Title: Stationary digital breast tomosynthesis with distributed field emission X-ray tube

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ABSTRACT

Tomosynthesis requires projection images from different viewing angles. Using a distributed x-ray source this can be achieved without mechanical motion of the source with the potential for faster image acquisition speed. A distributed x-ray tube has been designed and manufactured specifically for breast tomosynthesis. The x-ray tube consists of 31 field emission x-ray sources with an angular range of 30°. The total dose is up to 100mAs with an energy range between 27 and 45 kVp. We discuss the source geometry and results from the characterization of the first prototype. The x-ray tube uses field emission cathodes based on carbon nanotubes (CNT) as electron source. Prior to the manufacturing of the sealed x-ray tube extensive testing on the field emission cathodes has been performed to verify the requirements for commercial tomosynthesis systems in terms of emission current, focal spot size and tube lifetime.

Keywords: tomosynthesis, field emission, CNT, distributed sources, x-ray, mammography, breast imaging

1. INTRODUCTION

Digital breast tomosynthesis (DBT) systems have undergone a rapid development in recent years. The scan speed has been increased significantly to allow the reduction of patient induced motion blur [1][2]. The high scanning speed requires powerful x-ray tubes that need to provide high currents at a short pulse length. A possibility to avoid the motion blur is the step-and-shoot technique where the tube is stopped during the acquisition of the individual projection. This method bears the risk of vibration induced artifacts from the repeated acceleration and deceleration of the moving source [3]. Stationary digital breast tomosynthesis (sDBT) systems do not suffer from these requirements. The x-ray source in an sDBT system is completely stationary and the pulses from different viewing angles can be fired in a rapid sequence. Work on stationary sources from our group has been reported earlier [4][5]. In this paper we present a completely sealed stationary x-ray tube for mammography based on carbon nanotube (CNT) field emission electron sources. CNT field emitters provide electron beams with sufficient current and good stability for medical imaging applications. They are especially suited for distributed sources that contain a large number of individual electron sources in a common vacuum housing. The CNT technology offers a flexible source design combined with excellent controllability of the x-ray output. The electron beam is generated by applying an extraction voltage between the CNT cathode and a gate electrode (the principle cathode geometry is shown in Figure 1)[6]. Behind the gate, electrodes focus the electron beam onto the x-ray target. For sDBT systems the array size and number of sources can be tailored to the required viewing angle and desired number of projection views. Different imaging modes are possible by using only subsets of the electron sources. This allows e.g. wide angle scans at high speeds.

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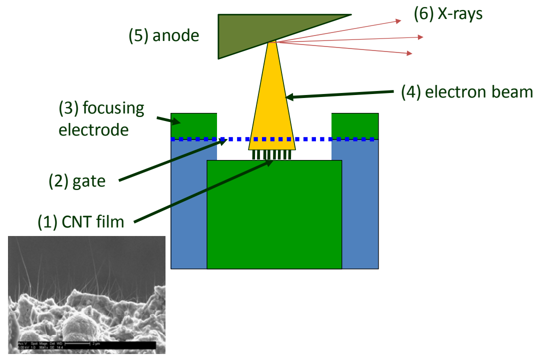


Figure 1: Principle CNT field emission source. Electrons are extracted from the CNT film (1) by the electric field between the cathode and the gate (2).

2. METHOD

The geometry that was chosen for the stationary x-ray tube is shown in Figure 2. A total number of 31 field emission cathodes with an equiangular separation of 1° (total scan angle of 30°) are installed in the tube housing. The center source to detector distance is 70cm and the center source to isocenter distance is 65cm (off-center sources are further away from the detector because of the linear geometry). Figure 3 shows a picture of the fully assembled x-ray tube. The tube housing contains an extended anode plate with 31 individual tungsten targets and a two-stage active focusing assembly for electron beam focusing. In the picture one can see the main housing components consisting of the HV feedthrough for the anode voltage input, two ion getter pumps that allow the monitoring of the pressure inside the tube, and the large x-ray window made from Aluminum. Mounting brackets for mechanical installation of the tube and for the mounting of the collimator are also shown. The backside opposite to the x-ray window (not shown) contains the electrical feedthroughs (type MHV) for the cathodes and for the focus electrodes.

