectrometer provides only modest spectral resolution, the high temporal resolution, absolute calibration, and stability of each detector offers reliable, shot-to-shot comparisons of a variety of target parameters. In addition, the ease with which this system can be synchronized to the irradiating laser pulse permits accurate, temporal comparison of the spectral characteristics of the x-ray emission. At present, no other diagnostic system can embody all these characteristics.

Figure 25.22 provides an example for the four-channel output from a single target shot in this series. This particular target was coated with a thin (0.035-μm) layer of gold. The drop in the signal observed in Channels 2–4 results from the penetration into the CH target by the plasma ablation region. Note that in order to calculate the pulse duration (FWHM) and integrated charge one must also plot the base-line response of the system acquired just prior to the event.

Time-Resolved X-Ray Spectrometry of Imploding Laser-Fusion Targets

The soft x-ray diode spectrometer has also been used to acquire data on DT-filled glass-microballoon targets. These experiments[19] were motivated by the question of how symmetric implosions of spherical shell targets could be driven by the 24 351-nm beams of the OMEGA facility. One such series of target shots used large targets with very high initial aspect ratios ($R/\Delta R \sim 200$). Targets of 700- to 800-μm diameters were irradiated at modest intensities ($< 2 \times 10^{14}$ W/cm^2). The soft x-ray emission generated in these experiments originates from two sources. This is clearly evident from the set of four-channel x-ray diode data shown in Fig. 25.23. In the initial stages of the interaction, the laser light heats the solid glass shell. X-ray emission results in this case from the hot, dense, coronal plasma surrounding the target. As the shell accelerates inward, it decompresses and the coronal plasma becomes somewhat more tenuous, resulting in a progressive drop in the x-ray emission. Then, as the shell stagnates near the target center, the temperature of the shell is heated, producing a second burst in emission. Deconvolution of the signal from each of these detectors can thus provide valuable information on the coronal conditions during the implosion, on the x-ray emission at peak compression, and on the implosion time. For example, in the data shown in Fig. 25.23, the implosion time of the target can be deduced from the temporal separation (about 700 ps) of the two peaks in x-ray emission.

Summary

We have described in detail the four-channel soft x-ray diode spectrometer activated on the OMEGA irradiation facility for laser-fusion and high-density plasma physics experiments. This instrument is now providing useful spectral, as well as calibrated, soft x-ray emission rate data from different target experiments.

The present instrument provides time-resolved ($\approx$ 160-ps) data of x-ray emission produced by nanosecond laser beams. However, the current system bandwidth is limited by the signal bandwidth of the x-ray diodes. Anticipated future improvements include the development of diode assemblies having a bandwidth greater than the signal bandwidth

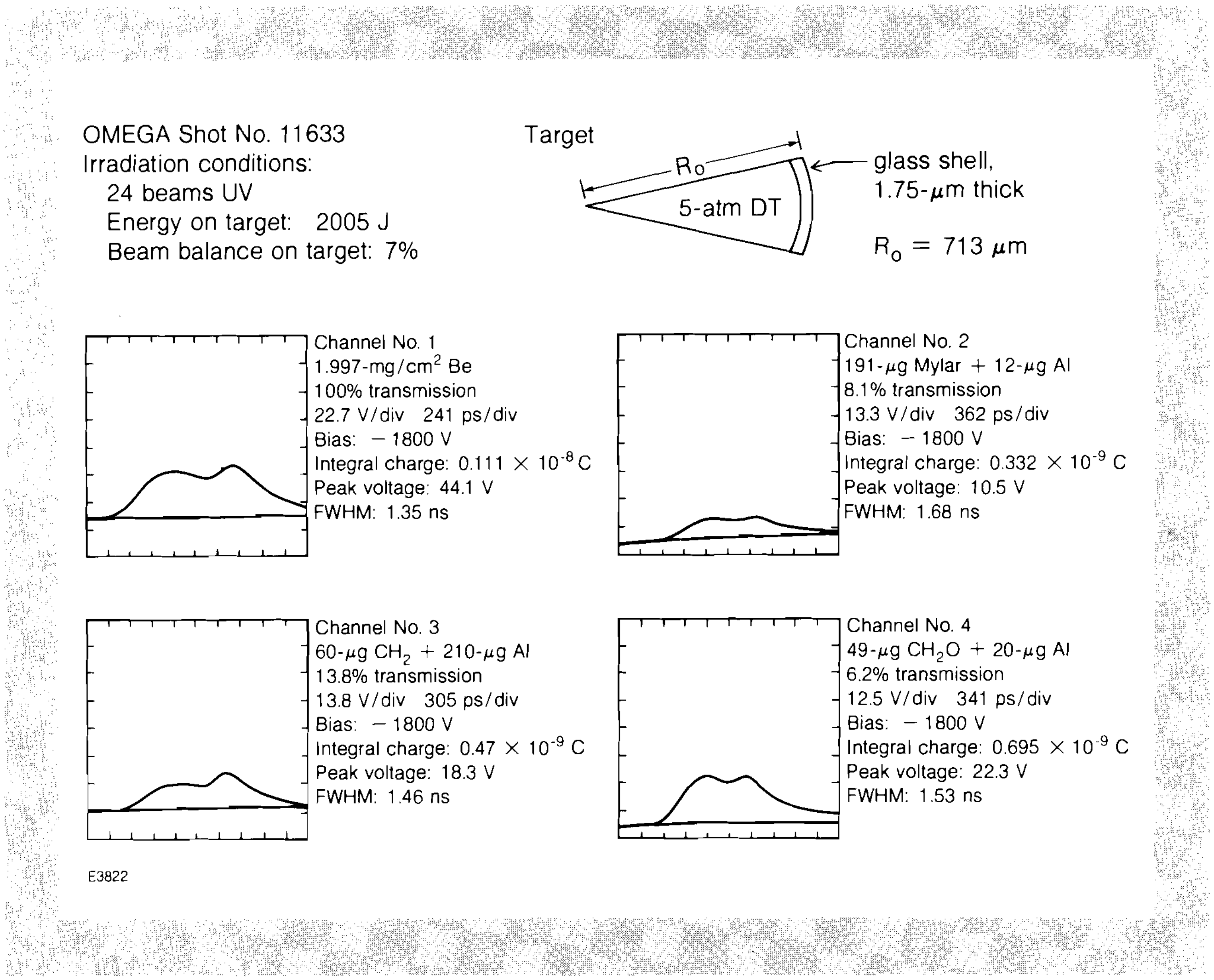


Fig. 25.23
Typical spectrometer data recorded on laser implosion experiments with large initial-aspect-ratio targets imploded at modest ($< 2 \times 10^{14}$ W/cm^2) irradiance.

of the recording digitizers. Such a development would permit the detection of x-ray emission with a time resolution of 100 ps.

The four-channel diode system described here uses foil filters for spectral resolution. These filters permit only a coarse interpretation of the x-ray spectrum. Future improvements would include the addition of more diode channels and the use of multilayer x-ray optical components to provide higher-resolution spectral discrimination.

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