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AUTHOR(S): P. B. Lyons, P-14

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TIME-RESOLVED X-RAY DIAGNOSTICS

P. B. Lyons

Los Alamos National Laboratory, P. O. Box 1663, MS 410, Los Alamos, NM 87545

ABSTRACT

Techniques for time-resolved x-ray diagnostics will be reviewed with emphasis on systems utilizing x-ray diodes or scintillators. System design concerns for high-bandwidth (>1 GHz) diagnostics will be emphasized. The limitations of a coaxial cable system and a technique for equalizing to improve bandwidth of such a system will be reviewed. Characteristics of new multi-GHz amplifiers will be presented. An example of a complete operational system on the Los Alamos Helios laser will be presented which has a bandwidth near 3 GHz over 38 m of coax. The system includes the cable, an amplifier, an oscilloscope, and a digital camera readout.

Nanosecond and sub-ns time resolution of low energy x rays may be achieved with at least three types of diagnostic systems. Photoelectric x-ray diodes or scintillators and optical detectors provide electrical signals for electronic recording and processing. The photoelectric process may also be used to provide a source of electrons for deflection in a streak tube.(1)

The first two types of diagnostic systems will be discussed in this paper. The paper is organized in sections that highlight specific sub-systems: the detector, the cable transmission system, the data recorder, supporting instrumentation, and system considerations. Examples will be drawn from experiences at the Los Alamos National Laboratory with the large CO_2 laser systems (primarily the Helios system). The final section reviews the parameters of an operational system at the Helios facility which is providing a 3 GHz bandwidth over 38 m of coax.

X-RAY DETECTOR

X-ray photoelectric diodes provide a very simple and, potentially, very high speed, detector for low energy x rays. The detector relies on x-ray interaction in an x-ray photocathode with subsequent release of photoelectrons, Auger electrons, and secondary electrons from the material surface.

The sensitivity of the detector is approximately proportional to the x-ray attenuation coefficient and demonstrates increased sensitivity in spectral regions (above x ray edges) with increased attenuation. The detector current is dominated by secondary electrons and is thus very sensitive to surface conditions. Surface conditions are, in turn, strongly influenced by the techniques used to prepare and store the photocathode. These concerns, as well as detailed sensitivity data, are available in published literature.(2-3)

The time response of an x-ray diode is governed by simple considerations. The detector geometry resembles a parallel electrode configuration. The response in such a geometry is simply calculated.(4) The rise time is given by the time for electrons to traverse the anode-cathode gap. The fall time is given by the RC time constant. The transition between the diode and the transmission line must be carefully engineered to minimize reflections. A poor transition can completely dominate the excellent time response possible with an optimized diode geometry. Rise and fall times below 50 ps have been demonstrated in an x-ray diode.(5) A FWHM for such a diode below 50 ps should be achievable.

Scintillators are also useful for low energy x-ray detection.(6) In a scintillator, the energy of incident x rays is transferred to excitation of the solvent (base plastic) molecules with subsequent transfer to other scintillating molecular species. The time response is dominated by the inter-molecular transfer times and the decay time of the final scintillator molecule. Standard commercial scintillators provide time response as short as 1.3 ns(7) and special scintillators provide time response below 200 ps with reduced light output.(8)

The choice between x-ray diodes and scintillators depends on several factors. The diodes will provide a faster system but require considerable care in surface preparation and protection for accurate measurements. A good vacuum, below at least 10^{-5} Torr, is essential for operation. Gain is achieved only with electronic amplification. The scintillators are less sensitive to vacuum requirements and care in storage but require that the photodetector be shielded from all extraneous sources of visible light. Gain is easily achieved if needed with photomultipliers (PMT), but the PMT may be susceptible to high energy background photons in the same environment.

In Fig. 1 a sensitivity comparison between NE111 plastic and a windowless Al x-ray diode is given. The plastic is assumed to be coupled to a photodiode with a typical S-20 surface. At lower energies, the x-ray diode sensitivity is superior. Some x-ray diode surfaces show sensitivity well above the Al diode.(2)

