Stacked, filtered multi-channel X-ray diode array

L. P. MacNeil[*a], E. C. Dutra[a], S. M. Compton[b], B. A. Jacoby[b], M. L. Raphaelian[a]
[a]National Security Technologies, LLC (NSTec), 161 S. Vasco Rd., Livermore, CA USA 94550
[b]Lawrence Livermore National Laboratory (LLNL), 7000 East Avenue, Livermore, CA USA 94551

ABSTRACT

There are many types of X-ray diodes that are used for X-ray flux or spectroscopic measurements and for estimating the spectral shape of the VUV to soft X-ray spectrum. However, a need arose for a low cost, robust X-ray diode to use for experiments in hostile environments on multiple platforms, and for experiments that utilize forces that may destroy the diode(s). Since the typical proposed use required a small size with a minimal single line-of-sight, a parallel array could not be used. So, a stacked, filtered multi-channel X-ray diode array was developed, called the **MiniXRD**. To achieve significant cost savings while maintaining robustness and ease of field setup, repair, and replacement, we designed the system to be modular. The filters were manufactured in-house and cover the range from 450 eV to 5000 eV. To achieve the line-of-sight accuracy needed, we developed mounts and laser alignment techniques. We modeled and tested elements of the diode design at NSTec Livermore Operations (NSTec / LO) to determine temporal response and dynamic range, leading to diode shape and circuitry changes to optimize impedance and charge storage. We fielded individual and stacked systems at several national facilities as ancillary 'ride-along' diagnostics to test and improve the design usability. We present the MiniXRD system performance which supports consideration as a viable low-cost alternative for multiple-channel low-energy X-ray measurements. This diode array is currently at Technical Readiness Level (TRL) 6.

Keywords: X-ray, Diode, XRD, MiniXRD

1. INTRODUCTION AND CONCEPT

The need for a small, customized X-ray flux measurement led to an NSTec Site Directed Research and Development project that developed and demonstrated the basic concept of using metal plates with small ceramic holders to create a mini X-ray diode (MiniXRD) prototype. The Initial concept was modified and proposed as a possible solution to a gap in the available diagnostics between the expensive XRD-31 X-ray diodes and the common silicon diodes, all normally used in a parallel array configuration. The MiniXRD was therefore developed for field applications where only a very small field-of-view may be provided, and yet basic energy-band flux (coarse spectrometry) measurements were needed.

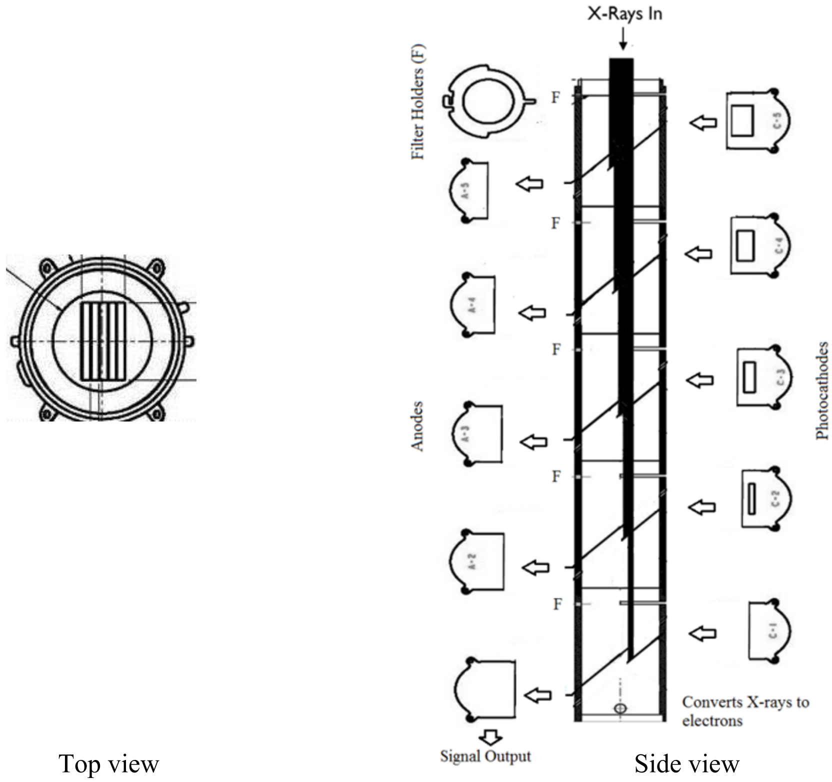
The primary diode component utilizes the photoelectric effect. The metal surface of the photocathode releases electrons when subjected to photons of sufficient energy. The anode collects the electrons producing a measureable current. The diode was constructed from two parallel plates, closely spaced and angled to allow the incident X-rays access to the photocathode. The photocathode surface was coated with a metal selected for its energy sensitivity. Apertures prevent direct exposure to X-rays to the anode, yet also allow X-rays to reach subsequent photocathodes 'stacked' below it. A negative high voltage is applied to the photocathode and the anode is held to ground through the digitizer, so the signal is read directly from the anode.

Each diode is designed in a modular manner and includes an insulating tube body, conductive photocathode and anode plates, up to two separate filters, and circuit boards. Each diode can then be stacked on top of another to enable arrays varying in size from 1 to 5 diodes. The bottom diode is mounted on an insulating base, which is then mounted to a flange with connectors. The front diode is attached to an aperture with an alignment mount. There is also provision for mounting a mirrored low-energy channel as the front diode[1].

It is assumed that the X-ray flux contains many photon energies, evenly distributed in the aperture area. The front photocathodes have large holes in them, with the rear photocathode being solid. The photocathode and anode pairs are placed at an angle so the X-rays land only on the small tip of the photocathodes. After the first photocathode, the X-rays

*macneilp@nv.doe.gov; phone 925 960-2576; fax 1 925 960-2555; www.nstec.com

gain access to all subsequent photocathodes through the hole in the previous photocathodes. Thus, equal sections of the X-rays are ‘trimmed off’ and the overall flux is divided equally among the photocathodes. See Figure 1.



Top view Side view

Figure 1. Conceptual models of plate configuration and X-ray path through 5-channel stacked array

Different plates and filters are used for each diode channel to provide different energy band sensitivity. Since the filters are also stacked, their effects sequentially influence each other in an additive manner, so only the higher energy X-rays reach the bottom channel. Thus, the channel we wish to be most sensitive to lower energies is placed in the front (toward the X-ray source) and the channels we wish to detect predominantly higher energies are placed behind each other in ascending order toward the base.

