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The determination of the focal spot size of an X-ray tube from the radiation beam profile

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HIGHLIGHTS

- A model of the X-ray beam profile allows the determination of the focal spot size.
- A general profile function fits the data measurements of the beam profile.
- Links between beam profile and line spread and edge spread functions are discussed.
- No need for additional or specific devices to estimate the focal spot size.

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ABSTRACT

The aim of this work is to show that the focal spot size of a given X-ray tube can be determined from the profile of the radiation beam without the use of devices specifically designed for that task. The approach presented relies on a simple model for the radiation beam profile and on an analytical function used to fit the beam profile data. The basics of the profile function are outlined and the relationship between the fitting and the profile parameters are deduced. The relationship of the proposed method with the edge spread function and line spread function concepts is discussed. The focal spot size of an X-ray tube used at the Laboratory for Metrology of Ionizing Radiation (LMRI) of IST was determined using the proposed method. In the analysis of the experimental results, the heel-effect was also evaluated.

1. Introduction

The focal spot of an X-ray tube is related with the beam profile and is a parameter of concern in both image and beam quality in diagnostic (Jain et al., 2014) and therapy (Baldwin and Fitchew, 2014). The X-ray beam profile at the detector plane can be characterized by the penumbra and the umbra generated by the combination of the focal spot and the collimation system (Baldwin and Fitchew, 2014) and the detector characteristics (Bub et al., 2007). Some of the characteristics of the detectors used in profile measurements can influence the final result such as the detector size, the material and the electrical properties. The response of the detector can be modeled using the convolution theorem that connects the true profile and the measured profile by a convolution with the detector response function (Sibata et al., 1991; Kulmala and Tenhunen, 2012). The beam profile can be measured with detectors such as digital flat panels, for example, which have some resolution aspects to be considered (Bub et al., 2007). Film dosimetry has been found to be a straightforward and reliable method to obtain the beam profile (Sibata et al., 1991). Digital flat panels have replaced film technology; however, Gafchromic film was introduced which has a high spatial resolution. The accuracy and sensitivity of Gafchromic film depends highly on a proper film handling and development protocols and on a suitable and calibrated densitometry system (Kulmala and Tenhunen, 2012).

It is often assumed that the sigmoid shape of the penumbra is due to a Gaussian focal spot, leading to the use of an error function

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for the simulation of the radiation beam profile (Dixon et al., 2005; Gambaccini et al., 2011; Salamon et al., 2008). However, other suitable sigmoid shaped functions, like the Fermi-Dirac function can be used without previous assumptions about the focal spot shape. In this work a Fermi-Dirac function was used as the basis of the beam profile model as suggested by Bistrovic (1978). An analytical function was used to fit the radiation intensity profile data of a given X-ray beam (Oliveira et al., 1995). The parameters of the profile function are directly related with the penumbras and umbra values. The profile function was used as a tool to determine the focal spot size adapting the well-known method of the edge spread function (Boone and Seibert, 1994; Gambaccini et al., 2011; Salamon et al., 2008).

Given a profile function and assuming a simple model for the radiation beam the necessary mathematical expressions to quantify the focal spot size can be derived.

At LMRI an X-ray tube was used to generate four different beams by varying the collimator openings. The profile data for each of the beams was experimentally obtained using an ionization chamber displaced along one of the axis on the detector plane.

Using the profile model the focal spot size was estimated and, furthermore, the heel-effect was also considered.

2. Materials and methods

2.1. The radiation beam set up

Due to technological reasons the actual focal spot size is different from the apparent focal spot size. The estimation of the apparent focal spot size, c, is the aim of this work. The electrons emitted from the filament are accelerated by the tube voltage striking the anode and defining the actual focal spot size. The inclination of the anode defines the apparent focal spot size, c, as illustrated in Fig. 1. In the model developed below the apparent focal spot is the projected focal spot in the anode–cathode direction which is independent of the anode inclination. The focal spot can be determined from the apparent focal spot multiplying by the sine of the anode inclination.