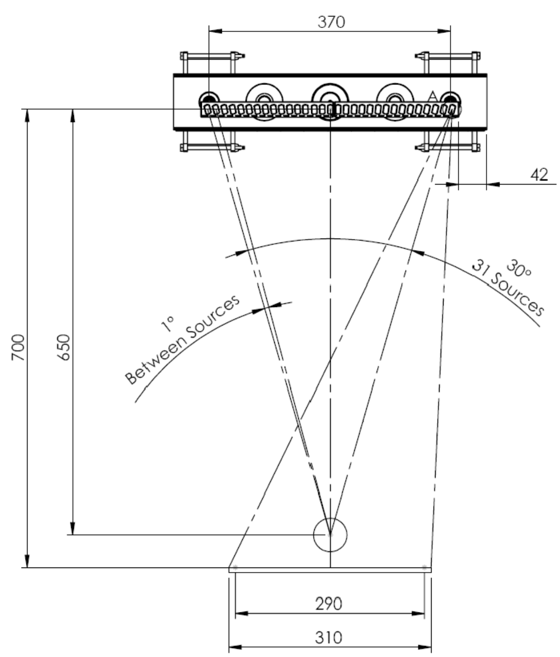


Figure 2: Geometry of the sDBT x-ray tube (all dimensions in mm). 31 cathodes are separated by 1º at 650mm from the isocenter. The source to detector distance is 700mm.

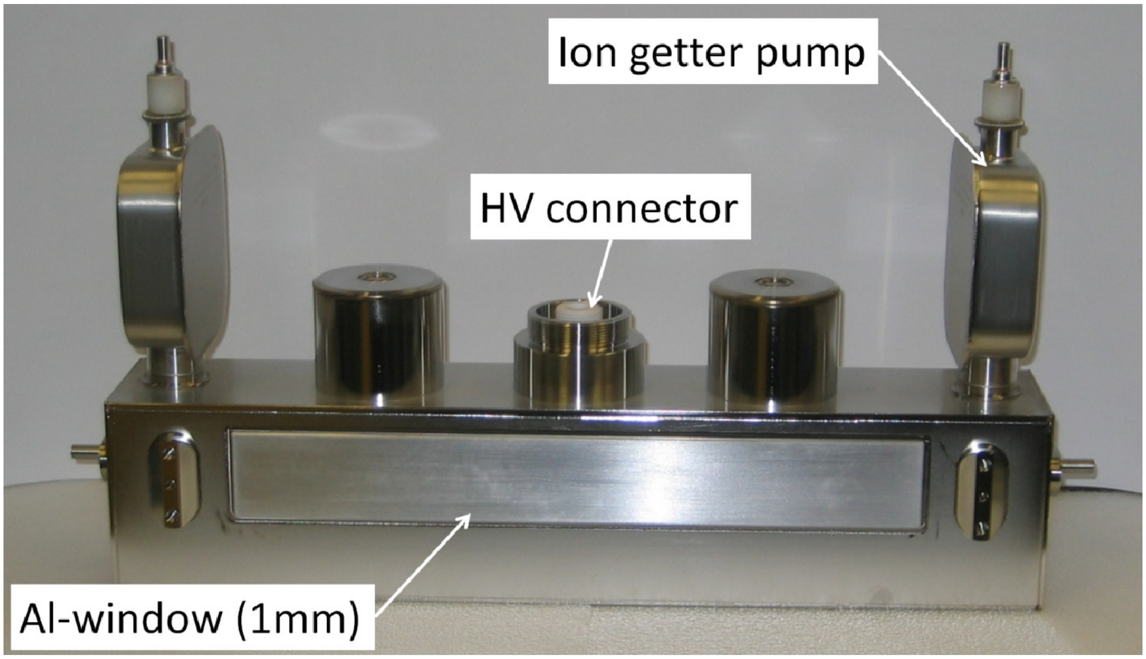


Figure 3: Overview sealed x-ray tube for sDBT. Stainless steel housing with 1mm Aluminum x-ray window. Ion getter pumps allow monitoring the pressure inside the tube.

The tube was designed to provide similar scan modes as conventional moving source systems. The maximum dose from one cathode is 6.5mAs with a maximum anode voltage of 45kV. The target material is tungsten in combination with a 1mm Aluminum filtration from the x-ray window. Additional filters and collimators can be installed on the tube housing. The anode angle measured perpendicular to the electron beam direction is 16°.