Typically the channel energy sensitivities overlap considerably, which is both a source of error and a challenge for the setup to control the dynamic range of the overall system. For two-channel filtered arrays, or arrays with mirrored channels, this is not much of an issue, and channels can be designed to be essentially discrete. However, for many-channel stacked arrays the filters must be selected with care to provide energy selection without attenuating the high-energy channel signals so much they are not detected. Since the filters are stacked, the higher-energy ranges are not blocked, but rather allowed to be seen by most channels. Only the lower energy ranges are typically blocked off sequentially as the X-rays pass through the filters, with the exception of certain low-energy bandpass regions allowed by the plastic substrates. When the source is broadband (mostly bremsstrahlung), the lower-energy channels typically have higher-amplitude signals since they receive more overall flux and the photocathode is generally more sensitive to lower energies. However, this method works well as a detection mechanism for higher-energy spectral lines, with proper characterization and methodology.

Methods were developed to include experimental setup protocols, accurate alignment, defined operational procedures, and checkpoints for verification of operation. Spreadsheets for important parameters were developed and linked into software, so that the data that was viewed was automatically normalized with characterized response functions. Thus the performance metrics were easily compared. Further, special alignment mounts were developed which allowed accurate inter-channel and overall system alignment to the target to be performed with high accuracy, greatly improving measurement consistency. Operation procedures allowed ease-of-use issues to be addressed and improved, and software was enhanced to provide calculations that were validated with independent comparisons.

Analysis was performed at several levels. When only simple timing or spectral line presence is desired, the raw data is often sufficient. Response functions of the diodes can be calculated from the characterizations of the filters and photocathodes, so when flux variations over time for a given energy range are needed, they can be calculated from setup parameters like distance and solid angle. The response functions of the diode can be obtained by subtracting several channels' overlapped response function to obtain the discrete flux for the various energy ranges. Further, temperature can be inferred by looking at the peaks flux of each channel, fitting those peaks to a blackbody temperature fit for each energy range, and using each channel's fit parameters to infer the radiation temperature-vs-time detected by the system.

During development, we followed and periodically assessed the Technical Readiness Level (TRL) of the work in a manner consistent with DOE G 413.3-4A, "Technology Readiness Assessment Guide," modified for our application and company directives. We developed the concept through several build versions, conducted internal and external tests, and performed several demonstrations in relevant and operational environments. The current system has completed TRL 6, demonstration of operation at relevant environments, and is ready for TRL 7, where it would be incorporated into experiments where the data would be correlated with data from other diagnostics.

The individual diode performance standard we compared against is held by the XRD-31 diodes used on the DANTE systems. They perform very well but are bulky in size and designed to work only with parallel diode arrays requiring a large line-of-sight. Standard analysis methods are tailored to parallel systems[2,3,4]. So the initial development of the MiniXRD was with single diodes with a single filter to enable verification of operation by comparing signals to the XRD-31. By optimizing performance and design, multiple stacked diodes with multiple filters and new analysis methods were developed. This stacked diode array became the modular MiniXRD system we use today.

The MiniXRD has been fielded numerous times. In this paper, we limit the discussion to summary comments of the work at certain facilities to emphasize key development steps. We developed and tested components and versions of this system at the NSTec / LO Labs and at Brookhaven National Labs (BNL). We fielded components and complete systems on the Omega laser at the Laboratory for Laser Energetics (LLE) at the University of Rochester, and the NIKE Laser at the Naval Research Laboratory (NRL), and the ZEBRA z-pinch at the Nevada Terawatt Facility (NTF) at the University of Nevada at Reno (UNR). During these tests, we demonstrated operation, measured performance, and improved the design of the overall system. This involved iterative improvements of elements of the MiniXRD diode array and development of the mounts and alignment tools and procedures used to improve performance. We then demonstrated operation of complete systems, including analysis of data. Table 1 summarizes the tests at these various locations.

Table 1. Summary of MiniXRD tests

Test Facility / Source	MiniXRD Rev.	TRL	Test Summary	Result
Manson X-ray Source (NSTec / LO)	0, 1	1-3	Basic X-ray detection	0.2-80 pA
Short Pulse Laser - UV (NSTec / LO)	0-3	1-3	Response Time, Dynamic Range	300 ps FWHM, DR=100
Long Pulse Laser - UV (NSTec / LO)	1-3	2-5	Shape Symmetry, Charge Storage	Within 5%, 100 ns
Microwave Optics Lab (NSTec / LO)	2-3	3-5	Impedance Matching	Ringing <5%
Omega Laser (LLE)	2-3	4-5	Shape and Response Comparisons	Shape match 10%
Beamlines U3C & X8A (BNL)	2-3b	3-5	Spectral Response (photocathodes and filters) and low energy channel	Energy range 200 eV - 5 keV
NIKE Laser (NRL)	3, 3b	5	Multichannel max range and alignment	Power at diode $3x10^4$ W
ZEBRA (NTF / UNR)	3, 3b	6	Multichannel alignment and response	Flux, Temp, DR>5000

2. DIAGNOSTIC DESIGN

Summary of Key Requirements and Design Considerations

The stacked configuration of the diode array was designed to meet some key requirements as shown below. Of these, the small line-of-sight and performance comparison were the largest challenges. Additional work was required to improve performance consistency, including the development of alignment lasers and adjustable mounts. A key requirement was to accept photons from a small collimated aperture (2-10 mm). Since a narrow, stacked approach was used, directionality was supported, allowing data to be viewed from a specific location while only minimally obstructing other diagnostics. Other key requirements included ease of manufacture, maintenance, setup, and operation. This was achieved by utilizing modular construction. See Table 2 for a summary of requirements and design considerations.

Table 2. Summary of key requirements and design considerations

Item	Requirement	Design Consideration
1	Plan on being destroyed upon use, yet be capable of re-use	Keep unit-cost low and possible contamination to a minimum; use modular assembly.
2	Allow for field-configuration of energy channels	Use slots on tube body and modular filter holders
3	Allow for a variety of energy band ranges, including typical DANTE channels	Make in-house custom filters to cover many possible energy bands.
4	Operate at approximately 1kV bias voltage	Test over 200V-3kV range
5	Accept a very small line-of-sight (2-10mm)	Use the 'stacked' design for multiple channels
6	Occupy a small footprint	Fit in a 1¼" diameter tube (2 ¾" flange front end), and use a max 4 ½" flange for the connectors. Array < 12" long.
7	Accept broad environmental conditions	Use Alloy 42 and Rexolite for major components
8	Allow for very short build-to-deployment times of a few days	Modular, so easy to build
9	Perform comparably to the XRD-31	Understood that performance is 2-3x slower, but same uses

3. INITIAL TESTS AT NSTEC / LO

Demonstration of basic principles (TRL 1)

Basic operation with the diode successfully detecting X-rays was first demonstrated on the Manson X-ray source. Pulsed operation was then demonstrated using 200 nm light from the Short Pulse Laser. The aluminum photocathode responded well, and we obtained strong signals. These were 200 femtosecond pulses of light, sufficiently short to enable accurate measurement of the diode response time.

