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Generated During Laser-Driven Fusion Experiments***

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(Cd,Mn)Te Detectors for Characterization of X-ray Emissions Generated During Laser-Driven Fusion Experiments

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Abstract—We present our measurements of (Cd,Mn)Te photoconductive detectors (PCDs), fabricated for the goal of measuring both the temporal and spectral dependences of X-ray emissions generated from laser-illuminated targets during the inertial confinement fusion experiments. Our $\text{Cd}_{1-x}\text{Mn}_x\text{Te}$ ($x = 0.05$) single crystals, doped with V, were grown using a vertical Bridgman method and, subsequently, annealed in Cd for the highest resistivity ($\sim 10^{10}$ Ωcm) and a good mobility-lifetime product ($\sim 10^{-3}$ cm^2/V). The 1-mm- and 2.3-mm-thick detectors were placed in the same housing as two 1-mm-thick diamond PCDs. All devices were pre-screened by a 7.6-mm-thick Be X-ray filter with a frequency cutoff of 1 keV. The incident shots from the OMEGA laser were 1-ns-long square pulses with energies ranging from 2.3 kJ to 22.6 kJ, and the PCDs were biased with 5000 V/cm. The response amplitudes and rise times of our (Cd,Mn)Te PCDs were comparable with the diamond detector performance, while the decay times were 4 to 10 times longer and in the 2-5 ns range. We observed two X-ray emission events separated by 1.24 ns. The first was identified as caused by heating of the target and creating a hot corona, while the second one was from the resulting compressed core. For comparison purposes, our testing was performed using ~ 1 keV X-ray photons, optimal for the diamond PCD. According to the presented simulations, however, at X-ray energies >10 keV diamond absorption efficiency drops to $<50\%$, whereas for (Cd,Mn)Te the drop occurs at ~ 100 keV with near perfect, 100% absorption, up to 50 keV.

I. INTRODUCTION

RADIATION detectors based on semiconductors is a very broad subject, ranging from single-photon optical counters to gamma-ray sensors, with many different optimizations for specific functions. Photoconductive

detectors (PCDs) are volume absorbers implemented for measurements of charge carriers generated by the detector transient absorption of ionizing radiation. Common materials for X-ray PCDs are diamond [1] and (Cd,Zn)Te (CZT) [2], with numerous configurations intended to address the balance tradeoffs, such as sensitivity, resolution, and spectral bandwidth. Recently much effort has been spent on making (Cd,Mn)Te (CMT) as a viable material for radiation detection, for it has many beneficial and inherent qualities [3], [4].

As a well-studied, diluted-magnetic semiconductor, $\text{Cd}_{1-x}\text{Mn}_x\text{Te}$ compound is commonly grown with various concentrations x of Mn (up to $x \sim 0.7$) and used for numerous applications ranging from magnetic field sensors and Faraday isolators to solar cells [5], [6]. Simultaneously, new research has been initiated on such CMT applications, as magneto- and electro-optic sampling [7], [8] and phonon generation and detection [9], [10]. As a material for radiation-detection applications, CMT shows a great potential, and is expected to be an inexpensive substitute for presently widely used diamond and CZT PCDs. CMT X-ray detectors have been recently proposed and tested by Burger *et al.* [11] and promising results were shown, when samples, highly doped with V ($7 \cdot 10^{18}$ – $5 \cdot 10^{19}$ cm^{-3}) were used.

One of the most notable advantages of CMT crystals over CZT is their homogeneity. The greater uniformity is due to two reasons: the first being a near unity segregation coefficient of Mn in CdTe, while for Zn in CdTe, the coefficient is ~ 1.3 , which results in significant Zn concentration variations throughout the ingot. The second is the strong dependence of the compound energy bandgap E_G on the Mn concentration (x). The E_G of CZT increases 6 eV per atomic % (at.%), whereas in CMT it increases by 13 eV per at.%, resulting in lower Mn x levels needed for the desired E_G . For example, when $x = 0.27$, the CMT $E_G = 1.9$ eV, which has been declared as an optimal value for the best CMT PCD performance [2], [12]. CZT on the other hand, needs a concentration of Zn equal to 0.59 to achieve a similar E_G . The amount of the third component is an important factor in the quality of the crystal, and in combination with the segregation coefficient, it is much more difficult to grow a homogeneous CZT crystals with Zn concentrations large enough for many X-ray applications [3]. There is, however, one difficulty faced when optimizing CMT for X-ray detection. The ionicities of bonds are higher in CMT than those in CZT. Higher ionicity

