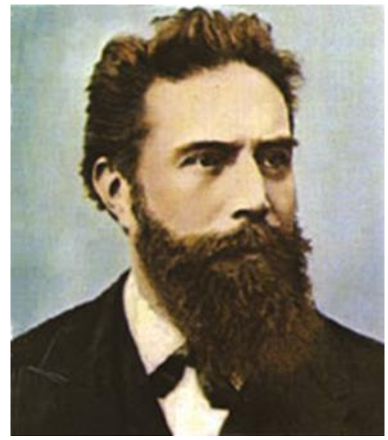
Chapter 4

X-Ray Physics/ EOM

History of X-Ray



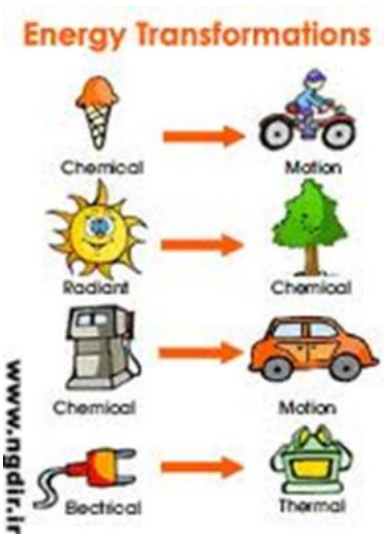
In late 1895, a German physicist, W. C. Roentgen was working with a cathode ray tube in his laboratory. He was working with tubes similar to our fluorescent light bulbs. He evacuated the tube of all air, filled it with a special gas, and passed a high electric voltage through it. When he did this, the tube would produce a fluorescent glow. Roentgen shielded the tube with heavy black paper, and found that a green colored fluorescent light could be seen coming from a screen setting a few feet away from the tube. He realized that he had produced a previously unknown "invisible light," or ray, that was being emitted from the tube; a ray that was capable of passing through the heavy paper covering the tube. Through additional experiments, he also found that the new ray would pass through most substances casting shadows of solid objects on pieces of film. He named the new ray X-ray, because in mathematics "X" is used to indicated the unknown quantity.

In his discovery Roentgen found that the X-ray would pass through the tissue of humans leaving the bones and metals visible. One of Roentgen's first experiments late in 1895 was a film of his wife Bertha's hand with a ring on her finger (shown below on right). The news of Roentgen's discovery spread quickly throughout the world. Scientists everywhere could duplicate his experiment because the cathode tube was very well known during this period. In early 1896, X-rays were being utilized clinically in the United States for such things as bone fractures and gunshot wounds.

The operation of the Coolidge tube is as follows. As the cathode filament is heated, it emits electrons. The hotter the filament gets, the greater the emission of electrons. These electrons are accelerated towards the positively charged anode and when the electrons strike the anode, they change direction and emit bremsstrahlung, i.e., x-rays with a continuous range of energies. The maximum energy of the x-rays is the same as the kinetic energy of the electrons striking the anode. In addition to the x-rays produced at the focal spot of the anode, some undesirable x-rays (stray radiation) are produced by electrons striking other tube components.

The key advantages of the Coolidge tube are its stability, and the fact that the intensity and energy of the x-rays can be controlled independently. Increasing the current to the cathode increases its temperature. This increases the number of electrons emitted by the cathode, and as a result, the intensity of the x-rays. Increasing the high voltage potential difference between the anode and the cathode increases the velocity of the electrons striking the anode, and this increases the energy of the emitted x-rays. Decreasing the current or the high voltage would have the opposite effects. The high degree of control over the tube output meant that the early radiologists could do with one Coolidge tube what before had required a stable of finicky cold cathode tubes. As a bonus, the Coolidge tube could function almost indefinitely unless broken or badly abused.

Without a doubt, the single most important event in the progress of radiology was the invention by William Coolidge in 1913 of what came to be known as the Coolidge x-ray tube. Nevertheless, despite its clear superiority, the Coolidge tube did not immediately replace cold cathode tubes - the latter continued to be manufactured into the 1920s and saw routine use into the 1930s. In fact, there were instances of cold cathode tubes being employed in radiology as late as the 1960s!

