

# Focal Spot Size Estimation for a 4 MeV Small-size Betatron Using Digital X-ray Detector

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**Abstract.** One of the main advantages of small-size betatrons is small focal spot size. However there is no conventional procedure of focal spot size measurement for betatrons. Techniques described in standards are suitable only for low- and mid-energy tubes. The task become more complex if the focal spot size should be estimated quickly using modern digital detectors. In this paper we present preliminary results of focal spot size measurement of a 4 MeV small-size betatron with two different procedures using digital x-ray detector.

## 1. Introduction

A betatron is a pulsed induction electron accelerator. The first operable betatron was created by Donald W. Kerst in 1940, although patents describing devices based on similar principles had been published decades before [1]. The development of betatrons until reaching the energy up to about 300 MeV was of increasing interest. Then the high energy betatrons have been gradually supplanted by linacs. Nevertheless, low energy machines remain effective sources of hard X-rays used in non-destructive testing.

One of the most promising fields of application of the betatrons is high-energy X-ray computed tomography (CT). The main advantage of the betatrons in CT over the other types of hard X-rays sources is small focal spot size [2]. Obtaining the focal spot sizes within the limits of 200...300  $\mu\text{m}$  is possible because of the cyclic nature of betatrons that allows multiple interaction of the accelerated electron beam with a bremsstrahlung target mounted inside the acceleration chamber. In contrast with linacs, the size of the target can be reduced with minor effect on the radiation intensity.

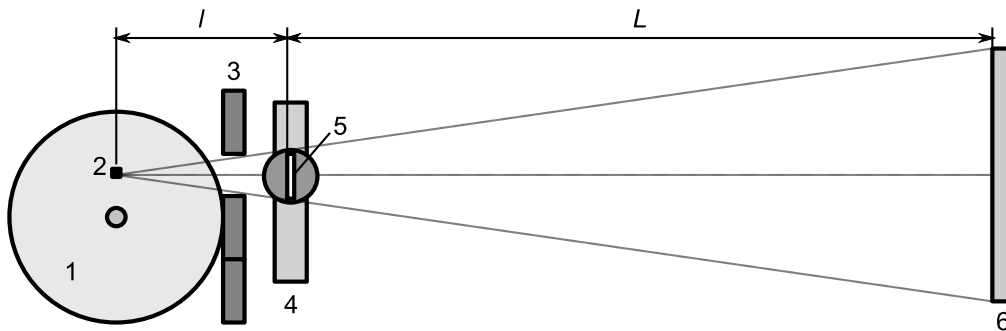
Focal spot size is one of the most significant parameters of the X-rays source for CT. However there is no conventional procedure of focal spot size measurement for betatrons. Techniques described in European Standard EN 12543 are applicable for x-ray tubes with voltage restricted to 500 kV. As well as Russian Standard GOST 22091.9–86 is suitable only for low- and mid-energy tubes. The task become more complex if the focal spot size should be estimated quickly using modern digital detectors.

The aim of this work is to present preliminary result of focal spot size measured of a 4 MeV small-size betatron with two different procedures using digital x-ray detector. The methods to be applied in the research are slit camera radiographic method and indirect method based on image unsharpness measurement using image quality indicator (IQI).



## 2. Experimental setup

The betatron (figure 1) used in the experiments is a small-size pulsed betatron MIB-4 with maximal bremsstrahlung energy 4 MeV and claimed focal spot size  $0.3 \times 3$  mm. Positioning was performed with a motorized positioning systems by PI GmbH & Co. KG.