The individually addressable cathodes allow for a great flexibility in the scan mode. All cathodes can be fired in a sequence or any smaller subset can be selected. This makes large angle scans at high speed possible. The maximum pulse length per cathode is 250ms (see Figure 4), shorter pulses are possible. The scan time for 16 cathodes with the maximum pulse length amounts to 4s plus detector readout time (total dose of 104mAs). For a reduced dose with a 125ms pulse length the time is reduced to 2s plus detector readout. The source in combination with a fast high resolution detector will allow scan speeds that are not possible with conventional moving source systems. The fastest systems today are able to do a small angle scan of 16° in a little under 4s [1]. However, the moving source systems suffer from motion blur due to the fast x-ray source motion. The x-ray pulse has to be kept very short in order to avoid blurring of the focal spot. Initially small focal spots of well below 1mm are smeared out to 1-2 mm (depending on the scan mode). The stationary tube however, maintains the same focal spot size at all scan configurations.

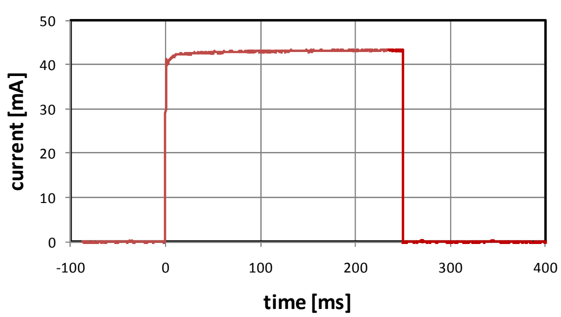


Figure 4: Pulse shape of the cathode emission current, 250ms pulse with 43mA emission current.

3. EXPERIMENTAL RESULTS

During the development phase of the x-ray tube extensive cathode testing was performed. All of the testing was done in a vacuum chamber with cathode test modules similar to the cathode module used in the final sealed x-ray tube. Below results from extended lifetime testing are shown. Figure 5 (left) shows the single cathode emission current for each of the applied emission pulses. The emission current was kept constant at 43mA with a pulse length of 250ms and a duty cycle of 1% by a regulation circuit. As shown in Figure 4 the pulse is very stable over the full pulse length with a slight increase of about 5% from pulse start to pulse end. For all lifetime measurements the anode voltage was set to 35kV. The current is measured on a pulse by pulse basis and if it deviates 0.2 % from the set value the extraction voltage is adjusted in small voltage steps to compensate for the change in cathode current. The good accuracy in the current regulation can be seen in Figure 5 (right). The difference to the nominal value of 43mA is plotted as a function of the pulse number and it can be seen that except for four spikes the fluctuation is around ~ ±0.2%. The spikes are artifacts from the regulation circuit not related to the cathode performance. The mean value for the first ~2500 pulses is slightly lower than for the following pulses. This is due to an adjustment of the regulation parameters and also not related to the cathode performance.

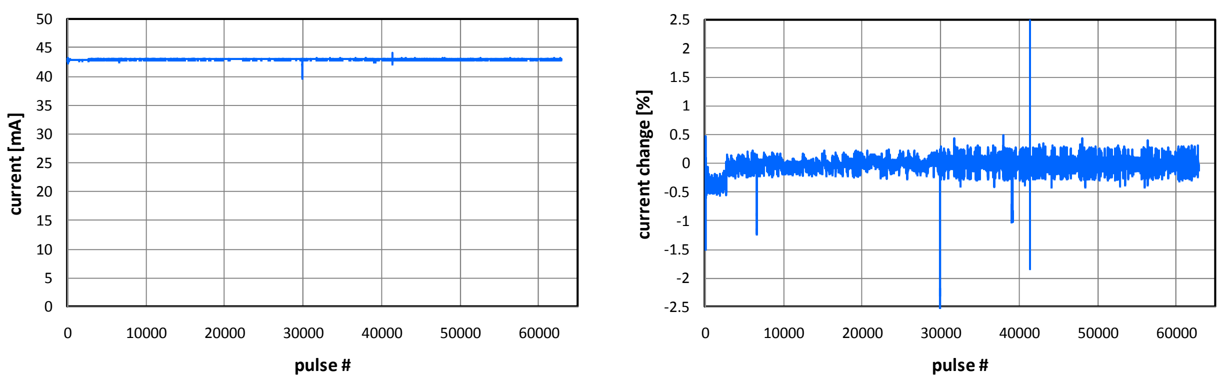
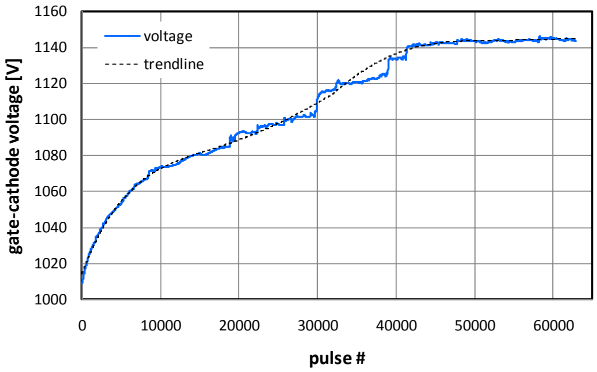


