A Novel Shielding Structure for Distributed X-ray Tubes

Authors: Tang Huaping, Chen Zhiqiang, Li Guoyu, He Wu, Wang Biao, Lai Sheng

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Abstract

Unlike the structural characteristics of conventional single-focus X-ray tubes, the radiation protection and shielding design of distributed multi-focus X-ray tubes requires targeted research. This paper employs Monte Carlo simulation methods to simulate and study the radiation field and shielding structure of distributed multi-focus X-ray tubes. The simulation results demonstrate that distributed multi-focus X-ray sources exhibit linear source characteristics, and a shielding design approach using uniform-thickness shielding bodies for all shielding surfaces, particularly along the focal spot distribution direction, is proposed. By simulating leakage dose rate levels at various shielding surfaces under different shielding thicknesses, a lead shielding structure with uniform thickness of 5–6 mm on each surface was designed and assembled with the X-ray tube. Under conditions of an anode high voltage of 160 kV and an anode current of 15 mA, leakage dose rate testing and shielding performance evaluation were conducted. The results indicate that for this novel distributed X-ray tube, employing a uniform-thickness shielding design for all shielding surfaces, particularly in the focal spot distribution direction, is feasible; the deviation between actual measurements at various points and Monte Carlo simulation results is less than 25%, predominantly on the lower side, showing good consistency; the points with higher leakage dose rates are located at the front lower middle and rear lower middle positions, measuring 2.4 Sv/h and 2.92 Sv/h respectively, while leakage dose rates at the top/bottom and left/right sides are below 2 Sv/h and 1 Sv/h respectively; after adopting the uniform-thickness shielding structure on all surfaces for the X-ray tube, the leakage dose rates at all points satisfy the requirement of being below the 5 Sv/h leakage dose rate limit.

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Study on Shielding Structure of Novel Distributed X-ray Tube

TANG Huaping[1,2], CHEN Zhiqiang[1], LI Guoyu[2], HE Wu[2], WANG Biao[2], LAI Sheng[2]
[1](Department of Engineering Physics, Tsinghua University, Beijing 100084, China)
[2](Nuray Technology Company Limited, Changzhou 213200, China)

Abstract

Unlike conventional single-focus X-ray tubes, distributed multi-focus X-ray tubes require dedicated research on radiation protection and shielding design. This study employs Monte Carlo simulation methods to investigate the radiation field and shielding structure of distributed multi-focus X-ray tubes. Simulation results demonstrate that distributed multi-focus X-ray sources exhibit line-source characteristics, leading to a proposed design methodology employing uniform shielding thickness across all shielding surfaces, particularly along the focal distribution direction. By simulating leakage dose rate levels across various shielding surfaces at different thicknesses, a lead shielding structure with uniform 5–6 mm thickness on each surface was designed and assembled with an X-ray tube. Leakage dose rate testing and shielding performance evaluation were conducted at an anode voltage of 160 kV and anode current of 15 mA. Results indicate that uniform-thickness shielding design is feasible for novel distributed X-ray tubes, particularly along the focal distribution direction. The deviation between measured and Monte Carlo simulated results at various points was less than 25%, with measured values predominantly lower, showing good consistency. Higher leakage dose rates were observed at the front lower middle (2.4 Sv/h) and rear lower middle (2.92 Sv/h) positions, while leakage at top/bottom and left/right surfaces remained below 2 Sv/h and 1 Sv/h, respectively. With uniform-thickness shielding on all surfaces, the leakage dose rate at every point satisfies the requirement of remaining below 5 Sv/h.