We used aluminum photocathodes with anodes made of both mesh and plates for comparison. With mesh, we found it best to measure the current draw from the photocathode with a bias T, since many of the electrons released from the photocathode pass through the anode mesh to the diode body or housing, so an anode measurement yields a small signal. However, the plate anode used in the MiniXRD design captures nearly all the electrons directed at it, so the signal is much larger over the detector surface area. Thus, a much smaller plate photocathode and anode area can generate a similar signal to a mesh anode diode for small area collimated X-rays. Basic pulses were measured with the Short Pulse Laser on single channel mesh and two-plate diodes over a dynamic range of about 1000 using ND filters, at bias voltages from 200 to 2000V. This demonstrated that the basic principle of the angled plate diode design worked well.

4. MODELING (TRL 2-3)

Formulating concept and application

The initial concepts were based on the goals to provide a coarse spectrometer capability over the low energy X-ray range of 450 eV to 5keV. The initial modeling considered three perspectives: the electric circuit represented by the diode to ensure a good signal, the electron ballistic modeling to predict response times and eliminate crosstalk, and the filter and photocathode response functions. The electric circuit design is kept simple and ensured three criteria: supply of charge to the diode so longer pulses do not decay prematurely, prevent electrical crosstalk, and impedance match the anode to the oscilloscope or digitizer. The electron ballistic modeling was done using Charged Particle Optics (CPO) and shows any stray electrons are cast to the side, rather than to another anode that would normally be located directly above. The filter and photocathode modeling data was obtained from the Center for X-ray Optics (CXRO) website[5] maintained by the University of California, Berkeley. (See Figure 2.)

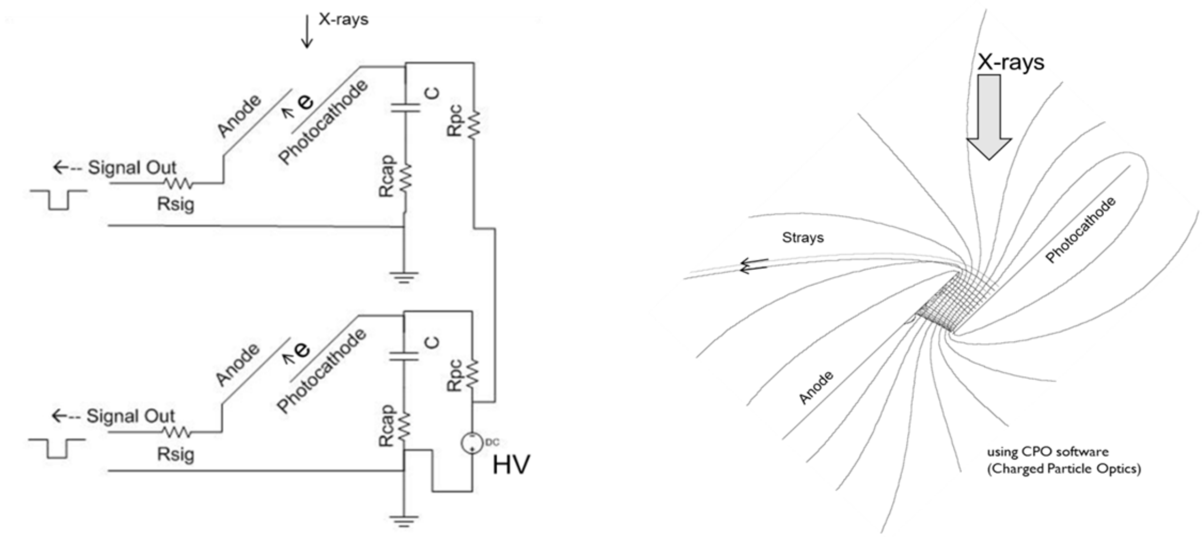


Figure 2. Circuitry model and electron-ballistic model

Demonstration of concepts analytically

We refined the models to support desired performance. The electric circuit modeling allowed us to show that we could easily deliver sufficient charge to offset the constraint of minimal cabling (often used to supply charge). We then calculated the resistor and capacitor values for the circuit. It was also shown that multiple channels were separate and distinct as the design steered electrons from misaligned plates away from nearby channels. See Figure 2, electron ballistic model. Plate size, distances and orientation in the electron ballistic model were adjusted to meet the requirement of response times less than 300 ps for bias voltages around 1 kV, and provide strong signals without reaching the Child-Langmuir limit too soon. Software was developed to combine the response function models obtained from CXRO and to show the expected response functions of diode assemblies. These analytical values drove the prototype design that was later built and tested.

5. CONSTRUCTION (TRL 3-6)

Originally, the need was for single-shot fielding, but as we progressed along the technical readiness path, there was a desire to use the MiniXRD on different experiments at several different facilities as well. This resulted in a growth of the system to include physical mounts, alignment methods, optimization, and development of analysis techniques. As each system was made, design improvements were made to rectify minor problems or enhance capabilities. Since the design was modular from its inception, these changes were easily incorporated along with design improvements derived from analysis of the observed performance.

The diode assembly

Early on it was decided to use a modular approach so an array could be easily configured with between 1 and 5 filtered channels as shown in Figure 3. Later this proved to be the right decision since it allowed alignment tools and provision for future low-energy mirrored channels in the front. To minimize contamination of the environment if the array was destroyed, we avoided some traditional metals. The tube body was constructed out of Rexolite, a plastic that has high dielectric strength and, unlike many other plastics, does not absorb water. It also machines easily like Lucite. This makes Rexolite ideal for vacuum applications. Since it is cost effective, and is easily machined, we were able to make precise parts with numerous slits for holding the meatal parts.

The primary metal is Alloy 42, a cost-effective variant of steel in the Invar family, which is temperature stable over the expected environment and tolerance conditions, so that alignment did not change over large temperature variations. We coated the Alloy 42 photocathode plates with the desired photocathode metal (Aluminum, Nickel, Chromium). The anode and photocathode plates were made with small tabs to ‘click’ into place and hold the plates against the slit stops on the Rexolite tube body for accurate alignment. Alloy 42 filter holders were made with holes where the filter material was attached. The filters were made in-house, and were composed of various metal thicknesses sputtered onto a thin mylar or parylene backing. See Figure 4.