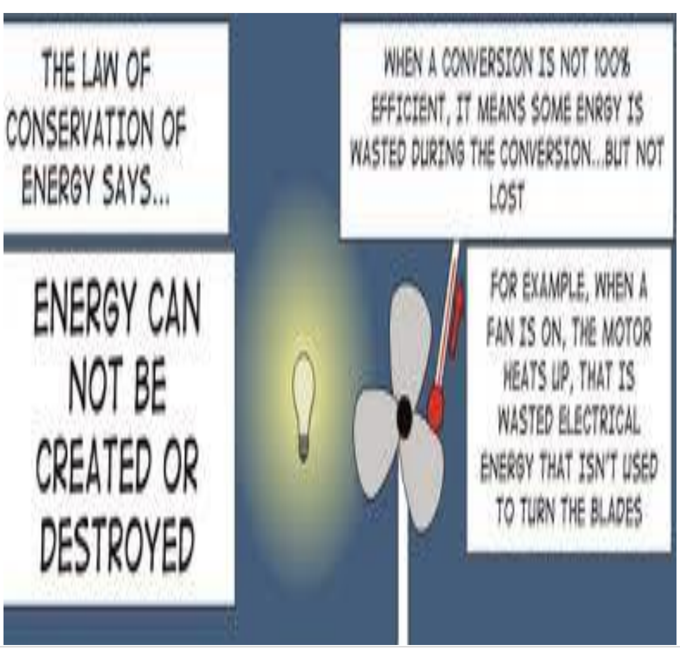


The characteristic features of the Coolidge tube are its high vacuum and its use of a heated filament as the source of electrons. There is so little gas inside the tube that it is not involved in the production of x-rays, unlike the situation with cold cathode gas discharge tubes.

Energy

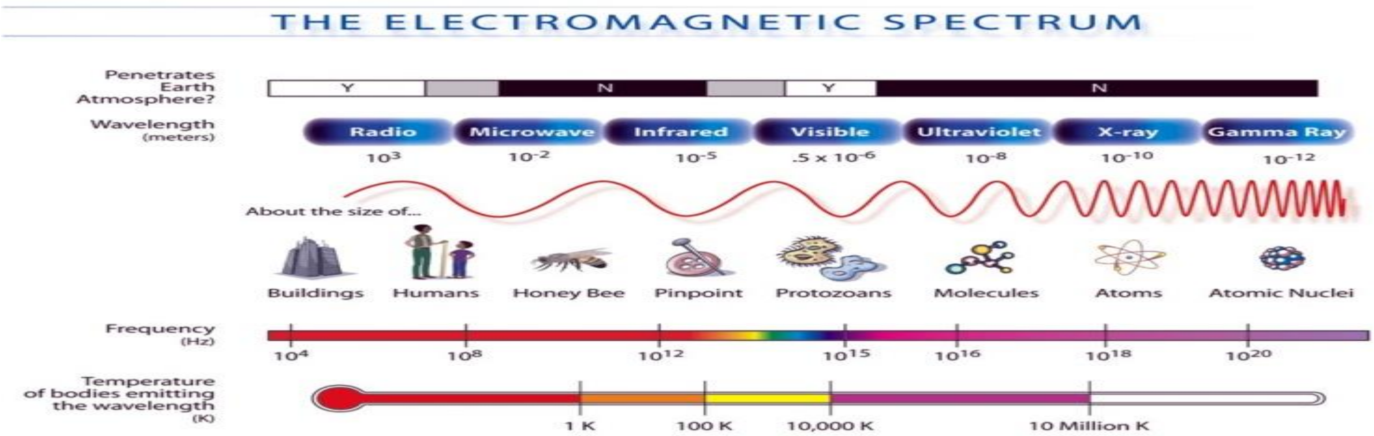
We have often heard phrases like, "Conserve energy; turn off the lights." To scientists, conservation of energy is something entirely different. The **law of conservation of energy** states that the total amount of energy in a system remains constant ("is conserved"), although energy within the system can be changed from one form to another or transferred from one object to another.