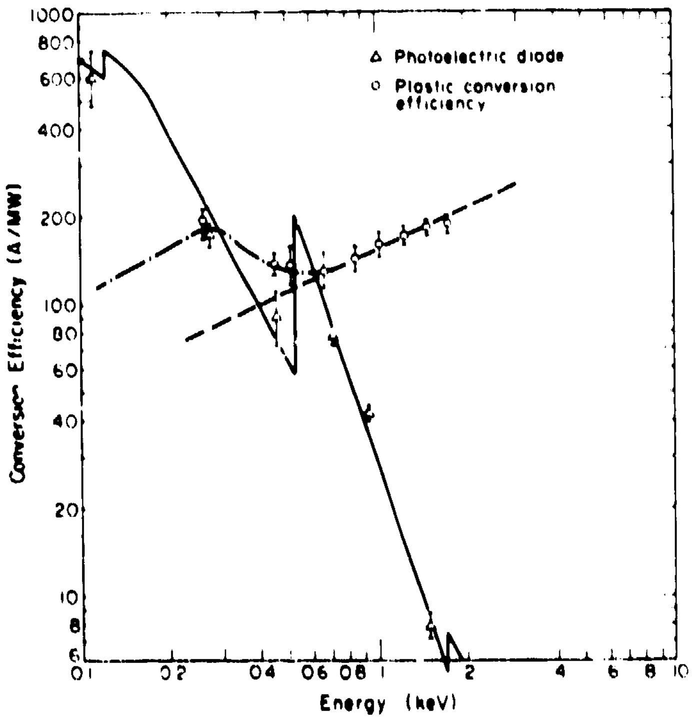

Fig. 1. Comparison of representative Al x-ray diode and scintillator sensitivity for low x-ray energies.

The scintillation must be measured with some type of photosensitive detector. This detector can be a simple biplanar photodiode or a photomultiplier (PMT) with significant gain. Several types of PMTs with sub-ns response are available.(9) The fastest suitable PMTs commercially available utilize a microchannel plate (MCP) as the gain stage and provide a FWHM of 200 ps. Biplanar diodes are available with FWHM of 100 ps, but do not provide gain. Faster solid state devices do exist, but their very limited detection areas are not usually compatible with scintillators. When a PMT is used, attention must be given to limitations on peak linear charge and/or current output capability of the unit. Most PMTs have definite limits on these output values which are largely independent of PMT gain. Operation of a PMT at high gain can restrict the dynamic range of the instrument to a very small value. For most applications, gains of 10^4–10^5 are optimum.

Either scintillator or x-ray diode systems can provide sensitivity in selected x-ray spectral regions. The x-ray diodes show a rapid variation of sensitivity with x-ray energy and demonstrate significant changes in sensitivity near x-ray edges of the cathode material (cf Fig 1). Scintillator sensitivity can be varied by changing the thickness of the scintillator, thereby altering the sensitivity at high energies. The system sensitivity can be further defined through the use of:

a) x-ray reflectors - providing reflection only below a critical energy.
b) x-ray filters - providing transmission as a function of the material attenuation properties. The use of x-ray edges can provide considerable spectral resolution.
c) x-ray fluorescers - providing (ideally) sensitivity only for x-ray energies exceeding the x-ray edge of the fluorescer.
d) Bragg reflectors - providing reflection only when the Bragg conditions are satisfied.
e) grazing incidence gratings - providing reflection when the grating equations are satisfied.

Low energy x-ray systems frequently require the use of very thin foils. Such foils can be rolled, stretched, or vacuum deposited depending on the particular material.

Many low-resolution systems use either a filtered diode or a filter-fluorescer geometry. Figure 2 provides an example of filter-fluorescer system sensitivity for a detection channel intended for temperatures near 1 keV. The system consists of a Ni pre-filter and a Ti fluorescer in the x-ray beam with a Ti post-filter and Al diode at 90°. This figure shows the variation in channel response vs x-ray energy as additional elements of the channel are included. Filter-fluorescer systems are much less sensitive than filtered diode systems. For many applications in ICF diagnostics, the filter-detector system is used(10) and typical responses are given in ref. 2.

DATA TRANSMISSION SYSTEMS

Coaxial cables are far from perfect transmission media. High bandwidth signals suffer serious distortion as they propagate along coax cables. The simplest solution would involve location of the recording instrumentation very close, within a few meters, of the detector. In practice, however, this is not a feasible alternative. Significant radiation and electrical background can be anticipated near the target area of any laser system and an e-beam pumped laser (like the Los Alamos Helios laser) would be an even more difficult environment. In addition, personnel are excluded from the target area during tests and the recording equipment would have to be remotely controlled.

Radiation background provides a particularly severe problem with modern high speed oscilloscopes(11) which utilize a micro-channel plate (MCP) gain element preceding the phosphor. The MCP exhibits significant radiation sensitivity.