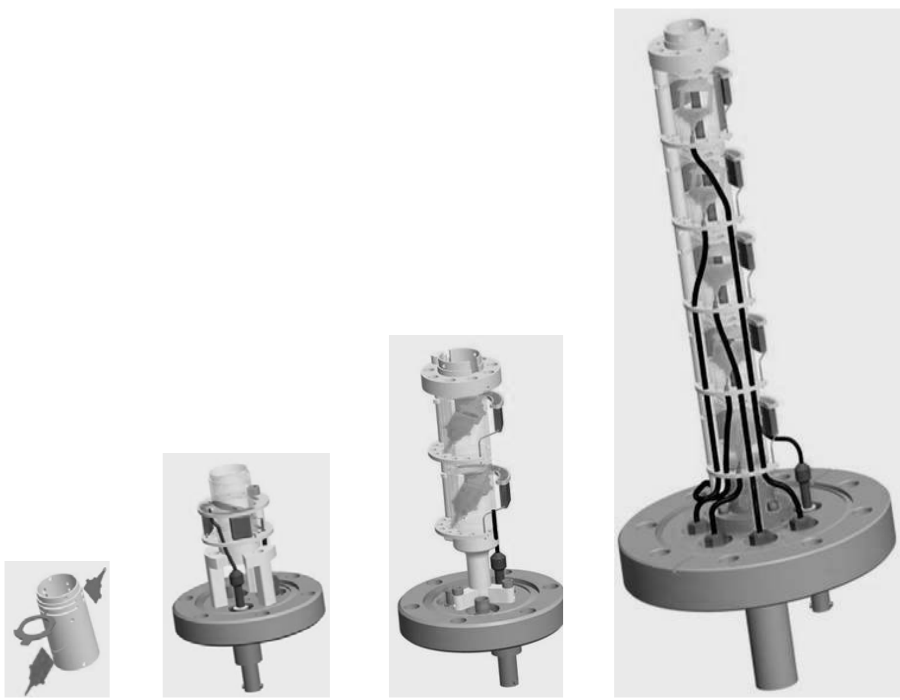


Figure 3. Conceptual models of single diode, and complete one, two, and five channel stacked X-ray diode arrays

The Rexolite tube bodies for each channel were indexed and stacked together, using a liquid Rexolite glue, which cured under low heat to Rexolite, for good vacuum properties and adhesion. Numerous pump-around holes were placed to minimize stress on filters during pumping and venting cycles. A Rexolite base connected to the stacked Rexolite tube bodies mounted to a metal flange. Several types of Rexolite end caps were designed which allowed for an Alloy 42 aperture, a lip for affixing the laser alignment tool or an attenuation mesh.

The first diode arrays were simple stacks on a flange, and the final array was typically contained in a commercial vacuum tube attached to the flange. The metal tube is not shown in Figure 5 so that the individual components can be seen, but it is normally used to draw off lost electrons, provide shielding for extraneous UV and X-rays, and to physically protect the array. Hermetically sealed connectors were arranged on the flange to accommodate up to six signal channels and one SHV bias high voltage.

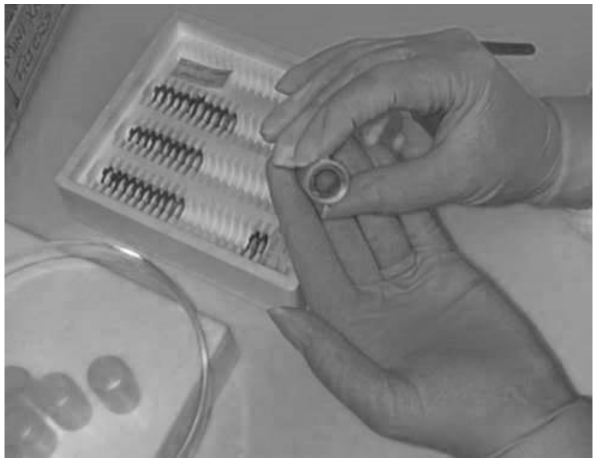


Figure 4. Test fit of filters into tube bodies

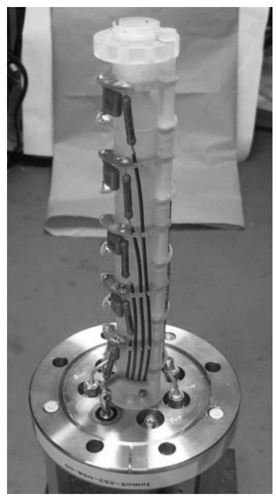


Figure 5. Five channel array

Mounts

Several types of mounts were developed to support and align the diode assembly to ensure consistent performance. These include single diode mounts on a 2 ¾" flange, XRD-31 compatible adaptor mounts for comparison studies, multi-channel fixed mounts, in-vacuum tilt mounts for NRL use, and a ball/socket mount for general chamber use that was tested at UNR. The fixed mounts work well for well-defined or secured X-ray input paths. The tilt mounts worked well inside a vacuum chamber and were highly accurate and easy to adjust between shots, but entry into a chamber makes servicing filters very difficult. A ball / socket mount was developed to act as an interface for the diode array to a vacuum chamber at a facility where multiple shots are planned. Since the ball / socket mount is in air, it allows the diode array to be accessed from one side (in air) for easy filter changes, while allowing good alignment accuracy through its vacuum interface. The ball / socket mount is only accessed when valved off from the chamber, or when the chamber is vented. Pictures of the various mounts are included in Section 7 for the NRL / NIKE and UNR / ZEBRA setups.

Alignment tools

Since the stacked array is an in-line assembly, alignment of the individual components and the alignment of the array to the target are very important. The multichannel array will accept signals within 1.5 degrees before signal degradation of the rear channels becomes an issue. Thus, we developed a multi-prong approach: we designed the elements to go together accurately; we developed tools to assist during assembly; and we developed a laser pointer alignment tool to use both in the lab and in the field.

Rexolite is easily machined to within a thousandth of an inch, so we worked with machine shops to develop methods for accurate production. This included angled slots for the photocathode and anode plates, so their alignment is fixed. We also developed and supplied to the machine shops, gauges to allow easy checking of the critical dimensions. The Alloy 42 plates are rigid and allow ‘snap-in’ assembly, and each part is numbered appropriately so assembly is easy and reproducible. Parts that mate together were designed with indexing so they fit together only one way.

Even so, there can be variations when assembling multiple modular components together, especially when gluing is involved. Thus, we made a simple ‘X-ray path’ tool (see Figure 6), with notches for each channel that can be placed down the ‘throat’ of the diode array to ensure proper alignment of the plates. We also made fixtures to stabilize the assembly while drying, and supports to use during cabling and circuit board assembly.

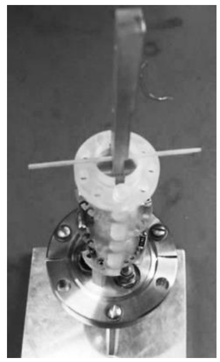


Figure 6. X-ray path / plate alignment tool

To ensure linear tube body and channel alignment, we utilized a laser pointer shining through the back of the plates to the front. This was then verified in the assembly lab, and the projected laser position noted. An end-cap was developed that uses interlocking parts with magnets to allow a small holder to be ‘clipped’ in a consistent yet temporary manner to the front of the diode array. By placing a laser diode pointer in that front piece, it can be aligned in the assembly lab with the beam path of the first laser pointer with screws located in that front alignment piece to ensure it is co-linear with the diode array axis. See Figure 7. Thus, during initial setup in the field, the front laser alignment tool is ‘clipped’ on the front of the diode array and the ball/socket mount or tilt mount is adjusted to steer the light to the desired location on the target. Once the diode array is aligned with the target, the laser alignment piece is ‘unclipped’ so the diode array has an unobstructed view of the target. This alignment method has proven to be an important setup requirement.