Electromagnetic Radiation



First we need to identify exactly what x-ray is. An x-ray is energy that travels through the air in waves. In this way it is similar to radio waves, microwaves and rays of light. The major difference is the length of the waves that travels through the air. The shorter that the wave length of the radiation is, the greater the energy is. For example, radio waves have very long wavelengths and very little energy. X-rays have very short wavelengths and very high energy.

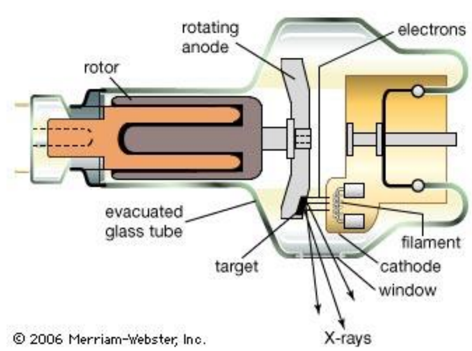
Electromagnetic radiation includes gamma rays, which originate from a nucleus of radioactive atoms. Gamma rays travel through the air in waves instead of particles and x-rays which originate from x-ray tube production. Both x-rays and gamma rays travel through the air at the speed of light and have no mass or electrical charge.



The X-Ray Tube

The x-ray tube is essentially a massive valve, or switch, completing an electric circuit. The x-ray tube consists of a cathode and an anode within a vacuum. The tube is enclosed within a housing. The negative end of the x-ray tube is called the cathode, and the positive end is called the anode. In any electric circuit, current flows from the negative side of a circuit to the positive side, and it is no different when an x-ray tube is involved.

Cathode The cathode is the negative side of the x-ray tube. The purpose of the cathode is to produce the thermionic cloud, conduct the high voltage current, and focus the emitted electrons (1). The cathode is more correctly called the cathode assembly. It consists of the filament (or filaments), the focusing cup and all the associated wiring. It is important to note that in radiography, the terms cathode and filament are generally interchangeable.



Filament Most radiographers, when talking about the cathode, are actually talking about the filament. The filament is actually a very tightly wound coil of wire made of tungsten. When an electric current is passed through the filament, it heats up to such an extent that some of the electrons have enough (thermal vibrational) energy to break free of the attractive (electrostatic) forces holding them inside the filament. This is called "**thermionic emission**". The amount of electrons that "break free" of the filament (or are emitted) is directly proportional to the amount of electrons flowing inside the filament (i.e., the current). The filament current is not quite the same as the mA that the radiographer controls, but they are related.
Focusing Cup The focusing cup (made of Molybdenum) is a shallow depression in containing the filament. The filament emits electrons, all of which have a negative charge. Since negative repels negative, the electrons that have been emitted have a tendency to diverge. As this is counterproductive in x-ray tubes, the focusing cup is a negatively charged housing that "encourages" the electrons to stay together. Essentially, the force that causes the electrons to repel each other is overpowered by the repulsive force of the focusing cup and the electrons tend to converge rather than diverge.
Discussion of the associated wiring is relatively questionable, except when discussing (a) focal spot size selection or (b) grid-biased (or grid-controlled or grid-pulsed) tubes. We will cover (a) later but not (b).

Anode The anode assembly, also made of tungsten, is the positive end of the x-ray tube. The anode assembly consists of the anode, the stator and the rotor. As a whole, the anode assembly is important as the source of the x-rays, as the primary conductor of heat out of the tube and as an integral part of the high voltage circuit.

The anode is a relatively flat (circular) disc that acts as the target for the stream of electrons that are emitted from the cathode. In modern x-ray tubes, the normal anode spins (very fast - around 3,500 rpm). This allows creates a larger target for the electrons. Think of it this way - have you ever put a pen on a spinning top (or wheel)? The tip of the pen is very small but you create one big line. Let's assume the electrons cover an arc of 1.2 degrees on the anode. If you spin the anode, the electrons are spread out over the full 360, increasing the target area by a factor of 300.

