Study on Novel Distributed X-ray Tube Shielding Structure

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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 investigate the radiation field and shielding structure of distributed multi-focus X-ray tubes. The simulation results indicate that the distributed multi-focus X-ray source exhibits line source characteristics, and proposes a shielding design methodology employing uniform thickness for all shielding surfaces, particularly along the focal spot distribution direction. By simulating the leakage dose rate levels of each shielding surface under varying 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 anode high voltage 160 kV and anode current 15 mA, leakage dose rate testing and shielding performance evaluation were conducted. The results demonstrate that for the novel distributed X-ray tube, employing a uniform-thickness shielding design for all shielding surfaces, particularly along 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, indicating good consistency; the points with higher leakage dose rates are located at the front lower middle and rear lower middle, measuring 2.4 Sv/h and 2.92 Sv/h, respectively; the leakage dose rates at the top/bottom and left/right sides are below 2 Sv/h and 1 Sv/h, respectively; after the X-ray tube adopts the uniform-thickness shielding structure on all surfaces, the leakage dose rates at all points satisfy the requirement of being below the 5 Sv/h leakage dose rate limit.

Full Text

Preamble

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Study on Shielding Structure of Novel Distributed X-ray Tube

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Abstract

[Background] The shielding structure is a critical guarantee for the safe application of X-ray tubes and plays a key role in engineering implementation. Unlike conventional single-focus X-ray tubes, the radiation protection and shielding design of distributed multi-focus X-ray tubes requires targeted research. [Purpose] This study aims to design and validate an effective shielding structure for distributed X-ray sources to ensure radiation safety while maintaining practical feasibility, providing a viable technical solution for shielding design and protection of distributed X-ray sources. [Methods] This paper employs Monte Carlo simulation methods to model and investigate 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 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 at various shielding thicknesses for each surface, a lead shielding structure with uniform thicknesses of 5–6 mm on each face was designed and assembled with an X-ray tube. Leakage dose rate testing and shielding performance evaluation were conducted under operating conditions of 160 kV anode voltage and 15 mA anode current. [Results] The results indicate that for novel distributed X-ray tubes, adopting a uniform thickness shielding design on all surfaces—especially along the focal distribution direction—is feasible. The deviation between actual measurements and Monte Carlo simulation results was less than 25% at all points, with measured values predominantly lower, demonstrating good consistency. The points with higher leakage dose rates were located in the front lower middle and rear lower middle positions, measuring 2.4 Gy/h and 2.92 Gy/h respectively, while leakage dose rates at the top/bottom and left/right surfaces were below 2 Gy/h and 1 Gy/h respectively. [Conclusions] By adopting a shielding structure with uniform thickness on all sides of the X-ray tube, the leakage dose rate at each point meets the requirement of being below the 5 Gy/h limit.

Keywords Distributed X-ray source, Shielding structure, Monte Carlo simulation, Line-source characteristic, Leakage dose rate
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The Shielding Design of Distributed X-ray Source

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Abstract

[Background] The shielding structure is an important guarantee for the safe application of X-ray tubes and plays a key role in engineering practice. Different from the structural characteristics of traditional single-focus X-ray tubes, the radiation protection and shielding design of distributed X-ray tubes require targeted research. [Purpose] This study aims to design and validate an effective shielding structure for distributed X-ray sources to ensure radiation safety while maintaining practical feasibility. This work provides a feasible technical solution for the design and protection of shielding structures for distributed X-ray sources. [Methods] This paper uses Monte Carlo simulation calculation methods to simulate and study the radiation field and shielding structure of distributed X-ray tubes. A design method of uniformly thick shielding structure was proposed for each shielding surface, especially along the focal distribution direction. Monte Carlo simulation was performed with 45 focal spots distributed linearly, operating at 160 kV anode voltage and 15 mA anode current. The simulation explored lead shielding thicknesses ranging from 1 to 6 mm. [Results] The simulation calculation results showed that the distributed X-ray source has line source characteristics. By simulating the leakage dose rate levels of various shielding surfaces at different shielding thicknesses, a lead shielding structure with thickness of 5–6 mm on each surface was designed and assembled with an X-ray tube. The results indicated that it was feasible to adopt a uniform thickness shielding design on all shielding surfaces for the new distributed X-ray tube, especially in the focal distribution direction. The deviation between simulation and actual measurements was consistently below 25%, validating the reliability of the simulation approach. The points with higher leakage rates were located in the front lower middle and rear lower middle, with leakage rates of 2.4 Gy/h and 2.92 Gy/h respectively, in accord with the characteristics of the line source and reflective target structure of a distributed X-ray tube. The leakage rates at the top, bottom, left and right were lower than 2 Gy/h and 1 Gy/h respectively. [Conclusions] By adopting a shielding structure with uniform thickness on all sides of the X-ray tube, the leakage dose rate at each point meets the requirement of a leakage dose rate limit of less than 5 Gy/h.

