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DESIGN OF A HIGH DOSE RATE MICRO-FOCUSED X-RAY SOURCE*

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Abstract

High energy X-ray computer tomography has wide application in industry, especially in quality control of complicated high-tech equipment. In many applications, higher spatial resolution is needed to discover smaller defects. Decreasing the spot size of the X-Ray source is a promising way to get higher spatial resolution. Rhodotron have been used to produce high power CW electron beam in hundreds of kilowatts level. In this paper, we propose to use an improved Rhodotron to generate high brightness electron beam with high average power. Beam dynamics study shows that when producing tens of kilowatts electron beam, the normalized RMS emittance can be lower than 10 µm, and the relative RMS energy spread can be lower than 0.2%. The beam can be focused to a spot size of about 100µm by using a set of quadruples, and converted to X-Ray by using a rotating target within several kilowatts beam power. Improved Rhodotron proposed in this paper is a good candidate of X-ray source for high resolution high energy industrial CT systems.

INTRODUCTION

High energy industrial CT has shown to be of great value in the research and development of the high-end equipment (large locomotives, engines, nuclear weapons, etc.). But it is still urgent need for higher resolution to detect smaller defects in high-end equipment. To meet the needs, a micro-focused accelerator with high dose rate will be needed.

Traditional accelerator used for this purpose is RF traveling or standing wave linear accelerator. There are many commercial companies such as VARIAN in America and GUHONG in China, providing linear accelerators for high energy CT inspection. The typical beam energy for high energy CT inspection is 9-15 MeV, the dose rate for 9 MeV is about 3000 Rad/min, and the X-ray spot size is about 1-2mm. There are many commercial products of micro-focused X-ray source utilizing a DC accelerating tube and a rotating target. X-ray spot-size of commercial micro focused X-ray source can be as small as 0.2mm at the maximum electron beam power of 750W and maximum beam energy of 750kV. For the CT inspection of some special equipment with large aerial density, especially in case of high resolution is needed, one need X-ray sources with the three properties meanwhile: high energy (not less than 9MeV), high dose rate (not less than 3000 Rad/min), and a very small spot size (not more than 0.2mm).

To generate micro-focused high dose rate X-ray, high brightness electron beam is needed. More specific, electron beam with high average power, low emittance and low energy spread is needed. On the other side, one should deal with the target temperature rise when producing high dose rate X-ray at a very small spot size. Accelerator with high duty factor should be chose to avoid the target melting, even when the rotating target system is used.

Several kinds of accelerators such as Rhodotron [1-8], Rdigetron [9] and Fabitron [10], can work at high duty factor, and sometimes can work at continuous wave mode. In this paper, it is proposed that using Rhodotron and a rotating target to generate high dose rate micro-focused X-ray. Proposed layout is shown in Figure 1. The Rhodotron in Figure 1 is designed to generate high power electron beam with high brightness.

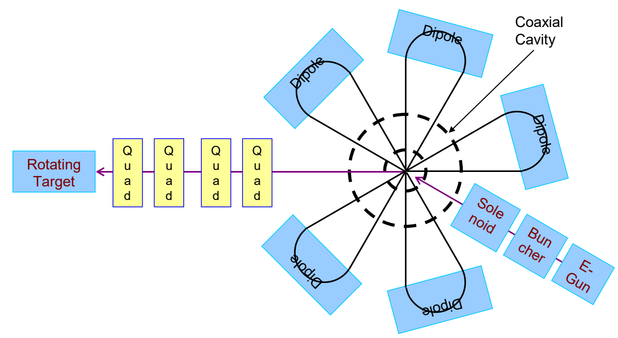

Figure 1: Layout of the proposed micro-focused X-ray source.

Main specification of the proposed micro-focus X-ray source is listed in Table 1.