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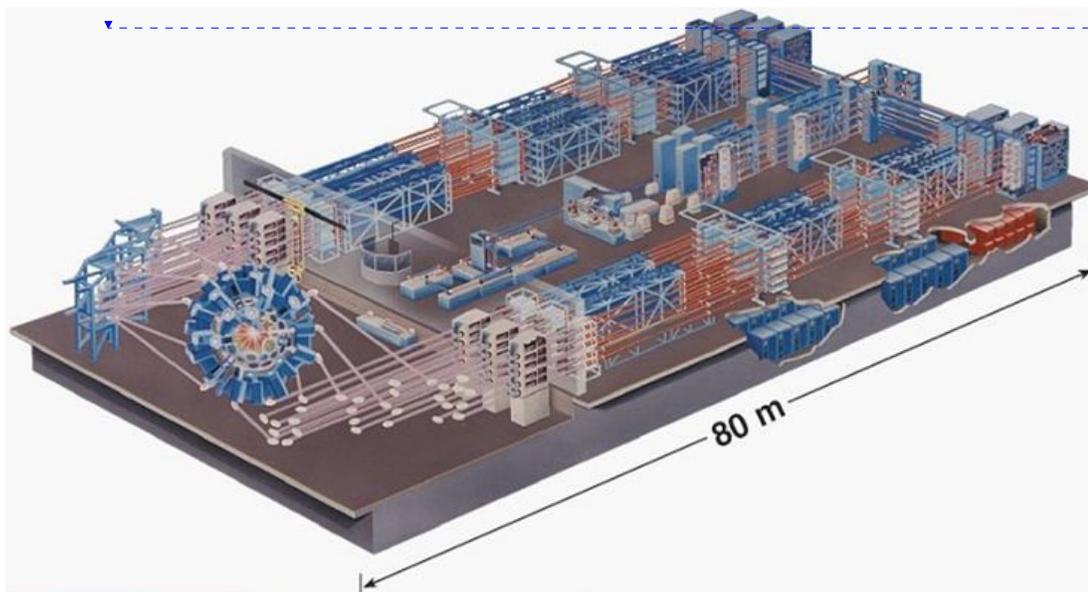


Fig. 1. The 60-beam OMEGA laser at the University of Rochester Laboratory for Laser Energetics.

is connected to a tendency towards crystallization in a hexagonal structure, and promotes twinning in the zinc blende crystal [13]. A relatively low mobility-times-lifetime product ($\mu\tau$) in CMT is also the result of a high concentration of ionized donors and acceptors in the crystal [4], [14].

In this work, we report our attempt to substitute CMT PCDs for diamond PCDs as a diagnostics X-ray detection tool used in the OMEGA facility at the University of Rochester Laboratory for Laser Energetics to conduct inertial confinement fusion (ICF) experiments. In the next section, we will briefly present the OMEGA laser and X-ray emissions generated from the laser-illuminated targets during the OMEGA shots. Section III outlines CMT detector preparation and presents our experimental setup, while Sec. IV is devoted to numerical simulations of the CMT PCD performance in direct comparison with the diamond PCD. Section V reports on our early experimental performance of 1- and 2.3-mm-thick CMT PCDs exposed to 1-keV X-ray photons. Finally, Sec. VI presents our conclusions and the future outlook of our research.

II. OMEGA LASER AND X-RAY DIAGNOSTICS OF INERTIAL CONFINEMENT FUSION EXPERIMENTS

The OMEGA laser (see Fig. 1) is a unique national facility, dedicated to the ICF experimentation, as well as a central tool for high-energy-density physics investigations of the interaction of intense radiation with matter. OMEGA routinely achieves high radiation uniformity with a flexible pulse shaping by directing sixty, 1-ns-long, ultraviolet (UV) beams with the total single-pulse energy up to 30 kJ on a laser-fusion target. The targets used are typically 1 mm in diameter plastic shells filled with a mixture of deuterium and tritium, and are suspended in the target chamber by a spider silk. The OMEGA laser has a short shot cycle of one hour.

