

# Calculation of Optimal Geometrical Magnification and Spatial Resolution of Betatron Tomograph

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**Abstract.** One of the perspective directions of development of non-destructive testing is the method of computed tomography. Computed tomography really enhances the ability of X-ray inspection, from thin and simple to thick and complex parts. There are many factors that influence the performance of computed tomography, the main parameters for computed tomography scanners and also scanner based on betatron, are geometric magnification and spatial resolution. Calculations of these parameters for the betatron tomograph are shown in this paper.

## 1. Introduction

Currently, X-ray tubes and linear accelerators are widely used as X-ray sources for industrial CT. Because of the low intensity, betatron is rarely used for industrial computed tomography (CT) [1], although it is widely used as a radiation source in the non-destructive testing [2-3] and successfully used in the inspection system [4]. Only in recent years, the company "PROMINTRO" and the Federal Research and Production Center "Altai" began to develop CT system with the use of betatron, the properties of which was improved and manufactured at the Institute of non-destructive testing of Tomsk Polytechnic University (INDT TPU). Advantages of betatron, if compares with linear accelerators with the same radiation energy, the cost of betatron is 3-4 times lower, and the focal spot size of betatron is much smaller.

Since the refine betatron characteristics were improved, so it become reality and possible to use betatron for industrial CT as a radiation source. Development of industrial CT based on betatron was carried out in "Russian-Chinese laboratory of radiation control and inspection" in cooperation with the Laboratory No. 42 (High Current Betatron) INDT TPU.

Betatron tomography system (Figure 1) consists of a betatron (X-ray source), the mechanical system, the detector, the control systems and the image reconstruction system.

## 2. Method of Calculation

The quality of a CT depends on several factors, the most important ones are the geometric magnification and spatial resolution. Spatial resolution refers to the ability of CT system to detect small details or contains of small features with respect to the reference point.

There are many factors that influence the spatial resolution of reconstructed images [5]: focal spot size of the x-ray source, detector characteristics, magnification, number of projections, reconstruction



algorithms and data processing method. Focal spot size plays a particularly important role in determining image quality and is one of the main factors limiting the spatial resolution [6]. CT systems therefore often classified by the focal spot size, and in our case, the betatron tomograph belongs to the macro-CT (the focal spot size 0.3 mm) [5].

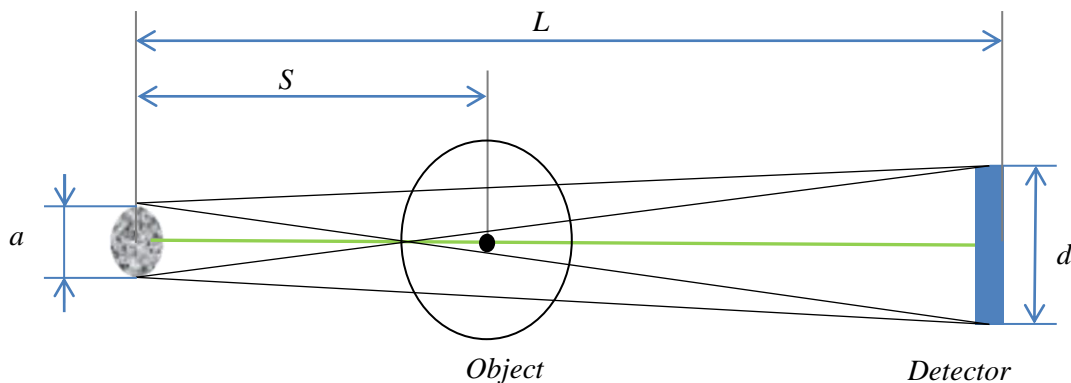


**Figure 1.** Betatron tomography system.

The calculation formula (1) was first proposed by Yester and Barnes [7] to determine the total unsharpness of the object. As later used to calculate the effective aperture [8], and then used to evaluating the spatial resolution in a given system [9]. We also apply this formula to determining the spatial resolution of betatron tomograph:

$$BW \cong \frac{\sqrt{d^2 + [a \cdot (M-1)]^2}}{M} \quad (1)$$

where  $BW$  is beam width, the major limitation on spatial resolution in a given CT system;  $a$  is focal spot size;  $d$  is detector aperture size;  $M$  is geometric magnification on the axis of rotation. The scanning scheme of a CT system is shown in Figure 2 [9-10], the geometric magnification  $M = L/S$  (where  $L$  is the distance from the radiation source to the detector,  $S$  is the distance from the radiation source to the axis of rotation).