Key words: Distributed X-ray source; Shielding structure; Monte Carlo simulation; Line-source characteristic; Leakage dose rate

1 Distributed X-ray Tube

In recent years, novel multi-focus distributed X-ray tubes have revolutionized radiation imaging technology, attracting widespread attention and research. Benefiting from the high penetration capability of X-rays and differential attenuation across materials, X-ray radiation imaging enables acquisition of internal object information, with broad applications in medical imaging, security screening, and non-destructive testing. Multi-focus distributed X-ray tubes refer to tubes containing multiple focal spots distributed at different positions within a single vacuum envelope, where each focal spot can independently and controllably generate X-rays [1]. Radiation imaging systems based on such tubes can perform perspective imaging of an object from different angles without moving the source, enabling rapid three-dimensional imaging such as stationary CT systems [2]. This avoids issues associated with conventional high-speed slip-ring mechanical structures, offering superior stability, higher detection speed, and greater efficiency. These advantages have spurred intensive research across numerous institutions [3-6].

Shielding structure is critical for safe X-ray tube application and plays a key role in engineering implementation. Current shielding design typically relies on ICRP report parameters combined with empirical X-ray attenuation formulas [7,8] or employs Monte Carlo modeling calculations [9,10]. However, existing radiation shielding research focuses on single-focus X-ray sources, generally calculating or simulating based on the focal spot as the center according to different energy and intensity distributions at various angular directions [11]. The operating mode and shielding structure of novel multi-focus X-ray sources differ significantly from single-focus sources.

Unlike single-point X-ray sources, multi-focus distributed X-ray sources feature an "off-center" emission position, approaching the line-source characteristics of radioactive sources [12,13], yet their X-ray emission pattern differs from uniform linear distribution of line sources, instead forming an intermittent point distribution. Consequently, dedicated research is required for their shielding design methodology. This study employs Monte Carlo simulation methods to investigate the radiation field characteristics of a 45-focus distributed X-ray tube operating in sequential focal rotation mode, revealing line-source properties. A shielding design methodology employing uniform thickness along the focal distribution direction is proposed. Using lead as shielding material, this work examines surface distributions of leakage dose rates under uniform-thickness designs, evaluates shielding effectiveness for distributed X-ray sources, and determines required lead thickness to meet the radiation protection dose limit of 5 μSv/h (per national standard GBZ 127-2002). Based on these results, a lead shielding structure was designed, assembled with the X-ray tube, and tested for surface leakage dose rates. Comparisons with simulation results validate the safety and effectiveness of uniform-thickness shielding design for novel distributed X-ray tubes. This work explores new technical methods for shielding design of distributed X-ray tubes and provides reliable solutions for radiation safety design in engineering applications.

1.1 Structural Modeling of Distributed X-ray Tube

The distributed X-ray tube studied herein features 45 focal spots arranged linearly on an elongated anode [14] within a rectangular enclosure, as shown in

Figure 1 [Figure 1: see original paper]. In addition to the rectangular main structure, the tube includes cylindrical high-voltage connection structures, oil cooling connections, exhaust tubes, ion pumps, and other auxiliary components.

The structural schematic is illustrated in Figure 2 [Figure 2: see original paper]. The 45 anode focal spots are equally spaced in a linear arrangement with overall left-right symmetry. The central focal position is defined as origin O, establishing an X-Y-Z coordinate system where the X-ray emission direction is designated as forward. To reduce Monte Carlo computational complexity and improve efficiency, the calculation model simplifies by excluding auxiliary components such as exhaust tubes, ion pumps, and terminal connections.

Shielding structure positions are shown in Figure 2, with distances from focal center O to front, rear, top, bottom, and side surfaces being 94 mm, 81 mm, 254 mm, 178 mm, and 362 mm, respectively.

1.2 Operating Parameters of Distributed X-ray Tube

The distributed X-ray tube operates with positive anode high voltage supplied by a high-voltage generator, multi-channel constant current control equipment (ECS) specifically developed for cathode control, real-time anode cooling by an oil chiller, and high vacuum maintenance by an ion pump controller. The system configuration and equipment setup are shown in Figure 3 [Figure 3: see original paper], with operating parameters listed in Table 1 .