These considerations require that the recorder be located some distance from the detector. Thus coax lines, typically 20-40 m in length, are required. The severe limitations of the cable then become a serious concern.

In Fig. 3 the attenuation in db is shown as a function of frequency for 37 m of several types of high frequency cable. Larger cable shows signficantly lower loss at all frequencies, but other considerations argue against the large cable. As practical matter, the largest cables are extremely difficult to handle. A non-linear phase characteristics of several cables are shown. Thus while the largest cable has the least attenuation, it shows the greatest phase distortion. A coax system will "ring" or oscillate at the approximate frequency, f_R, where the dispersive, or nonlinear, phase shift exceeds 180°. In practice a system will be stable if the ringing frequency is attenuated by 7-10 db below the attenuation at the half power frequency, f_{3db}.

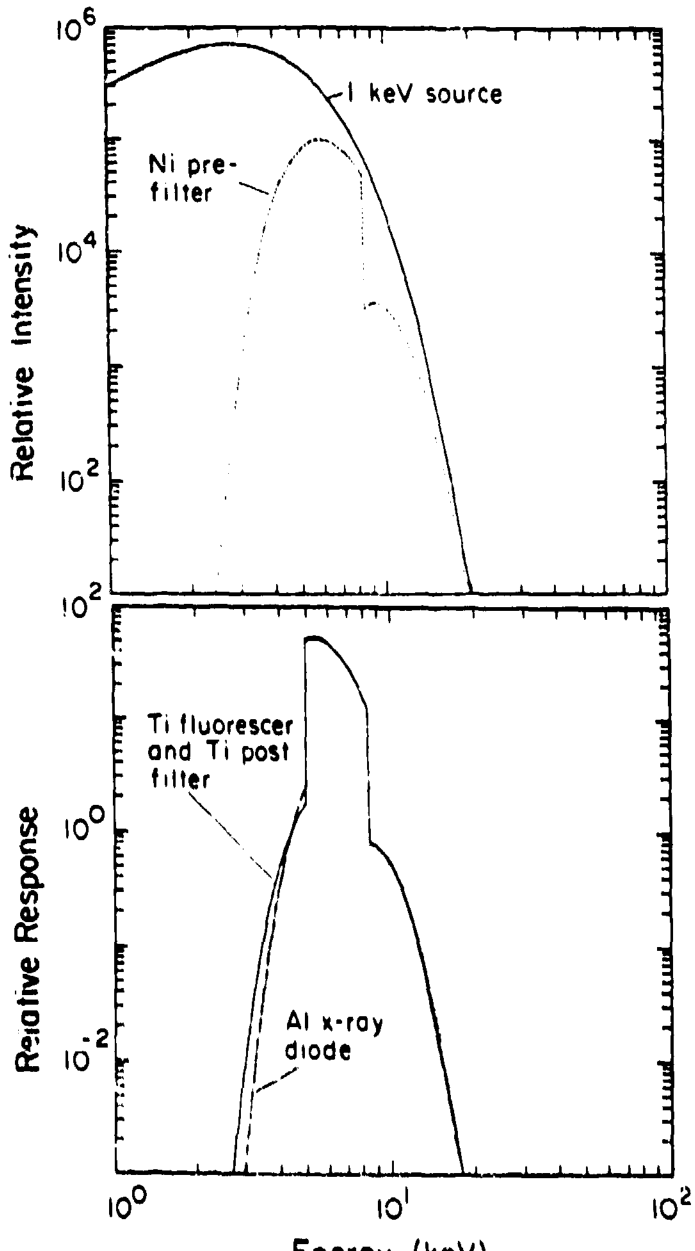

Fig. 2. System sensitivity for a Ni pre-filter-Ti fluorescer- Ti post-filter - Al diode configuration. In Fig. 2a the 1 keV Planck source is attenuated by transmission through the Ni pre-filter. When the Ti fluorescer is added in Fig. 2b, only energies above the Ti-K edge contribute fluorescence at 90°. All energies also scatter off the Ti fluorescer foil. A Ti post-filter provides slight additional shaping and prevents any UV light from reaching the Al diode. The Al diode (with a Be entrance window) then detects the predominantly Ti fluorescence in the 90° beam. The resulting channel has almost all of its sensitivity between the Ti-K and Ni-K edges.

In Fig. 3, the ringing frequency, f_R, is shown for each cable. Note that the largest cable rings at about 2.5 GHz. The ringing frequency can also be thought of as the approximate frequency above which modes other than TEM can propogate. Cable ringing is shown experimentally in Fig. 5 where a short pulse was used to excite a 15-m length of large diameter cable. The output was measured with a sampling system.