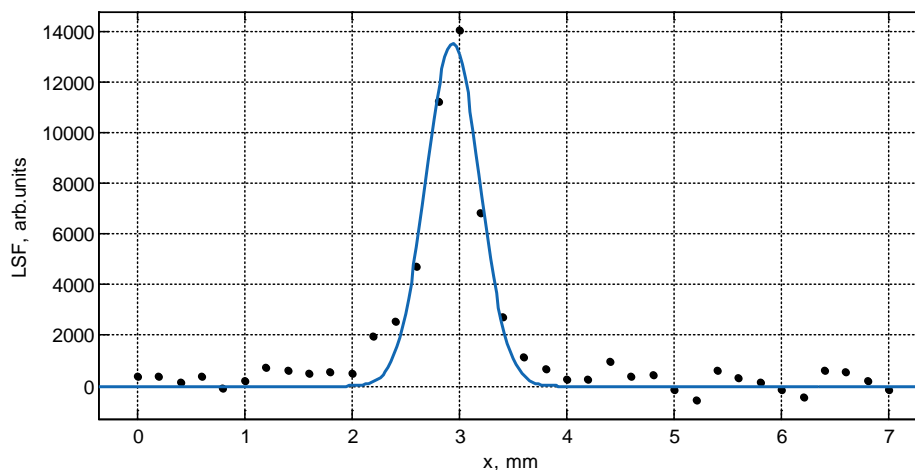


**Figure 1.** Experimental setup layout: 1 – betatron; 2 – tungsten target mount inside acceleration chamber; 3 – collimator; 4 – positioning system; 5 – test object; 6 – imaging system.

A digital X-ray detector Perkin Elmer XRD 1622 was used as the imaging system (figure 1). Total pixel number is  $2048 \times 2048$  with pitch  $200 \mu\text{m}$ . An important characteristic of the X-ray detector that must be taken into account and corrected is line spread function (LSF). Full width at half maximum (FWHM) of the X-ray beam  $FWHM_I$  can be found from the image obtained using the relation [3]:

$$FWHM_R = FWHM_I + FWHM_{LSF} \quad (1)$$

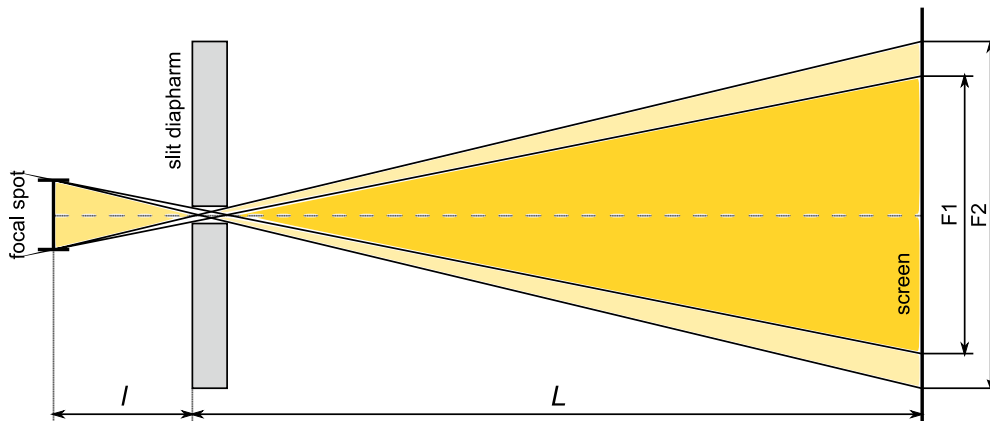
Where  $FWHM_R$  is FWHM of the obtained image and  $FWHM_{LSF}$  is FWHM of detector's LSF. Likewise it was done in [3] the LSF of the detector system was found by differentiation of the edge spread function (ESF) obtained by contact radiography of the test object with sharp edge. Gaussian approximation of the LSF is shown on figure 2.



**Figure 2.** Gaussian approximation of the LSF.  $FWHM_{LSF} = 0.6\text{mm}$ .

## 3. Slit camera method

Focal spot size measurement using pinhole and slit cameras is based on the camera obscura principle. Figure 3 indicates the common layout of the experimental setup used for this method.



