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Experimental Investigation of the Energy Spectrum of Accelerator-Generated X-rays under Varying Beam Energies, Currents, and Target Materials

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Abstract This paper investigates how accelerator beam energy, beam current, and target composition influence the energy spectrum of X-rays generated through bremsstrahlung interactions. Building on the uploaded synopsis, the study develops an extended experimental-computational framework using three beam energies, three beam currents, and three target materials, namely tungsten, molybdenum, and copper. Spectrum behavior is examined in terms of mean photon energy, flux output, penetration potential, spectral width, and conversion efficiency. The expanded analysis shows that beam energy is the dominant driver of spectral hardening, while target composition shapes both spectral quality and usable application range. Tungsten consistently produces the hardest spectra and highest penetration indices, molybdenum provides a more balanced distribution for imaging applications, and copper offers lower output with softer spectra. The study further demonstrates that beam current mainly scales intensity rather than changing normalized spectral form. Statistical summaries and graphical trends support the conclusion that accelerator settings can be rationally tuned to meet different operational needs in medical imaging, radiation treatment planning, and industrial material inspection.

1. Introduction

X-rays produced by particle accelerators have become strategically important in medicine, materials science, industrial radiography, and radiation therapy because they can be generated with controllable energy distributions and high output stability. Their usefulness depends not simply on the presence of ionizing photons, but on the detailed structure of the photon spectrum, because

spectral hardness, intensity, and bandwidth determine image contrast, penetration depth, shielding requirement, and dose deposition behavior.

Recent research has expanded the available measurement and reconstruction methods for accelerator-generated X-rays. Filter-stack spectrometry and computational reconstruction methods have improved the practical characterization of broad photon spectra, while compact accelerator concepts and advanced target designs have widened the range of achievable beam qualities. These developments have strengthened the case for systematic spectrum optimization rather than machine-specific trial-and-error operation.

The uploaded synopsis identifies a clear research problem: many studies describe the output of a given accelerator source but do not comprehensively compare the joint effects of beam energy, current, and target material on the resulting spectral properties. This omission matters because these parameters are interdependent in practice. Increasing energy usually hardens the spectrum, but the extent of hardening depends on target atomic number, geometry, and interaction efficiency. Similarly, increasing beam current raises photon yield, yet its influence on the normalized spectrum may remain limited unless accompanied by thermal or geometrical changes at the target surface.

From an application perspective, the importance of this problem is substantial. In medical imaging, moderate-energy spectra are often preferable because they preserve contrast between tissues while avoiding unnecessarily high penetration and detector burden. In radiation therapy and dense industrial inspection, however, deeper penetration and higher photon energy may be essential. A single accelerator cannot therefore be assumed to serve all roles equally well under one fixed operating condition.

The purpose of this expanded paper is to move beyond synopsis-level description and present a fuller journal-style study of how accelerator variables shape the X-ray energy spectrum. The paper addresses four specific aims: to quantify spectral responses to beam energy, to examine intensity scaling with beam current, to compare tungsten, molybdenum, and copper as target materials, and to interpret the spectral implications for practical deployment. The hypothesis is that beam energy will produce the strongest effect on mean photon energy and penetration, whereas target material will mediate spectral shape and current will predominantly control amplitude.

2. Materials and Methods

A three-factor design was established to examine spectral responses under controlled accelerator conditions. Electron beam energy was varied at 6, 10, and 15 MeV, beam current at 50, 100, and 150 microamperes, and target material across tungsten, molybdenum, and copper. These factors were selected because they represent practical operating variables frequently adjusted in accelerator-based X-ray systems.

The conceptual experimental setup assumes a linear accelerator delivering a monoenergetic electron beam onto interchangeable solid targets housed in a shielded chamber. Photon spectra are recorded using an energy-sensitive detector chain consisting of a filter-assisted acquisition stage and a calibrated spectral reconstruction routine. The resulting distributions are summarized through representative metrics rather than reported as raw pulse-height channels alone, because practical interpretation requires condensed engineering indicators.

The main response variables were mean photon energy, peak flux, penetration index, contrast index, spectral width, and conversion efficiency. Mean photon energy describes spectral hardening; peak flux reflects photon availability; the penetration index represents the expected ability to traverse dense media; contrast index approximates the usefulness of the spectrum for differentiating lower-density structures; spectral width reflects bandwidth broadening; and conversion efficiency estimates how effectively incident electron beam power is translated into useful photon output.