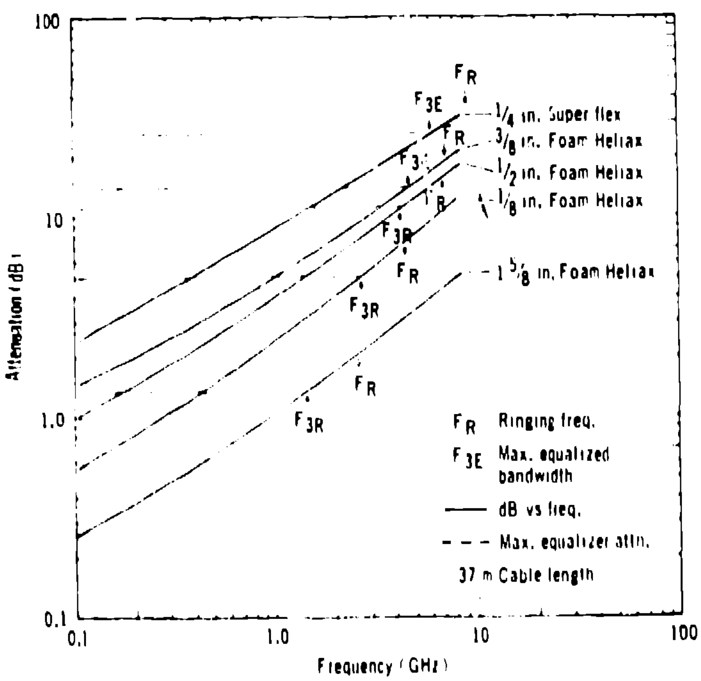

Fig. 3. Attenuation vs. frequency for selected high-frequency coaxial cables. See text for discussion of figure abbreviations.

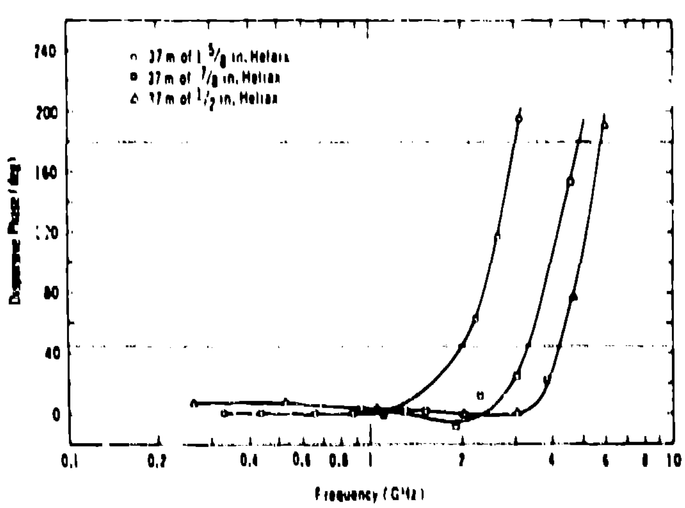

Fig. 4. Non-linear phase characteristics for 37 m lengths of several coaxial cables.

The bandwidth of any system can be improved through equalization. This technique involves the introduction into the line of a high pass filter whose frequency characteristics compensate for the frequency roll-off of the original system. The system sensitivity is reduced but an improved system bandwidth results. This is illustrated in Fig. 6a. It is important to note that equalization may be applied to any electrical system whose frequency characteristics are known. The "system" may be only a cable, only an oscilloscope, or a complete detector/cable/amplifier/oscilloscope combination.

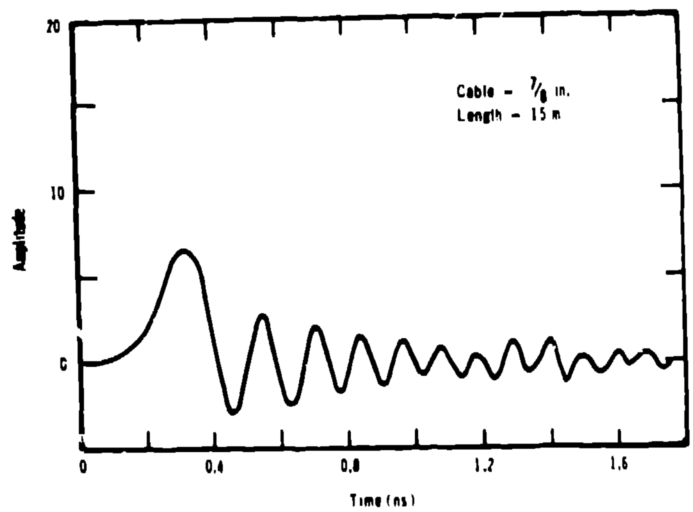

Fig. 5. Cable ringing in a 15 m sample of 7/8 inch coaxial cable.

