Investigation of micro-focus X-ray tube for radiography.

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ABSTRACT

The radiography with micro focus x-ray tube is very promising for use in non-destructive industrial control, medical and biological x-ray imaging. We investigated a micro focus x-ray tube with hollow anode to find the smallest available focal spot sizes under the different values of the X-ray tube load. The electron beam focusing system of the x-ray tube was designed with the use of the deflection-coil assemblies and a short focusing lens. Under varying the tube power load from 20W to 70W we found that the X-ray focal spot size (full width at half maximum-FWHM) is changed from 25 μm to 54 μm. The methods of focal spot size measurements are shortly described. Examples of radiographic images of the pair-line object target (phantom CIRS 11A) are presented. The phantom study showed the resolving power 18 pl/mm÷20 pl/mm. Practical applications of the developed X-ray apparatus are discussed in the report.

Key words: Kumakhov's lens, x-ray tube, focal spot size, direct magnification mammography, nondestructive testing.

INTRODUCTION

Recent development X-ray equipment for cone-beam X-ray micro-tomography [1], macromolecular crystallography [2], magnification mammography [3-5], high resolution X-ray computed tomography [6] and phase-contrast imaging needs the X-ray sources with minimal size of focal spots and maximal power load, as it is possible. Besides, micro focus X-ray tubes with capillary Kumakhov's lenses are very promising for the use in X-ray fluorescence analysis, X-ray microscopy and diffraction facilities.

A micro-focus X-ray tube with the size of focal spots 0.02÷0.1mm with power tube load from 40W up to 200W seems suitable for solving these modern tasks. Some aspects of developing these X-ray generators are considered bellow.

2. METHODS AND SET UP

The measurements of the focal spot sizes were performed in accordance with recommendations of the Russian Standard [7] and the European (British) Standard [8, 9]. These methods are based on indirect measurements of the focal spot size by measuring the geometric un-sharpness. Such un-sharpness is the result of the combination of the x-ray source intensity distribution and the source to object (R_0) and object to detector (R_1) distances. This combination causes a blurring of the x-ray pattern because of penumbra effects. For this purpose sharp edges of the wire (ball) test object are registered by means of the CCD- camera. The test object was a set of tungsten wires having diameters: 0.1mm, 0.2mm, and 0.3mm with the diameter accuracy of ±5%. The test object with such wire diameters allowed us to use both the edge and wire methods of the focal spot size measurements. The distances R_0 and R_1 can be installed in accordance with standards. The distances R_0 and R_1 allowed the projective magnification (M) between x5 and x30. The wire diameters were at least three times more than the focal spot size, f, and the minimal distance R_0 was at least five times the wire diameter, d in

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accordance with the standards. The expected accuracy of the focal spot size measurements can be about ±30% for the wire and edge methods (i.e. no more than it is declared in the Russian Standard).

Besides the wire test–object, we used tissue equivalent mammography phantom[10] (model 11A; 4.5 cm of thickness). The use of the phantom was caused by the two objectives in mind. First, the study of the phantom radiographs could give a good example of practical application of the developed X-ray apparatus in the fields of a conventional mammography screening and in a direct magnification mammography. Second, the phantom contains the certified 'line pair test target' with 5 to 20 pair lines per millimeter [pl/mm]. On observing the resolved elements of the line pairs of the target we can give any conclusion about the X-ray apparatus quality. Under conducting these experiments we used MIN-R-/L/S mammography film-screen systems. Although, the typical limiting resolution values for mammography screen-film combinations varies from 15 lp/mm to 20 lp/mm (according to the work [11]), we have used these detectors as a first step of the quantity examination of the developed X-ray unit. The final images of the resolving power of the line pair target were obtained by the use of the scanner UMAX-2400 with resolution 2400 dot per inch. In addition, under the phantom irradiation study we measured the entrance surface dose by using the thermo-luminescent dosimeters (TLD). It permitted us to estimate the entrance surface dose and to check the uniformity of the X-ray field at the entrance and at the exit of the phantom. For it 13 pieces of TLD's were placed before the phantom and 11 pieces of TLD's were situated behind the phantom.