The ICF process involves heating and compression of the target fuel by actions of the intense OMEGA beams. As the UV light shines directly on the target, X-rays are emitted from the hot corona. Simultaneously, the beams implode the target and compress the fuel, heating it to thermonuclear temperatures. Once the target is ignited and burns, the nuclear fusion process occurs, by which the hydrogen isotopes join and form helium atoms. At this phase, X-rays are emitted again, but this time from the compressed core.

The standard detectors for the X-ray diagnostics in the OMEGA laser are diamond PCDs. Their main advantages are the high sensitivity for low-energy (soft) X-rays and very high-speed of operation, allowing to time resolve different emission events (from hot corona and burning core) occurring during the ICF shot. There are, however, many beneficial qualities of the CMT PCDs that make them ideal candidates for the measurement of the X-ray emissions from the OMEGA laser-driven fusion experiments. The latter include very large resistivity, highly tunable bandgap of the $\text{Cd}_{1-x}\text{Mn}_x\text{Te}$ compound, good electro-transport properties, and inherently high X-ray stopping power, for which the photoelectric effect shows near flat, approximately 100% absorption spectrum up to ~ 50 keV. It is the intent of our research to demonstrate CMT PCDs as a viable option that will improve both the temporal and the medium-to-high spectral characterization of X-ray transients generated during the ICF event.

III. DETECTOR PREPARATION AND EXPERIMENTAL SETUP

Our CMT crystals were grown using a vertical Bridgman method, and their fabrication process was presented in detail in [4]. Here we only want to stress that great care was taken in making the CMT samples of the highest quality with the necessary parameters for X-ray radiation detection. Although a typical, as-grown, CMT crystal shows resistivity as low as 1

k Ω -cm, several methods have been implemented to produce specimens with suitably high resistivity (10^{10} Ω -cm). The CMT is naturally a p -type semiconductor with a low resistivity due to Cd vacancies (CdV) acting as acceptor centers and produced when Cd atoms escape during the growth process [14]. The processes by which the crystal resistivity is increased to the 10^{10} - Ω -cm level, include purification all raw materials to 6N, effective compensation of free holes with a donor element, e.g., V, and, finally, annealing the sample in Cd. By annealing in Cd vapor, not only the concentration of native Cd_v acceptors is decreased, but also the overall quality of the crystal is improved by diminishing numbers of large defects, precipitates, and inhomogeneities [12].

The CMT crystals used by us as PCDs in the OMEGA laser-fusion studies were (111) oriented platelets cut out of the Cd_{0.95}Mn_{0.05}Te ingot. The Mn concentration $x = 0.05$ was chosen in order to minimize twinning. All our samples were doped with $2 \cdot 10^{16}$ cm⁻³ of V and, subsequently, annealed in Cd. The resulting resistivity of the specimens was $>10^{10}$ Ω -cm, and the $\mu\tau$ product was estimated to be at the 10^{-3} cm²/V level [4].

Fig. 2 demonstrates how the CMT crystals were mounted to a modified subminiature type A (SMA) connector, using copper contacts and a hardened silver paste. The crystal main dimensions were 1x3 mm² with the length along X-ray propagation varying between 1.0, 1.5 and 2.3 mm. Gold contacts were deposited on the top and bottom surfaces to facilitate the Cu electrode contacts, separated by 1 mm. On the four side surfaces, a protective wax was placed. The six PCDs (one 0.5-mm-thick and two 1-mm-thick diamond samples and the three CMTs of different thickness) were then mounted to a collar and holder containing six individual Be filters. The entire PCD array was affixed to a special vacuum interface, isolated from the target chamber to facilitate changes to the PCDs and filters. The Be filters defined the X-ray sensitivity for each detector, as well as provided an aperture to limit the detector solid angle. In our case, the filters were selected for the soft, 1-keV, X-ray photons, in order to assure a fair comparison between the diamond and CMT detectors. A series of pinholes were also placed in front of the PCDs in order to further limit their field of view.