Table 1 Parameters of Multi-Beam X-ray tube

Item	Technical data
Maximum anode voltage / kV	160
Maximum anode current / mA	15
Continuous operation power / kW	2.4
Number of focal spots / pcs	45
Single point working pulse width / μs	50~2000

2 Monte Carlo Simulation Design

Based on the distributed X-ray tube structural model shown in Figure 2, shielding structures were positioned at the red wireframe locations using lead as shielding material, with dose sampling points established on shielding structure outer surfaces. The simulation modeled multi-focus X-ray tube cathode structures with X-ray generation via electron bombardment of the anode target. Electron source parameters followed Table 1 settings, with tungsten anode target material. 160 keV electron beams bombarded 45 focal positions to generate X-rays with tungsten characteristic peaks and bremsstrahlung [15-18]. The model distributed 15 mA anode current across 45 focal spots to achieve 2.4 kW anode power. Simulation yielded an X-ray radiation field with approximately 110 keV average energy and angular/distribution characteristics consistent with line-source properties. Uniform thickness shielding was applied to six external tube surfaces. Leakage dose rates near central points (point O in Figure 2) were analyzed for lead shielding thicknesses ranging from 1–6 mm. The resulting attenuation curves are plotted in Figure 4 [Figure 4: see original paper].

The results show that each 1 mm increase in lead shielding thickness reduces leakage dose rate by approximately one order of magnitude for the 160 kV X-ray tube. Using the 5 Sv/h leakage dose rate limit as a reference, shielding thicknesses of 4–6 mm on each surface satisfy radiation protection requirements.

Based on Monte Carlo results from Figure 4, uniform lead thickness along the focal distribution direction was implemented, with identical thickness across each shielding surface area. This simplifies shielding structure design, fabrication, and assembly. After incorporating appropriate safety margins, the designed lead shielding layer thicknesses are shown in Table 2 .

Table 2 Thickness of lead shield at different locations

Location	Lead shielding thickness / mm
Front upper	5
Front lower	6
Rear upper	5
Rear lower	6
Top	5
Bottom	6
Left upper	5
Left lower	6
Right upper	5
Right lower	6

Under these lead shielding thicknesses, Monte Carlo calculations show all surface leakage dose rates meet the 5 Sv/h requirement. Surface distribution characteristics for front, rear, and bottom surfaces are shown in Figure 5 [Figure 5: see original paper]. Each small square in the figure represents a detector, dividing the surface into small areas for statistical analysis of leaked X-rays passing through. Monte Carlo statistical fluctuations cause jagged edges in the distribution patterns.

The results indicate maximum leakage dose rates on front and rear panels occur 3–5 cm below focal positions. Bottom, front lower, rear lower, left lower, and right lower panels use 6 mm shielding thickness, greater than the 5 mm thickness for top, rear upper, left upper, and right upper panels, consistent with higher X-ray yields in forward and downward directions from the reflective target structure. Uniform shielding thickness along the elongated anode length achieves safety objectives, demonstrating line-source characteristics of the 45-

focus distributed X-ray source. Leakage dose rates at anode ends are lower than central positions, showing end truncation effects of line sources.

3 Shielding Structure Design and Testing of Distributed X-ray Tube

Based on Monte Carlo simulation results, shielding structures were designed for the distributed X-ray tube according to thickness specifications in Table 2. After fabrication, structures were assembled with the tube and tested under standard operating parameters from Table 1 to verify radiation protection effectiveness.

3.1 Shielding Structure Design

Shielding design must consider fabrication and assembly feasibility. The design and assembly process involved: (1) constructing a rectangular hexahedron around the tube with structural frames at edges; (2) designing 4 mm thick mounting plates at both tube ends for fixing the tube to the frame; (3) using 5 mm thick lead plates at top, rear upper, rear lower, left upper, and right upper positions; (4) using 6 mm thick lead plates at front upper, front lower, bottom, left lower, right lower, and rear lower positions; (5) adding appropriate labyrinth structures externally at cable and cooling oil pipe penetration points. The final shielding structure design is shown in Figure 6 [Figure 6: see original paper].