The CCD camera from the Photonic Science was used as "on –line" X-ray detector for the focal spot sizes measurements. The two-dimensional images of W-wires were stored, and the treatment was performed according to our approach of the focal spot size estimation (see this issue). The CCD-camera has the spatial resolution about ~0.02 mm (~1000x1300 pixels with 6.5 microns pixel size) and the dynamic range of ~2000. The thickness of the entrance scintillator layer of oxy sulphide gadolinium is optimized for working in the X-ray energy range from 6 keV to 30 keV.

The experimental X-ray apparatus is shown in Fig.1. It consists of the generator housing, an x-ray tube, the magnetic lenses, a water cooling system, and a collimator. The x-ray unit was mounted on the goniometer, the test – objects (W-wires and the phantom) and the CCD-camera were installed on the stages, which could move along the rail and securely can be locked in any position. A simple radiation protection sheets were used for safety.

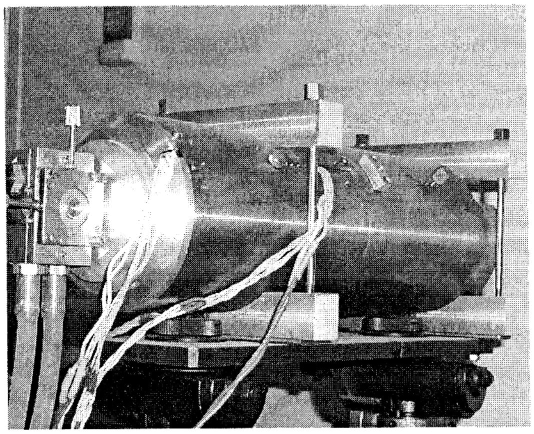

Fig.1. Photograph of the X-ray generator. It consists of the generator housing, the x-ray tube with outrigger target, the magnetic lenses (deflection-coil assemblies and the short focusing lens), a water cooling system, and a collimator. Angle between electron beam and the anode of X-ray tube (the plane of actual focal spot) is 45°. Angle between electron beam and central ray is 90°. The high voltage supplier can be running in the range from 5 kV to 50kV. The output current is up to 3mA. The stability of the high tube voltage is ±0.01% / hour. The built-in test amperemeters and voltmeter allow us to measure the values the cathode current(I_C), the tube current (I), the high tube voltage (U), and the magnetic lenses current (I_L) with an accuracy ±5%.

3. MEASUREMENTS AND RESULTS

The shape of an x-ray tube focal spot intensity distribution is usually complicated and varies with many parameters such as the tube current and the tube voltage and so on. In this study, we assume, that the shape of the X-ray tube focal spot is the round and the intensity distribution of emitted X-rays follows the Gauss distribution with the full width at half maximum (FWHM): $f^{\wedge}=2.36\cdot f_G$, where f_G represents the Gauss intensity distribution parameter. Here $f^{\wedge}$ is the estimate of focal spot size. In our approach, it is possible to obtain values of $f^{\wedge}$ by using both the edge and wire methods simultaneously. To do it we should measured the intensity profile in the full region of the W-wire image.

The results of the measurements of the focal spot size versus the tube power load are shown in Fig. 2. The x-ray tube with Mo-target was running at 38 kV high tube voltage, and the tube current was ranging from 0.6mA to 1.9mA Dependence of the focal spot size on the tube power load was measured by means of varying the tube current under constant the high tube voltage. Values of the tube current and the high tube voltage were measured indirectly by means of built-in devices with an accuracy of ±5%, as it is declared by manufacturer of the high voltage supplier. Under conducting these experiments, a fine electron beam focusing methods were used to find the minimal focal spot size for every chosen values of the tube current and the high tube voltage. The focusing system includes manual operations for installation of the cathode current(I_C), the tube current (I), the high tube voltage (U), and the magnetic lenses current (I_L) in a small range of the changing of the nominal values (less than ±10%). The curves denoted as 'Max' and 'Min' represent a small deviation of the measured focal sizes (±10%) which is produced by using manual fine tuning of the values I_C, I, U and I_L in the range of their changing within ±10% (from their nominal values). Compare our results with the known empirical Flynn's law [1] we conclude that we have the X-ray tube power load density two times higher than it was given by the Flynn's law. Although, the result of this comparison is preliminary one because of the Flynn's law describes low power load (no more than ~10 W), in the further study we are going to find appropriate approximation of the focal spot size dependence on the power tube load. Then it will be possible give correct compare, we hope.

