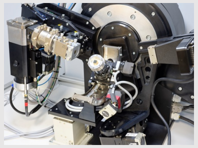
Exploring Physics in Proto Manufacturing's X-Ray Tube Department

Lily Symons

University of Windsor

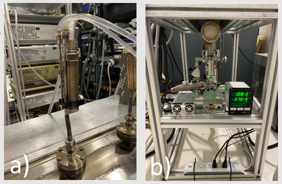
Proto Manufacturing - Improve Your Science

Proto Manufacturing is a leader in X-ray diffraction and one of the fastest growing X-ray diffraction companies in the world. For over 30 years Proto Manufacturing has been developing and providing innovative instruments for the characterization of materials. These include various x-ray diffraction (XRD) instruments such as: residual stress and retained austenite measurement systems, powder diffractometers, Laue single-crystal orientation systems and high-resolution diffractometers. Additionally, Proto Manufacturing supply's X-ray tubes which will be the focus of this presentation.



Evacuation of an X-Ray Tube and the Conditioning Process

After an X-ray tube is designed and constructed it must be placed onto a vacuum system to be evacuated before the conditioning process begins. An X-ray tube must contain a vacuum to accelerate the electrons from cathode to anode with maximum efficiency. Once the X-ray tube is evacuated, a cooling manifold is placed onto the tube in order to regulate the temperature of the anode and ultimately prevent damage. Finally, the tube is connected to a high-voltage power supply using a high voltage cable. The full set up of the X-ray tube can be viewed in image a), while the vacuum system which is placed below the tubes can be viewed in image b). Ideally, the vacuum system will remain between 1.0 x 10^{-6} mbar and 1.0 x 10^{-9} mbar while the power supply is turned on and the voltage and current are slowly increased in set intervals until the desired settings are reached.



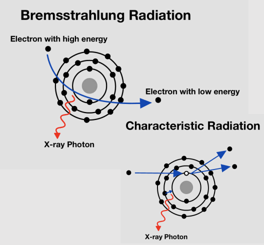
My Role at Proto Manufacturing

Throughout my work term at Proto Manufacturing, I aided the company in many areas, many of which are highlighted here in this presentation. My main role as a coop student, was to carry out the conditioning process of the X-ray tubes before they were placed into storage or sent out to customers. This is a mandatory process, and essential for the X-ray tubes to run efficiently once pinched off the vacuum system. More about this process is discussed in the "Evacuation of an X-Ray Tube and the Conditioning Process" section.

How are X-ray Photons Generated

X-ray photons are generated using an evacuated metal and ceramic tube with components that convert electrical power (high voltage) into x-ray radiation.

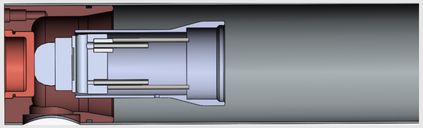
In order to produce x-ray radiation, a high voltage power supply is used to provide an electrical current to a tungsten filament. This electrical current heats up the filament, causing some of the electrons in the tungsten to obtain enough thermal energy to escape the metal. An electrical current is applied across the cathode to the anode forcing the free electrons to accelerate at high speeds towards the anode. The filament is placed so that it is surrounded by the cathode cup it is designed to focus the electron beam to a precise line or spot on the anode. After the electrons travel from cathode to anode, each electron gains energy in kilo-electron volts equal to the kilovolts applied to the system. X-ray photons are generated when the free electrons collide with the anode in two processes:

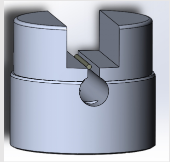


Bremsstrahlung radiation is the dominant process of X-ray emission and appears as a smooth curve on an emission spectra. When an electron comes close to an atomic nucleus it will experience a change of velocity due to the attractive positive force of the nucleus. When a charged particle changes velocity it emits an x-ray photon with an energy that depends on how much kinetic energy the electron losses from the interaction with the nucleus.

Characteristic radiation is specific to each element and appears as sharp peaks on an emission spectra. This process occurs when an electron collides with an inner orbital electron, resulting in it being ejected from the orbital. An outer shell electron then fills this vacancy by the release of energy in the form on an x-ray photon. This photon has an energy equivalent to the energy level difference between the outer and inner shell.

