Laser-Driven X-Ray Source Array Design for Nuclear Weapons Effects Testing

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Abstract

This research develops nine x-ray source arrays to simulate nuclear weapons effects through stimulated x-ray emission. The sources are low-density foams that are irradiated by intense short-pulse laser beams to stimulate x-ray emissions. Each array is designed to adhere to a specific target fluence given a set number of source targets and a total amount of incident energy. Furthermore, each source array is required to maintain 80% surface x-ray fluence uniformity at the desired average fluence. The specifications provided for each source array are designed to simulate significant nuclear weapons x-ray effects, specifically Blowoff Impulse and Shock (BIS), Thermo-Structural Response (TSR), and System Generated Electro-Magnetic Pulse (SGEMP). Results generated using Monte Carlo N-Particle (MCNP6) simulations identify the potential for enhancing as well as filling in gaps in current United States (U.S.) radiation effects testing capabilities.

Introduction

Xcimer Energy Corporation (XEC) is a private company focused on achieving both Inertial Fusion Energy (IFE) and an x-ray effects test capability using their novel krypton fluoride (KrF) laser. XEC is building on the impressive recent fusion ignition and gain results at Lawrence Livermore National Laboratory's (LLNL) National Ignition Facility (NIF) to propose a pathway to fusion energy. LLNL has now achieved a total of eight results on NIF exceeding fusion ignition with the largest yield being 8 MJ. The XEC proposal to the Department of Energy earned them a nine-million-dollar award from the Office of Fusion Energy Sciences for the first year of a multi-year milestone-driven agreement. After successfully demonstrating their KrF laser concept in an XEC facility called Phoenix by March 2026, XEC intends to design and build a 4-MJ KrF laser and chamber to achieve a 200-MJ inertial confinement fusion (ICF) yield demonstrating economic breakeven for IFE. A second chamber would be added for nuclear weapons effects testing (NWET) using the same KrF laser.

The US began voluntarily adhering to the Comprehensive Test Ban Treaty in 1992, which stopped all nuclear weapon underground tests – including x-ray effects testing. Since then, the US has been limited in its ability to conduct testing for BIS, TSR, and SGEMP effects on full systems. This inability to conduct comprehensive radiation effects testing for full systems has left a shortfall for US national security – a shortfall that the XEC KrF laser has been designed to address.

The development of XEC's target arrays is an interdisciplinary project that combines multiple lines of effort to develop a system for simulating NWET. Through a Cooperative Research and Development Agreement (CRADA) between the United States Military Academy (USMA) and XEC, this research applies computational analysis using the radiation transport code, MCNP6, to accurately design source arrays for a radiation effects testing chamber.[1]

Theory

The XEC KrF laser utilizes novel laser scattering effects to achieve very high energy flux without solid-state media. This substantially reduces the overall cost of this laser compared to a solid-state laser like the NIF. The laser utilizes Stimulated Brillouin Scattering (SBS) to compress laser pulses as well as Stimulated Raman Scattering (SRS) to combine laser pulses together. These two processes enable the KrF laser to combine multiple laser pulses into a single, short, high-intensity pulse.[2] XEC is currently building a research KrF laser to demonstrate the successful application of these techniques. The KrF laser design has unique dual use capabilities for ICF and NWET and can service two chambers.

The XEC KrF laser creates a unique opportunity for x-ray effects testing with the potential to significantly increase x-ray source outputs with distributed source arrays. Intense laser energy deposition into specific low-density materials can be used to generate x-rays as electrons de-excite (typically from L- or K-shells).[3] These "underdense" sources have shown useful high laser-to-x-ray conversion efficiencies.[4] The NIF houses the world's largest laser, which generates two megajoules of laser energy, yet this is not sufficient to cover the relevant spectrum of energies for NWET at the desired fluence-area products as shown in Figure 1. The XEC KrF laser at energies of 4- to potentially 12-MJ or higher will be able to address this gap.

Methodology

This research focuses on designing nine unique source arrays that successfully simulate the full range of nuclear weapon x-ray effects. The nine cases are detailed in Table 1 and focus on simulating three relevant radiation effects – BIS, TSR, and SGEMP.