Table 1: Main Specifications of the Proposed X-ray Source

Parameters	Value
electron beam energy	9 MeV
dose rate of X-ray at 1m from target	≥ 3000 Rad/min
X-ray spot size (FWHM)	≤ 0.2mm
time structure	10% duty factor, and at 100 Hz

TEMPRATURE RISE OF THE ROTATING TARGET

For the parameters listed in Table 1, one need electron beam with power of about 1 kW. The average dissipated power in the rotating target is about 0.4 kW, and the peak dissipated power in the rotating target is about 4 MW. The temperature rise of the rotating target can divided into two parts: one is steady state temperature rise supposing the target is in thermal balance state, another is pulsed temperature rise. In steady state, the radiated power equals to the average power dissipated in the target. For a target with diameter of about 30 cm, the steady state temperature rise calculated by FEM software is lower than 400 degrees for the parameters listed in Table 1. The temperature distribu-

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tion of the rotating target is shown as Figure 2. Pulsed temperature rise of the rotating target was estimated supposing the target is adiabat while electron beam is hitting the target. For electron bunch train with duration of 1 ms, the energy deposited in the target is about 10 J, and the moved distance of the target during the electron bunch is 30 mm supposing the rotating speed is 30 m/s. One can estimated that the pulsed temperature rise is about 300 degrees.

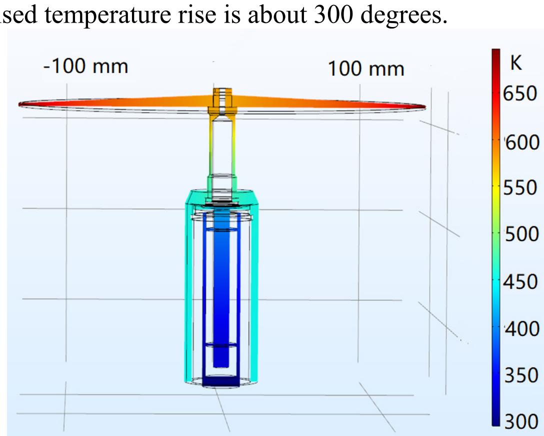

Figure 2: Steady state temperature rise of the rotating target simulated by FEM calculation.

Together with the steady state temperature rise, the maximum temperature rise is about 700 degrees. Further thermal simulation shows that the temperature rise is about 150 degree at the bearing position of the rotating target. Using a bearing that can work at 400 degrees is quite safe for the rotating target.

PRELIMINARY BEAM DYNAMICS DESIGN

To generate the proposed dose rate, the needed average power of the electron beam is about 1kW. This value is far less than that has been achieved in high power Rhodotron, in which several hundreds of kW electron beam was generated. So the beam current in our design is relatively low, and the electron beam can be bunched to shorter phase width to acquire smaller energy spread, and a smaller cathode can be used to archive smaller emittance. Additional to the buncher used in low energy section, the acceleration phases in the RF cavity are also chosen to bunch the electron beam. In other words, the acceleration phase choice and the non-zero R56 of the dipoles make every dipole can work as a magnetic compressor. At injection, the phase width of the electron beam is 120 degrees in full length, and the energy of electron beam is 40 keV. The phase width of the electron beam was less than 10 degrees at the end of the accelerator.

The code PARMELA was used to simulate the beam dynamics in the accelerator with space charge effect included. At the end of the accelerator, the normalize RMS emittance of x and y direction are both lower than 8 mm·mrad, the peak current is about 1 Ampere, and the RMS energy spread is about 0.2% (Figure 3). Within the injection pulse width, no particle loss was observed in the simulation during acceleration.

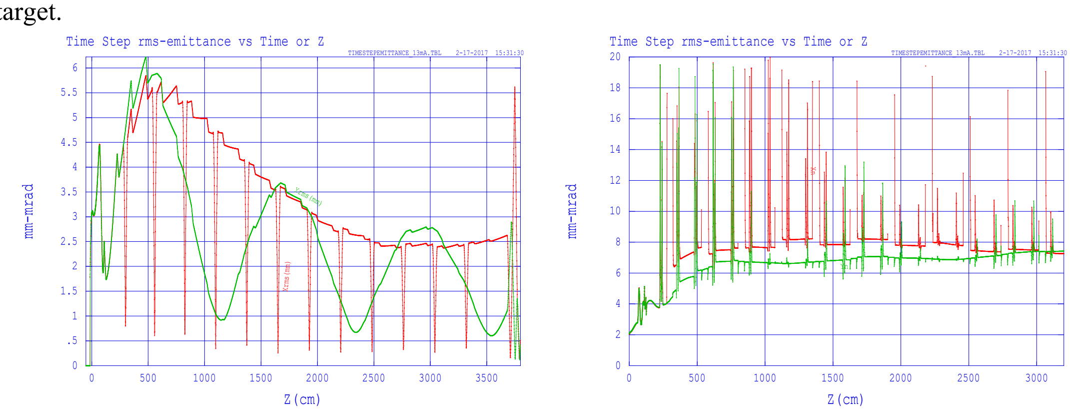

Figure 3: The beam envelope (left, in millimeters) and normalized emittance (right, in mm • mrad) of the electron beam in the accelerator.

