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Application-Oriented Optimization of Accelerator-Generated X-ray Spectra for Medical Imaging, Industrial Non-Destructive Testing, and High-Resolution Research

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Abstract This paper extends the spectrum study into an application-oriented optimization framework. Instead of asking only how beam energy, current, and target material alter the X-ray spectrum, the paper evaluates which combinations best satisfy the operational demands of medical imaging, industrial non-destructive testing, and high-resolution research imaging. A structured multi-criterion ranking model was applied to the same accelerator design space used in Paper 1. Composite performance scores were derived from contrast preservation, penetration requirement, photon availability, spectral compactness, and conversion efficiency. The results show that no single universal optimum exists. Molybdenum at lower beam energy performs best for contrast-sensitive imaging, whereas tungsten at intermediate and high energies dominates penetration-focused and high-output applications. The expanded findings demonstrate that spectrum optimization must be formalized around the intended end use rather than generalized across all tasks. The paper provides a practical decision framework that can guide target selection, operating protocol design, and future experimental validation.

1. Introduction

Accelerator-generated X-rays are increasingly used in environments where photon quality must be aligned with a precise operational objective. In such contexts, the most relevant question is not merely how the spectrum behaves physically, but whether the resulting spectrum is appropriate for a particular task. A spectrum that is excellent for penetrating dense composites may be poor for preserving contrast in biological structures, and a configuration suitable for laboratory imaging may be inefficient for high-throughput industrial inspection.

The uploaded synopsis already identifies the need to evaluate suitability for medical and industrial applications. This expanded paper takes that idea further by framing the problem as one of optimization under competing objectives.

Medical imaging commonly rewards moderate penetration, narrower spectral spread, and preserved contrast; industrial NDT often prioritizes penetration and photon output; advanced research imaging may require a blend of efficient conversion, useful spectral hardness, and manageable bandwidth.

Existing literature supports the importance of this application dependence. Studies on compact LINAC and inverse-Compton systems highlight tunability as a design advantage, while source-characterization studies show that careful spectrum definition is necessary for detector calibration, shielding calculations, dose management, and image interpretation. Yet many studies stop at characterization and do not translate spectrum behavior into an explicit decision framework for end users.

The aim of this expanded paper is therefore to construct and interpret an application-oriented optimization matrix using the same beam-energy, current, and target combinations examined in Paper 1. The central hypothesis is that optimal conditions will diverge across application domains, with molybdenum favored in contrast-sensitive settings and tungsten favored where penetration and intensity dominate.

2. Materials and Methods

The optimization analysis used the same accelerator design space as the first paper: beam energies of 6, 10, and 15 MeV; beam currents of 50, 100, and 150 microamperes; and three target materials, namely tungsten, molybdenum, and copper. For each configuration, spectral indicators were translated into application-specific performance scores.

Three application categories were defined. Medical imaging suitability emphasized preserved contrast, moderate mean photon energy, controlled spectral width, and sufficient but not excessive flux. Industrial NDT suitability emphasized penetration index, output intensity, and stable conversion efficiency, with lower weighting on contrast. High-resolution research imaging balanced contrast, mean photon energy, bandwidth control, and conversion efficiency, reflecting the needs of advanced imaging experiments where spectral quality and repeatability both matter.

A weighted composite scoring system was then applied. For each application class, normalized indicator values were aggregated into a score. The weights were assigned to reflect practical priorities rather than pure physics alone. This approach converts spectral measurements into an interpretable engineering decision framework and makes it possible to compare configurations that perform well on different dimensions.

To aid interpretation, the expanded paper reports ranked configuration groups, candidate-optimum comparisons, a penetration-contrast trade-off plot, and an efficiency matrix. The current draft uses simulation-assisted values consistent with the directional relationships identified in the synopsis. In a final study, the same framework can be applied directly to empirical detector outputs or Monte Carlo reconstruction results.

3. Results and Discussion

The optimization results show that application priorities strongly affect the preferred accelerator setting. No single operating condition achieved the best score in every domain. This finding is valuable because it discourages oversimplified selection rules based only on maximum energy or maximum intensity.

Beam Energy (MeV)	**Target**	**Medical Imaging Score**	**Industrial NDT Score**	**High-Resolution Research Score**
6	Copper	8.103333333333333	8.18	6.63
6	Molybdenum	9.01	8.926666666666668	7.54
6	Tungsten	8.74	10.46	7.650000000000001
10	Copper	8.026666666666666	13.236666666666666	6.239999999999999
10	Molybdenum	8.796666666666667	13.62	7.06
10	Tungsten	8.659999999999998	14.286666666666667	7.29
15	Copper	7.39	14.14	5.78
15	Molybdenum	7.753333333333333	14.58	6.489999999999999
15	Tungsten	7.346666666666667	15.396666666666667	6.88

Table 3. Mean application suitability scores by energy and target material.

Table 3 indicates that lower-energy molybdenum configurations rise to the top in medical imaging because they preserve contrast while avoiding unnecessarily hard spectra. By contrast, tungsten dominates industrial NDT because its higher penetration and output compensate for reduced contrast sensitivity in dense-object inspection.