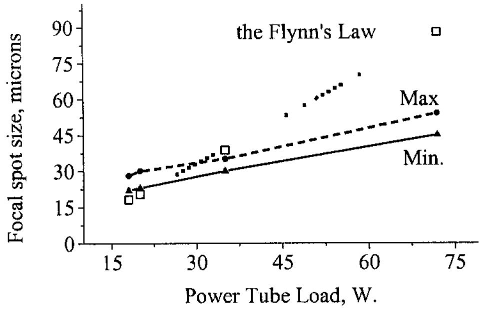

Fig.2. Dependence of the measured focal spot sizes on tube power loading. The focal spot sizes are varying from 0.025mm to 0.054mm under the changing of the tube power load from 20W to 70W (U=38kV, Mo-target).
The Flynn's law declares[1], that maximal power tube load (P) is proportional to focus spot size (f^): $P=1.4\ (f^{\wedge})^{0.88}$, where the respective units are in [W] and [μm].
The curves denoted as 'Max' and 'Min' represent a small deviation of the measured focal size (±10%) which is produced by manual fine tuning of the values I_C, I, U and I_L in the range of their changing within ±10% (from nominal values).

For illustration of the practical application of the developed X-ray unit we performed the full-field phantom irradiation study to obtain the resolving power of pair line target for the developed X-ray unit and the required dose for it. The X-ray tube with Mo-target was running at 30 kV high tube voltage, and the tube current was 2mA. Kodak MIN-R-S/L mammography film-screen systems were used as x-ray detectors. The line pair test target of the phantom CIRS 11A (the last has dimensions 9x18 cm and thickness of 4.5cm) was used as the test resolving power object, which is situated on the edge of the phantom at the distance of ~ 6cm from the center of the phantom. The distance R_0 was 20cm, and distance R_1 can be changed from 16cm to zero value. The choice of distance R_0 and R_1 was caused by two objectives. First, for the developed X-ray unit the maximum available diameter of the X-ray field is 18cm under the distance 20cm from the focus. So, the minimal value of R_0 can be no more than 20cm. Second, due to the air gap between the phantom and the detector, the level of the scattered radiation (emerging from the phantom) can be significantly reduced and thus a better quantity of the pair line target image we could have [12]. In a conventional mammography, to minimize geometrical blurring, the values f^ and R_1 should be minimized, whereas R_0 should be maximized. In our experiment we have used both the minimal distances R_0 and R_1 to demonstrate possibilities of the developed X-ray unit. The results are illustrated in Fig. 3 (R_0 =20cm; R_1=16cm) and Fig. 4 (R_0 =20cm; $R_1 \approx 0$cm). It is clear seen from the radiograph image of the line pair test object (Fig. 3.), that the resolving power is 19 pl/mm÷20 pl/mm. For compare purposes, note that for conventional clinical mammography units upper limit of the resolving power is ranged from 13 pl/mm to 16 pl/mm as it had been investigated by J. Law for 28 mammography X-ray sets in the UK [13]. In addition, by using the developed X-ray unit, the resolving power 17 pl/mm ÷19 pl/mm is obtained without any air gap (Fig. 4) under the radiation exposure time ~2 seconds (the exposure load ~ 4 mA·sec). The entrance dose under this study was measured by TLD dosimeters, and it was ~ 6 mGy/sec (the average value for the central part of the phantom: 'optical density reference zone').

For compare of the developed X-ray unit power load with a conventional mammography unit power load, we obtained radiograph of the CIRS-phantom by using the mammography unit MD-PA [14] (Russia) and found that the resolving power of the mammography unit (MD-PA plus MIN-RS system) was from 16 pl/mm to 17 pl/mm under the following experimental conditions: $R_0 \approx 54$cm; $R_1 \approx 1$cm; 30 kV high tube voltage; Mo-target (30μm Mo filter); the exposure load ~

28 mA·sec. Taking into account the used distances R_0 for both examinations we can conclude that the needed tube power to produce the radiograph images of the same resolving power can be ~ 5 times lesser in the case of using the proposed X-ray unit.