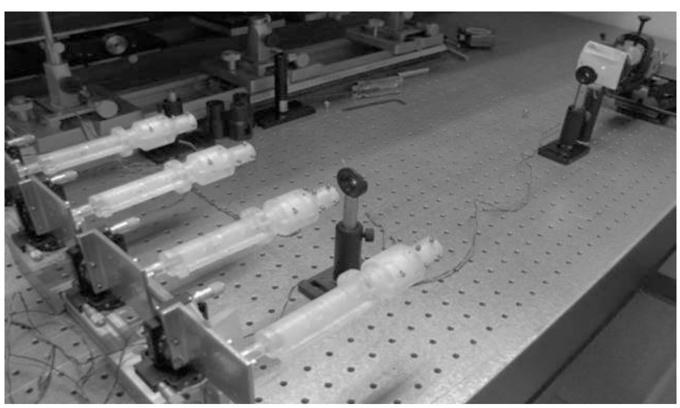


Figure 7. Quad two-channel arrays for NRL undergoing alignment at LO labs using laser alignment end-cap

6. INITIAL LABORATORY TESTS (TRL 3-4)

Demonstration of concepts experimentally

With the prototype components, we demonstrated performance. Using the UV pulse from the Short Pulse Laser, we measured the actual performance and compared to modeled behavior. Figure 8 shows the result of 270-300 ps FWHM at 1000 V, which compared favorably to the 150 ps FWHM of the XRD-31 diodes biased at 5000 V.

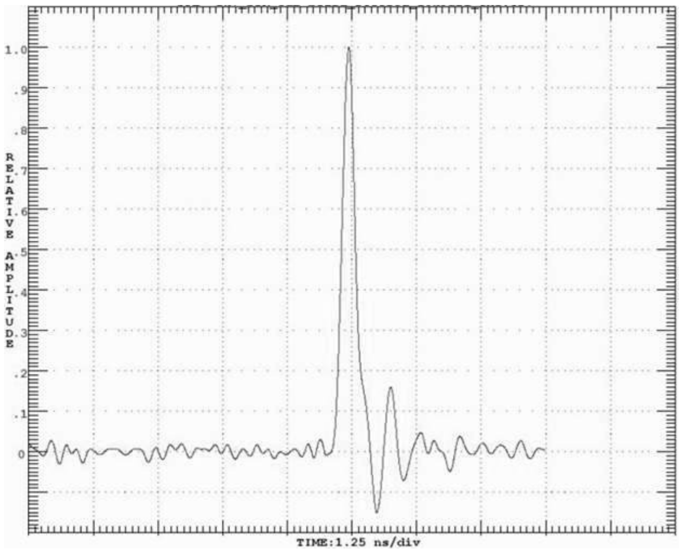


Figure 8. Early plot of pulse showing pulse width FWHM to be 275 ps – using Compare2011 (courtesy of Brent Davis)

Since many of the desired experiments did not allow long high voltage cables, we could not rely on the cables supplying enough charge for the signal. We therefore used high-quality vacuum-compatible capacitors to provide the charge. This supplied sufficient charge for both fast (300 ps) and slow (100 ns) pulses.

An early issue was 'ringing' in the resultant signal due to impedance mismatch of the diode plates and the introduced capacitor and resistor to the oscilloscope. We modeled both the circuit and simulated the ringing in a laboratory environment using a pulse generator capable of picosecond response. These impulses allowed us to modify our circuit to reduce impedance mismatch. We added small resistors to eliminate the ringing and reduced the size of the resultant circuit to two small circuit boards directly connected to the anode and photocathode.

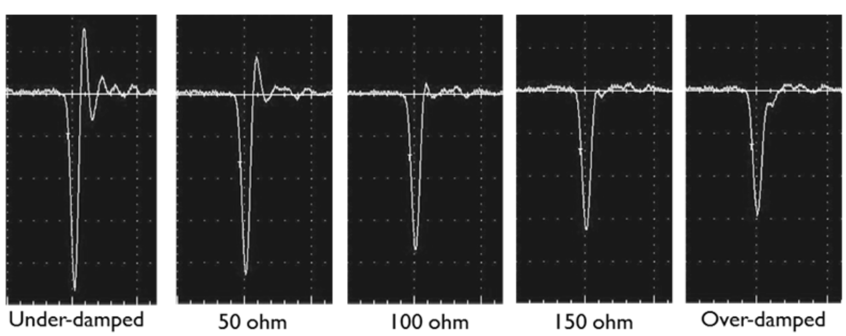


Figure 9. Comparison plots showing the effects of proper impedance matching

Basic operation at longer pulses (100 ns) was tested using 213 nm light from the Long Pulse Laser at NSTec / LO. We compared angular sensitivity of both the mesh and plate formats. Although the coarse mesh diode demonstrated minor amplitude variations with angle, the two-plate diode is very angular sensitive, requiring 1.5 degree accuracy for consistent results. This was consistent with modeling and drove the development of alignment tools.

Crosstalk was demonstrated to be minimal as expected. To test this, an aperture that was smaller than the smallest dimension of the photocathode active area allowed laser light to hit only one photocathode at a time. This was 'walked' across the diode. Sequential channels each responded separately and uniformly. We also illuminated all channels to get multiple responses, and then blocked individual channels while all channels were monitored and observed to respond independently.

Several sample filters and photocathodes were made at NSTec / LO and the filter transmission and photocathode responses were measured at BNL on the U3C and X8A beamlines. These measurements compared favorably to the models. See Figure 10.

Demonstration of key elements in laboratory environments

Diode operation, circuit operation, and the operation of both individual diodes and arrays of diodes were demonstrated extensively in the laboratories at both NSTec / LO and BNL. Pulsed operation of multichannel diodes arrays was demonstrated in the on the NSTec / LO short and long pulse lasers, and assembly and operational procedures were developed.

Several sample filters and photocathodes were made at NSTec / LO. A filter wheel was designed to leverage the existing automated filter measurement capability. Thus, both the filter transmission and photocathode response for every fielded diode were measured at BNL at on the U3C and X8A beamlines. (See Figure 10.)

