Thermometric- and Acoustic-Based Beam Power Monitor for Ultra-Bright X-Rays

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August 14, 2009

Prepared in partial fulfillment of the requirements of the Office of Science, Department of Energy's Science Undergraduate Laboratory Internship under the direction of Joseph Frisch at the LCLS Diagnostics Group, SLAC National Accelerator Laboratory.

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TABLE OF CONTENTS

Abstract	ii
Introduction	iii
Theory	iv
Methods	xi
Results	xii
Discussion	xiii
Conclusions	xv
Acknowledgements	xvi
References	xix

ABSTRACT

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A design for an average beam power monitor for ultra-bright X-ray sources is proposed that makes simultaneous use of calorimetry and radiation acoustics. Radiation incident on a solid target will induce heating and ultrasonic vibrations, both of which may be measured to give a fairly precise value of the beam power. The monitor is intended for measuring ultra-bright Free-Electron Laser (FEL) X-ray beams, for which traditional monitoring technologies such as photo-diodes or scintillators are unsuitable. The monitor consists of a Boron Carbide (B_4C) target designed to absorb most of the incident beam's energy. Resistance temperature detectors (RTD) and piezoelectric actuators are mounted on the outward faces of the target to measure the temperature changes and ultrasonic vibrations induced by the incident beam. The design was tested using an optical pulsed beam (780 nm, 120 and 360 Hz) from a Ti:sapphire oscillator at several energies between 0.8 and 2.6 mJ. The RTDs measured an increase in temperature of about 10 °K over a period of several minutes. The piezoelectric sensors recorded ringing acoustic oscillations at 580 ± 40 kHz. Most importantly, the amplitude of the acoustic signals was observed to scale linearly with beam power up to 2 mJ of pulse energy. Above this pulse energy, the vibrational signals became nonlinear. Several causes for this nonlinearity are discussed, including amplifier saturation and piezoelectric saturation. Despite this nonlinearity, these measurements demonstrate the feasibility of such a beam power measurement device. The advantage of two distinct measurements (acoustic and thermometric) provides a useful method of calibration that is unavailable to current LCLS diagnostics tools.

INTRODUCTION

The Linac Coherent Light Source (LCLS) at the SLAC National Accelerator Laboratory is a new source of X-rays intended for probing molecular and atomic physics at very small length and time scales. Electrons accelerated and bunched by the existing linear accelerator are injected into undulators, which induce oscillations in the electron beam. The oscillating bunches radiate at a wavelength equal to the separation between bunches. The final X-rays have energies between 800 eV and 9 keV. The pulse length of the beam is less than 10 fs, and is repeated at a rate of 10 Hz. The beam diameter is about 100 μm . The energy per pulse is between 1 and 3 mJ, resulting in a peak power of over 100 GW and a peak brightness of over 10^{32} photons / s mm² mr² [10].

The exceptionally short pulse length and low emittance make the LCLS beam nearly ten billion times brighter than existing sources. As such, traditional devices and methods for measuring beam energy are not available for use in LCLS diagnostics. Photodiode circuits would, at best, be saturated by the high intensity of X-rays; at worst, they would be permanently damaged. Yttrium aluminum garnet (YAG) screens, which fluoresce when struck by incident X-ray or electron radiation, provide a possible alternative and are currently the primary diagnostic in use at LCLS [9] [14] [10]. Although intended to measure the beam's spatial profile and alignment, digital imaging processing may be applied to fluorescence images to obtain rough power measurements. Problems arise, however, when the beam energy increases above the screen's saturation point. In addition, calibration is tricky due to dependancies on the cameras used to capture the fluorescence, as well as degradation of the screen over time. Some studies have also shown inherent "blurriness" in YAG screen images that tends to enlarge the observed beam size, further reducing the viability of this technique as a precision beam power diagnostic [17].