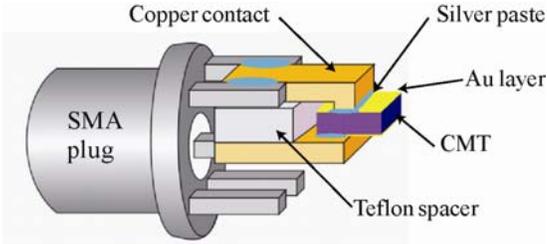


Fig. 2. CMT PCD fabricated using a modified SMA connector and copper contacts separated by a Teflon spacer.

Fig. 3 presents our experimental and data collection setup. The CMT and diamond PCDs were coupled in pairs and channeled to a Tektronix 694C digital oscilloscope. The signals from the CMT devices were delayed by 30 ns with respect to the output of a complimentary diamond PCD. The first channel of the oscilloscope was used for a timing fiducial, generated by a laser synchronized to the OMEGA laser. The remaining three channels recorded signals from tested PCDs. Multiplexing of the complementary PCDs was achieved using a high-bandwidth passive adder, after which the subsequent signal was subjected to an attenuator to decrease the signal amplitude below the oscilloscope's threshold.

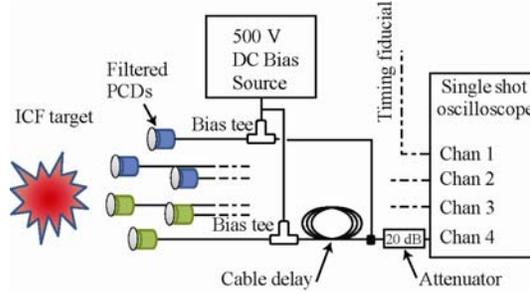


Fig. 3. X-ray detection, measurement, and data acquisition setup.

IV. X-RAY PHOTOCONDUCTIVE DETECTOR SIMULATIONS

We calculated the simulated absorption spectra for the diamond, Cd_{0.95}Mn_{0.05}Te, and Cd_{0.73}Mn_{0.27}Te PCDs based on the photoelectric cross-sections of C, Cd, Mn, and Te, obtained from the European Synchrotron Radiation Facility's database for X-ray applications (DABAX). The mass absorption spectrum for the ternary alloys was calculated using the formula:

$$(\mu/\rho)_{CMT} = (\mu/\rho)_{Cd} \frac{\rho_{Cd}}{\rho_{CMT}} + (\mu/\rho)_{Mn} \frac{\rho_{Mn}}{\rho_{CMT}} + (\mu/\rho)_{Te} \frac{\rho_{Te}}{\rho_{CMT}}, \quad (1)$$

where (μ/ρ) are the mass absorptions and ρ_{Cd}/ρ_{CMT} , ρ_{Mn}/ρ_{CMT} , and ρ_{Te}/ρ_{CMT} are the density ratios of the elements Cd, Mn, and Te over the ternary density, respectively.

The absorption fraction was given by:

$$1 - \frac{I}{I_0} = 1 - \exp[-(\mu/\rho)\rho \cdot l], \quad (2)$$

where I_0 is the initial radiation intensity, I is the intensity after the length l , and ρ is the crystal density. For diamond $\rho = 3.5$ g/cm³, while for CMT ρ was defined by a linear fit

$\rho(x) = 5.866 - 1.078x$ through the data collected by Maheswaranathan *et al.* [15].

Fig. 4 presents our simulation results and compares the photoelectric absorption spectra for the 1-mm-thick, diamond, $\text{Cd}_{0.95}\text{Mn}_{0.05}\text{Te}$, and $\text{Cd}_{0.73}\text{Mn}_{0.27}\text{Te}$ PCDs. We have selected these two particular Mn concentrations, since, as we have mentioned before, the CMT crystals with $x = 0.27$ should, according to Toney *et al.* [2], assure the optimal performance as X-ray detectors, while the $x = 0.05$ Mn concentration results in CMT samples with the best crystalline quality (lowest occurrence of twins). As it is demonstrated in Fig. 4(a), the diamond crystal has a near 100% absorption only for very low energy X-rays and exhibits a 3-dB roll-off for X-ray energies around 10 keV. At the same time, the studied CMT specimens are nearly indistinguishable for X-ray energies below 100 keV, and their 3-dB roll-off is well above 100 keV. Fig. 4(b) shows a small absorption dip due to the Cd photoelectric cross-section, but this feature is not expected to affect the performance of any practical CMT devices.