Figure 5: Results from cathode lifetime testing. Cathode current (left) and current stability (right) as a function of the number of extracted pulses (left). The extraction voltage is adjusted from pulse to pulse in order to maintain the constant current.

The increase of the extraction voltage is shown in Figure 6. The left graph shows the gate-cathode voltage together with a trend line adjusted to the measured data points. The trend line consists of a polynomial fit combined with a linear curve. As one can see the extraction voltage increases steadily over time. This is a result of continued cathode degradation due to oxidation of the CNTs and ion bombardment from ions in the rest gas. The CNT film contains a large number of CNT emitters. Not all of the emitters are active at the same time because some are shorter than others and do not see the same strong electric field as the long CNTs. Over time the longest CNTs become shorter and some previously inactive CNTs will become active. This dynamic is expressed in the increased driving voltage. Figure 6 (right) shows the derivative of the trend line that corresponds to the degradation rate of the cathode measured in voltage increase per pulse. The degradation rate drops by a factor of 10 from 0.01 to 0.001 V/pulse within the first ~15000 pulses. It then slightly increases to ~0.0025 V/pulse before it drops to 0.0001 V/pulse for the last 10000 measured pulses. The test was stopped after a total of ~63000 pulses but the cathode was still working without problems. In terms of absolute voltage change on the extraction voltage this corresponds to an increase of 136V. The decrease in the degradation rate can be explained by continued outgassing of the anode and gate mesh that leads to improved local vacuum conditions. The measured number of pulses corresponds to an estimated lifetime in a tomosynthesis system of ~2.6 years under the following assumptions: system is operated 8h per day with a new patient imaged every 10 min, 2 scans each with a total of 250 days per year resulting in 24000 scans/year. Similar degradation rates have been achieved with shorter tests on cathodes with the same deposition area.



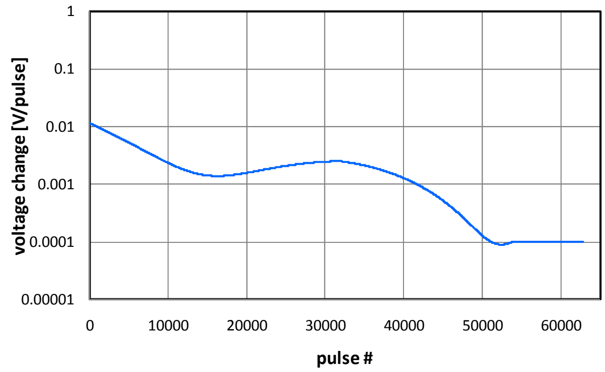


Figure 6: Results from cathode lifetime testing. Voltage difference gate-cathode (left) and voltage change (right) as a function of the number of extracted pulses. The extraction voltage increases over the lifetime to compensate for the slow cathode degradation.

In parallel to the cathode testing the x-ray tube components have been manufactured. After the tube assembly the tube was conditioned to the full operational parameters (current, pulse length, anode voltage) and the focal spots from all 31 cathodes have been measured with a 100µm pinhole and an x-ray camera. The tube has two active focus electrodes that allow controlling of the focal spot size by changing the applied voltage. A typical focal spot is shown in Figure 7. The graph shows a cut through the center of the pinhole image (black and white insert picture). The solid black line is a Gaussian curve fitted to the data points with good overall agreement. Figure 8 shows the results from all measurements at 43mA emission current. The average focal spot size is 0.64±0.04 x 0.61±0.05 mm^2 (width x length) measured at FWHM. The width direction is defined as being parallel to the cathode array orientation (scan direction). The maximum size both in width and length was measured to be slightly above 0.7 mm and the smallest size is around 0.5 mm. Compared to the blurred focal spot in continuously moving source systems the focal spot width is significantly smaller for all measured focal spots. The focal spot size can be varied by up to ~20% in both directions by a potential change on the focus electrodes on the order of several hundred volts. The electron transmission through the extraction gate mesh is slightly dependent of the focusing voltage and can be optimized in combination with the focal spot size.