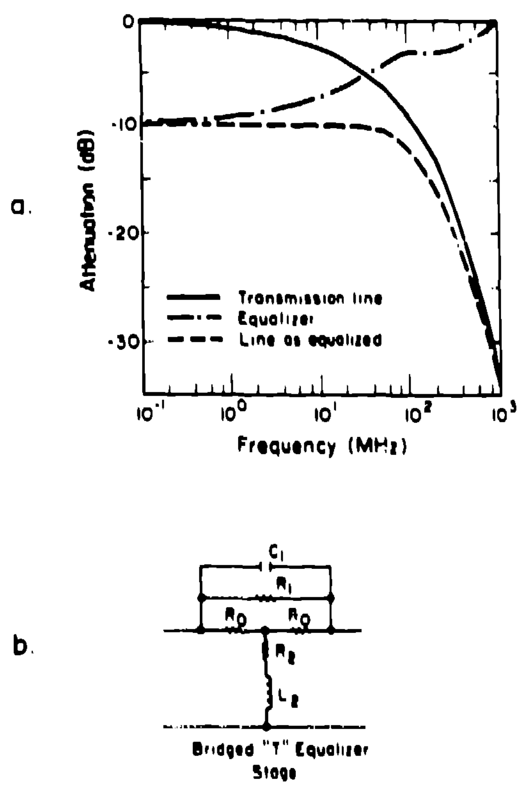

Fig. 6. a) An example of the concept of equalization and b) one possible equalizer configuration.

Many texts deal with equalizer technology[12] and describe a variety of equalizer constructions involving resistive, inductive, and capacitive elements. Equalizers may be matched to the line characteristics to provide a "matched" or "non-reflective" equalizer or may be reflective. While reflective equalizers are simpler to design and fabricate, care must be exercised to assure that either 1) the coaxial cables are of sufficient length that the reflections do not impair the data, or 2) that the system is suitably back-terminated to prevent mulitiple reflections. A standard type of matched equalizer, the "bridge-tee" construction, is shown in Fig. 6b.

The various coaxial cable systems discussed earlier can be equalized. However as previously described we must assure that f_R is attenuated well below the final cable f_{3db}. With this concern as a guide, the maximum equalized bandwidth for each cable is presented in Fig. 3 and labeled as f_{3db}.

Standard components may be used to construct equalizers with frequency characteristics providing f_{3db} into the 500-1000 MHz range. However, as frequencies exceed 1 GHz, the standard discrete components have too much stray and/or distributed reactance to allow construction of computer-generated designs. A new type of equalizer has been originated to address this high frequency area.(13) This equalizer consists of a microstrip transmission line to which one or two microstrip stub lines are added. Each stub line is terminated in a resistor and the stubs may be different impedances and lengths. The reflections from the various line/stub and stub/resistor interfaces can be tailored to give suitable high pass filter characteristics.

Hybrid thick film circuit technology has also been explored for construction of multi-GHz equalizers (using conventional designs like the bridge-tee of Fig. 6b), but to date has not approached the stub equalizer success. The stub equalizers can be built with conventional printed circuit techniques and closely approach computer calculations of expected performance.

To conclude this section, Fig. 7 is constructed from the data of Fig. 3. The attenuation of four possible cable types is shown. From Fig. 7 the optimum cable choice for a 37 m cable length and a specific bandwidth can be quickly determined.

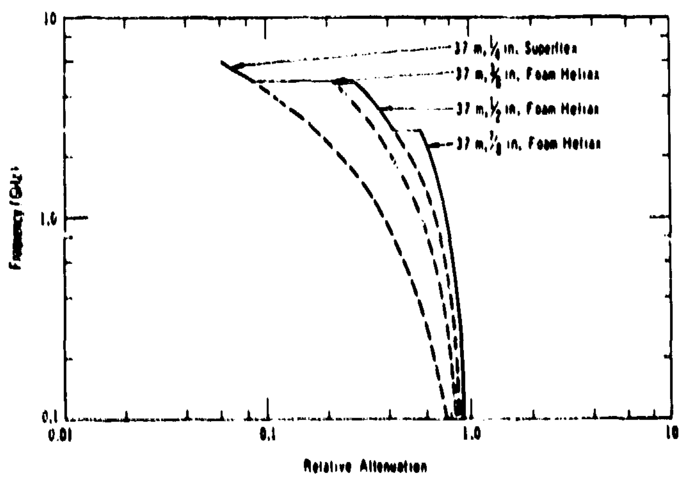

Fig. 7. Frequency and attenuation for 37 m high frequency cables within the operating range of each cable.