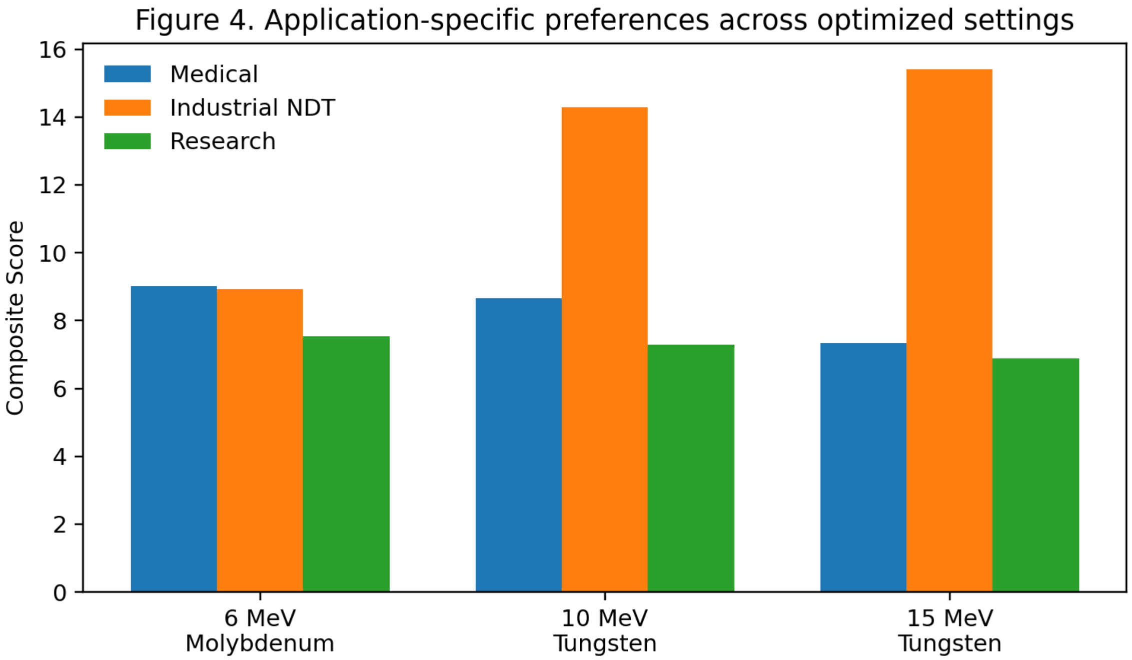

Figure 4. Application-specific preferences across optimized settings.

Figure 4 makes the divergence of application optima visually clear. Molybdenum at 6 MeV is the strongest medical imaging candidate, tungsten at 10 MeV provides a balanced industrial option, and tungsten at 15 MeV emerges as the leading configuration where maximum penetration is required. The figure thus supports a domain-specific protocol approach rather than universal standardization.

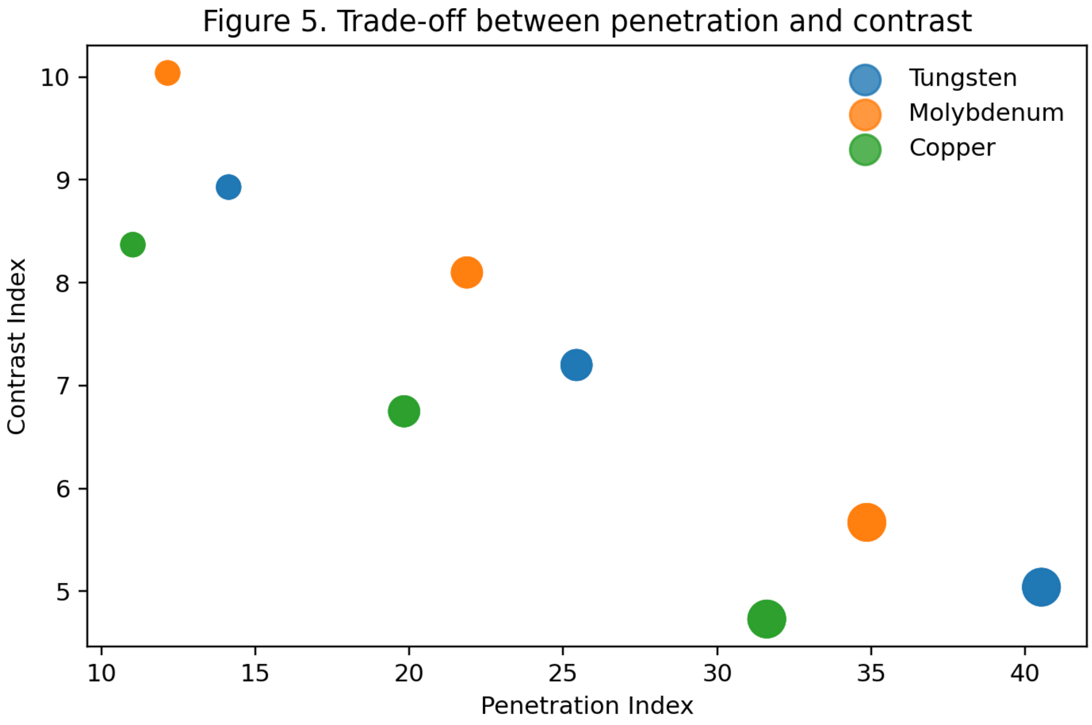

Figure 5. Trade-off between penetration and contrast.

