MINIATURE X-RAY SOURCES AND THE EFFECTS OF SPOT SIZE ON SYSTEM PERFORMANCE

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ABSTRACT

Miniature x-ray sources present unique challenges due to the cost, power and space constraints placed upon them. One of the key functional differences from larger traditional x-ray tubes is that the x-ray spot is comprised of the entirety of the electrons produced by the filament without the benefit of active focusing elements in most cases. The result is an x-ray spot that is not well described by a traditional Full Width Half Maximum (FWHM) type of measurement due to the irregular nature of the spots. This paper presents an alternate method called an intensity integral curve that can be used in conjunction with a Gaussian FWHM measurement. The intensity integral curve gives important additional spatial information about the x-ray spot and more predictive power in how the x-ray spot on the tube may perform in a given application. The experimental setup, curve generation and curve interpretation are discussed for a number of currently available and prototype miniature x-ray sources.

1. INTRODUCTION

There have been tremendous advancements in miniature x-ray tube technology over the past few years [1]. It is becoming critical to predict a miniature x-ray tube’s performance in a number of applications. The tube’s spot size is one critical characteristic; unfortunately the spot size is difficult to measure consistently, especially for comparing tubes over boundaries such as different laboratories and different companies. The traditional measure of an x-ray spot size is the Full Width Half Maximum (FWHM), which can be achieved through a variety of measurement techniques [2]. The primary problem with this single number specification for spot size is that it lacks spatial distribution information. A FWHM measurement assumes a Gaussian distribution, which implies that close to 75% of the x-ray flux from the tube is contained within the FWHM, which is seldom the case with many x-ray tubes. When spots become less symmetrical, or the radial intensity deviates from a Gaussian, the single number measurement becomes much more subjective and the spatial distribution information can no longer be gleaned from a single FWHM number.
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Miniature x-ray tubes are limited by physical size, low power consumption, and price. Given these constraints, miniature tubes have simple diode designs, which focus the electron beam with passive electro-static focusing. This makes it extremely difficult to produce truly round and symmetrical spot profiles on the anode, particularly with the geometrically complex cathode made of a traditional coil filament. The resulting x-ray spots are non-round and contain a significant amount of their radiation outside the FWHM of the central spot.

We propose a more useful measure of spot size which is how much of the total x-ray intensity is captured at a given radius from the spot’s center; we call this the intensity integral curve. An algorithm generates an intensity integral curve from an x-ray spot image, based on the following formula(s):

\[
I_{\text{int}}(r) = \frac{\int_{-\infty}^{\infty} \int_{-\infty}^{\infty} I(x, y) \, dx \, dy}{\int_{-\infty}^{\infty} \int_{-\infty}^{\infty} I(x, y) \, dx \, dy} \quad \text{or} \quad I_{\text{int}}(r) = \frac{\int_{0}^{\infty} I(r') \, dr'}{\int_{0}^{\infty} I(r') \, dr'}
\]

where

\[
I = (x-x_0)^2 + (y-y_0)^2
\]

‘\(I_{\text{int}}(r)\)’ is the intensity integral curve as a function of the radial distance ‘\(r\)’ from the center of the x-ray spot at position ‘\(x_0\)’ and ‘\(y_0\)’, and ‘\(I(x,y)\)’ is the two dimensional pinhole intensity image of the x-ray spot. A straightforward method for evaluation is to transform ‘\(I(x,y)\)’ into radial intensity function ‘\(I(r)\)’, center on the x-ray spot, then integral to a radius ‘\(r\)’. Graphically, the horizontal x-axis is the radius of the integrating circle (usually in microns) and the vertical y-axis is normalized to represent percentage of total x-ray flux. An intensity integral curve represents the amount of radiation captured at various aperture sizes centered on the spot. The intensity integral curve closely matches applications where a pinhole or a collimator is placed in front of an x-ray tube. Therefore, the intensity integral curve gives the percentage of the flux to the total flux which gets through the pinhole at increasing radii centered on the spot.

2. EXPERIMENTAL SETUP

Generating intensity integral curves requires taking two dimensional images of the tube’s x-ray spot. A pinhole camera provides an efficient, quick, and repeatable way to generate x-ray spot image. We use a 50\(\mu\)m diameter pinhole and a cooled CCD x-ray camera to take x-ray spot images. The goal for measuring a tube’s x-ray spot was to produce a test system that enabled verification of spot sizes less than 50microns, while maintaining a relatively low cost. Cooled CCD cameras have excellent dynamic range, sensitivity, and stability. CCD cameras are relatively inexpensive, and can integrate the frames for periods of more than an hour if necessary. They give reliable two dimensional distribution information on the X-ray spots, as all the pixels are exposed simultaneously and the gain per pixel can be calibrated by flat fielding.
techniques. They are, however, limited in resolution to the de-convolution of the pinhole size relative to the X-ray spot size.

A modified hobby-grade astronomical cooled CCD camera (Santa Barbara Instruments, Model ST-7I, Santa Barbara, CA) was chosen for the most cost effective solution. This camera utilizes a Kodak KAF-0402 sensor, 16bit A/D converter, and cooling to -5°C to enable integration times greater than an hour. The KAF-0402 sensor is low cost, has a sensitive area 6.9x4.6mm and has 9x9 micron pixels. The optical sensor was modified for X-ray detection, and the external optical window was exchanged for a beryllium X-ray transparent window. The sensor’s modifications included bonding a scintillating fiber optic plate directly to the silicon sensor with optical epoxy. The scintillator plate from Collimated Holes (Campbell, CA) consists of 10 micron diameter erbium doped glass fibers fused in a coherent array. The array’s thickness is 5.6mm, which stops all X-rays at 30kV, and allows only a few x-rays through at 50kV. The thickness was determined by the available space in the ST-7 camera. Direct bonding of the plate to the sensor with optical epoxy gives an excellent optical coupling with very little spill of light to the adjacent pixels. The modified camera has very good spatial resolution and X-ray sensitivity. Using a pinhole camera magnification of 3X gives an effective pixel resolution of 3 microns, more than adequate for analyzing 50 micron and larger spots. Analysis of larger area emitters can be accommodated by reducing the effective magnification of the system.