Design Modifications for Electron Beam Focusing



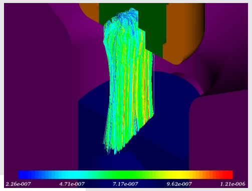


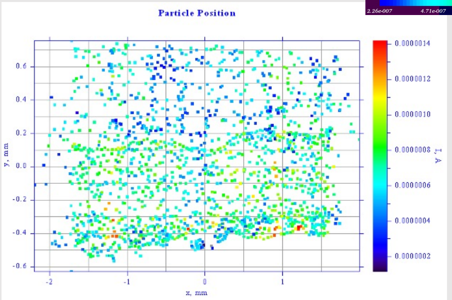
Modifications to the X-ray tube design are always occurring, especially to the cathode cup. The goal of the cathode cup is to focus the electron beam trajectory, obtaining the smallest spot size possible. A common practice would be to analyze competitor's cathode cup designs and try to duplicate and/or innovate that design to make it better. A few ways the design of the cathode cup would be altered are: cathode to anode spacing, shape of the filament cup, and angle of the focusing cup.

Alternative Methods?
An alternative way to testing the designs of various cathode cups would be to physically create the x-ray tube and take filament images to analyze the electron beam trajectory. This would be timely and expensive, ultimately making the simulations to be the superior method.

Electron Beam Simulations

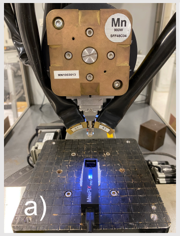
To theoretically test the performance of the X-Ray tube designed in SOLIDWORKS, the design is imported into a software that will simulate the electrons accelerated towards the anode. This will give an approximation to the spot size of the electron beam and determine if this design is worth manufacturing for overall testing.

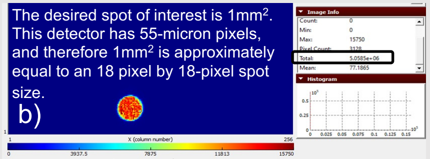




Displayed above is a representation of the electrons travelling from cathode to anode in a line focus X-ray tube. Also shown to the left is a particle position plot which ultimately plots where each electron collides with the anode.

Photon Counting using a Miniaturized Spectral Imaging Camera





A) Experimental set up with the source focused on the detector.
B) Digital display of the photons hitting the detector with a 1mm aperture.

<u>Approximate Sample Calculation</u>

Important Units:
Flux Density [p/s/mm^2]
Divergence [mrad]
Brilliance [p/s/mm^2/mrad]

Note: Detector is 61mm from the source, and the source is running at 3W.

Flux Density = $1.14*10^7\ p/s/mm^2$

Divergence: $\theta = 2\arctan\left(\frac{0.5}{61}\right)$

$$\theta = 0.93°$$

$$\theta = 16.23\ mrad$$

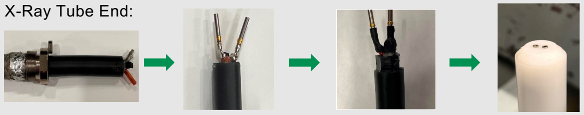
Brilliance = $\frac{1.14*10^7 p/s/mm^2}{16.23 mrad}$

Brilliance = $4.3*10^4\ p/s/mm^2/mrad$

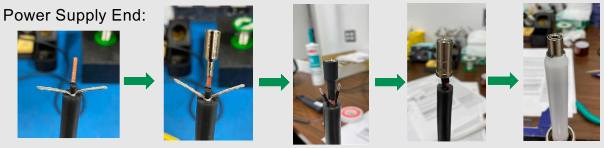
Future Work: In future work the attenuation of x-rays through air will be considered to give an accurate approximation to how many photons are being produced.

High Voltage Cable Assembly

X-Ray Tube End:

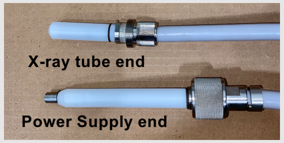


Power Supply End:



Conclusion

Overall, my experience at Proto Manufacturing was extremely beneficial to my education and taught me useful skills I will continue to use throughout the entirety of my career.



References:
https://www.protoxrd.com/

Acknowledgments: Special thanks to Scott Teall and Brian Simpson for giving me the opportunity to work at Proto Manufacturing in the X-ray tubes department and gain experience in the field of physics and engineering. I am also thankful for the coop and physics departments for continuously supporting me throughout this placement.