In Table 1, each test case calls for a different laser energy as well as a different number of x-ray sources to optimize for that specific x-ray effect. The source type describes the metallic foam target material – which is selected for its x-ray emission energy – that emits characteristic x-rays in the relevant energy range for the desired radiation effect (BIS, TSR, or SGEMP). Furthermore, the source type efficiency describes the percentage of incident energy that is maintained in the emission of relevant x-rays. The spectra produced by each source type was provided by XEC and is filtered using Kapton® or aluminum to remove low energy x-rays that are not relevant for the desired radiation effects testing. The specifications provide a desired fluence for each array based on client expectations to simulate NWET at relevant distances for each radiation effect from the point of detonation. The array design must have a minimum of 80% uniformity across the test article surface to align with design requirements. Lastly, the test article material is important for energy deposition analysis and serves to mimic relevant components that would be studied for the given radiation effect (for example SGEMP is significant for electronic components that are commonly made of silicon).

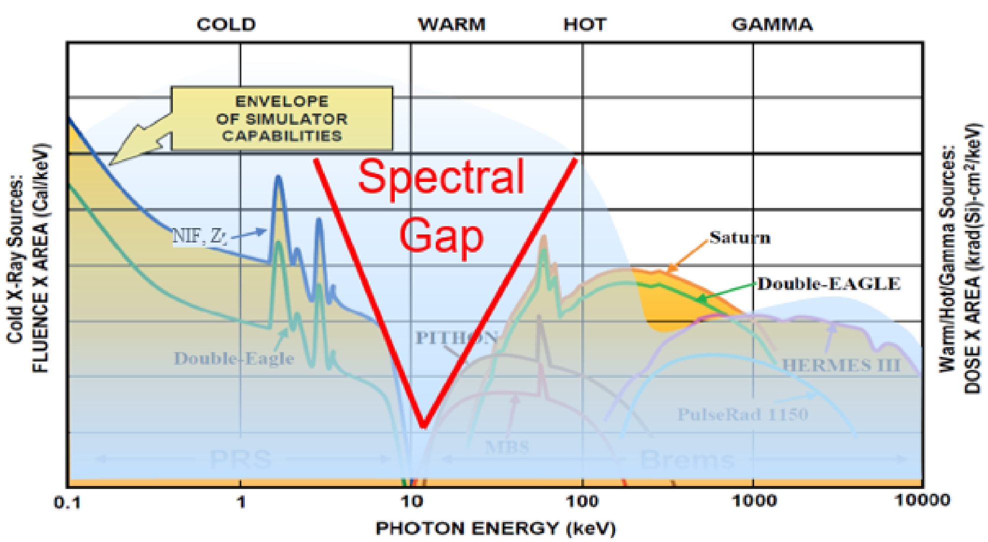

Figure 1: Graphical depiction of current radiation effects testing capabilities over different photon energies. The spectral gap highlights the region that current capabilities cannot sufficiently simulate.[5]

TABLE 1: NINE LASER-DRIVEN X-RAY SOURCE ARRAY SPECIFICATIONS

X-Ray Source Spectrum	Laser Energy (MJ)	Number of X-Ray Sources	Energy Per Source (kJ)	Source Type (Efficiency)	Filtering Material and Thickness (um)	Goal Fluence (cal/cm^2)	Test Article Material
	4	8	500	Ag (35%)	-	10	Carbon
Cold-BIS	12	24	500	Ag (35%)	-	10	Carbon
	24	24	1000	Ag (35%)	-	20	Carbon
	4	4	1000	Cu (3.5%)	Kapton (37.5)	5	Aluminum
Warm-TSR	12	12	1000	Cu (3.5%)	Kapton (37.5)	5	Aluminum
	24	12	2000	Cu (3.5%)	Kapton (37.5)	10	Aluminum
	4	4	1000	Cu (1%)	Aluminum (37.5)	3	Silicon
Warmer-SGEMP	12	8	1500	Cu (1%)	Aluminum (37.5)	3	Silicon
	24	12	2000	Cu (1%)	Aluminum (37.5)	5	Silicon

This research assumes that x-ray sources in an array can be modeled as “n” isotropically emitting points located some distance from a test object. Figure 2 depicts the assumed x-ray output using isotropic sources compared to a uniform wall of x-rays, which can be used to model x-ray effects from a nuclear weapon on some system in line-of-sight, yet far from the point of detonation, of that weapon.