**Figure 2.** Scanning scheme of CT system.

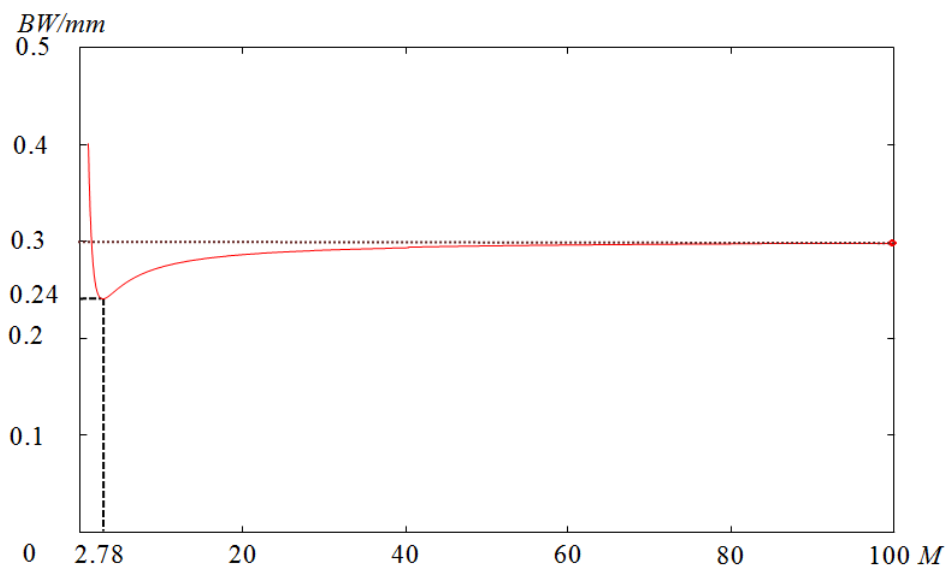
Detailed mathematical analysis of formula (1) was made by Chen J. [10], in his work, he converted formula (1) to expression (2):

$$BW = ((a^2 + d^2) \cdot \left( \frac{1}{M} - \frac{a^2}{a^2 + d^2} \right)^2 + \frac{a^2 \cdot d^2}{a^2 + d^2})^{\frac{1}{2}} \quad (2)$$

It is known that, as one kind of X-ray resource, betatron has the focal spot size of  $a = 0.3$  mm; and for betatron tomograph the detector aperture size  $d = 0.4$  mm. Substituting the values of  $a$  and  $d$  in expression (2), we obtained the dependence  $BW$  of  $M$  (3):

$$BW = (0.25 \cdot \left(\frac{1}{M} - 0.36\right)^2 + 0.058)^{\frac{1}{2}}, [\text{mm}] \quad (3)$$

With the help of Mathcad, we got a plot of the dependence  $BW$  of  $M$  ( $1 < M < 100$ ), shown in Figure 3.



**Figure 3.** Dependence  $BW$  of  $M$  with the use of betatron.

With the analysis of dependence  $BW$  of  $M$ , it is noticeable that with the increase of  $M$ , the value of  $BW$  decreases rapidly and reaches a minimum value  $BW = 0.24$  mm where  $M = 2.78$ . Then, with the increase of  $M$ , the value of  $BW$  increases and converges to a constant whose value is equal to the size of the focal spot.

### 3. Result and Discussion

Development of betatron tomography system isn't an easy task, the definition and evaluation of spatial resolution is only one of a number problems. Since the spatial resolution depends on many factors, so in the process of developing the betatron tomograph should find a compromise between these factors to ensure optimal performance.

During the development process of betatron tomograph, we use X-ray tube MXR-451HP/11 (Figure 1) with focal spot size  $a_1 = 1$  mm to make a comparative analysis. Substituting the values of  $a_1$  and  $d$  in expression (2), we got the relationship  $BW$  from the  $M$  (Figure 4).

It is noticeable that with the increase of  $M$ , the value of  $BW$  decreases rapidly and reaches a minimum value  $BW = 0.37$  mm where  $M = 1.14$ . Then, with the increase of  $M$ , the value of  $BW$  increases and converges to a constant whose value is equal to the size of the focal spot.

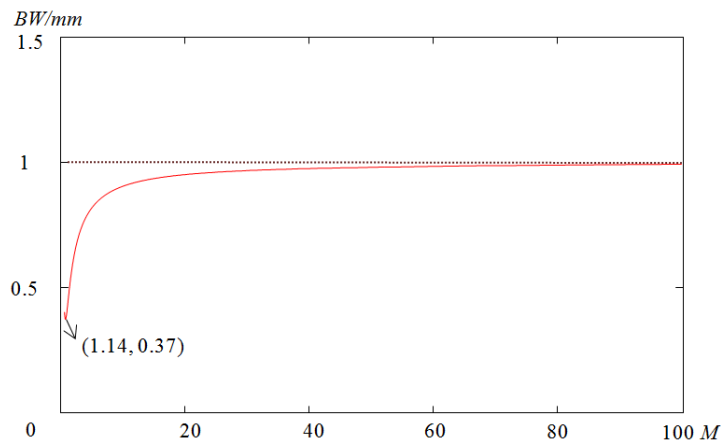
Further we analyzed the formula (2) with a mathematical method. We know that  $M$  is from 1 to  $\infty$ .