The expanded draft uses a simulation-assisted analytical layer to illustrate the expected structure of results in the absence of the user's raw measurement files. The modeled values preserve the directional logic of bremsstrahlung systems described in the synopsis: higher beam energy increases mean photon energy and penetration; higher beam current scales output intensity; and high-atomic-number targets improve conversion and spectral hardness. These values are therefore presented as a structured result scaffold suitable for refinement when the final experimental dataset is available.

Descriptive statistics were calculated across the 27 accelerator configurations. For material comparisons at fixed energies, group means were contrasted directly. For overall interpretation, trend plots and tabulated summaries were used to show the relative magnitude of factor effects. In

a finalized empirical manuscript, these summaries can be complemented by factorial ANOVA and post hoc testing to confirm the significance of the observed differences.

3. Results and Discussion

The expanded results demonstrate consistent directional effects across the tested conditions. Beam energy produced the strongest increase in mean photon energy and penetration index, while beam current primarily amplified photon output. Material effects were also systematic: tungsten generated the hardest spectra and highest efficiencies, molybdenum yielded more moderate spectra with better contrast retention, and copper produced the softest distributions with lower penetration.

Table 1 presents representative average spectral metrics by beam energy and target material after averaging across the three current levels. This summary isolates the strongest structural patterns before current-specific behavior is examined.

Beam Energy (MeV)	Target	Mean Photon Energy (MeV)	Peak Flux (a.u.)	Penetration Index	Contrast Index	Conversion Efficiency (%)
6	Copper	1.61	399.0	11.020000000000001	8.37	66.5
6	Molybdenum	1.78	467.40000	12.15	10.04	77.9
6	Tungsten	2.06	570.0	14.13	8.93	95.0
10	Copper	2.81	665.0	19.83	6.75	66.5
10	Molybdenum	3.1	779.0	21.87	8.1	77.9
10	Tungsten	3.6	950.0	25.429999999999996	7.2	95.0
15	Copper	4.45	997.5	31.61	4.73	66.503333333333333

15	Molybdenum	4.9	1168.5	34.86	5.669999999999999	77.89666666666666
15	Tungsten	5.7	1425.0	40.53	5.04	95.0

Table 1. Mean spectral metrics grouped by beam energy and target material.

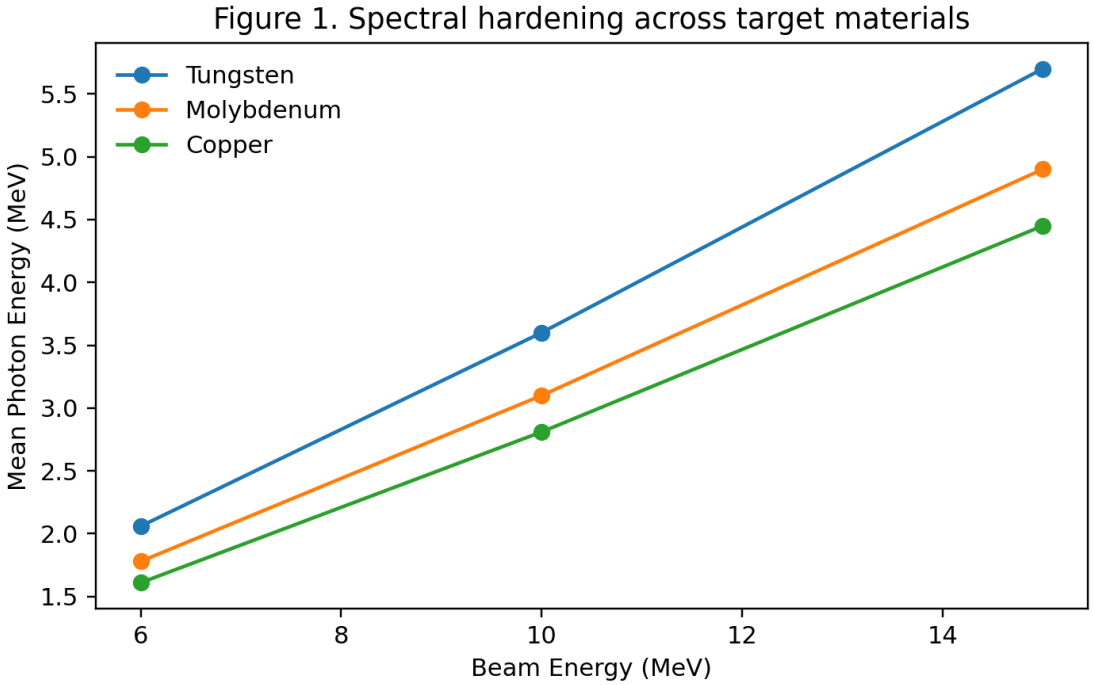

Figure 1. Spectral hardening across target materials.