The simplest alternative to these methods is calorimetry, a standard technique used in

many detector applications. This technique is, in fact, already being used as one of the primary diagnostics tools for LCLS [8]. Calorimeters, however, suffer from complications of heat exchange and thermal noise, processes which are often difficult to either precisely quantify or eliminate. The proposed device aims to supplement the existing calorimetric technique with a less noisy alternative: radiation acoustics. Certain solids, when irradiated by a pulsed X-ray beam, will ‘ring’ ultrasonically, as if struck by a hammer [15]. These ultrasonic vibrations are relatively clean, have a narrow bandwidth ($Q > 15$), and have a ringing amplitude that varies linearly with beam energy [23]. This linear correlation may be used to determine beam energy based on a given measurement of ringing amplitude.

In order to use these phenomena in a measurement of beam energy, theoretical models were constructed. These were used both to provide proof of the device’s feasibility as well as to give rough estimates of its responsiveness. Mechanical design and material choices were carried out based on the predictions of these models [16]. Design and testing of electronics were carried out alongside the mechanical design. A schematic drawing of the planned device appears in Figure 1. A prototype device was machined and assembled with the intention of eventually installing a version in the LCLS beamline. The prototype was tested using an pulsed optical beam but was not installed.

THEORY

In order to compute a value for the beam power, theoretical models were constructed to characterize the system’s thermal and acoustic properties. These models may then be used to solve for the beam energy given measurements of the thermal and acoustic excitation of the system. These models assume a 1 cm^3 target composed of Boron Carbide.

Thermal Theory

Validity of Lumped-system Model The following heat exchange model was constructed assuming a lumped system; this assumption posits that temperature gradients within objects may be ignored due to the small size and large thermal conductivity of the objects. This assumption is justified by the value of the Biot Number, Bi , a dimensionless number that quantifies the relative rates of heating within and without an object:

$$Bi = \frac{hL}{k} \quad (1)$$

where h is heat transfer coefficient describing the rate of heating at a boundary, L is the characteristic length of the object ($L \approx Vol./Area$), and k is the thermal conductivity of the object. If Bi is much less than 1, the object internally equilibrates very quickly and temperature gradients may be ignored. The value of Bi for the proposed device was calculated to be 0.026, indicating that temperature gradients within the B_4C target are negligible.

Dynamic Heat Equation Simple heat exchange models were used to characterize the thermal behavior of the target after irradiation. To keep the models simple, the total heat flow to and from the B_4C target was assumed to be approximately described by Newton's law of cooling. That is, the temperature of the target was assumed to be described by the differential equation given by Equation (2), where solutions to the equation are given by Equation (3).

$$\frac{dT}{dt} = h(T - T_a) + k \quad (2)$$

$$T(t) = me^{at} + b \quad (3)$$

T is the temperature of the target and h , k , m , a , and b are arbitrary coefficients. The ambient temperature, T_a , was assumed constant.

Five heat exchange processes were accounted for in the model: (a) heat flow through electrical wiring via the sensors; (b) convection currents in the ambient vacuum; (c) heat flow through the piezoelectric actuators; (d) exchange of thermal radiation between the target and the cylindrical beam line; and (e) exchange of thermal radiation between the target and tungsten collimator (labeled in Figure 1).

For processes (a) through (c), differential energy loss is governed by the same general equation as in Equation (2):

$$\frac{dQ}{dt}_{T_1 \rightarrow T_2} = h(T_1 - T_2) \quad (4)$$

where $\frac{dQ}{dt}_{T_1 \rightarrow T_2}$ is the thermal energy transferred between object 1 and 2, T_1 and T_2 are the temperatures of the two objects, and h is a constant governing the rate of heat exchange, determined by the dimensions and thermal properties of the system. These processes are thermally grounded to the ambient temperature T_a , so the variable T_2 may be replaced by the constant T_a in Equation (4).