**Figure 3.** Slit camera experiment layout.

In the ideal case the thickness of the edges is negligible small that is practically unachievable. Taking into consideration the finite slit camera thickness, intensity distribution shown on figure 2 can be introduced.  $F1$  and  $F2$  can be calculated through geometrical optics approach:

$$F1 = (f - d) \frac{2L + h}{2l - h} - d \quad (2)$$

$$F2 = (f + d) \frac{2L - h}{2l + h} + d \quad (3)$$

Where  $f$  is focal spot size,  $d$  is slit size,  $h$  is slit camera thickness.  $F1 - F2$  indicates the penumbra size. Influence of the finite slit camera thickness can be corrected by using the FWHM of the X-ray beam profile.

$$f = \frac{FWHM_l}{M - 1} - d \left( 1 - \frac{1}{M} \right) \quad (4)$$

$$M = \frac{L + l}{l} \quad (5)$$

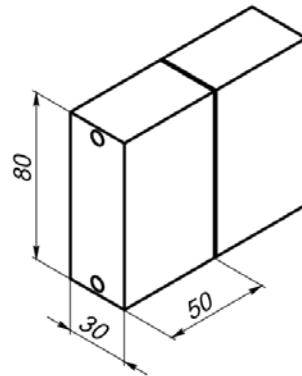
Setting  $h$  and  $d$  equal to 0 (thickness is negligible small) expressions can be transformed to the ideal case (no penumbra is observed):

$$F1 = F2 = f(M - 1) \quad (6)$$

Taking into consideration (2) and (3) one can figure out an expression for the edge thickness and slit size limits by solving the equation  $F1 - F2 = 0$ . The solution is as follows:

$$h_{max} = \frac{2dl}{f}; d_{min} = \frac{fh}{2l} \quad (7)$$

Using the expressions (7) as well as the expression for linear attenuation coefficient for the desired material of the slit camera one can evaluate boundaries for the geometrical size of the camera. Figure 4 indicates geometry of the steel diaphragm used in the experiment.

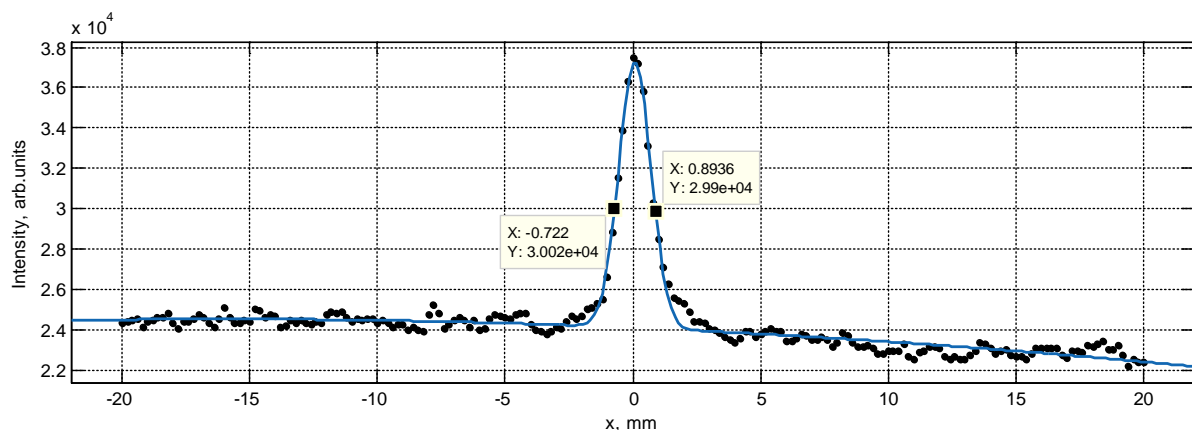


**Figure 4.** The camera with variable slit size used in the experiment.

The focal spot size (horizontal value) of the 4 MeV betatron is claimed to be  $f = 0.3$  mm. So assuming the distance  $l = 250$  mm (figure 1) and slit size  $d = 0.1$  mm one can make certain that the maximal slit camera thickness does not exceed the maximal value allowed. The slit camera is chosen to be made of steel because of simplicity of manufacturing.

In article [3] slit camera made of tungsten was used to measure the focal spot size of a 5 MeV linac. In comparison to the linac the betatron has lower radiation intensity as well as smaller spot size. It diminishes the requirements for slit camera material used in our experimental setup. Also usage of the digital X-ray detector in our experimental facility (figure 1) allows enhancing contrast of the images obtained in comparison of an X-ray film. However an experiment with tungsten-made slit camera is planned.