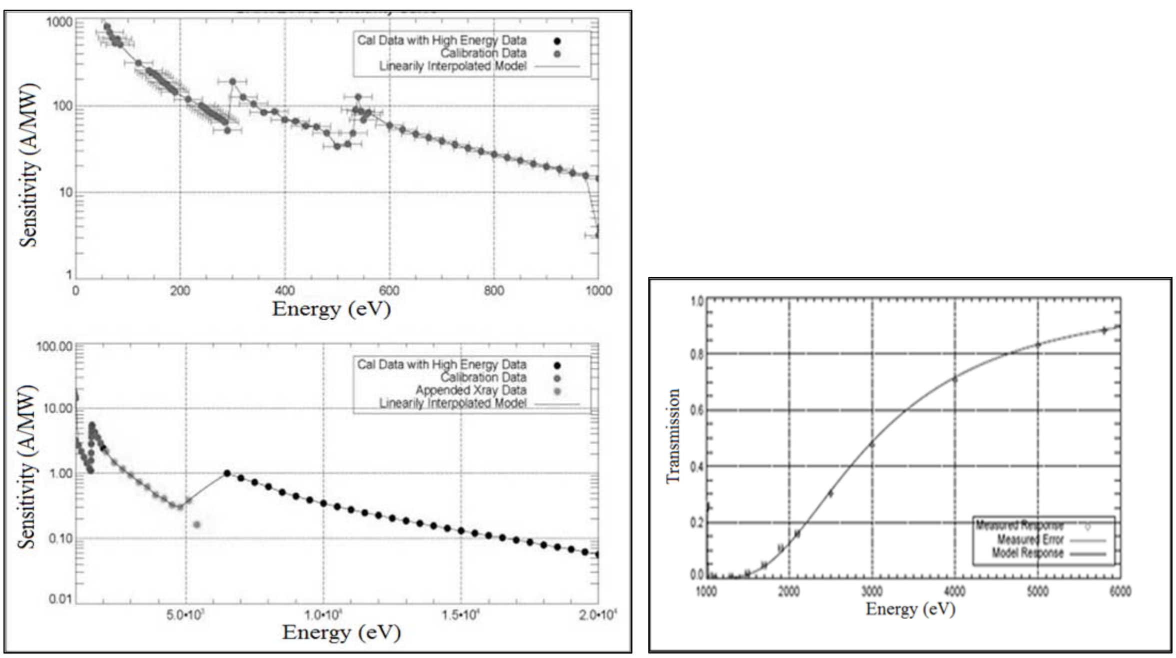


Figure 10. Data for a photocathode (left) and filter (right) made at NSTec / LO and measured at BNL

The diode behavior for different bias voltages was measured and compared favorably to models. This allows operation at voltages lower than 1000 V when response time of the diode is not a critical, and voltages higher than 1000 V if best response time is needed. See Figure 11.

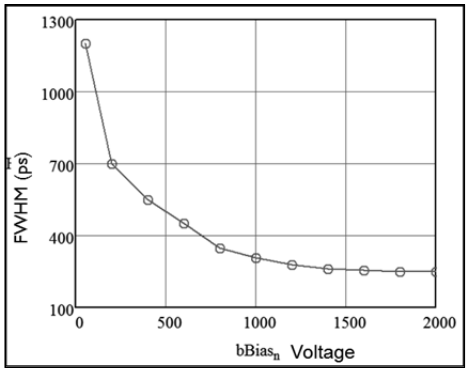


Figure 11. Plot showing initial tests of pulse width vs. bias voltage

7. DEMONSTRATIONS IN RELEVANT FACILITY ENVIRONMENTS (TRL 4-6)

Demonstration of key elements

Basic individual diode function was demonstrated on diodes fielded at Omega. Several individual diodes were assembled and placed on a XRD-31 adaptor mount, so they could be run on a Dante at LLE Omega laser for comparison between the MiniXRD prototypes and the XRD-31 diodes. Some early tests still included ringing on the signal, but response and use matched our expectations well and prompted further development, including elimination of ringing on future diodes. The signals are inverted because the MiniXRD reads the signal from the anode, and the XRD-31 Dante channel reads the signal from the photocathode bias-T.

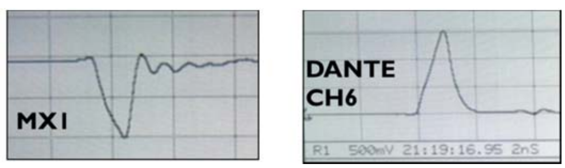


Figure 12. First comparison of MiniXRD to XRD-31 on DANTE

The basic diode array function and filter combinations were also demonstrated in numerous configurations at NRL. All functions worked well within modeled parameters and comparative measurements were made between different configurations. Physically, we demonstrated mounting techniques, installation, and alignment by facility personnel, setup and operation of combinations of 8 channels (the 19 possible channels were limited by available oscilloscope channels), and field repair of in-chamber diodes and systems. Individual diode function was verified and problems identified and mitigated.

It was observed that very thin lower-energy filters were easily damaged when venting or when shocked, so practical low-energy cutoff is around 900-1000 eV when the filters are expected to survive repeated shots in a vacuum chamber.

The core requirements started with some straightforward performance and environment criteria. Then, as we progressed along the technical readiness path, there was a desire to use the MiniXRD on different experiments at several different facilities. This resulted in a growth of the system to include physical mounts, alignment methods, optimization, and development of analysis techniques. As each system was made, design improvements were made to rectify minor problems or enhance capabilities. Since the design was modular from its inception, these changes were easily incorporated along with design improvements derived from analysis of the observed performance, making it adaptable as single-channel application to multiple channels covering several energy bands.

Demonstration of complete systems at NRL

Several comparative complete systems were fielded at the NIKE laser facility at NRL as ancillary ‘ride along’ diagnostics. We fielded a parallel array of six single diodes, four sets of two-channel arrays, and a five-channel array on numerous shots over a two-week period. These arrays were mounted inside the chamber to allow measurements from a very close proximity. Special mounts were designed for each type of array: a butterfly tilt for the parallel array, a micrometer driven two-dimension tilt for the two-channel arrays, and a larger tilt for the five-channel array. The front of each of the diode arrays was fitted with a laser alignment cap and easily aligned to the target. The alignment cap was then replaced with mesh to attenuate the signal as appropriate. Setup inside the chamber was difficult due to access restrictions, but facility support personnel were very helpful, and this was the first time someone without formal training in the use of the diodes was able to install and align them. See Figure 13.

Figure 13. Five-channel, quad 2 channel, and parallel array at NRL / NIKE (photo courtesy of Jacob Grun)

We obtained more than 100 data sets and compared results from different diode array types. Due to short chamber vent times and the array proximity to the source of X-rays, the front low-energy filters were subjected to forces that destroyed them within the first few shots. Only filters designed for transmission above 900 eV survived repeated shots. This is easily seen when examining the data as a tail that does not rapidly return to the ground baseline. Due to the design of the stacked array, it was easy to accommodate the filter change and recalculate the adjusted channel energy bands and keep all other channels functional. We also saw more noise on the partially-unshielded diode arrays compared to the fully-shielded arrays, so in future we will always shield them in the metal tubes. The difficulty of servicing the diode filters inside the chamber drove the design of the ball / socket mount to include easy filter changes.