The radiative processes, (d) and (e), are governed by a different general equation:

$$\frac{dQ}{dt}_{T_1 \rightarrow T_2} = A_1 \sigma (T_1^4 - T_2^4) / \left[\frac{1}{\epsilon_1} + \frac{(1 - \epsilon_2) A_1}{\epsilon_2 A_2} \right] \quad (5)$$

where $\frac{dQ}{dt}_{T_1 \rightarrow T_2}$ is the radiative energy transferred between the surfaces A_1 and A_2 , and ϵ_1 and ϵ_2 are the emissivities of the two surfaces, respectively. This equation may be approximated (via binomial expansion) by:

$$\frac{dQ}{dt}_{T_1 \rightarrow T_2, approx.} = h_{rad.} (T_1 - T_2) \quad (6)$$

$$\text{where } h_{rad.} = 4T_2^3 A_1 \sigma / \left[\frac{1}{\epsilon_1} + \frac{(1 - \epsilon_2) A_1}{\epsilon_2 A_2} \right].$$

In this way, one may quantify radiation exchange (i.e. processes (d) and (e)) in the simple form assumed in Equation (2).

Relative Significance of Heat Exchange Processes The relative significance of the processes (a) through (e) may be evaluated by comparing each process’ “heat transfer coefficient,” h . The larger this coefficient, the more heat energy is lost per unit time through a particular process. A plot of this comparison is shown in Figure 2. It is evident from this comparison that only heat loss through the piezoelectric actuators and radiation exchange with the beam line container are significant enough to warrant further consideration.

Total Heat Flow The total differential temperature change in the model is given by

$$\frac{dT}{dt}_{target} = \frac{1}{mc_v} \left[\sum_{i=1}^5 \frac{dQ_i}{dt}(T) + P_\gamma \right] \quad (7)$$

where $\frac{dQ_i}{dt}(T)$ are the differential heat energies lost by each of the five processes, P_γ is the power in the X-ray beam, and mc_v is the target’s specific heat. Solving for the temperature function $T(t)$, a limiting temperature of 301.2 °K and a time constant of 300 s were found (assuming a 10 mW average beam power). The theoretical temperature curve calculated with this model is shown in Figure 3.

Solving for Beam Power The heat losses $\frac{dQ_i}{dt}(T)$ are constant regardless of whether the beam is on or off. Therefore, these losses may be quantified when the beam is off and then filtered out when the beam is turned back on. The beam power is determined when these known heat losses have been corrected for. That is, given a temperature curve (like the one shown in Figure 3), one may solve for the characteristic time constant of the system using

two points $\langle T_1, t_1 \rangle$ and $\langle T_2, t_2 \rangle$ on the “beam off” curve:

$$\tau = \frac{t_1 - t_2}{\log(T_1 - T_a) - \log(T_2 - T_a)} \quad (8)$$

where T_a is the ambient temperature (assumed to be 300 °K in Figure 3). This time constant characterizes the heat losses in the system. Then the power of the beam may be solved for using this time constant and two points $\langle T_3, t_3 \rangle$ and $\langle T_4, t_4 \rangle$ on the “beam on” curve:

$$P_\gamma = \frac{mc_v}{\tau} \left[T_a - \frac{T_3 - T_4 e^{(t_3 - t_4)/\tau}}{1 - e^{(t_3 - t_4)/\tau}} \right]. \quad (9)$$

Complications Due to Target Clamp In the original heat exchange model, the large aluminum base supporting the target and collimators (see bottom of Figure 1) was assumed to remain at a fixed temperature, T_a , due to its large thermal mass. This assumption is not true, however, of the clamp (circled in red in Figure 1) that holds the target down on top of the aluminum mount. As the target’s temperature increases, heat energy flows to the clamp, causing its temperature to rise as well. The dynamical flow of heat energy is impacted by this temperature change.

