Nuclear Instruments and Methods in Physics Research A 853 (2017) 70–77

Contents lists available at ScienceDirect

Nuclear Instruments and Methods in Physics Research A

journal homepage: www.elsevier.com/locate/nima

Characterization of continuous and pulsed emission modes of a hybrid micro focus x-ray source for medical imaging applications

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ARTICLE INFO

Keywords:
Pulsed beam emission
Spatial resolution
Beam quality
Continuous beam

ABSTRACT

The aim of this study was to quantitatively characterize a micro focus x-ray tube that can operate in both continuous and pulsed emission modes. The micro focus x-ray source (Model L9181-06, Hamamatsu Photonics, Japan) has a varying focal spot size ranging from 16 µm to 50 µm as the source output power changes from 10 to 39 W. We measured the source output, beam quality, focal spot sizes, kV accuracy, spectra shapes and spatial resolution. Source output was measured using an ionization chamber for various tube voltages (kVs) with varying current (µA) and distances. The beam quality was measured in terms of half value layer (HVL), kV accuracy was measured with a non-invasive kV meter, and the spectra was measured using a compact integrated spectrometer system. The focal spot sizes were measured using a slit method with a CCD detector with a pixel pitch of 22 µm. The spatial resolution was quantitatively measured using the slit method with a CMOS flat panel detector with a 50 µm pixel pitch, and compared to the qualitative results obtained by imaging a contrast bar pattern. The focal spot sizes in the vertical direction were smaller than that of the horizontal direction, the impact of which was visible when comparing the spatial resolution values. Our analyses revealed that both emission modes yield comparable imaging performances in terms of beam quality, spectra shape and spatial resolution effects. There were no significantly large differences, thus providing the motivation for future studies to design and develop stable and robust cone beam imaging systems for various diagnostic applications.

1. Introduction

Non-Destructive imaging (NDI) comprises a wide group of analytical techniques used in medical science and industry to evaluate the properties of an organ, tissue, material, component or system without causing damage [1–4]. Common NDI methods include micro computed tomography (micro-CT), digital radiography, optical imaging, penetrating liquids, vibration analyses, infrared thermography, acoustic emission analyses, and ultrasonic imaging, among others [4]. Modern x-ray based NDI systems are used in the preclinical and clinical environments for tumor detection and its monitoring, and investigation on the effectiveness of drugs in disease treatment [5–8]. One of the key component of modern x-ray NDI systems is the x-ray source that generates an x-ray beam for illuminating the sample for imaging purposes. Micro focus x-ray sources have been frequently used in the micro computed tomography (micro-CT) and specimen radiology for high resolution and high throughput imaging of small animals and specimens in the preclinical and clinical environments [9–15]. The small focal spot sizes of these sources allow to effectively utilize the magnification geometry which is not possible with the conventional sources due to the blurring associated with their large focal spot sizes. An emerging field that has become a hot research area in the past decade is the phase contrast imaging (PCI). One PCI method that works relatively well with polychromatic x-ray sources is the in-line or propagation-based imaging [16–18]. For exhibiting in-line PCI, the polychromatic x-ray wave illuminating the sample/tissue should be partially coherent which is characterized in terms of lateral coherence length given as $L_\perp = \lambda R/s$ [18–20], where λ is the wave length of the x-ray wave, R is the source-sample distance and s is the focal spot size of the source. Micro-focus x-ray tubes operated with sufficient source to object distances (SODs) can provide relatively large transverse coherent lengths and are frequently used for the implementation of in-line PCI [21–24]. One of the main reason that is limiting the wide use of micro focus x-ray sources in the patient imaging is the long exposure

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http://dx.doi.org/10.1016/j.nima.2017.02.030
Received 10 October 2016; Received in revised form 5 February 2017; Accepted 12 February 2017

time associated with them to acquire a scan due to their limited output powers. Nevertheless, the technological developments have encouraged the design of new inline PCI set-ups which have permitted to extend the range of applications towards higher x-ray energies [25–27]. Numerous studies have implemented the in-line phase contrast tomosynthesis with micro-focus x-ray sources in preclinical studies with breast tissue samples, fish bone, mouse and rabbit lungs [28–30].

The micro focus x-ray sources used in the mentioned modalities operate in a continuous mode that emits x-rays constantly during its operation, and the x-ray detector records the spatially modulated wave emerging from an object/sample. Continuous emission sources utilize thermionic or field emission cathodes for the emission of electrons. Pulsed x-ray diagnostics and inspection are potentially capable of reducing the radiation dose considerably. Generating x-rays as a sequence of short flashes instead of continuous radiation is a distinguishing feature of the pulse x-ray source. Pulsed x-ray sources are commonly used in diagnostic imaging such as breast and lung screening. They provide the advantage of removing the shutter commonly utilized in breast tomosynthesis and cone beam breast CTs to block the x-rays during the source movement from one acquisition angle to the next, which avoids issues with image blur.

In this study, we aim to characterize a micro focus x-ray source that operates in both continuous and pulsed emission modes. For translating this hybrid micro focus x-ray source for advanced applications such as specimen radiography, tomosynthesis and cone beam breast CTs, it is vital to quantify its core performances in the projection imaging mode. This report is intended to provide a future baseline for the developers and scientists using hybrid x-ray sources for the development of efficient high resolution imaging modalities. To the best of our knowledge, this is the first detailed evaluation report of the continuous and pulsed emission modes of a hybrid micro focus x-ray source.