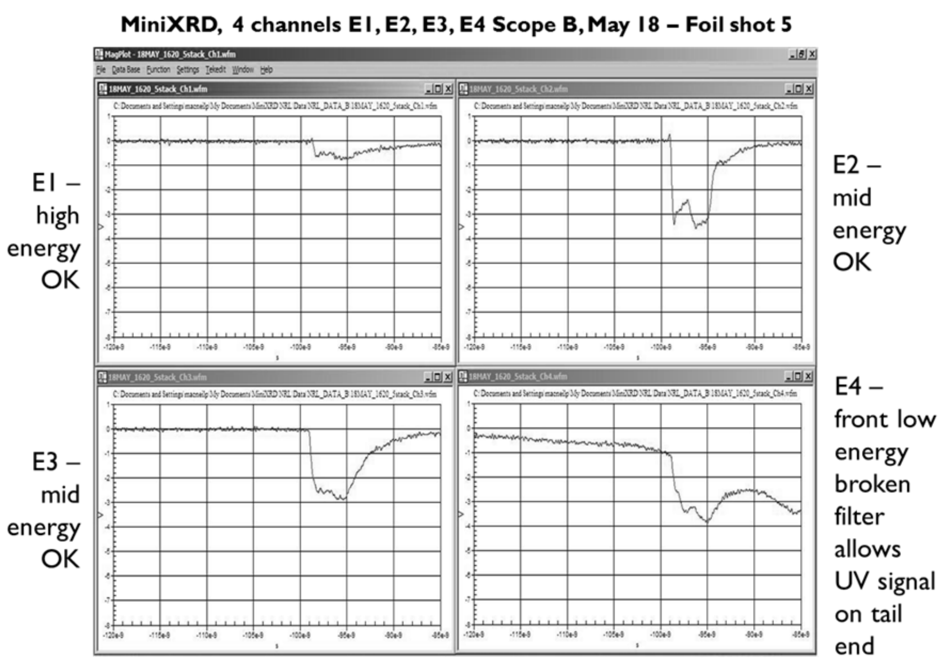


Figure 14. Sample of data from NRL / NIKE – using MagPlot

Demonstration of complete systems at UNR

We used a variety of existing software, some proprietary to NSTec like Compare2011 and MagPlot. While these programs worked very well, we eventually developed a more integrated software program to allow us to more easily plan for the experiment, document the experiment, and analyze the data. Plans involved determining the needed filters and photocathodes using the data from the CXRO website to provide the desired response function of each channel, ability to record and accommodate mesh and attenuators, link to large sets of data files, read and check signals for known noise issues, and correlate the characterization and channel data with the setup parameters to analyze the data rapidly and consistently. This software was used extensively for the experiment setup, correlation of data, and analysis of data during the NRL and UNR experiments. See Figure 15.

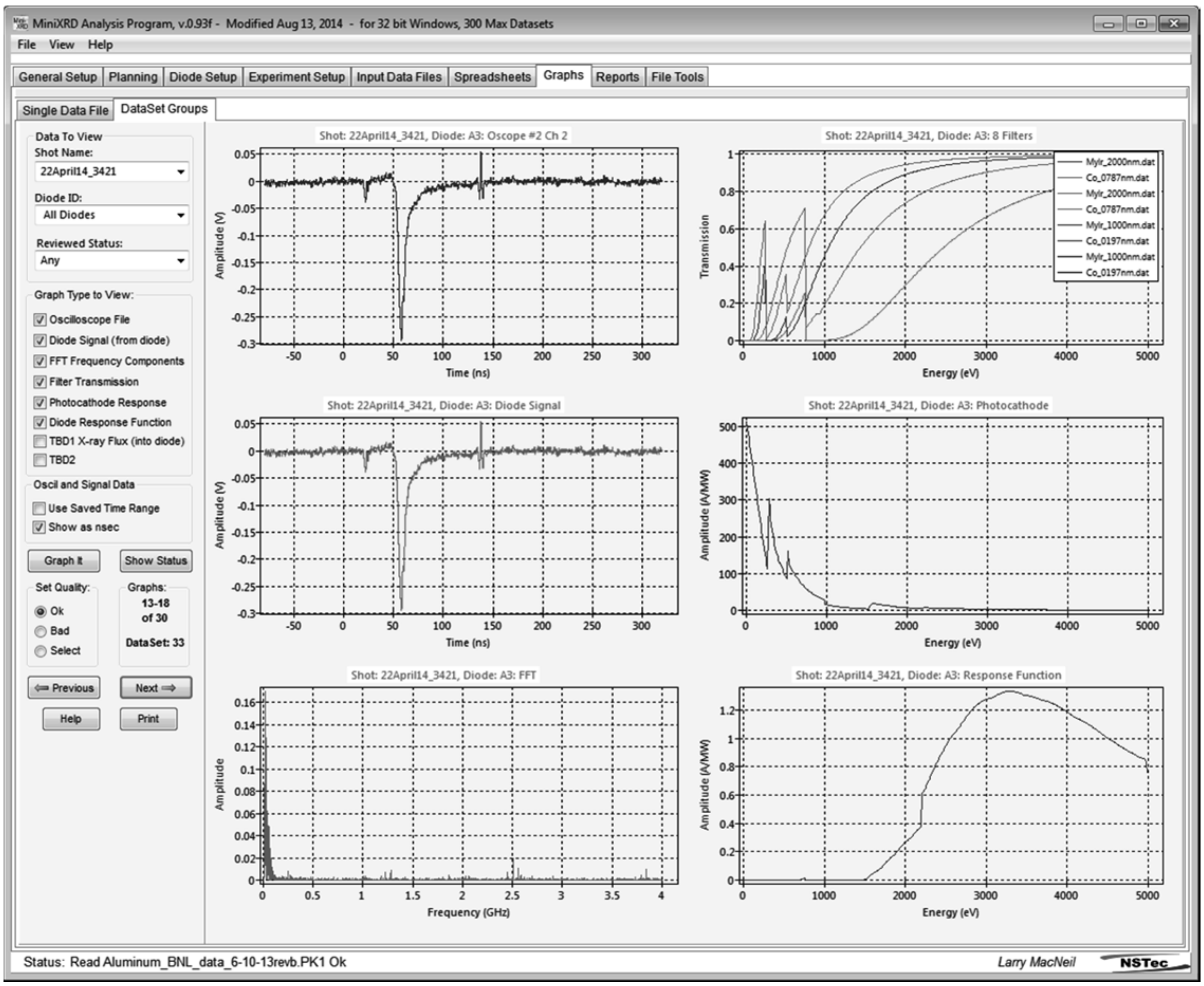


Figure 15. Prototype MiniXRD analysis software used to plan, record, and analyze experimental data

Our last fielding of the MiniXRD system was a five-channel array directed at the ZEBRA z-pinch located at the Nevada Terawatt Facility at UNR. Here we fielded a fully functional ball / socket mount as shown in Figure 16 and a five-channel array on numerous shots as an ancillary ‘ride-along’ diagnostic over a two-week period. Four of the channels were designed to detect different energy bands, and the fifth was a duplicate of one of the channels (no extra filters in front) to confirm repeatability. We obtained some excellent data that allowed us to detect features over time of the X-ray flux, and we were able to infer the temperature vs. time profile using multiple channels. See Figure 17.