The radiation beam of a given X-ray tube defines a radiation profile at the image detector plane. Let us consider an X-ray tube with a given apparent focal spot (mentioned below as focal spot) that will generate a beam defined by a given collimator.

If the beam is oriented along the positive Z axis of a given referential, then the beam profile is defined in the XY plane (detector plane) as represented in Fig. 1. The beam profile can be described by a function along a given direction in the XY plane, for example along the X axis as a function f(x).

The intensity distribution emitted from the focal spots falls between a rectangle and that of a two hot-spot sources or even more complex shapes (Wagner et al., 1974). In the simple model presented below, the focal spot are treated as a rectangle corresponding to a line segment in the 2D projection of Fig. 1.

The focal spot *c* and the collimation opening w of the beam are the cause of a certain level of penumbra in the radiation profile, at both sides of the edge of the beam, which can be named left (p_L) and right (p_R) penumbras. Due to the inclination of the anode the left and right penumbras are caused by different apparent focal spot sizes, c_L and c, respectively. Between the left and right penumbras an umbra, U, region is defined, corresponding to the main section of the beam, sometimes named “top flat zone” or “plateau”, where the dose or radiation intensity is ideally constant. The full width at half maximum (FWHM) can be defined as the distance between the middle points of both penumbras. A more rigorous definition of FWHM will be given below.

2.2. Focal spot size estimators

In this section three estimators for the focal spot size will be obtained. Let us consider that the collimator opening, *w*, is larger than the focal spot, *c*, by a value b_1 and b_2, respectively on the left and right sides of the ZZ′ axis (see Fig. 1) so that

$$b_1 + b_2 + c = w \tag{1}$$

At the XY image (or detector) plane the umbra value, U, depends on the magnification geometry. From Fig. 1, it follows that

$$a_1 + a_2 + c = U \tag{2}$$

From the equivalence of triangles we can write

$$b_2/F_c = a_2/F \tag{3}$$

Let us define a magnification factor, *M*, given by the ratio between *F* and F_c:

$$M = F/F_c \tag{4}$$

Where *F* and F_c are, respectively, the focal spot detector distance and the focal spot collimator distance. From Equations (3) and (4) follows

$$M = a_2/b_2 \tag{5}$$

Meaning that the value of a_2 is the magnification of b_2 or $a_2 = M\, b_2$. A similar equation is found for a_1 and b_1. Then, the sum $a_1 + a_2$ is given by

$$a_1 + a_2 = M(b_1 + b_2) \tag{6}$$

Inserting Equation (6) in Equation (2) gives

$$M(b_1 + b_2) + c = U \tag{7}$$

From Equation (1) we have

$$(b_1 + b_2) = w - c \tag{8}$$

To finalize, from Equations (7) and (8) the focal spot size is given by

$$c = (Mw - U)/(M - 1) \tag{9}$$

The meaning of this equation is that if the magnification factor, *M*, the collimation opening, *w*, and the umbra, *U*, are known then it is possible to estimate the focal spot size, *c*.

Let us now consider both left and right penumbras shown in Fig. 1. Again by the equivalence of triangles we have

$$(c + b_2)/F_c = (c + a_2 + p_R)/F \tag{10}$$

Solving for *c* it turns out that:

$$c = p_R/(M - 1) \tag{11}$$

This is another expression for the focal spot size estimation obtained from the right penumbra, p_R, and the magnification factor, *M*. The same argument can be used for the left penumbra, p_L. Considering the anode inclination the apparent focal spot is now c_L instead of *c* (Fig. 1). Due to the equivalence of triangles

$$(c_L + b_1)/F_c = (c_L + a_1 + p_L)/F \tag{12}$$

As above, this leads to another expression for the focal spot size:

$$c_L = p_L/(M - 1) \tag{13}$$

Let us point out that from Equations (11) and (13) both the