DATA RECORDERS

Few options exist for data recording above 500 MHz bandwidth. No commercial A/D converter or transient digitizer (except the 7912/direct access) can presently approach this bandwidth with acceptable resolution (8 bits). Sampling techniques do achieve this bandwidth but customarily are used only with repetitive signals. Many parameters (cost, mode of operation, detailed frequency response, over-voltage protection, etc.) must be addressed in selecting equipment for each application. However, as a major over-simplification, several presently available recorders are compared in a two-dimensional space (f_{3db} bandwidth vs. sensibility) in Fig. 8.

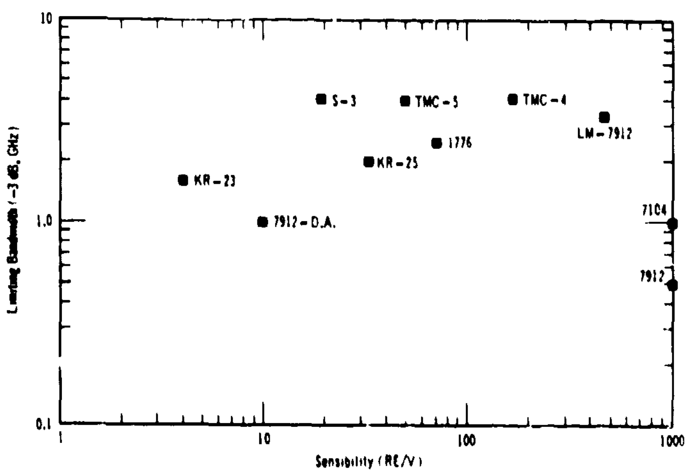

Fig. 8. Bandwidth and sensibility for several commercial recorders. See text for details.

Sensibility is defined as the number of resolution elements per input volt. A resolution element is defined either as a trace width for an oscilloscope or a least-significant-bit for a digitizer. The actual value of sensibility quoted for each recorder is open to considerable interpretation and is not an exact quantity. (Various trace widths or sensitivities may be seen in different samples of a given recorder.) The sensibility values in Fig. 8 should be treated as rough guides only. The equipment described in Fig. 8 is made by Tektronix, Inc. (7912-direct access, 7912, 7104), by EG&G, Inc. (KR-23 and KR-25), by Lockheed(14) (LM-7912), by Lockheed and EG&G(15) (S-3), by a Los Alamos/Tektronix collaboration(11) (1776) and by Thomson-CSF (TMC-4 and TMC-5). The Thomson-CSF, the 1776, and the KR-25 scopes use MCP current amplification.

All of these recorders are electron beam devices (conventional oscilloscopes or scan converters) except the single-shot-sampler (S-3) system. This system utilizes sixteen 4 GHz Tektronix, Inc. sampling heads strobed and timed by a single trigger pulse. The input signal is distributed to the 16 sampling heads. Sixteen high bandwidth samples are thus recorded. Additional units can be used to expand beyond 16 samples.

The 1776 oscilloscope is used in moderate quantities in several Los Alamos programs. It serves as another example of equalization technology. The response of the basic scope, without equalization, is shown in Fig. 9. The unequalized sensitivity is about 450 mV/cm with a 700-800 MHz bandwidth. Since the attenuation curve is fairly smooth, the unit can be equalized to much higher bandwidths. (Not shown in Fig. 9, but of equal importance is that the phase characteristics are well behaved past 6 GHz.) Shown in Fig. 9 is one configuration of the 1776 used in several applications. A 4 db stub equalizer is used to provide a 1.6 GHz bandwidth at a sensitivity reduced to 700 mV/cm. The example in Figure 8 was equalized to about 2.5 GHz and provided 1.1 V/cm sensitivity. The trade-off between bandwidth and sensitivity must be guided by the specific experiment.