During actual fabrication and assembly, seamless joining at hexahedron edges proved difficult. Therefore, lead strips were applied inside structural frame edges to seal assembly gaps and screw holes, ensuring radiation protection integrity.

3.2 Radiation Protection Effectiveness Testing

During shielding tests, the primary beam port was sealed with shielding tooling using 8 mm thick lead sheet overlapping the main beam window by approximately 40 mm. With the X-ray source activated, an F451p ionizing radiation monitor measured leakage rates at 5 cm from the shielding surface, with data recorded by zone. Leakage dose rate test results are shown in Figure 7 [Figure 7: see original paper] (right and left panels were similar and not separately marked). All measurements at 5 cm from the shielding surface were below 5 Sv/h, achieving predetermined radiation protection objectives.

Typical representative points from front/rear, top/bottom, and left/right surfaces were selected to compare measured and Monte Carlo simulated leakage dose rates, as shown in Table 3 .

Table 3 Comparison of simulated and actual measured dose distribution after lead shielding

Location	Simulated dose rate / $\mathrm{Sv \cdot h^{-1}}$	Measured dose rate / $\mathrm{Sv \cdot h^{-1}}$	Deviation between measurement and simulation
Front lower middle	3.1	2.4	-23%
Rear lower middle	3.6	2.92	-23%
Bottom center	2.1	1.8	-16%
Bottom front	2.5	2.0	-20%
Bottom right	1.3	1.1	-15%
Right lower	1.2	1.19	-1%

Table 3 shows deviations between measured and simulated results for the 45-focus distributed X-ray tube are within 25%, demonstrating that Monte Carlo simulation can effectively guide development and design of X-ray tube radiation protection and shielding structures.

Differences between measurements and calculations primarily result from simplified modeling of top high-voltage connections, oil cooling structures, exhaust tubes, ion pumps, and other auxiliary components, as well as shielding frame structures and labyrinth flanges that actually block radiation in practice, making most measured values slightly lower with varying deviations by location. Both Monte Carlo simulations and actual tests confirm leakage dose rates for the 45-focus distributed X-ray tube remain below 5 Sv/h, satisfying shielding design requirements and radiation protection dose rate limits.

This study employed Monte Carlo simulation to model a 45-focus distributed X-ray tube, investigated its line-source distribution characteristics, and proposed uniform-thickness shielding design, particularly along the focal distribution direction. By modeling uniform-thickness shielding and simulating relationships between surface thickness and leakage dose rate, the study found that 4–6 mm lead shielding thicknesses satisfy the $ $5 Sv/h limit. Accordingly, a shielding structure with uniform 5–6 mm thickness on different surfaces was designed and fabricated. Assembly and testing demonstrated all locations met the $ $5 Sv/h radiation protection standard, achieving design objectives. This validates the reliability of uniform-thickness shielding design for distributed X-ray sources, particularly along focal distribution direction, simplifying design, fabrication, and assembly. Maximum leakage dose rates occurred at front lower middle (2.4 Sv/h) and rear lower middle (2.92 Sv/h), consistent with line-source characteristics and reflective target structure. Comparison between measurements and simulations shows deviations below 25% with good consistency, confirming Monte Carlo simulation feasibility for designing novel distributed X-ray tube shielding structures. This research explores shielding technology for distributed X-ray tubes and provides technical references for radiation protection research on novel X-ray sources.

Author Contributions Statement

TANG Huaping conducted line-source characteristic studies of distributed X-ray source radiation fields, proposed uniform-thickness shielding design along focal distribution direction, guided Monte Carlo simulations and shielding structure design, and prepared the main manuscript. CHEN Zhiqiang provided technical guidance throughout the research, including Monte Carlo physical models and result analysis. LI Guoyu led shielding structure development and participated in assembly and testing verification. HE Wu and WANG Biao performed X-ray source system construction, shielding structure assembly, testing, and data analysis. LAI Sheng conducted Monte Carlo modeling and simulation analysis, data processing, and participated in manuscript preparation.

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Note: Figure translations are in progress. See original paper for figures.