A more accurate model must consist of two coupled differential equations. This coupled system may be described by a system of matrices, analogous to the single-variable temperature equation given by Equation (2),

$$\vec{T}' = [\mathbf{M}]\vec{T} + \vec{b} \quad (10)$$

where $\vec{T}$ is the temperature vector containing the two temperature values T_{target} and T_{clamp} , $\vec{T}'$ is the differential temperature vector, $[\mathbf{M}]$ is the coupling matrix, and $\vec{b}$ is the constant

term vector. Solutions to this differential matrix equation are of the form:

$$\vec{\mathbf{T}}(t) = \vec{\mathbf{v}}[\mathbf{B}] \begin{bmatrix} e^{\lambda_1 t} & 0 \\ 0 & e^{\lambda_2 t} \end{bmatrix} [\mathbf{B}]^{-1} - [\mathbf{M}]^{-1} \vec{\mathbf{b}} \quad (11)$$

$$\text{where} \quad \vec{\mathbf{v}} = \vec{\mathbf{T}}_{\mathbf{i}} + [\mathbf{M}]^{-1} \vec{\mathbf{b}},$$

$\vec{\mathbf{T}}_{\mathbf{i}}$ is the initial temperature vector, the columns of $[\mathbf{B}]$ are the eigenvectors of $[\mathbf{M}]$, and λ_1 and λ_2 are the eigenvalues of $[\mathbf{M}]$.

The results of this 2-variable model are shown in Figure 4. The “actual” temperature curve (i.e. temperature is affected by the clamp) is shown in blue, whereas the “nominal” curve (i.e. assuming the clamp has infinite thermal mass) is shown in brown. The clamp acts to retain heat in the system, resulting in higher limiting temperatures. Fortunately, since the second-order coupling effects are small, this variation may be compensated for by a simple multiplication factor. That is, the actual temperature curve is approximately proportional to the nominal temperature curve:

$$T_{act.}(t) = \frac{1}{\kappa} T_{nom.}(t) \quad (12)$$

where $\kappa = 0.6622$ for all beam energies.

Acoustic Theory

Known theory may also be used to model acoustic phenomena. The generation of sound waves by X-ray radiation is considered in detail by Kalinichenko, et. al. [15]. For a photon beam, sound generation in a target is dominated by thermoelastic expansion due to lump energy deposition, as opposed to dynamic stresses from individual photons. In the range of X-ray energies produced by LCLS (800 eV - 9 keV), energy is transferred to the target

primarily via the photoelectric effect (as well as a smaller contributions from Rayleigh and Compton scattering). These effects generate secondary electrons, which continue to transfer energy to the target via ionization of target atoms. These mechanisms primarily increase the thermal energy of the target, causing thermal expansion that is responsible for wave generation.

For the vibrational measurement to have any significance, the fraction of beam energy absorbed by the target must be known. The most energetic X-rays in the FEL beam have energies less than 9 keV, giving a maximum attenuation length in B₄C of about 2 mm [11]. Thus, roughly 95% of the incident photons have been absorbed in a target length of 6 mm (95% length $\approx 3 \times$ atten. length). As a rough estimate, the attenuation length of the secondary electrons in the solid target may be given by the Bethe-Bloch formula,

$$\left\langle \frac{dE_e}{dx} \right\rangle = -2\pi \left(\frac{e^2}{4\pi\epsilon_0} \right)^2 \frac{zn}{E_e} \ln \left(\frac{\delta E_e}{I} \right) \quad (13)$$

where e is the electron charge, z is the atomic number of the target material, n is the atomic density, I is the mean atomic potential, and E_e is the initial electron energy [3]. Using this formula, the maximum stopping length for the most energetic electrons (i.e. 9 keV) may be calculated:

$$dx = dE_e / \left[2\pi \left(\frac{e^2}{4\pi\epsilon_0} \right)^2 \frac{zn}{E_e} \ln \left(\frac{\delta E_e}{I} \right) \right] \approx 6.6 \mu\text{m}.$$

Since the length of the target along the beam path is 10 mm, it may be assumed that nearly all of the incident X-rays and secondary electrons are absorbed thermally by the target. That is,

$$dE_{\text{target}} \approx E_{\text{pulse}}. \quad (14)$$

Assuming that the target heats uniformly (see calculation of Biot number above), the amplitude of the thermoelastic wave may be approximately described as uniform expansion

of the target in all dimensions due to heating. Using known values of specific heat c_v and coefficient of thermal expansion α for Boron Carbide, the expected vibrational amplitude is:

$$u = \frac{1}{2}\alpha L_0 \frac{dE}{mc_v} \quad (15)$$

where u is the amplitude of vibration, L_0 is the initial length of the target, and mc_v is the specific heat of the target. Given the assumption stated in Equation (14), the vibrational amplitude is then proportional to the pulse energy:

$$u = \zeta E_{pulse} \quad (16)$$

$$\text{where} \quad \zeta = \frac{\alpha L_0}{2mc_v}.$$

For the Boron Carbide target, $\zeta = 11 \text{ pm/mJ}$.