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

In recent years, novel multi-focus distributed X-ray tubes have enabled significant transformations in radiation imaging technology, attracting widespread attention and research. Benefiting from the high penetrability of X-rays and the differential attenuation of X-rays by different materials, X-ray radiation imaging can obtain internal object information and is widely used in medical, security inspection, and non-destructive testing applications. A multi-focus distributed X-ray tube refers to an X-ray tube in which multiple focal spots are distributed at different positions within a single vacuum tube cavity, with each focal spot capable of independently and controllably generating X-rays [1]. Radiation imaging systems based on multi-focus distributed X-ray tubes can perform perspective imaging of the same object from different angles without requiring movement of the X-ray source, enabling rapid three-dimensional imaging of the object, such as in stationary CT systems [2]. This avoids the impact of traditional high-speed slip-ring mechanical structures, offering better stability, higher detection speed and efficiency, with obvious advantages that have attracted research from numerous institutions [3–6].

The shielding structure is a critical guarantee for the safe application of X-ray tubes and plays a key role in engineering implementation. Existing shielding structure designs typically rely on parameter guidance from ICRP report charts combined with empirical formulas for X-ray attenuation [7, 8], or employ Monte Carlo modeling calculations as guidance [9, 10]. Current radiation shielding research has focused on single-focus X-ray sources, typically using the focal spot as the center to perform calculations or simulations based on the different energy spectrum distributions and intensity distributions of X-rays in various angular directions [11]. However, the operating mode and shielding structure of novel multi-focus X-ray sources differ significantly from those of single-focus X-ray sources.

Unlike single-point X-ray sources, the shielding design and performance study of multi-focus distributed X-ray sources represents a completely new research topic due to the "non-centered" characteristic of X-ray emission positions. This type of source has non-centered features approaching the line-source characteristics of radioactive sources [12, 13], but its X-ray emission mode is not equivalent to the uniform linear distribution of a line source; instead, it consists of intermittent point sources. Therefore, targeted research is required for its shielding design methodology. This paper employs Monte Carlo simulation methods to investigate the radiation field morphology of a 45-focus distributed X-ray tube under sequential rotation operation of each focal spot, revealing line-source characteristics. A shielding design methodology employing uniform thickness shielding layers along the focal distribution direction is proposed. Using lead as the shielding material, this study investigates the surface distribution of leakage dose rates for the X-ray tube under various uniform shielding thicknesses on each surface, evaluates the shielding effectiveness of the uniform-thickness approach for distributed X-ray sources, and determines the required lead shielding thickness to meet the radiation protection dose limit of 5 µGy/h (national standard GBZ 127-2002). Based on these results, a lead shielding structure was designed and assembled with the X-ray tube, and actual surface leakage dose rate measurements were conducted and compared with simulation results, validating the safety and effectiveness of the uniform-thickness shielding design methodology for novel distributed X-ray tubes. This work explores new technical methods for shielding design research of distributed X-ray tubes and provides a reliable solution for radiation safety design in the engineering application of such sources.

1 Distributed X-ray Tube

The distributed X-ray tube investigated in this study features 45 focal spots arranged in a linear distribution on a long strip anode [14], housed within a rectangular frame structure, as shown in FIGURE:1. In addition to the main rectangular structure, the tube includes cylindrical high-voltage connection structures, oil cooling connection structures, and auxiliary components such as exhaust pipes and ion pumps.

1.1 Structural Modeling of Distributed X-ray Tube

A schematic diagram of the distributed X-ray tube structure is shown in FIGURE:2. The 45 anode focal spots are arranged in a linear equidistant pattern with overall left-right symmetry. The central focal spot position is defined as the origin O, and an X-Y-Z coordinate system is established, with the X-ray emission direction defined as forward. To reduce Monte Carlo computational difficulty and improve calculation efficiency, the computational model was simplified by excluding auxiliary components such as exhaust pipes, ion pumps, and lead terminals.