V. CMT PCD CHARACTERIZATION

X-ray temporal characterizations of our CMT PCDs were very promising. For 1-keV energy X-rays, the CMT performance was comparable to those of diamond detectors. Fig. 5 compares the several tested PCDs when the OMEGA laser pulse intensity was low enough, so there was only a single X-ray emission from the hot corona. The voltage signal-to-noise ratios for the diamond, 1- and 2.3-mm-thick CMT detectors were 28.8, 16.8, and 16.4 dB, respectively. Our third CMT detector with the length of 1.5 mm was, unfortunately, damaged and we have no data. The cause of failure is considered to be a human error during the curing process of the silver paste.

Although the diamond PCD response, presented in Fig. 5 is clearly larger and faster than that of CMT, it must be stressed that these measurements were taken at the optimal X-ray energies in the diamond absorption spectrum. Future measurements will be conducted for the hard X-rays (12 – 50 keV), well beyond the capabilities of the diamond PCDs. Future experimentation is also necessary to accurately describe the effect of thicker crystals on sensitivity and temporal resolution. One point of interest is that the 2.3-mm-thick PCD exhibited only a single exponential decay time constant of 3.41 ns, and therefore a faster response time. Whereas similar to the diamond PCD, the 1-mm-thick CMT had both the fast and slow relaxation constants equal to 0.90 ns and 5.68 ns, respectively.

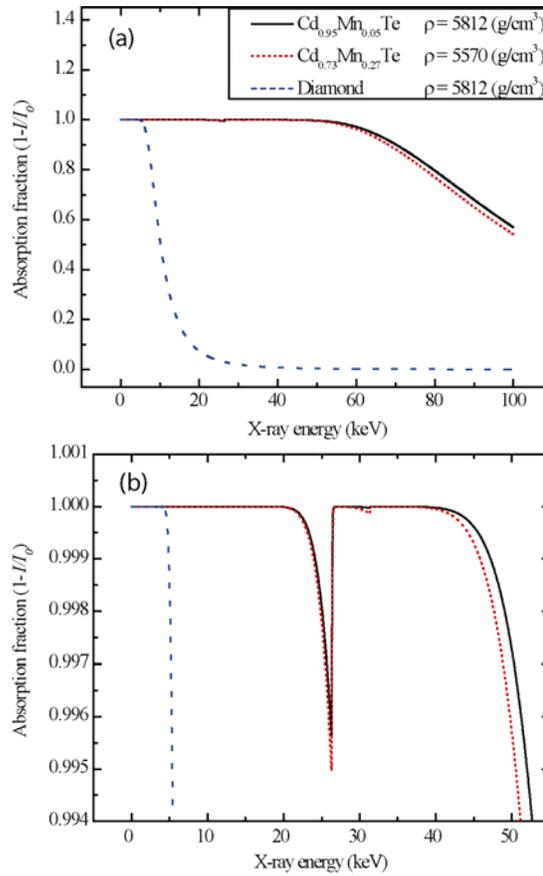


Fig. 4. (a) The simulated absorption spectra for 1-mm-thick samples of $\text{Cd}_{0.95}\text{Mn}_{0.05}\text{Te}$, $\text{Cd}_{0.73}\text{Mn}_{0.27}\text{Te}$, and diamond (see legend for details). (b) A close up of the medium-energy absorption spectra, showing an absorption dip due to the Cd photoelectric cross-section. **Fix the density of diamond in the caption at 3.5.**

The double-excitation responses were observed when the intensity of the OMEGA pulse was high enough to produce the fuel burn. In Fig. 6, two separate peaks are clearly distinguished by our CMT PCD; however, due to the CMT relatively long relaxation time, the first peak is somewhat suppressed and only a shoulder is visible. Nevertheless, the measured 1.24-ns time separation between the hot corona and the compressed core x-ray emissions was exactly the same as that recorded by the complementary diamond PCD.