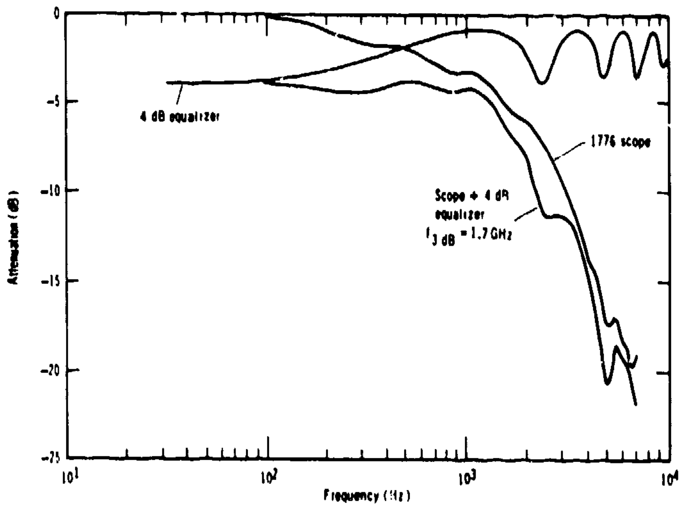

Fig. 9. Frequency response of the 1776 scope in an unequalized mode and in one equalized (4 db) mode. The equalizer response is also shown.

SUPPORTING INSTRUMENTATION

This section briefly addresses three classes of instrumentation which are critical in high bandwidth systems: amplifiers, test instruments, and scope digitizers.

An amplifier of suitable bandwidth can increase the sensibility values shown in Fig. 8. However, the amplifier must be carefully tested to insure that it is not introducing significant distortion into the recorded system. Some amplifiers can introduce severe ringing or other artifacts into signals. The amplifier must also have enough linear output to deflect the chosen oscilloscope.

Test instruments are required to verify the pulse response of each component of a system. Both impulse and step generators provide suitable data for subsequent Fourier analysis.(16) Both amplitude and phase must be inspected in the Fourier analysis to insure adequate pulse fidelity. Pulse generators may use either step-recovery diodes(17) or mercury pulsers.(18) These diodes can deliver up to 30 V at high repetition rates in a 60 ps impulse while the mercury pulsers can provide much larger voltages in a single shot mode. Tunnel diode pulsers(19) can provide 20 ps risetimes with 250 mV output. Mercury pulsers fabricated at Los Alamos, similar to those described in ref. 18, have demonstrated a 37 ps risetime.(20) For many applications a set of calibrated step generators(21) which provide well behaved and characterized step shapes from 50 to 200 ps is very useful and can be ordered from NBS. Delay lines are required to provide trigger advance times to the recorder system and ideally would provide ~50 ns delay without pulse distortion. Cryogenic lines at liquid He temperatures with superconducting coaxial cables have been documented with 70 ns delay and >20 GHz bandwidth.(22) Similar lines constructed with 2.1 mm diameter semi-rigid coax in liquid N_2 constructed at Los Alamos provide 60 ns delay with a bandwidth of 5 GHz. The Los Alamos delay line requires 7 db equalization to achieve the bandwidth.

Sampling techniques are needed to document the performance of sever[illegible] of the components discussed in this paper. Samplin[illegible] [illegible]asurements can provide bandwidth data up to [illegible] GHz.(23)

The importance of test instrumentation cannot be overemphasized. Attempts to rely exclusively on manufacturer's specifications or literature descriptions of specifications for similar systems will usually be met with serious failure. High bandwidth systems require careful attention to all details of system construction and test facilities are essential. Any equalization also demands detailed knowledge of system response.

The final area of useful instrumentation concerns oscilloscope digitizers. For systems using scopes, film recording may be used. An alternative would use a vidicon tube to scan the scope face. Such systems, based on SIT vidicon tubes, are in use at Los Alamos.(24) In a rapid test schedule, the desirability of such devices is apparent.

SYSTEM CONSIDERATIONS

The choice of a complete system must be guided by the experimental requirements. The concept of sensibility, introduced earlier, has proven to be very useful in characterizing experimental requirements. Each experiment can be characterized by a bandwidth and sensibility needed to adequately record the anticipated data. The sensibility is deduced from a review of the required resolution and the anticipated output signal levels.

As an example of such system considerations, graphs like Fig. 10 may be constructed to show the achievable bandwidth and sensibility for several recorder systems operating through 18 and 37 m cables. If an experiment required 3 GHz bandwidth, if 100 resolution elements (R.E.) are required, and if 10 volts peak signal are expected (requiring 10 RE/V), then the 1776 and TMC-4 systems can be used with 0.5 inch cable.