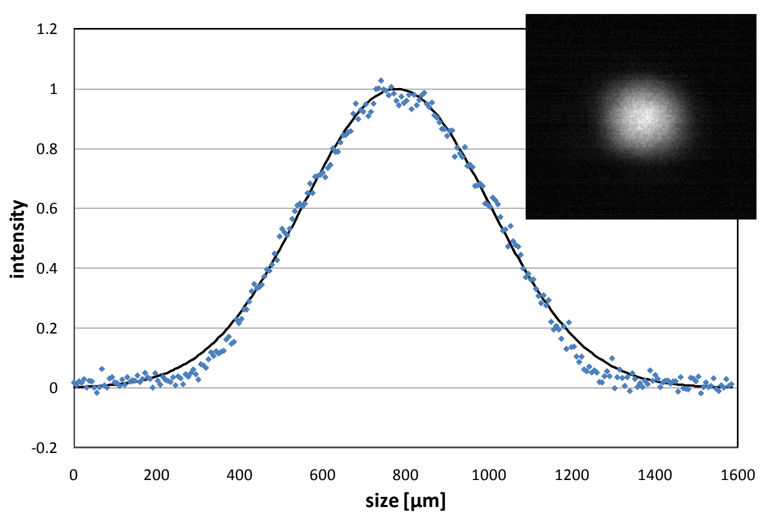


Figure 7: Focal spot profile with fitted Gaussian curve. The focal spot size is calculated from the FWHM. The insert picture shows the full focal spot image taken with a 100µm pin hole.

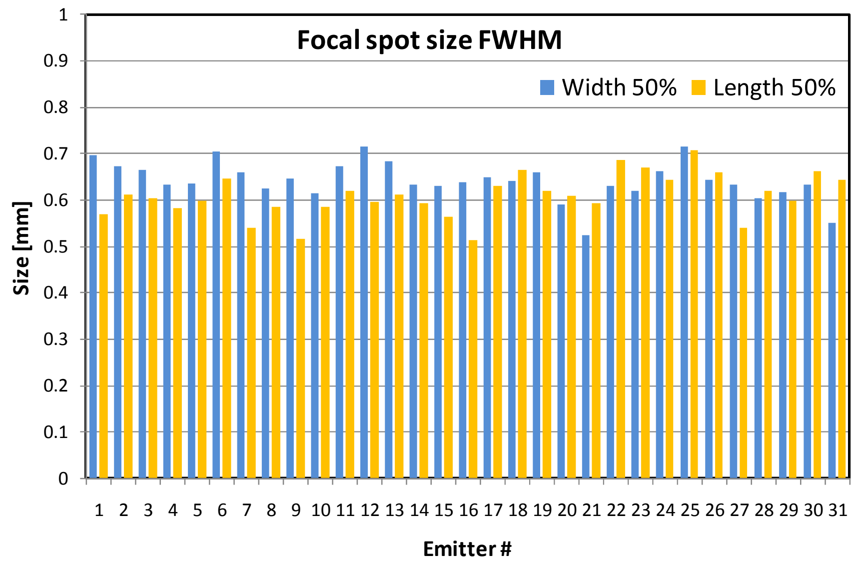


Figure 8: Focal spot dimensions at FWHM from all 31 cathodes in the sealed x-ray tube. The width (along scan direction) is plotted in blue and the length in red.

4. CONCLUSIONS

A fully functional sealed distributed source x-ray tube has been developed and tested. The tested lifetime of the individual cathodes is very promising for the use in commercial systems. The focal spot size at comparable dose is smaller compared to moving source systems (taking into account the motion blur) which will allow for higher resolution imaging. The next steps will be to integrate the tube with a detector and to do imaging with phantoms. System parameters like MTF and CNR will be measured.

5. ACKNOWLEDGEMENTS

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