The shielding structure positions are shown in FIGURE:2, with distances from focal spot center O to the 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 high voltage supplied by a high-voltage generator, with a specially developed multi-channel constant current control device (ECS) controlling different cathodes, an oil cooler providing real-time cooling of the anode, and an ion pump controller maintaining high vacuum inside the tube. The X-ray tube system and equipment setup are shown in FIGURE:3, with operating parameters listed in TABLE:1.

TABLE:1 Parameter of Multi-Beam X-ray tube
Item | Parameter
–|–

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 frame locations using lead as the shielding material, with dose sampling points set on the outer surfaces of the shielding structures. In this simulation, a multi-focus X-ray tube cathode structure model was established using electron bombardment of the anode target to generate X-rays. Electron source parameters were set as shown in TABLE:1, with the anode target material set as tungsten. A 160 keV electron beam bombarded the 45 focal positions to generate X-rays with tungsten characteristic peaks and bremsstrahlung [15–18]. Since Monte Carlo programs cannot easily configure multiple electron sources at different positions to sequentially bombard the anode target, 45 separate programs were written, each with a single electron source. The 15 mA current was distributed across the 45 focal spots to achieve 2.4 kW operating power, with data processed through superposition. The simulation yielded an X-ray radiation field with an average energy of approximately 110 keV and angular distribution consistent with line-source characteristics. Uniform thickness shielding was then applied to the six outer surfaces of the tube. When lead shielding thickness on each surface ranged from 1–6 mm, leakage dose rates were analyzed at positions near the center point (point O in FIGURE:2) on each surface. The resulting attenuation curves of leakage dose rate versus lead thickness are shown in FIGURE:4.

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

Based on the Monte Carlo results in FIGURE:4, using uniform lead thickness along the focal distribution direction, the study further applied uniform lead thickness across each shielding surface area, simplifying shielding structure design, manufacturing, and assembly. After incorporating appropriate safety margins, the designed lead shielding layer thicknesses at different locations are shown in TABLE:2.

TABLE:2 Thickness of lead shield at different locations
Location | Lead shielding thickness / mm
–|–
Bottom front | 6
Bottom front | 6

Bottom | 6
Bottom right | 6
Bottom right | 6

Under the lead shielding thicknesses shown in TABLE:2, Monte Carlo calculations indicate that leakage dose rates on all surfaces meet the 5 Gy/h requirement. The surface distribution characteristics of leakage dose rates for the front, rear, and bottom surfaces are shown in FIGURE:5. Each small square in the figure represents a detector, dividing the entire surface into small panels to count leakage X-rays passing through. Due to relative errors in Monte Carlo calculations causing fluctuations, the edges of the distribution maps appear irregular.

The results show that maximum leakage dose rates on the front and rear panels occur in regions 3–5 cm below the focal spots. The bottom, front lower, rear lower, left lower, and right lower panels have 6 mm shielding thickness, greater than the 5 mm thickness used for the top, rear upper, rear lower, left upper, and right upper panels, consistent with the reflective target structure of the tube where X-ray yield is higher in the forward and downward directions. Along the length direction of the anode focal distribution, uniform shielding thickness in each region achieves shielding effectiveness meeting safety objectives, demonstrating the line-source characteristics of the 45-focus distributed X-ray source. At both ends of the elongated anode, leakage dose rates are lower than in the central region, exhibiting the truncation effect at line-source ends.

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

Based on Monte Carlo simulation results, shielding structures were designed for the outer surfaces of the distributed X-ray tube according to the lead shielding thicknesses in TABLE:2. After manufacturing, the shielding structures were assembled with the distributed X-ray tube. Leakage rate testing was conducted using standard operating parameters from TABLE:1, with actual operating parameters set to anode voltage 160 kV and anode current 15 mA (each focal spot pulse width 95 µs, pulse interval 5 µs, pulse current set to 15.8 mA, with 45 focal spots operating in sequential rotation through multiple cycles) to verify radiation protection effectiveness.