The beam diagnostic system for the Helios and Antares laser was constructed from similar considerations.(25) Thirty-eight meters of 0.5 inch cable, amplification(26), a 1776 oscilloscope, and a digital camera were used. System modeling guided the choice of a 3 GHz system bandwidth. Without equalization the system was cable limited to ~250 MHz. The system frequency response (Curve A) is shown in Figure 11 along with the calculated performance (Curve B) of a stub equalizer with 18 db equalization and the calculated final system response (Curve C). A 2-3 GHz system resulted and provided the measured response of Fig. 12.

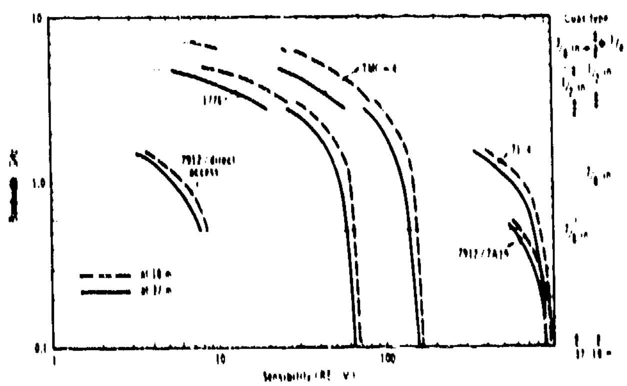

Fig. 10. System sensibility for systems based on five recorder choices at two distances. The 7A19 refers to a Tektronix, Inc. preamplifier.

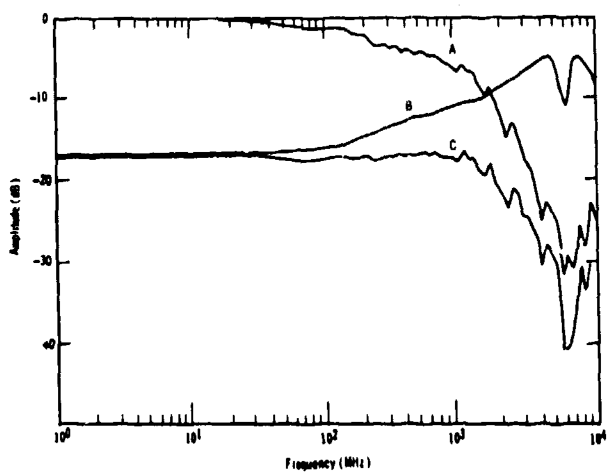

Fig. 11. Measured system frequency response for the Helios beam diagnostic channel consisting of 38 m of 0.5 inch coax, an amplifier, a 1776 oscilloscope, and a scope trace digitier. Calculated equalizer response and anticipated system response are also shown.

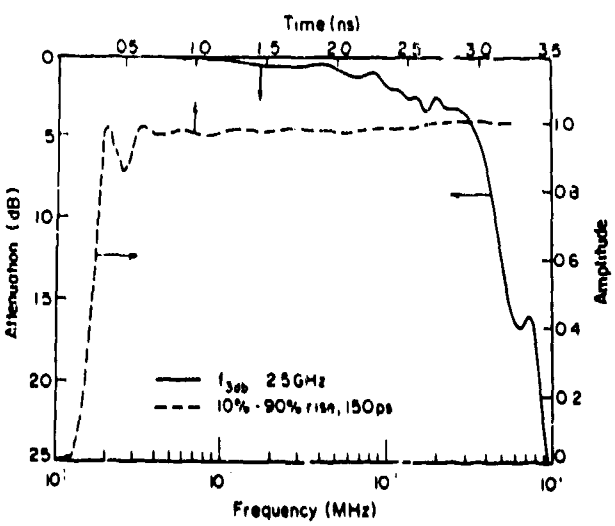

Fig. 12. System response of the Helios beam diagnostic channel.

CONCLUSION

In this paper the elements of an x-ray detector system have been presented. System responses over 3GHz may be constructed from the technology presented herein.

As a final topic, the subject of data unfolding should be mentioned. Unfolding, or deconvolution, may be used to recover additional system bandwidth.(27) The bandwidth that can be recovered by deconvolution is highly dependent on noise either in data or in system response. In several situations at Los Alamos, bandwidth has been increased by recovering frequency attenuation of about 15 db, but this value depends critically on the individual system. Attempts at excessive deconvolution introduce serious noise into the data and can actually degrade, rather than improve, system performance.

Proper system design is providing multi-GHz recording capabilities at the Los Alamos National Laboratory.

ACKNOWLEDGMENTS

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