When  $M \rightarrow 1$ , the formula (2) has the form:

$$\lim_{M \rightarrow 1} BW = \left( (a^2 + d^2) \cdot \left( \frac{1}{M} - \frac{a^2}{a^2 + d^2} \right)^2 + \frac{a^2 \cdot d^2}{a^2 + d^2} \right)^{\frac{1}{2}} = d.$$

When  $M \rightarrow \infty$ , the formula (2) has the form:

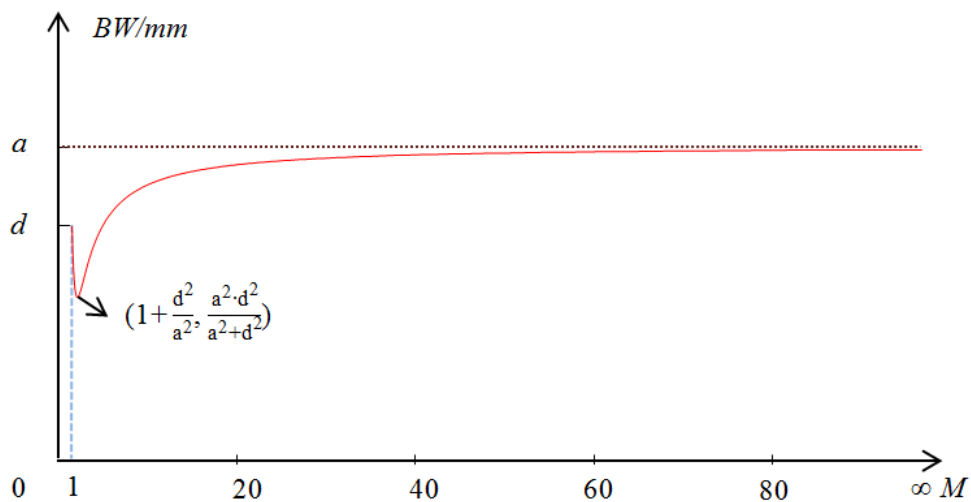
$$\lim_{M \rightarrow \infty} BW = \left( (a^2 + d^2) \cdot \left( \frac{1}{M} - \frac{a^2}{a^2 + d^2} \right)^2 + \frac{a^2 \cdot d^2}{a^2 + d^2} \right)^{\frac{1}{2}} = a.$$



**Figure 4.** Dependence  $BW$  of  $M$  with the use of X-ray tube.

The minimum value of  $BW$  is obtained by  $\frac{1}{M} - \frac{a^2}{a^2+d^2} = 0$ , which means  $M = 1 + \frac{d^2}{a^2}$ . Therefore we got the minimum value  $BW = \frac{a^2 \cdot d^2}{a^2 + d^2}$ . Then we got the dependence  $BW$  of  $M$  in Figure 5.

With the analysis of dependence  $BW$  of  $M$  in Figure 5, we can see that the initial value of  $BW$  with  $M = 1$  is equal to the detector aperture size  $d$ . Then with the increase of  $M$ , the value of  $BW$  decreases and reaches a minimum value of  $BW = \frac{a^2 \cdot d^2}{a^2 + d^2}$  mm where  $M = 1 + \frac{d^2}{a^2}$ . After that, with the increase of  $M$ , the value of  $BW$  increases and converges to a constant whose value is equal to the size of the focal spot  $a$ .



**Figure 5.** Dependence  $BW$  of  $M$ .

If we put the values of  $a$  and  $d$  that used above, we can also get the same results that were shown in Figure 3 and Figure 4. This work will be helpful for determining the geometric magnification and spatial resolution in the future. And it also helps to find the most suitable value  $M$  for a CT system in practice.

#### 4. Conclusions

Since the beam width  $BW$  is a major limitation on the spatial resolution of a CT system, it is possible to evaluate the spatial resolution of a CT system indirectly by evaluating the  $BW$ .

From the analysis of the dependence  $BW$  of  $M$ , we can make the following conclusions:

- $M = 2.78$  is theoretically the optimal magnification for betatron tomograph;

b) optimal spatial resolution can be obtained by  $BW = 0.24$  mm;

c) the geometric magnification  $M$ , used for betatron tomograph has a value of  $1 < M < 20$ .

The result of the calculation of  $M = 2.78$  enters the experimentally determined values of the interval  $M$ :  $1.5 < M < 3$ .

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