3.1 Shielding Structure Design

Shielding structure design must consider manufacturing and assembly convenience and feasibility. The design and assembly process is as follows: (1) Construct a square hexahedron outside the X-ray tube with structural frames at the edges; (2) Design 4 mm thick installation steel plates at both ends of the tube for fixing the tube to the frame structure; (3) Use 5 mm thick lead plates for the top, rear upper, rear lower, left upper, and right upper positions; (4) Use 6 mm thick lead plates for the front upper, front lower, bottom, left lower, right lower, and rear lower positions; (5) Supplement appropriate labyrinth structures externally at locations where connection cables and cooling oil pipes pass through. The final shielding structure design is shown in FIGURE:6.

In actual manufacturing and assembly, seamless assembly at the edges of the six lead plates is difficult to achieve. Therefore, lead strips were attached to the inner sides of the structural frame edges to seal assembly gaps and mounting screws, ensuring radiation protection effectiveness.

3.2 Radiation Protection Effectiveness Testing

During shielding testing, the main beam port was sealed with a shielding fixture using 8 mm thick lead sheets overlapping the main beam window by approximately 40 mm. The X-ray source was activated, and an F451p ionizing radiation monitor was used to conduct survey measurements at 5 cm from the shielding body, with data recorded by zone. The leakage dose rate test results are shown in FIGURE:7, where the right and left panels are essentially identical and not separately marked. The test data show that leakage dose rates at 5 cm outside the shielding body are all less than 5 Gy/h, achieving the predetermined radiation protection objective.

Representative points on the front/rear, top/bottom, and left/right surfaces were selected to compare measured leakage dose rates with Monte Carlo simulation values, as shown in TABLE:3.

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

Location	Simulated dose rate / $\mathrm{Gy \cdot h^{-1}}$	Measured dose rate / $\mathrm{Gy \cdot h^{-1}}$	Deviation between measurement and simulation
Bottom front	2.9	2.2	-23%
Bottom front	2.6	2.0	-23%
Bottom	2.2	1.8	-16%
Bottom right	1.5	1.2	-20%
Bottom right	1.3	1.1	-15%
Front	2.4	2.4	-1%

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

Differences between measured and calculated results primarily arise because the simplified top high-voltage connection structure, oil cooling connection structure, exhaust pipes, ion pumps, and other auxiliary components in the simulation, as well as the shielding fixation frame and flange labyrinth structures, actually block radiation in practice, making most measured values slightly lower with varying deviations at different locations. Both Monte Carlo simulation and actual test results show that leakage dose rates of the 45-focus distributed X-ray tube are below 5 Gy/h, meeting radiation shielding design requirements and complying with radiation protection dose rate limit standards.

This study employed Monte Carlo simulation methods to establish a computational model of a 45-focus distributed X-ray tube, investigated its X-ray field distribution characteristics as a line source, and proposed a shielding design methodology using uniform thickness on all surfaces, particularly along the focal distribution direction. By establishing shielding models with uniform thickness on each surface, the relationship between shielding thickness and leakage dose rate was simulated, revealing that lead shielding thicknesses of 4–6 mm at different locations can meet the leakage dose rate limit requirement of below 5 Gy/h. Based on these findings, a shielding structure with uniform thickness on each surface (5–6 mm on different surfaces) was designed and manufactured. Assembly and measurement demonstrated that leakage dose rates at all locations are below the 5 Gy/h radiation protection dose rate limit standard, achieving radiation protection design objectives. This validates the reliability of uniform-thickness shielding design for distributed X-ray sources, particularly along the focal distribution direction, which simplifies shielding design, manufacturing, and assembly. Maximum leakage dose rates appeared in the middle of the front lower and rear lower positions (2.4 Gy/h and 2.92 Gy/h respectively), consistent with the line-source characteristics and reflective target structure of multi-focus distributed X-ray tubes. Comparison between measured and simulated results shows deviations below 25% with good consistency, demonstrating that Monte Carlo simulation is feasible for designing novel distributed X-ray tube shielding structures. This research explores shielding technology for novel distributed X-ray tubes and provides technical and experiential references for radiation protection research in this new type of X-ray source.

Author Contributions Statement

TANG Huaping conducted research on the line-source characteristics of the distributed X-ray source radiation field, proposed the uniform-thickness shielding design methodology along the focal distribution direction, guided Monte Carlo simulation and shielding structure design, and performed the primary manuscript writing. CHEN Zhiqiang guided technical issues throughout the research process, including physical models and result analysis for Monte Carlo simulations. LI Guoyu was responsible for developing the distributed X-ray tube shielding structure 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 simulation modeling and analysis, data processing and analysis, and participated in manuscript writing.

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