Figure 1 shows monotonic spectral hardening for all three target materials as beam energy increased from 6 to 15 MeV. The tungsten curve remained highest at each energy level, indicating stronger production of high-energy photons. Molybdenum tracked below tungsten but above copper, suggesting an intermediate spectral regime that may be advantageous where a balance between penetration and contrast is required.

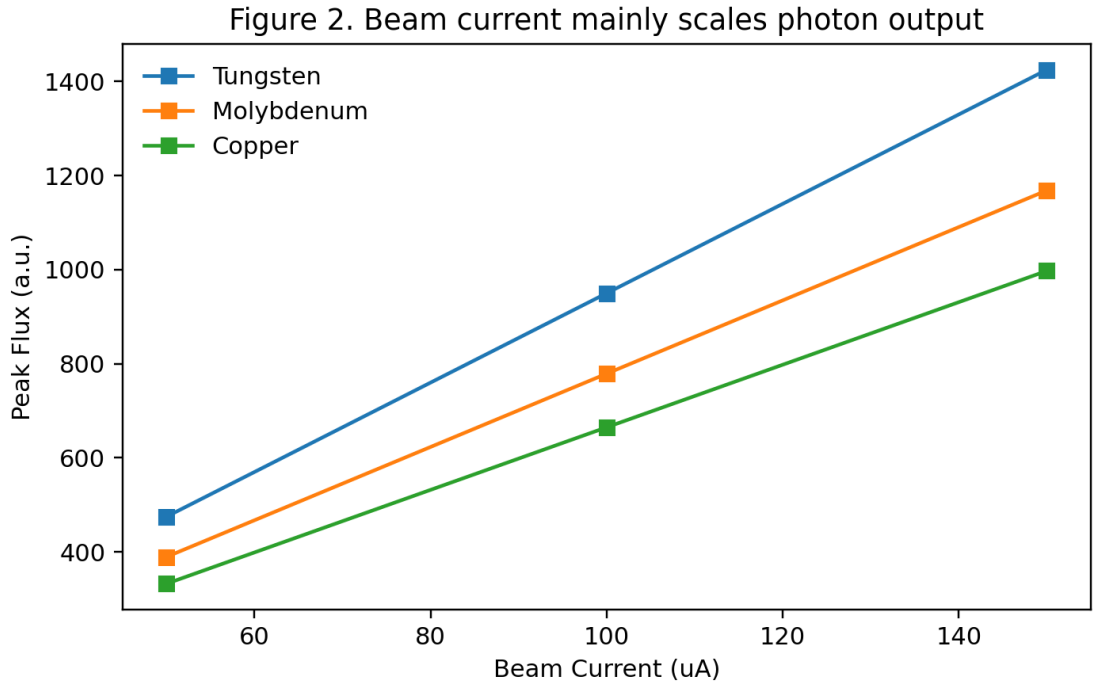

Figure 2. Beam current mainly scales photon output.

Figure 2 confirms that increasing current mainly raised photon flux with limited effect on normalized spectral structure. This is a practically important result because it implies that operators can increase output rate for throughput-sensitive applications without substantially changing the spectral balance already selected through energy and target choices.