Profile of the image obtained with 100  $\mu\text{m}$  slit is shown on figure 5.



**Figure 5.** Slit camera image profile.

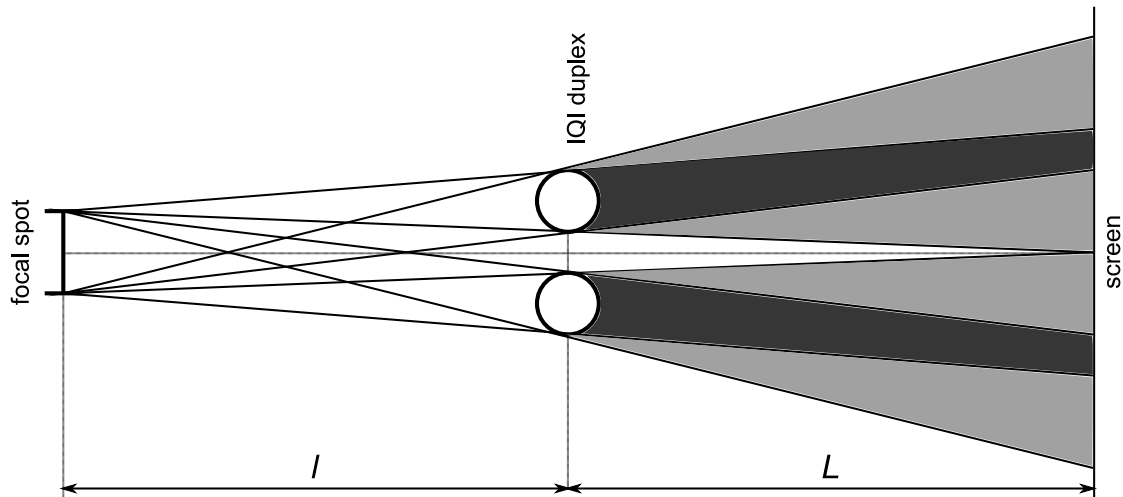
The focal spot size can be now found using (1) and (4) with following parameters:  $l = 250$  mm,  $L = 1000$  mm,  $M = 5$ ,  $d = 0.1$  mm. The evaluated value is  $f = 0.1738$  mm.

#### 4. Indirect measurement using IQI

The indirect method is based on relation between basic spatial resolution and focal spot size. Equation (8) taken from ASTM E 2698 [4]. It can be used for focal spot size assessment by measuring the basic spatial resolution  $SRb$  and image unsharpness  $U_i$ .

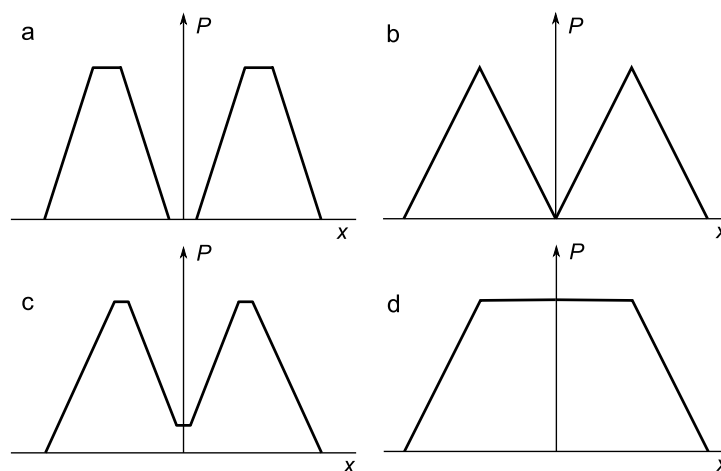
$$f = \frac{M}{M-1} \sqrt[3]{U_i^3 - \left(\frac{2.0}{M} SRb\right)^3} \quad (8)$$

One of the most widely used method for measurement of  $SRb$  and  $U_i$  uses duplex wire type IQI.