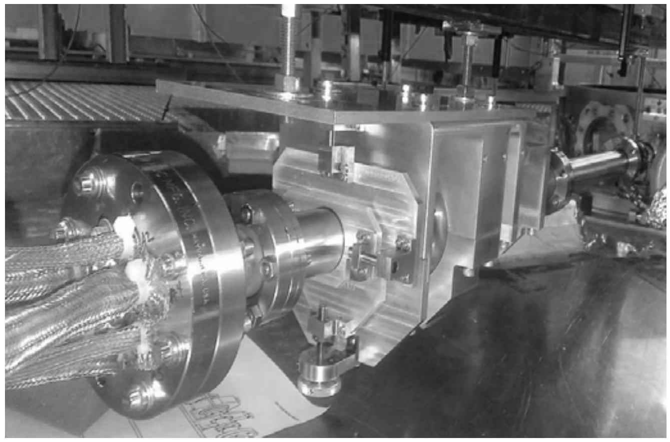


Figure 16. Ball / socket mount and five-channel array at UNR

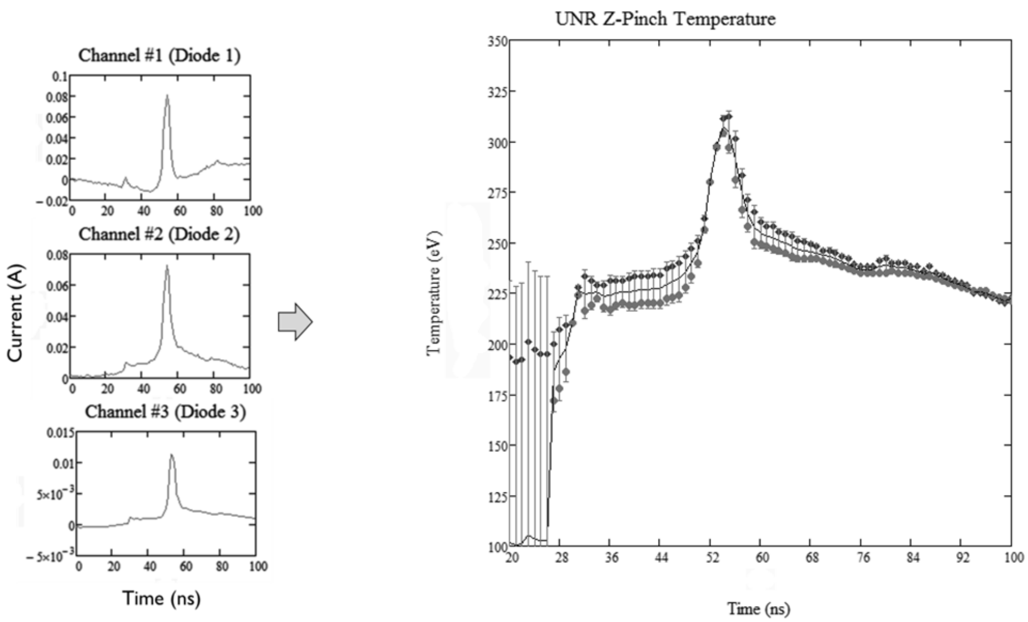


Figure 17. Inferred temperature vs. time for one shot at UNR

As expected, the inferred temperature profile generally has increased errors at the lower relative temperatures due to fewer channel contributions and lower signal levels, but the inferred temperature around the peak agrees between the different channels.

8. CONCLUSIONS

A stacked, filtered multichannel X-ray diode array called the MiniXRD was developed and tested, and works well. This capability fills a niche in the available soft X-ray diagnostics to provide an inexpensive coarse spectrometry capability for both field and facility use. The system meets all requirements and has been successfully tested and fielded to measure low-energy X-rays from 450 eV to 5 keV for single-shot use, and 900 eV to 5 keV for repeated facility use. The modular design of the system facilitates ease of setup, repair, and replacement. The filters that were manufactured in-house worked well, and characterization methods at NSTec/LO and BNL worked well to support successful fielding at multiple facilities. Measurement consistency was addressed with assembly and alignment techniques that ensure line-of-sight accuracy. Analysis techniques were developed to ensure both proper setup and data treatment. This diode array is currently at TRL 6.

9. NEXT STEPS

Completion of system qualification as needed

TRL 7 status will require utilizing the system as a more integral part of an experiment series, where scientists (users) are more involved in the fielding and analysis to thoroughly validate the process. TRL 8 and 9 would involve taking the system into turnkey status with general applications. Currently this work is not funded, but custom applications of the existing design are still possible under special arrangement.

Further development:

- The lowest-energy channels use the thinnest filters and are subject to the most shock since they are in the front of the stacked array. Thus, with close-in applications, the filters break after only one or two uses. For single-shot use that may still work, but for repeated use at facilities or when more accuracy and dynamic range of the overall system is needed, we investigated an alternative front-channel solution and started development of a mirrored low-energy channel that is placed at the front of the stacked filtered array. This shows promise as an addition to the stacked array concept. In this new channel, an aperture separates a portion of the X-rays that go through a very small (so more robust) light blocker to cut off the UV and then utilizes a mirror to select the upper energy cutoff (typically <1 keV). The rest of the X-rays pass through unchanged into a standard filtered array beneath the mirrored channel.[1]
- The alignment methods we used worked well, but there are several refinements that can be made to make it more useful for the mirrored channel in conjunction with the filtered channels.
- Analysis methods and software should be developed further and more rigorously validated.
- Models show that energies to 10 keV or higher are entirely feasible. The upper limit needs to be verified.

REFERENCES

[1] Dutra, E. C., MacNeil, L. P., Compton, S. M., Jacoby, B.A., Raphaelian, M. L., "Mirrored low energy channel for the MiniXRD," Proc. SPIE 9591-7 (publication pending).

[2] Kyrala, G. A., Seifter, A., "Different methods of reconstructing spectra from filtered x-ray diode measurements," R. Sci. Inst. **79**, 10F323 (2008).

[3] May, M. J., Widmann, K., Sorce, C. Park, H-S., Schneider, M, "Uncertainty analysis technique for OMEGA Dante measurements," R. Sci. Inst. **81**, 10E505 (2010).

[4] Dewald, E. L., Campbell, K. M., Turner, R. E., Holder, J. P., Landen, O. L., "Dante soft x-ray power diagnostic for National Ignition Facility," R. Sci. Inst. **75**, 3759 (2004).

[5] Center for X-ray Optics, www.cxro.lbl.gov

ACKNOWLEDGMENTS

The authors are grateful for the support from many people. A partial list is: Tom Waltman, Gene Hunt, Randy Flurer, Jeff Fornes, Don Max, Mary Ann Karrick, Gabe Torres, Susan Cyr, John Yuhas, Don Pellinen, Ke-Xun Sun, Robert Buckles, Ted Perry, Mark May, Leon Berzins, the folks at the various facilities, and all the LO team – thanks!