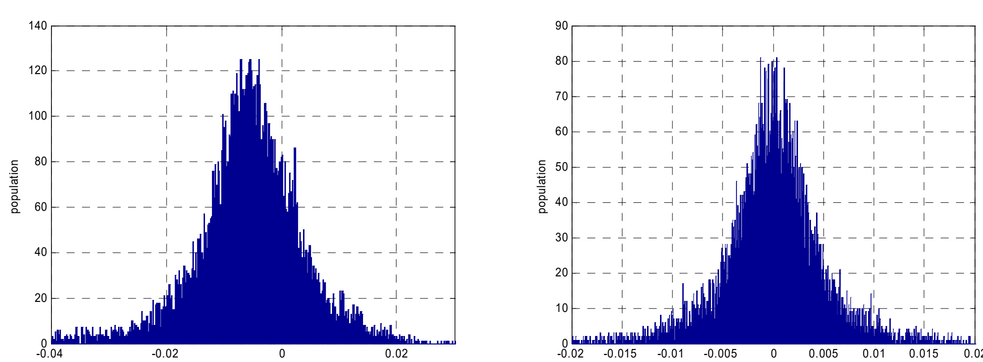

Figure 4: Distribution of the electron focus spot in x and y direction.

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Using the focus system consisting 4 quadruples, the electron beam can be focused to be smaller than 0.15 mm (FWHM, see Figure 4). The dispersion effect and the chromatic effect are included in the simulation by the code PARMELA. When transferring to X-ray in the rotating target, the electron beam is scattered by the target material, hence the spot size of X-ray beam may be larger than the beam size simulated by the beam tracking code. The scattering process of the electron in the target is simulated by the code GEANT4. The simulation shows that there is no obvious difference between the X-ray spot size and the electron beam spot size even with a focus spot of 0.1 mm.

KEY TECHNOLOGY NEEDED TO REALIZE THE PROPOSED DESIGN

Key technologies needed to realize the proposed design in this paper are coaxial cavity with large dimension, dipole magnet with high accuracy to provide proper transverse focusing and rotating bremsstrahlung targets in vacuum. Besides these key technologies, high voltage pulsed power supply with very high repetition rate is needed to avoid the overlapping of the beam track in the central part of the accelerator. To avoid the beam overlapping, we proposed to generate one electron bunch every 10 RF cycles. That is to say, for a RF frequency of 108 MHz, the power supply of the grid controlled electron gun should work at repetition rate of 10.8 MHz. And the electron gun should produce a pulse of FWHM less than about 3 nanoseconds which is about 1/3 of one RF period. There is a R&D project in progress to develop key technologies including the generation of electric pulse with needed repetition rate, RF cavities, the high accuracy dipole magnet, rotating target, and also the beam dynamics optimization of Rhodotron.

CONCLUSION AND FUTURE WORK

Method of using improved Rhodotron as micro-focused X-ray source is proposed in this paper. Main improvements include adopting a buncher after the gun, adopting magnetic compression by choosing proper acceleration phase and adopting an electron gun with high repetition rate and short pulse to avoiding beam overlapping in central region of Rhodotron. Beam dynamics design of the improved Rhodotron are carried out to generate X-ray with high dose rate and very small focus spot. Beam dynamics study shows that when producing tens of kilowatts electron beam in CW mode, the normalized RMS emittance can be lower than 10 μm, and the relative RMS energy spread can be lower than 0.2%. The beam can be focused to a spot size of about 100 μm.

There is a R&D project in progress in CAEP to develop key technologies including the generation of electric pulse with needed repetition rate, RF cavities, the high accuracy dipole magnet, rotating target, and also the beam dynamics optimization. The RF cavity has been designed and is in machining process [11].

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