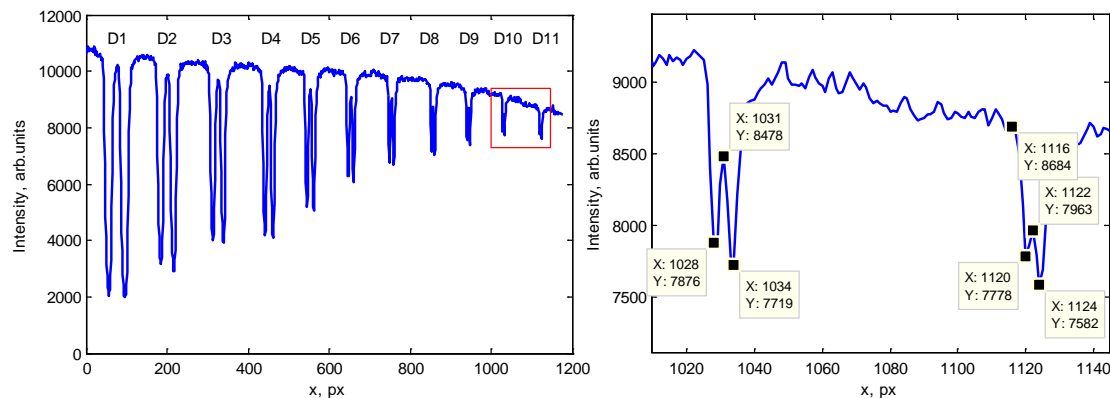
**Figure 6.** Duplex wire type IQI experiment layout.

The penumbra areas indicated on figure 6 merge when focal spot size  $f$  matches wire diameter and spacing  $D$ . Gray level profiles for various cases are shown on figure 7. Results of geometrical optics modeling provide an intuitive representation of the technique. But the relations are hardly to apply practically, by virtue of the fact that the wires are penetrable for the hard x-rays. Also probabilistic nature of interaction of radiation with matter as well as detector noises should be taken into account. For this reason a method based on spatial resolution measurement can be applied.



**Figure 7.** Gray level profile: a)  $f < D$ ; b)  $f = D$ ; c)  $f > D$ ; d)  $f = 2D$ .

Profiles of radiograph captured on the real experiment are shown on figure 8. The experiment is based on the layout presented on figure 1 with  $l = 245$  mm,  $L = 1045$  mm,  $M = 5.265$ .



**Figure 8.** Radiograph profile of duplex wire IQI.

Obtained radiograph can be used to assess a spatial resolution  $SRb$  and image unsharpness  $U_i$  by measurement of modulation depth (dip) for neighboring IQI wires. The results are shown in table 1.

**Table 1.** Results of dip measurement

IQI Element No	D8	D9	D10	D11	D12
Measured dip, %	75.9	73.39	52.35	28.36	0
Maximum Unsharpness, mm	0.32	0.26	0.20	0.16	0.125
Maximum Basic Spatial Resolution, mm	0.16	0.13	0.10	0.08	0.063

Finally the focal spot size can be found from (8) using  $SRb$  and  $U_i$  values for D11. The evaluated value is  $f = 0.1972$  mm.

## 5. Conclusion

Focal spot size of a 4 MeV betatron was measured using slit camera and resolution methods. The results of the experiments are very close and do not exceed claimed focal spot size 0.3 mm. However the presented results are coarse and have to be verified. Ways to get more accurate measurements are as follows:

- Use of the slit camera made of tungsten.
- Precise measurement of the LSF of the imaging system.
- Reiteration of the experiments using different detectors to collect statistics.
- Monte-Carlo simulation of the experiment to obtain extra data.
- Use of a betatron with a changeable bremsstrahlung target.

## References

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- [4] Bavendiek K, Ewert U, Riedo A, Heike U and Zscherpel U (2012) New Measurement Methods of Focal Spot Size and Shape of X-ray Tubes in Digital Radiological Applications in Comparison to Current Standards *18th World Conf. Nondestruct. Test.* 16–20