This design mimics a planar wall of photons. Point sources cannot perfectly recreate a planar wall with sufficient fluence; so, arrays are designed to meet

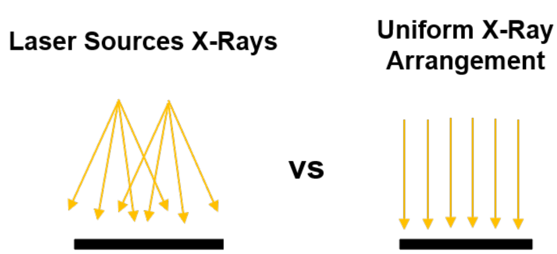

Figure 2: Laser source x-rays compared to a uniform x-ray photon arrangement.

the 80% uniformity specification. To determine the uniformity of simulated results, the minimum fluence is divided by the maximum fluence for a given simulation. Arrays are modelled in MCNP6, where tallies can be added with the appropriate multiplier to assess the total energy deposited across the area to ensure sufficient uniformity is maintained. It is important to note that these calculations can be computed analytically by assessing the flux of specific points from all associated sources; however, this analytical process becomes much more challenging when the number of sources significantly increases and the number of critical points on the test article significantly increases. Thus, MCNP6 offers a unique means of overcoming this problem set.

The fluence for test objects must meet the specifications provided in Table 1, while maintaining 80% uniformity at the surface. These strict requirements demonstrate the fidelity of utilizing XEC’s KrF laser design to provide the US with a comprehensive means of assessing critical nuclear weapons effects. With an optimal arrangement of sources and sufficient laser energy, it is possible to simulate radiation effects on full systems for NWET. This would eliminate any future need to resume underground NWET by providing a facility for understanding x-ray radiation effects on any desired system.

To determine x-ray fluence uniformity, a lattice mesh design is constructed to model the desired test article. This base design utilizes a square plate for the desired test article. A 15 x 15 lattice is used for 4- and 8- source arrays and a 23 x 23 lattice for the 12- and 24-source arrays to provide greater resolution for more complex designs. Energy fluence uniformity incident on the top surface of the plate is only dependent on the amount of incident energy, and not on the specific energy spectra applied, so 3-keV photons are applied to all surface uniformity calculations to simplify MCNP6 inputs and associated tally multipliers for the initial analysis. Regarding uniformity, the photon flux (F4 tally) is evaluated for each lattice cell. By dividing the minimum fluence from the maximum fluence, the uniformity across the test article can be easily determined. This procedure is then repeated for each array design to identify the optimized target array for NWET.

This research applies two fundamental methods for optimizing array designs: progression and revision. Progression focuses on starting with the most basic array design (4-source arrays) and taking the lessons learned from that design into the more complex arrays progressively (8-, 12-, and 24- source arrays). Revision requires utilizing a multitude of designs to assess the optimal array for each source case. One example of revision is provided in Figure 3 for the 24-source model. The array on the top utilizes the same basic design as the 8-source array iterated three times to maximize distance; however, this creates a significant minimum to occur along the edges between the middle and corner sources. Because the edges are typically where a minimum is most likely to occur, the array on the bottom is developed. This array accounts for the significant role of the edges in determining uniformity by placing more sources along the edges and using fewer sources to balance out the center of the array. Aside from all sources needing to be in the same x-y plane, there are no restrictions on how sources can be arrayed, so each array has an infinite orientation of sources that all yield a distinct target size that meets the design requirements. For this reason, array designs should be constantly reassessed and built upon to identify unique array orientations that may yield a larger target size. Ultimately x-ray source arrays will be standardized to control costs and to allow well understood environments to be repeated as needed.