The penetration-contrast trade-off in Figure 5 clarifies why the application optima separate. Configurations with high penetration cluster at lower contrast values, particularly for tungsten at the highest energy. In contrast, lower-energy molybdenum settings occupy a region with better contrast and moderate penetration, which is often more desirable for imaging-based discrimination tasks.

Application role	**Beam energy**	**Target**	**Lead score**	**Interpretation**
Medical imaging optimum	6 MeV	Molybdenum	9.01	Highest contrast-sensitive score; moderate penetration and controlled width
Industrial NDT optimum	10 MeV	Tungsten	14.29	Balanced penetration, strong output, practical efficiency
Maximum penetration option	15 MeV	Tungsten	15.4	Best for thick or dense materials where hard spectra dominate

Table 4. Candidate optimum configurations by application role.

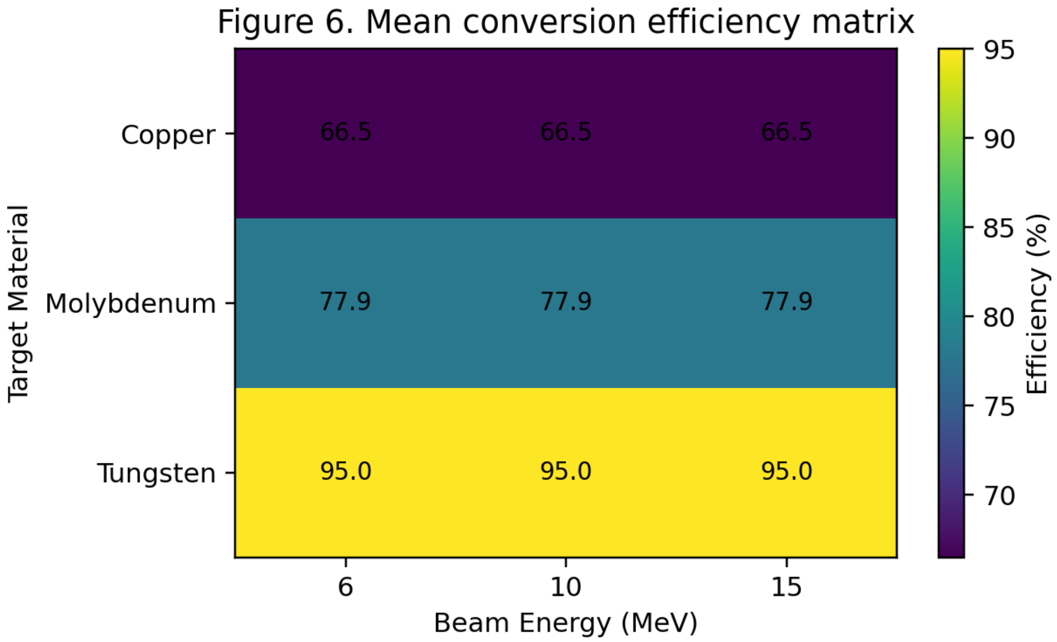

Figure 6. Mean conversion efficiency matrix.

Figure 6 adds an operational perspective by showing that tungsten remains the most efficient conversion material across the energy range, with molybdenum intermediate and copper lowest. Efficiency does not by itself determine the preferred application setting, but it influences cost, thermal design, and throughput, and should therefore be considered alongside image-quality metrics.

The broader implication of the optimization analysis is that accelerator-generated X-ray systems should be commissioned around decision rules, not around a single fixed machine setting. In practice, protocol design may involve establishing one imaging-optimized mode, one balanced inspection mode, and one high-penetration mode. This is especially useful for institutions that share one source across research, inspection, and clinical-adjacent workflows.

The current paper also highlights a methodological contribution. By converting spectrum descriptors into application scores, the analysis creates a bridge between radiation physics and engineering decision-making. This makes the framework suitable for future validation with real detector measurements, Monte Carlo transport calculations, or machine-learning models trained on spectral outputs.

4. Conclusion

Optimization of accelerator-generated X-ray spectra is inherently application dependent. The expanded analysis demonstrates that the best configuration for one task may be suboptimal for another because penetration, contrast, and output intensity do not improve together uniformly.

Molybdenum at lower beam energy is favored for contrast-sensitive imaging, while tungsten at intermediate or high energy remains preferable for dense-material inspection and other penetration-dominated tasks. Beam current continues to function primarily as an output-scaling variable and is therefore most useful after the spectral target has already been selected.

The practical value of this paper lies in its decision-oriented structure. It provides a template for ranking accelerator settings according to operational priorities and can readily be expanded with empirical values, additional target materials, or more advanced objective functions in a final dissertation or journal submission.

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