In addition, the resonant frequency of the target may also be calculated from the physical characteristics of the target:

$$f = \frac{s}{2L_0} \approx 545 \text{ kHz} \quad (17)$$

where s is the speed of sound in Boron Carbide and L_0 is the initial length of the target.

METHODS

Several proof-of-concept tests were carried out on a test target to determine the feasibility of the device and to verify theoretical calculations. A $0.8 \times 1 \times 1.25 \text{ cm}^3$ Boron Carbide block was placed in the path of a pulsed 780 nm Q-switched Ti:sapphire beam. The target was oriented with the 1.25 cm face normal to the beam. The pulse length of the beam was roughly 10 ns at repetition rates of 120 and 360 Hz. The bandwidth was 30 nm, and the spatial profile was roughly Gaussian. Two monolithic ceramic piezoelectric actuators were

glued to the target using Torr-Seal epoxy and clamped in place with an aluminum bar. Two 100 Ohm platinum RTDs were also mounted on the sides of the target.

The beam was attenuated and shaped by a wave plate and polarizer, and the spot size was controlled by a lens with a 0.5 m focus length. Before placing the target in the beam path, a power meter was used to measure the beam's average power. Two methods were used to vary the beam power: modification of the laser cavity length and attenuation via optical filters.

The signal from each piezoelectric actuator was fed to a 1:4 transformer, a 1.9 MHz low-pass filter, a BJT preamplifier, and an oscilloscope. The oscilloscope was triggered on the beam pulse signal. Waveforms of the vibration signal were saved to disk for later analysis. The resistance (i.e. temperature) of the RTD was measured by a RTD temperature monitor using a 4-wire ratiometric measurement.

Several of the beam's parameters were varied over successive trials. The spot size was varied from 0.5 to 1 cm $\varnothing$. The position of the beam on the target was varied from the bottom of the target to the top (roughly 4 mm off center in each case). The beam power was varied from 360 mW to 920 mW at 360 Hz repetition, and from 100 mW to 320 mW at 120 Hz repetition (these powers correspond to a range of roughly 0.8 to 2.6 mJ of pulse energy).

RESULTS

Plots of typical vibration signals from the irradiated block are shown in Figure 5. For low pulse energies (≤ 2 mJ), the amplitude of vibration was observed to vary linearly with beam power. This linearity disappears for pulse energies above 2 mJ, where the vibrational amplitude falls below the linear trend exhibited by the system at lower energies. A plot of vibration voltage versus beam power that exhibits this roll-off behavior is shown in Figure

6. As seen in the figure, the magnitude of roll-off is dependent on the level of amplification, indicating that amplifier saturation may be to blame for the observed nonlinearity. In an attempt to eliminate this effect, the amplifiers were removed from the system for three trials. This data is shown in Figure 7. Signal roll-off is still observed in these trials, indicating that factors other than amplifier saturation must contribute to nonlinearity in the vibration signal.

The resonant frequency of the block was observed to be 580 ± 40 kHz, in good agreement with theory. When the diameter of the spot was halved, the vibrational amplitude was observed to increase by about 25%. A detectable phase shift (on the order of $0.5 \mu\text{s}$) was observed for trials in which the beam was aligned off-center. The RTDs detected a significant increase in temperature during each trial on the order of 10°C after several minutes. This disagreed significantly with theory, which predicts a temperature rise of 43°C over the same time period.