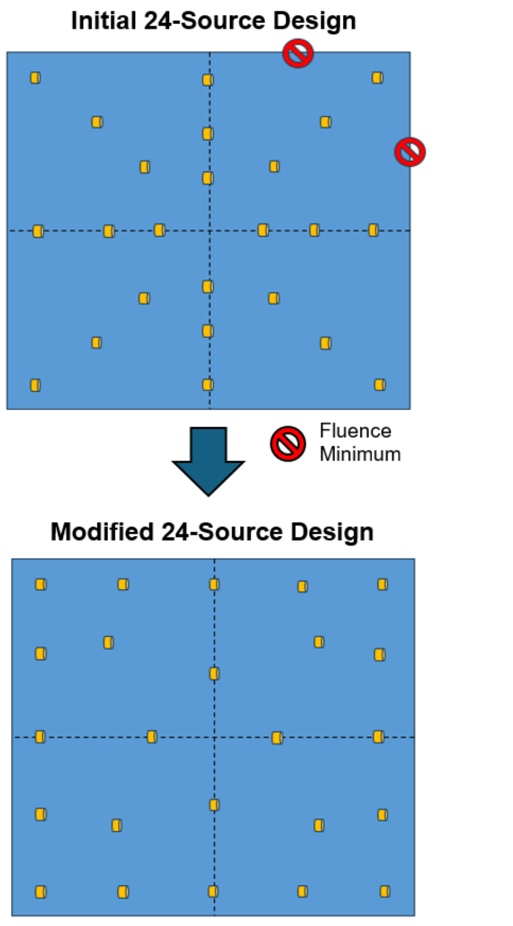

Figure 3: Revision utilizing the 24-source model.

The critical design requirement to make the optimal array for NWET across all array designs is ensuring that minimum surface uniformity is maintained. Most designs require a constant process of revision and reassessing source orientation to maintain uniformity while maximizing target size. If fluence did not meet the goal fluence with 80% uniformity, then the source array is modified until all design requirements are met. Once all design specifications are met, the area of the test object is then increased until it fails the uniformity requirement, and then the array geometry is adjusted again. This process continues until the maximum area that maintains all design requirements is identified. A concept drawing of the 8-source SGEMP source array is depicted in Figure 4. Flux uniformity plots, such as Figure 5 are generated utilizing a Julia parser script that compiles the results from the F4 mesh tallies across each cell from MCNP6.

Once the optimal array design is identified, the given source arrays can be applied using the appropriate photon energy with the given target material (as specified by Table 1) to analyze x-ray energy deposition. For x-ray energy deposition, the lattice mesh used to analyze surface uniformity is iterated into 15-layers that progressively increase in size to measure both the deposition (F6 tally) within the x-y plane and the z-axis of the test article. Similar to uniformity calculations, tallies are placed in each cell. To generate meaningful results for energy deposition calculations, it is critical to understand that the mean free path of x-rays in the relevant materials is small, so the most important regions within the material are those closest to the surface. Therefore, the total depth increases progressively from 1 nm to 3 nm, to 10 nm, then to 30 nm, and so forth until a total thickness of 1 cm is achieved. The thickness of each lattice increases with depth.

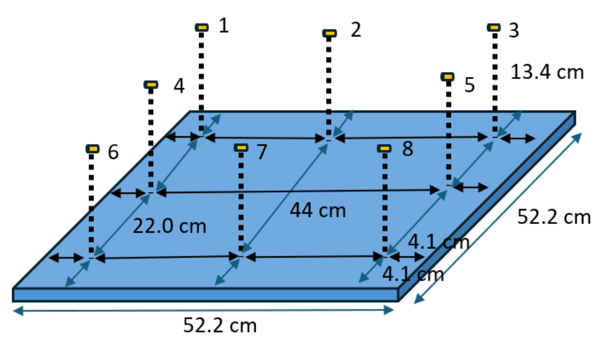

Figure 4: Full-sheet initial concept drawing of the 8-source SGEMP 12 MJ source array.