So why is this important? It turns out that when the electrons hit the target, they slow down very fast (think crashing a Ferrari into a brick wall at high speed). This means that they lose energy, and lots of it, very fast. Most of that energy (about 99%) is in the form of heat. Since there is a lot of energy, there is a lot of heat. By spinning the anode, the heat is spread across the whole of the target area. This helps keep it cool, and extend the life of the anode (and tube). The other 1% of the energy is in the form of x-rays.

Envelope The cathode and anode are housed inside a glass "tube" and contained within a vacuum. All gasses are removed from the envelope resulting in a vacuum. The vacuum permits electrons to flow from the cathode to the anode without encountering gas atoms and greatly increases the tube efficiency. The envelope is made of glass or metal. Metal envelopes eliminate the problem of tungsten vaporization. The window is the part of the envelope where the primary beam exits the envelope. The window may be thinner than the rest of the envelope to decrease x-ray attenuation (1).

Housing The housing is a protective barrier against leakage and scatter radiation. It additionally isolates high voltages and aids in tube cooling.

X-ray Production

There is a difference in voltage between the cathode and the anode. This voltage difference is controlled by the kVp on your control panel.
So what happens when you change the mAs and kVp?

When you change the mAs, a few things happen. The most important thing is that the number of x-rays produced increases proportionally. If you double the mAs, you get double the number of x-ray photons heading towards the patient. Remember the process of thermionic emission that produced the electrons? Well let's say that 10% of all electrons flowing through the filament are emitted. If you double the number of electrons in the filament (the *filament current*), you therefore double the number of electrons that are emitted (this is the *tube current*)

So…when you increase the mA, you increase the filament current, which in turn increases the tube current - this leads to more x-ray photons being created.

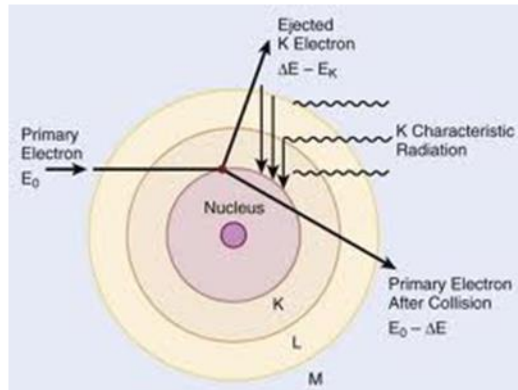
It is useful now to think of each x-ray photon as an information carrier. The more photons you have, the more information you have - up to a point. Any radiography student knows you can have too much information (at which point nothing makes sense). As the x-ray photons pass through the body, some of them gather useful information, others gather useless information, and sometimes there is simply not enough information at all. I tend to teach that too much information is Spatial or Information Redundancy and that too little information is Noise or Quantum Mottle.

X-rays are produced inside the x-ray tube when electrons from the cathode strike the atoms of the anode. The kinetic energy of these electrons, called projectile electrons, knocks an electron out of the atom that is struck. When an electron in a higher orbital shell falls down to replace the electron bumped out, an x-ray photon is produced. This is one of the two ways x-ray photons are produced.

Remember that projectile electrons are produced inside the x-ray tube when electrons are "boiled off" the cathode filament and accelerated to the anode by the electric potential difference between the cathode and the anode. This potential is controlled by the kVp setting for the x-ray tube. The kVp setting, therefore, determines the kinetic energy of the projectile electrons. If you recall from the earlier module on the electromagnetic spectrum, x-ray radiation covers a wide range in this spectrum, with frequencies ranging approximately from 10 to the 16th power to 10 to the 20th power hertz. X-rays at higher frequencies have more energy than x-rays at lower frequencies. Because of their differences in energy, they interact in different ways when they strike atoms in the air and in the body of the patient undergoing an x-ray examination. Therefore it is important to consider the energy of x-rays produced and the different effects at different energy levels.

The electrons within an atom each have a specific amount of binding energy that depends on the size (atomic number, Z) of the atom and the shell in which the electron is located. As described in a previous chapter the binding energy is the energy that would be required to remove the electron from the atom. It is actually an energy deficit rather than an amount of available energy.