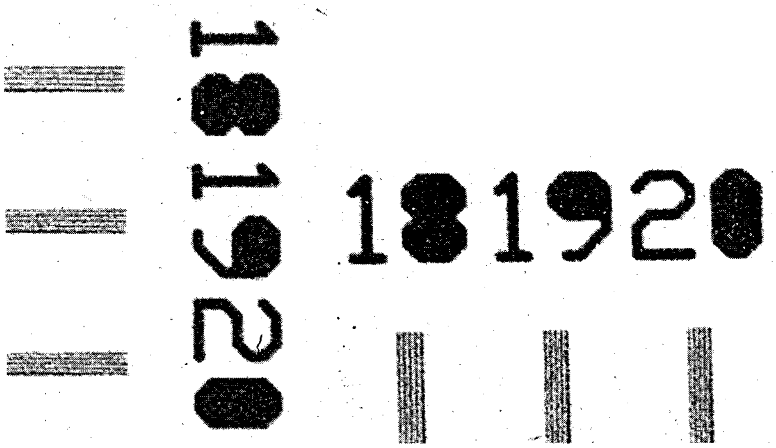

Fig.3. Radiograph of the line pair test target of the phantom CIRS. Radiographs are taken in two perpendicular directions The source to the object distance was R_0= 20cm, the object to the detector distance was R_1= 16cm.

For the proposed X-ray unit the resolving power is 19 pl/mm ÷20 pl/mm, as it is clear seen.

For conventional mammography X-ray units the resolving power is 13 pl/mm ÷16 pl/mm as it was reported [13].

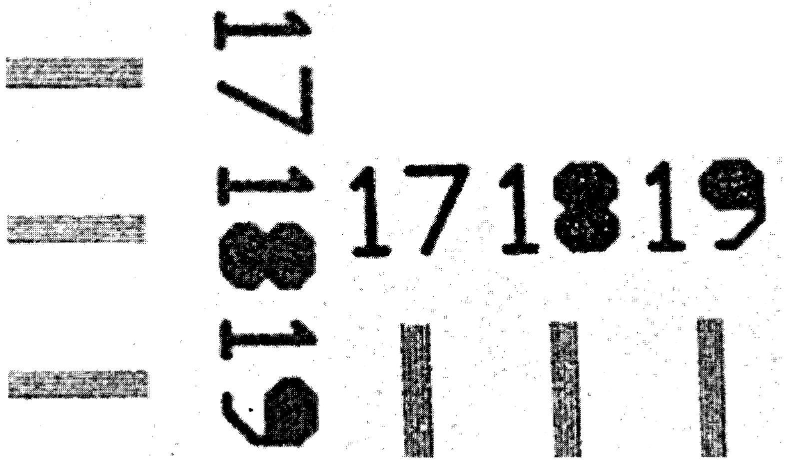

Fig.4. Radiograph of the line pair test target of the phantom CIRS. Radiographs are taken in two perpendicular directions The source to the object distance was R_0= 20cm, the object to the detector distance was $R_1 \approx 0$cm (no air gap).

In conventional mammography, to minimize geometrical blurring, the distance R_0 should be maximized. In our case, it is possible to have a high resolving power under short the source to the object distance, R_0= 20cm.

For the proposed X-ray unit the resolving power is 17 pl/mm ÷19 pl/mm, as it can be clear seen.

CONCLUSIONS

We have developed the magnetically focused electron beam system for the X-ray tubes with the hole anode. It was shown that the measured size of focal spot for the proposed X-ray apparatus is ranging from 25μm to 54μm under power loadranging from 20W to 70W (38kV high tube voltage; Mo-target).

It is promising result encourage us for further work at the prototype of the powerful micro focus X-ray source for radiography. These can include 1)-conducting the measurements: the X-ray field uniformity measurements, the X-ray yield measurements, the thermal stability investigation, and the phantom study (including discovering micro calcifications, round cancer masses and fibrils) and 2)-changing of the X-ray unit design: creation of a new focusing system, the enhancement of a power tube load to 200 W and up, development of the cooling system and so on.

The developed X-ray unit has a lot of applications including imaging thin industrial parts and light materials, plastics, ceramics, composite materials, mammography and radiography.

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