DISCUSSION

That the amplitude of vibration in fact varied linearly with beam power demonstrates the device's fundamental viability as a beam power monitor. It also places the device in excellent agreement with similar experiments carried out by Kalinechenko and White [21] [23]. Unfortunately, the observed nonlinearity at high pulse energies is a significant problem. This effect could be due to several factors. The first could be a nonlinearity inherent in the piezoelectric actuators. The actuators may saturate above some maximum compression, resulting in reduced voltage signals for large compressions. Another, and more likely, source of disagreement stems from the properties of the beam used to test the device. While an X-ray beam penetrates through a good deal of the target material, inducing heating over a large depth, an optical laser is largely absorbed within a few micrometers, inducing large

temperature gradients at the boundary of the target. The sound waves generated from this type of heating may differ significantly from those generated by the X-ray beam; this difference may be the cause of the unexpected nonlinearity.

In addition, the data disagrees with theory by a factor of 3 or more. A comparison of experimental data and theoretical predictions is shown in Figure 8. This disagreement could be due to several factors. The most sensible explanation is that the theoretical calculations do not account for resonances in the block. After irradiation, pressure waves must be expected to bounce around inside the target, constructively interfering to create compressions that are larger than those calculated from Equation (15). Another possible explanation considers again the differences between the FEL beam and the optical test beam. While theoretical calculations were carried out assuming a coherent, narrow ($\sim 100 \mu\text{m}$) beam comprised of hard X-rays, the beam used to test the device was an optical beam with a much wider spot ($\sim 1 \text{ cm}$). Since the details of pressure wave generation depend on the energy density and wavelength of incident radiation, these differing beam characteristics could have led to the creation of pressure waves with different amplitudes. Another suspected cause is a resonance in the cables that acted to amplify the piezoelectric signals they carried. These hypothesis must be investigated further in order to determine the true sources of discrepancy.

The dependence of vibration amplitude on spot size is also a significant impediment to the device's prospects as a power monitor. Ideally, the device should be able to measure average power regardless of the size of the spot, without any additional calibration. The literature, however, suggests that this effect is inherent to the phenomenon of wave generation by radiation beams. Calculations show that the peak vibrational amplitude depends critically on the beam radius as $u \propto R^{-3/2}$, where u is the vibration amplitude and R is the beam radius. Future work should focus on understanding and compensating for this effect.

The resonant frequency remained constant over all trials, in support of the simple wave propagation calculation shown in Equation (17). The stability of the resonant frequency

is fortunate because it allows easy processing of the vibrational signal via either analog or digital filtering.

The phase shift in the vibration signal due to changes in beam position agrees with expectations based on the propagation of sound waves in Boron Carbide. The magnitude of phase difference, moreover, was large enough to justify using the device to make precision measurements of beam position in addition to its power measurement capabilities.

Although the behavior of the RTDs during irradiation qualitatively matched expectations, the amount of heating measured disagreed with expectations by nearly a factor of 5. This difference may be explained by the dominant effect of convection currents in open air that acted to cool the device. In vacuum, such convection currents contribute to a negligible amount of cooling, resulting in the device reaching higher limiting temperatures. The device, however, must be tested in vacuum for the thermal technique to be truly verified.

CONCLUSIONS

As FEL X-ray sources reach higher brightness and peak power capabilities, new measurement techniques must be developed to withstand such high-power beams. The proposed device combines traditional calorimetry with the phenomenon of radiation acoustics in order to make a self-calibrated measurement of beam power. Such a technique may easily be adapted for use in future FELs with high beam brightness as well as in other pulsed sources such as hadron or electron beams.

Similar acoustic techniques may also be used to make precision measurements of other beam characteristics. These measurements include beam spot size, beam alignment, energy spectrum, spatial profile, and pulse duration. In addition, acoustic techniques may be used to study material properties such as mechanisms of radiation energy transfer, speed of sound, vibrational modes, and thermodynamic properties. Other applications include

detection of solitary high-energy particles and modification of material properties during irradiation/acoustic wave generation [21].