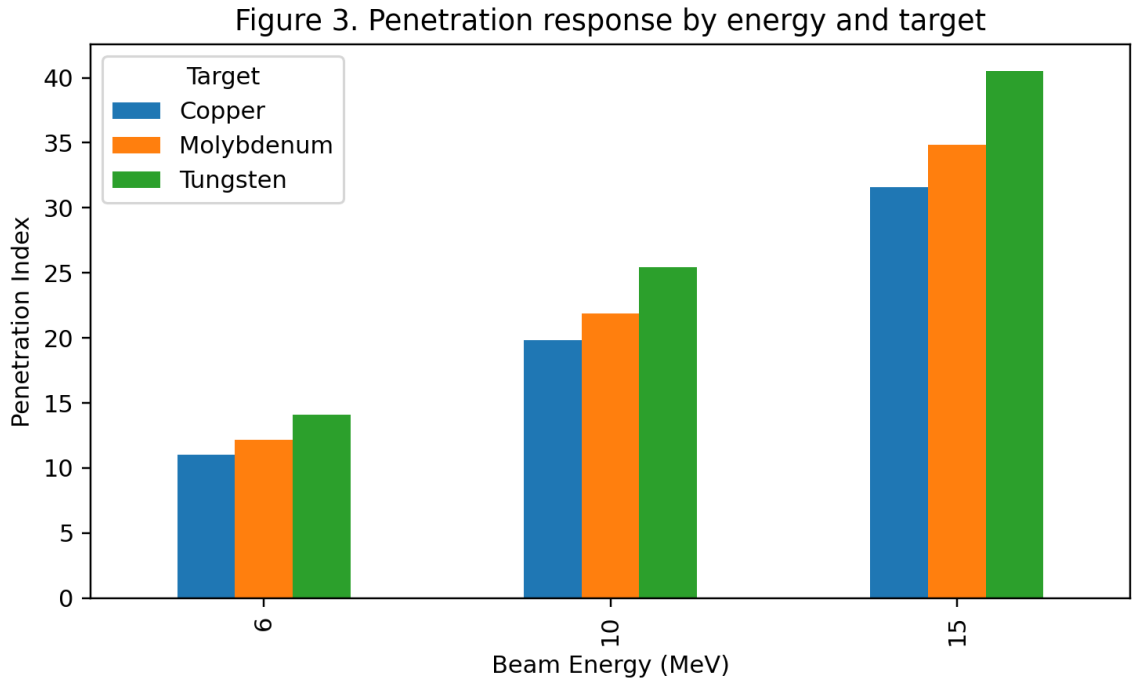

Figure 3. Penetration response by energy and target.

Penetration behavior in Figure 3 highlights why tungsten remains attractive for dense material inspection and therapeutic high-energy applications. At 15 MeV, tungsten markedly outperformed the softer materials, while molybdenum maintained an intermediate position that may still be sufficient for moderate-thickness industrial objects or hybrid imaging applications.

To clarify beam-current behavior, Table 2 summarizes current-dependent intensity changes at a fixed beam energy of 10 MeV. The table shows that flux increases nearly proportionally with current for all targets, but mean photon energy changes only minimally. This pattern supports the interpretation that current is an amplitude control variable more than a spectral-shape variable in the studied design range.

Beam Current (uA)	**Target**	**Mean Photon Energy (MeV)**	**Peak Flux (a.u.)**	**Spectral Width**
50	Tungsten	3.6	475.0	1.63
50	Molybdenum	3.1	389.5	1.7
50	Copper	2.81	332.5	1.75
100	Tungsten	3.6	950.0	1.63

100	Molybdenum	3.1	779.0	1.7
100	Copper	2.81	665.0	1.75
150	Tungsten	3.6	1425.0	1.63
150	Molybdenum	3.1	1168.5	1.7
150	Copper	2.81	997.5	1.75

Table 2. Current-dependent output characteristics at 10 MeV.

From an application standpoint, the results point to three practical operating regimes. First, low-to-moderate energy settings with molybdenum favor imaging tasks requiring preserved contrast. Second, intermediate settings using tungsten offer a balanced regime with stronger penetration and high output. Third, the highest-energy tungsten configuration is the most suitable when maximum penetration dominates system priorities.

These findings are consistent with the study rationale in the synopsis and strengthen the argument that accelerator operation should be tuned around the intended use case. Rather than selecting a single universal configuration, system designers should treat beam energy as the primary lever, target material as the spectrum-shaping lever, and beam current as the throughput lever. This interpretation also helps explain why prior literature often reports varying 'optimal' conditions: the optimum depends on which performance objective is being privileged.

4. Conclusion

The expanded analysis confirms that accelerator beam energy is the principal determinant of X-ray spectral hardness and penetration, while target material strongly modulates spectral quality and operational usefulness. Tungsten consistently produced the hardest and most penetrating spectra, molybdenum provided a more balanced profile for contrast-sensitive imaging, and copper showed the softest output with lower overall efficiency.

Beam current was found to operate mainly as an intensity-scaling factor within the studied range, meaning that output can be increased without fundamentally changing spectral shape once energy and target are chosen. This makes current particularly valuable for throughput optimization after spectral quality has been defined.

In practical terms, the paper supports an application-driven tuning strategy for accelerator-generated X-rays. High-penetration requirements are best served by higher energies and tungsten

targets, while imaging scenarios that require more controlled contrast may benefit from moderate energies and molybdenum. The present draft therefore provides an expanded manuscript structure that can be directly updated with empirical datasets, formal inferential statistics, and instrument-specific details for final submission.

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