TABLE 2: SUMMARIZED RESULTS FOR EACH CASE

X-Ray Source Spectrum	Laser Energy (MJ)	Number of X-Ray Sources	Energy per Source (kJ)	Source Type (Efficiency)	Goal Fluence (cal/cm^2)	Area for 80% Uniformity (cm^2)	Max Fluence (cal/cm^2)	Surface Uniformity (%)
Cold-BIS	4	8	500	Ag (35%)	10	9,801	11.13±0.01	80.40
	12	24	500	Ag (35%)	10	46,785	11.19±0.01	81.35
	24	24	1000	Ag (35%)	20	46,785	22.37±0.02	81.35
Warm-TSR	4	4	1000	Cu (3.5%)	5	1,089	5.544±0.008	80.46
	12	12	1000	Cu (3.5%)	5	5,715	5.458±0.006	82.56
	24	12	2000	Cu (3.5%)	10	5,715	10.92±0.01	82.56
Warmer-SGEMP	4	4	1000	Cu (1%)	3	548	3.374±0.004	80.05
	12	8	1500	Cu (1%)	3	2,724	3.307±0.004	82.26
	24	12	2000	Cu (1%)	5	3,969	5.451±0.005	80.44

Results and Analysis

This research successfully identifies nine x-ray source arrays to simulate nuclear weapons effects. Once each source array is finalized, the results for each design present a generally consistent pattern as each array is developed to meet the required design specifications. For that reason, one source array design, the 8-source SGEMP 12-MJ array, is presented to discuss the general pattern from all results garnered. The surface uniformity, energy deposition, and energy deposition uniformity for the 8-source SGEMP 12-MJ array are presented in Figure 5, Figure 6, and Figure 7, respectively. Furthermore, Table 2 provides summarized results for all nine cases.

The simulation results demonstrate important increases in target size for current testing capabilities as well as the potential for novel testing capabilities that would fill the spectral gap. Table 2 identifies the maximum target areas that maintain the design specifications to be 9,801 cm^2 and 46,785 cm^2 for the Cold-BIS simulations. These values represent roughly a two order of magnitude increase from the current testing capabilities.[6] Additionally, the Warm-TSR and Warmer-SGEMP capabilities illuminate the potential to use XEC's KrF laser to simulate relevant radiation effects that are beyond current US testing capabilities. XEC's KrF laser design makes this testing feat possible by generating a laser beam with sufficient power to stimulate relevant x-ray emissions from a low-density copper source.

The MCNP6 results demonstrate that the surface uniformity requirement is maintained for all nine test cases. Moreover, the maximum energy deposition is proportional to the maximum fluence across the surface of the test article; however, it is also pertinent to discuss the uniformity at depth as depicted in Figure 7. Uniformity at depth should be distinguished from surface uniformity as uniformity at depth reveals how the mean free path of the aggregate x-rays move through the target, while surface uniformity merely describes the total amount of x-rays that pass through the surface of the target. The 80% uniformity requirement applies exclusively to surface uniformity, but uniformity at depth may also be relevant due to

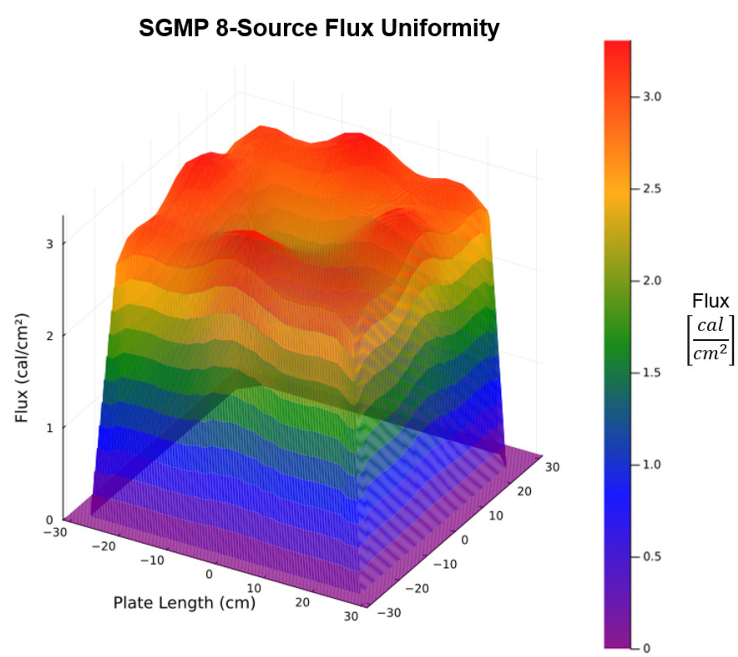

Figure **5:** The results of x-ray uniformity across the test article for SGEMP with 8-sources and 12-MJ of incident energy.