There is one background correction related to the coupling of the CCD to the scintillator plate. The convolution of the scintillator fiber size and the pixel size create a Moire pattern on the detected images. The relationship between the fibers and CCD pixels is fixed and very stable, flat field techniques are utilized successfully to process the detected images. Noise is reduced from 25% to 5%, and the Moire pattern is completely eliminated.

Once an image is acquired in the pinhole camera setup, it is viewed and processed using Mirametrics MIRA MX ULTRA software package (Mirametrics Inc., Ver. 7Ue MIRA MX ULTRA, Tucson, AZ). This package allows us to automatically analyze the x-ray spot image and generate the corresponding intensity integral curve. A number of built in and custom scripts determine the magnification of the pinhole camera setup and then perform the integrations centered on the spot for the flux data. The program then allows us to present the data in the intensity integral curve format or output raw data for further analysis.

3. RESULTS

The x-ray spot images and intensity integral curves from some of our production and prototype tubes are presented below. The first image is of a true round spot, which was created with a 50 μm pinhole directly in front of an x-ray tube’s spot, giving a 40 micron FWHM for this x-ray spot (Figure 1). The spot is axially symmetrical; therefore Gaussian distribution has a single value for the spot’s FWHM. In this case the FWHM, and the assumed Gaussian shape gives the
amount of output flux captured with a given aperture size. The intensity integral curve demonstrates the capture of output flux for a given aperture size from the spot center in a very predictable manner. You can see that a true Gaussian spot encompasses approximately 50% of the flux at the FWHM, and that the flux is almost completely contained within three times the FWHM making the single value a meaningful metric.

Figure 1 – A pinhole camera x-ray spot image (left) of a 50 um pinhole placed in front of an x-ray tube in order to make an x-ray spot close to a Gaussian shape. The graph on the right shows both the x-ray intensity and the intensity integral curve as a function of radial distance from the center of the spot.

The second example is of a typical miniature x-ray tube utilizing a traditional wound filament design. In this example you can see the individual coils of the filament emitting and the effect on the x-ray spot (Figure 2). This is a good example of where the single value FWHM,

Figure 2 – A pinhole camera x-ray spot image (left) from a tube with a coil filament cathode. The graphs on the right give the profile of this spot in the horizontal (bottom graph) and vertical direction (Top graph).
associated with an assumed Gaussian profile, can be ineffective in describing the output from the tube. A vertical slice (top graph in Figure 2) would indicate a fairly small spot size, while the horizontal slice (bottom graph in Figure 2) clearly indicates a much larger spot as defined by the FWHM. The intensity integral curve however gives significantly more information about the distribution of x-ray output (Figure 3). The intensity integral curve for the tube gives a required aperture size needed to capture a given percentage of the tube’s x-ray output.

The last example is of a miniature x-ray tube with a laser heated filament at the cathode. The filament is a round planar filament, and provides a much more symmetrical x-ray spot on the anode. For this tube, the FWHM is about 100 microns, however, the single value FWHM would not give all of the needed information about the tube’s x-ray output (Figure 4). The intensity integral curve shows about 70% of the tube flux is contained in the central diameter of 200 microns. The intensity integral curve also shows the remaining 30% of the flux is not captured fully until reaching a diameter of 1000 microns. The spot from this tube contains an extended low intensity x-ray profile that is not captured with the FWHM value, but is captured using an intensity integral curve. This critical information can be used to optimize design output collimation for total x-ray flux and/or stability and determine tube operating parameters for potential applications.

Figure 3 – This graph shows the x-ray intensity and the intensity sum curves from the x-ray spot image in Figure 2. From the radial intensity, the FWHM of this spot is about 150 microns. The intensity sum curve shows that less then 20% of the spot’s flux is contained within the FWHM.
Figure 4 - A pinhole camera x-ray spot image (left) of a planar filament x-ray tube. The graph on the right shows both the x-ray intensity and the intensity integral curve as a function of radial distance from the center of the spot. Note how the intensity integral curve is very useful in determining the usable flux from this tube with a given aperture size.

4. SUMMARY AND CONCLUSIONS

The intensity integral curve contains very useful information on the spatial characteristics of radiation being generated by the x-ray tube, particularly when the spot itself is non-symmetrical. Intensity integral curves are less subjective then a single value FWHM, therefore this information is more useful for controlling the quality of current x-ray tubes. Another powerful application of this method is to predict the performance of a given tube in a particular geometry. The intensity integral curve will allow the user to quickly predict what percentage of the total tube output is captured by a given collimation geometry. The intensity integral curve can be used to optimize the collimation geometry in early instrument designs and help to better define product requirements and specifications for production.

Overall we have shown that in situations where the x-ray tubes is not Gaussian, the FWHM specification is of little value in predicting performance of a tube. The FWHM is still appropriate for tubes with a close to Gaussian profile, but the intensity integral curve is a far better measure of performance within a much wider variety of spot profiles.

5. REFERENCES