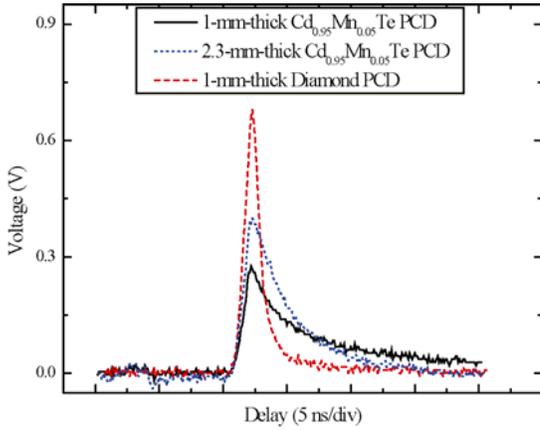


Fig. 5. Voltage response transients for the OMEGA shot #50594, measured using our 1-mm-thick, 2.3-mm-thick CMT PCDs, and the 1-mm-thick diamond PCD (see legend for details).

The CMT PCD responses collected during all our experiments were fitted using a single/double Gaussian excitations (depending if the response was single/double peaked) and convolved with the double-exponential relaxation decay. The dominant, long-decay time constants for the CMT PCD are plotted in Fig. 7, where we see an inverse dependence on the OMEGA laser pulse energy.

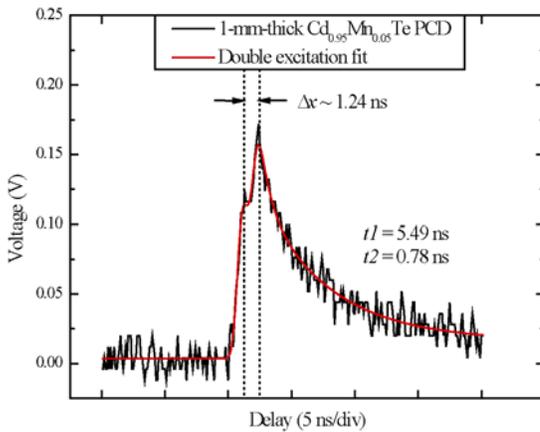


Fig. 6. Voltage response transient for the OMEGA shot #50597 with pulse energy ~16.2 kJ measured using our 1-mm-thick CMT PCD fitted with a double-excitation and double-decay fit (solid). The time separation between the two X-ray emissions Δt was calculated from the fitting.

VI. CONCLUSION

We have presented the first implementation of CMT PCDs for characterizations of soft X-rays generated by OMEGA laser during the ICF experiments. The measurements were compared to the data collected concurrently by diamond PCDs. The response of two of the three CMT PCDs was

comparable to the diamond detector, however, with the decay time constants an order of magnitude longer. The two, X-ray emissions from the target hot corona and the fuel burn with the time separation of 1.24 ns were clearly distinguished. We need to stress that these our initial measurements were performed for low-energy, soft, X-rays, optimal for diamond PCDs and not for CMT. Future tests, focused on hard, >10 keV X-rays are planned, as according to our presented simulations, CMT PCDs maintain their near 100% absorption efficiency up to 50 keV, while diamond PCDs are ineffective. Furthermore, by the addition of more impurities (e.g., by tripling the V doping to $2 \cdot 10^{17} \text{ cm}^{-3}$) and/or introducing controlled defects in our CMT crystals, we expect to significantly improve the CMT detector time resolution, while only slightly sacrificing its responsivity. Successful implementation of the new CMT PCDs with their promising wide spectral absorption characteristics, seems to a very viable upgrade to the diamond PCDs, currently implemented as the X-ray diagnostic tool in the OMEGA target chamber.

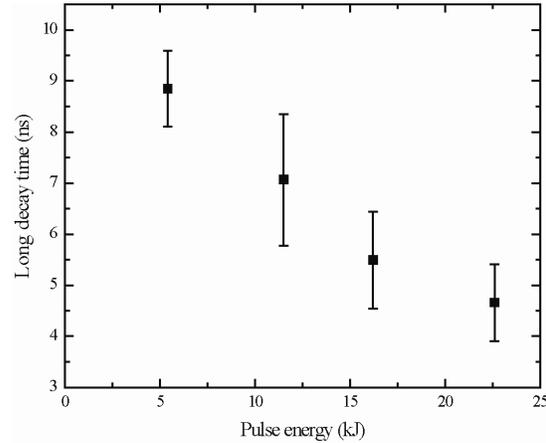


Fig. 7. The CMT PCD long decay time of the radiation response transients recorder for 1-keV X-rays, generated when the target was illuminated with the OMEGA laser pulses of different energies (ranging from 5 kJ to 22.6 kJ).

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