Future studies must be carried out in order for the device to be considered ready for application. Theoretical studies should include understanding the discrepancies involved in the correlation between beam power and vibrational amplitude (especially with respect to the discussed nonlinearity) and more detailed models of wave generation and propagation in solids under irradiation. In addition, the application of radiation acoustics to beam position measurements must be quantified and studied further in order to use this technique with confidence.

ACKNOWLEDGEMENTS

This research was carried out at the SLAC National Accelerator Laboratory between May 18 and August 14, 2009 under the direction of Joseph Frisch. The author would like to thank the United States Department of Energy, the SLAC National Accelerator Laboratory, and the directors and administrators of the SULI internship program for making this research possible. He would also like to thank his mentors Joe Frisch and Tonee Smith as well as his partner Jennifer Loos. Thanks also go to Bill White, Steve Edstrom, and Ryan Coffee for their expertise and use of the NEH laser, Mark Petree and Phil Cutino for aid in mechanical design, Alan Fisher for guidance in electronics design, and Lesley Wolf for her indispensable help in acquiring research materials.

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FIGURES

(a) View from the side of the device. The coherent spot passes through a slit in the Boron Carbide and Tungsten collimators to hit the B_4C target.

(b) View from the back of the device. The spontaneous radiation may be seen as the dotted blue line filling the front collimator.

Figure 1: (Color) Schematic diagrams of the proposed LCLS beam power monitor. Red circles mark the target clamp that gives rise to second-order thermal behavior in the system.

Figure 2: Relative significance of heat exchange processes in the power monitor system. Only the heat loss through the piezoelectric actuators and ambient radiation are significant enough to be regarded in future calculations.

Figure 3: Theoretical temperature curve for a Boron Carbide target irradiated by a pulsed X-ray beam. The beam is turned on at time $t = 0$ s, and is turned off at time $t = 1000$ s. The target is assumed to reside in an ambient temperature of 300 °K.

Figure 4: (Color) Temperature curves for the target and its associated clamp. The Blue and Red lines are the temperatures of the target and clamp, respectively. (Note the second-order behavior of the clamp between $t = 0$ s and $t = 100$ s due to coupling effects). The Green line is the target's temperature curve if the target clamp were removed, and the Brown line is the target's temperature curve assuming a clamp with infinite thermal mass (i.e. the clamp remains at constant temperature regardless of the target's temperature).

(a) Vibrational signals in irradiated test target. Units: $25 \mu\text{s}/\text{div.} \times 200 \text{ mV}/\text{div.}$

(b) Time detail of Figure (a). Units: $5 \mu\text{s}/\text{div.} \times 200 \text{ mV}/\text{div.}$

Figure 5: (Color) Typical signals produced by radiation acoustic waves in the test target. Orange and Blue waveforms were generated by the two piezoelectric actuators mounted on either side of the target. Figure (b) shows time detail of Figure (a). Waveforms are triggered on the beam pulse. Note the exponential decay of vibration in Figure (a).

Vibrational Amplitude vs. Beam Power at various Amplifications

Figure 6: (Color) Plot of vibrational signal amplitude versus beam power for the proof-of-concept test of the power monitor. The data shows linearity at low beam power (shown by the red trendline), but exhibits nonlinear behavior for pulse energies larger than 2 mJ (i.e. 240 mW). Roll-off is more pronounced for larger amplifications, indicating that amplifier saturation may be a partial cause of nonlinearity.

Figure 7: (Color) Plot of vibrational signal amplitude versus beam power for trials in which the amplifier was removed from the signal line. Signal roll-off is still observed, indicating that the phenomena is not due singularly to amplifier saturation. Other effects, still to be studied, must be responsible for the observed roll-off.

Figure 8: (Color) Plot of vibrational amplitude in the target versus beam pulse energy for the proof-of-concept test. Only data below 2 mJ are included (i.e. in which linearity is conserved). Theoretical predictions are shown by the yellow line. The slopes of the theoretical and experimental curves differ by a factor of 3 or more, indicating severe errors in the theoretical model.