2. Hybrid micro focus x-ray source

The micro focus x-ray source (Model L9181-06, Hamamatsu Photonics, Japan) is referred to as Hybrid due to the fact that it operates in both continuous beam and pulsed emission modes. The continuous emission mode operates with tube voltage and tube current ranging from 40 kV to 130 kV and 10–300 μA. The guaranteed x-ray tube voltage and current range in the pulsed emission mode is 80–130 kV and 50–300 μA. The target material (anode) of the source is tungsten (W) and the x-ray output window material is Beryllium (Be) with a thickness of 500 μm. The source has varying focal spot sizes ranging from 16 μm to 50 μm depending on its output power (W), which is the product of the source output voltage and current. The focal spot to output window distance (FOD) is 13 mm while the x-ray beam angle is approximately 100°, as shown in Fig. 1(a). In the pulsed emission mode, the source self-emits the x-ray beam at a frequency of 1.67 Hz, which corresponds to a pulse duration of 600 msec. The 50% duty cycle of the pulse ensures on and off times of 300 msec as depicted in Fig. 1(b). During the off time, the current (μA) drops to zero while the tube voltage (kV) remains at the preset value. During the on time, the current ramps up to the preset value allowing the x-ray emission to occur. The source can be synchronized to an external signal generator which allows to adjust the pulse width, duration and frequency in accordance to the 5 V input square wave signal that the source would receive. The source has a full duplex serial interface communication method via RS-232 cable at 38400 bits per second data transfer speed. The physical dimensions (W×H×D) of the source are 167 mm×319 mm×172 mm, with a weight of approximately 10 kg.

3. Characterization of the source

After successfully installing the x-ray source on an optical rail, it is very important to characterize and monitor the source in both continuous and pulse emission modes on an ongoing basis to ensure reliable performance. Pulse emission mode was characterized with its self-running frequency (f) of 1.67 Hz with a pulse duration of 600 msec. This ongoing and periodic evaluation will help to detect changes that may result in a clinically significant degradation in the image quality or a significant increase in radiation exposure. This characterization will provide a baseline for future evaluations and comparisons. The source output, beam quality, focal spot measurements, kV accuracy, spectrum analyses and spatial resolution were measured in this study.

4. Continuous emission mode results

4.1. Source output

We utilized an air filled ionization chamber (Model 9095, Radcal Corporation, CA, USA) for the measurement of the source output for various tube voltage (kVp) values. The source output was measured with the ionization chamber placed at 100 cm away from the x-ray focal spot as per the guidelines of the American Association of Physicists in Medicine (AAPM) [31–33]. The current varied from 50 μA–300 μA and the relationship between the current (μA) and exposure rate (mR/min) for various kV values are plotted in Fig. 2. The curves are fitted to the linear equation: $y=mx+c$. One can see that the exposure in the continuous emission mode linearly increases ($R^2=1$) as the current increases.

The source output measured in the beamline with an ionization chamber placed at source to image distances (SIDs) of 50 cm, 100 cm and 150 cm under various kVs. The exposure values were fitted to $y=k.x^{-2}$, where y is the exposure rate, x is distance (cm) and k is a constant. From Fig. 3(a), one can see that the output exposure values

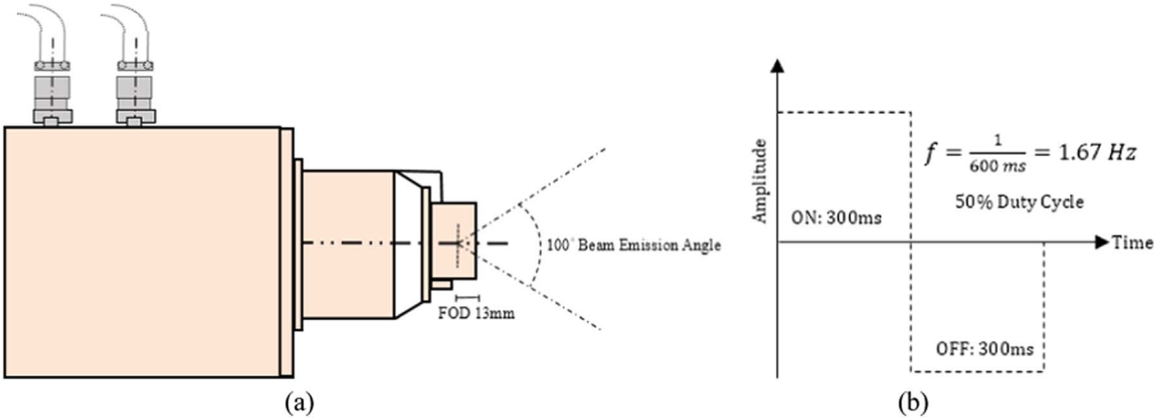

Fig. 1. (a) The schematics of the L9181-06 x-ray source (b) Self-running pulsed emission mode operating a frequency (f) of 1.67 Hz.