A Field-Emission Monochromatic Micro-X-ray Source

Brady C. Smith, Charles E. Hunt, Cameron A. McLeod
Department of Electrical and Computer Engineering
University of California -- Davis
Davis, California, U.S.A.
brcsmith@ucdavis.edu

Abstract—**Phase-contrast x-ray imaging as a developing technology requires unprecedented performance from an electron-gun tube-type source. Such a source is designed to provide the requirements of 20 mA through a 25 µm spot.**

Keywords-phase-contrast; x-ray; reticulated vitreous carbon; RVC; mammography; monochromatic x-rays

I. Introduction

X-ray phase-contrast imaging is a recent development with the strong possibility of improving the effectiveness of x-ray imaging, especially in medicine, while greatly reducing dose over conventional absorption-contrast x-ray imaging [1]. In mammography, the reduced dose alone would result in saving the lives of at least 1 in 20,000 women by age 80 who undergo the current recommended yearly breast cancer screening [2]. The challenge has been that no x-ray source has had sufficient flux to provide a reasonably short exposure time for mammography, other than synchrotron sources, which are highly impractical for this application. The highest-flux practical source would be a micro-focus x-ray tube, the technology targeted in this work. Unprecedented performance is required, though, and this will be made possible by the use of a macroscopic field-emission cathode.

The cathode material chosen is reticulated vitreous carbon (RVC) that has been irradiated by argon ions to induce self-assembly of micro- and nano-structures, including carbon nanotubes, in a random array over the material surface. This material has demonstrated higher current density at lower electric field compared to other field-emission sources [3]. Some other cathodes, also involving carbon nanotubes, show similar performance, however at greater cost [4]. Other cathodes have been found to perform insufficiently for this application. These low fields allow the cathode to be implemented in a high-performance x-ray tube without arcing.

A guideline for tube parameters is elucidated in Wu and Liu [5], who specify 25 mA through a 25 µm diameter spot in molybdenum, though they are assuming a thick anode at 35 kV producing polychromatic radiation. The work presented here uses an 80 kV thin anode with x-rays collected antiparallel to the electron beam, greatly increasing monochromaticity, as explained by Harding, et al. [6], leading to significantly relaxed requirements, when compared to Wu and Liu. The state of the art in commercial tubes is exemplified by the Apogee XTF5011 with 1 mA through a 35 µm spot at 4 - 50 kV or the Trufocus TFX-8100SW capable of 0.3 mA, 8 µm, and 40 kV.

In this work, simulation has shown that using the treated RVC cathode 20 mA through a 25 µm diameter spot at 80 kV anode voltage is achievable.

II. Design Considerations

For x-ray phase-contrast imaging, a higher monochromatic x-ray content results in a lower overall flux requirement, compared with other x-ray imaging techniques. Furthermore, the phase-contrast method is naturally more suited to monochromatic sources. For x-ray generation by impact of electrons with a solid, the spectrum of x-rays generated peaks in monochromaticity antiparallel to the electron motion. Large deflection of an electron beam is impractical because the aberrations involved increase the minimum focus size of the beam substantially; therefore, the x-rays in this work are emitted *through* the cathode. Any electrode parts in the electron gun, through which x-rays used will pass, must be essentially transparent at that wavelength. An additional advantage to this design is that the semitransparent electrodes will filter lower energy x-rays (the desired Mo line is at approximately 20 keV).

Monochromaticity can be increased in other ways as well. First of all, the effectiveness of using antiparallel radiation depends upon limiting the thickness of the x-ray producing anode [6]. In the design demonstrated here, 100 nm is an appropriate thickness. The anode voltage is also an important parameter for monochromaticity. For Mo, the ratio of the characteristic to bremsstrahlung photons, a measure of monochromaticity, peaks at an anode voltage of 100 kV. However, implementing a voltage of this magnitude in an electrostatically-focused electron gun is challenging. The design here, using an anode voltage of 80 kV, results in a high monochromatic to bremsstrahlung flux, very near to the 100kV peak, yet with a considerable advantage in tube robustness and simpler design.

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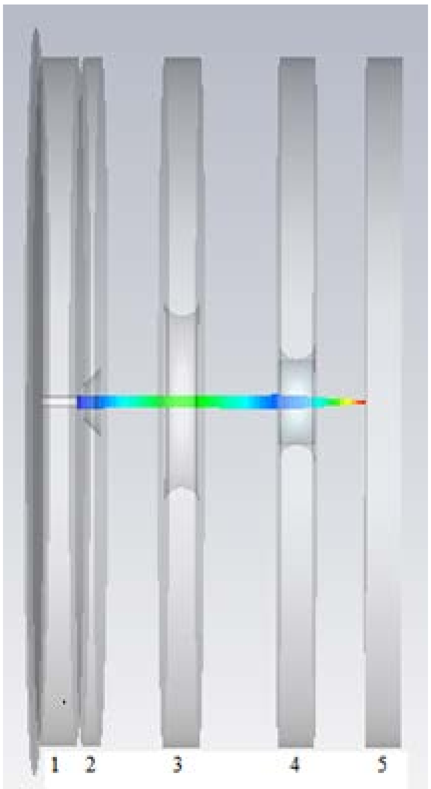
III. SIMULATION

Many combinations of electron gun geometry and potentials were investigated with the simple goal of having the highest current through a spot of not more than 25 μm diameter. A simulation achieving desired beam parameters is shown in Fig. 1. An Einzel lens of lower central voltage was employed as a low-aberration, strongly-focusing lens at the anode (electrodes 3, 4, and 5 in Fig. 1). Extraction of the electrons is achieved by two extraction electrodes next to the cathode (one of which is also part of the Einzel lens.) The electrode farther from the cathode sets up the basic electric field and the closer one acts as a control electrode for beam blanking.



	Electrode	Voltage
5	anode	80000
1	cath	0
4	einzel	-7400
2	ex1	2900
3	ex2	80000

Fig. 1. Simulation of electron gun achieving 20mA at 25μm spot size.

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Because the anode current density is 4 kA/cm^2 (for 20 mA through a 25 μm diameter spot), a pulsed beam will be implemented to prevent the evaporation of the thin-film Mo anode. Based upon the material properties of the anode foil, an 11 ns dwell time and a 4 μs off time are required, maximizing the tolerable beam time without anode melting, while ensuring adequate time for heat dissipation between pulses. The 0.3% duty cycle pulse is to be applied to the control electrode (2 in Fig. 1) thereby varying the potential from 1.2 to 2.9 kV to have an off-current of 0.1mA and an on-current of 20 mA. This also results in the off-current not being focused at the anode surface.

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