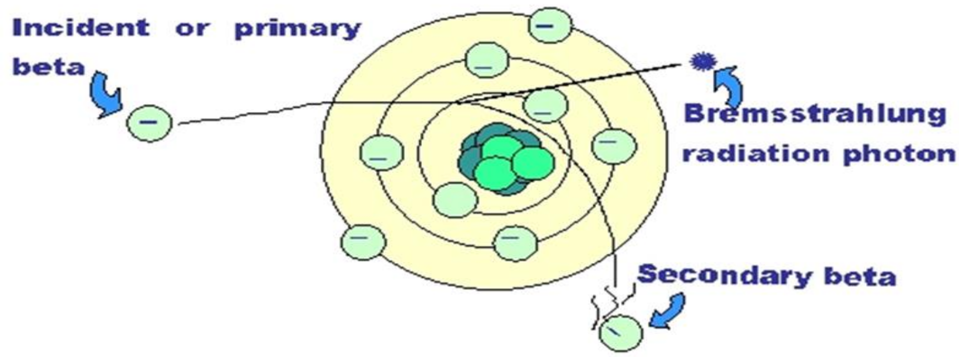
The binding energy of electrons within an atom plays a major role in the production of characteristic x-radiation.



Characteristic Radiation The projectile electron strikes an atom and knocks an electron out of its orbit. This leaves the atom in an unstable state, and an electron from a higher orbit moves down to the space left by the electron bumped out. In so doing, it gives off a photon of x-ray radiation. The energy of this x-ray photon is equal to the difference in binding energy between the higher electron orbit and the new electron orbit.

Unstable atoms tend to change to become more stable. A balanced number of electrons and protons contributes to stability—the negative charges balanced by the positive charges. The absence of an electron in an inner shell is immediately "corrected" in the atom by another electron jumping down to fill its place. The binding energy of the original inner shell electron was overcome when it was knocked out of the atom. A higher-level electron then moves down to the inner shell. The difference in binding energy between the electron orbits is released as an x-ray photon. This is called a characteristic x-ray because the energy of an x-ray photon produced at a certain electron shell is always the same as any other x-ray photon generated at the same electron shell.

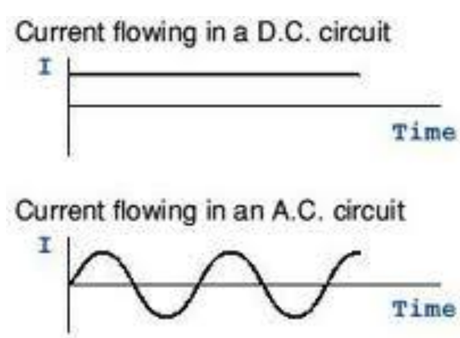
Bremsstrahlung Radiation The second process by which x-rays are produced is called bremsstrahlung radiation, named from a German word for slowing down or braking. If the projectile electron entering an atom in the metal of the anode does not strike any of that atom's electrons, it may continue toward the center of the atom and come near the nucleus. Remember that the electron has a negative charge and the nucleus has a positive charge. Therefore the passing projectile electron is attracted to the nucleus. This attraction slows the electron down as it passes the nucleus and alters the direction of the electron's path as the nucleus "pulls" on the electron.



The slowing of the electron means that it loses kinetic energy—and this energy takes the form of a photon of x-ray energy being released. The amount of energy in a bremsstrahlung x-ray photon depends on the original kinetic energy of the projectile electron and the amount of energy that it loses. The amount of energy lost depends on how close to the nucleus the electron passes. The electron can convert all its kinetic energy into x-ray photon energy, part of its kinetic energy into lower x-ray photon energy, or no kinetic energy at all into x-ray photon energy (that is, producing no x-ray)—or any amount in between

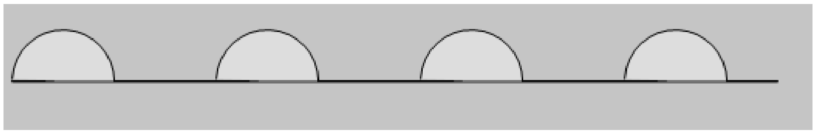
X-Ray Generators

Current in which the electrons oscillate flowing in one direction then the other direction is referred to as **alternating current.** Alternating current flows from negative to positive then from positive to negative. Current that flows in only one direction is referred to as **direct current.** Direct current flows only from negative to positive. The current that comes into our homes and businesses is alternating current. X-ray tubes can only operate on direct current. Alternating current applied to an x-ray tube would damage the tube.