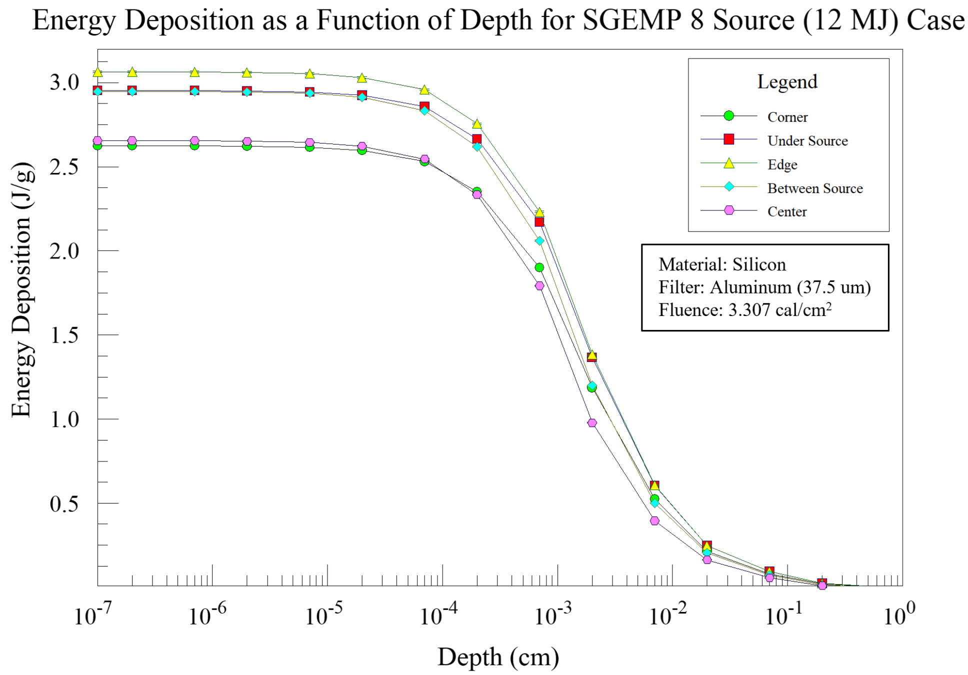

Figure **6:** The results of energy deposition into the test article for SGEMP with 8-sources and 12-MJ of incident energy.

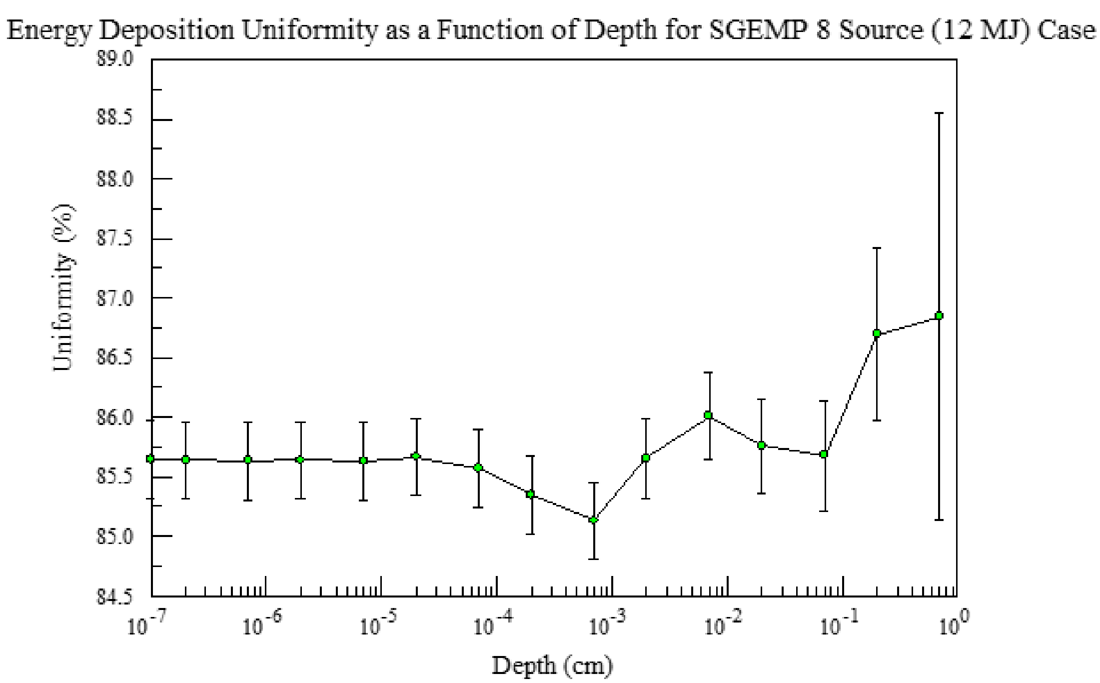

Figure **7:** The results of energy deposition uniformity at depth for SGEMP with 8-sources and 12-MJ of incident energy.

the sharp incident angles of x-rays emitting from distinct point sources. From Figure 5 and Table 2, the SGEMP 8-source, 12-MJ array has a surface uniformity of 82.26%; however, Figure 7 reveals that there is greater uniformity at depth (closer to ±85.6%).

The differences between surface uniformity and uniformity at depth are greatest for the 24-source BIS array. This is symptomatic of both the radiation effect being analyzed as well as the design strategy used to achieve 80% surface uniformity. SGEMP exhibits higher uniformity at depth given warmer x-rays, while BIS exhibits lower uniformity at depth. This difference is likely due to the angle of incident x-rays onto the larger BIS target becoming much more acute. X-rays that are incident at a sharp angle, rather than orthogonal to the target surface (like those from a planar source), penetrate the target less effectively and deposit more energy toward the surface with less energy deposition at depth. This contrast becomes starkly relevant at the edges and minimums of a given target because the edges and minimums generally have the most x-rays incident at acute angles. Furthermore, the larger the target, the more acute the incident angles become, causing greater variance in uniformity at depth for the 24-source arrays. From Table 2, the 24-source BIS array has the largest target area, and its uniformity at depth is only 70%. With increased areas, the effects of using isotropic sources become more pronounced. While surface uniformity may be met, not all x-rays may be depositing energy in a manner consistent with the nuclear weapon effects that are being simulated.

Ultimately, these results highlight the benefit of designing nine source arrays using low-density foam sources to simulate relevant radiation effects from a nuclear weapon. All nine designs meet the specifications requested by XEC, and each case greatly increases the testable target surface area relative to current radiation effects testing capabilities. These results demonstrate areas that are potentially one to two orders of magnitude higher than current testing capabilities. The results suggest using XEC's KrF laser for radiation effects would greatly increase US capabilities in this area.

Conclusions

This research effectively designs nine x-ray source arrays to simulate nuclear weapons effects through stimulated x-ray emission. The designs are guided by strict requirements to maintain sufficient target surface uniformity with a desired fluence. The successful design of each array identifies the fidelity in utilizing XEC's KrF laser to greatly bolster current radiation effects testing, while expanding US testing capabilities to become more comprehensive. These results demonstrate a first look into the usefulness of this novel laser design for NWET; however, many questions lie ahead before these simulation capabilities can be used to their fullest potential. In future research, target dimensions should be more complex to replicate systems that may be of interest for radiation effects testing. Complex designs will require significant modifications and add complexity to the optimization of area, as that process was completed manually for the square plate. Future studies may be able to utilize AI to analyze the optimal orientation and optimal number of sources to achieve sufficient fluence across a given target design. Additionally, BIS energy deposition profiles may be used in multi-physics codes such as ALE3D to investigate impulse compared to nuclear threat spectra results to further understand test fidelity. Ultimately, these source array designs operate as a powerful proof of concept to highlight the potential for XEC's KrF laser in expanding US NWET capabilities. ■

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Notes

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