The current must be converted from alternating current to direct current. To do that we use a rectifier. The most basic type of rectifier is called a “half wave” rectifier because only half of the AC wave form appears on the out output. This would not work well for our purposes. It would essentially waste half of the power supply

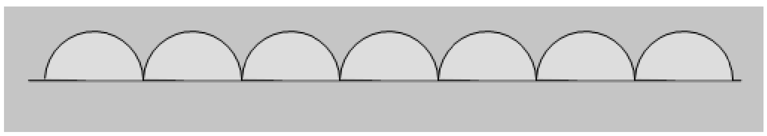
Direct Current – Half wave rectification



It is possible to devise a circuit that would utilize the entire AC waveform. This form of rectification is referred to as "full wave" rectification. The negative half of the waveform isn't eliminated it is reversed so that positive current is always directed across the x-ray tube. A **single phase** x-ray machine operates in this manner.

Direct Current – Full wave rectification

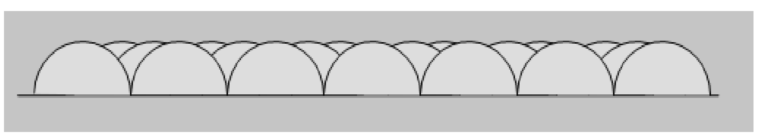
- **Single Phase**
- **100% Ripple**



The x-rays produced when the single phase voltage is near zero are of very little value. To overcome this limitation three phase equipment has been developed. Three phase operates with three single phase currents overlapping one another. The value therefore never reaches zero. As one phase decreases at least one of the other two phase's increases.

Direct Current – Full wave rectification

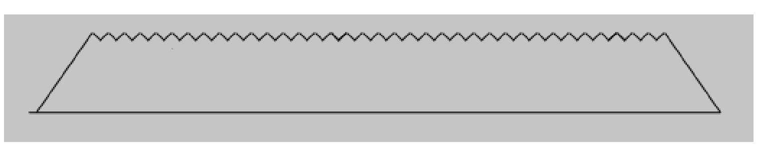
- **Three Phase**
- **14% Ripple**



Three phase equipment is very expensive as is the service coming into the x-ray room to operate it. High frequency generators use an inverter to convert single phase waveforms to nearly constant potential voltage waveform. High frequency generators are smaller and more cost effective than three phase generators and more efficient single phase machines.

Direct Current – Full wave rectification

- **High Frequency**
- **4% Ripple**



NOTES

Chapter 4 Quiz
X-Ray Physics/ EOM

1. X-rays were discovered in 1895 by:
   A. Coolidge.
   B. Crookes.
   C. Roentgen.
   D. Edison.

2. The inventor of the hot cathode x-ray tube was:
   A. Crookes.
   B. Edison.
   C. Roentgen.
   D. Coolidge.

3. The filament of an x-ray tube is made of:
   A. glass.
   B. a coil of stainless steel wire.
   C. a coil of tungsten wire.
   D.a fluorescent tube.

4. The target of the x-ray tube is made of:
   A. tungsten.
   B. glass.
   C. stainless steel.
   D. fluorescent phosphors

5. An “electron cloud” surrounding a hot cathode is referred to as a:
   A. focusing cup.
   B. photon.
   C. filament.
   D. space charge.

6. Free electrons for x-ray production come from the:
   A. filament.
   B. target.
   C. anode.
   D. kilovoltage.

7. The principle underlying the creation of a space charge in the x-ray tube is:
   A. electromagnetic induction.
   B. variable resistance.
   C. thermionic emission

8. The anode, or target, of the x-ray tube is ______ charged.
   A. positively
   B. negatively
   C. neutrally
   D. radioactively

9.The cathode end of the x-ray tube is ______ charged.
   A. positively
   B. negatively
   C. neutrally
   D. radioactively

10. What is the principle advantage of a high-speed rotating anode?
   A. More efficient production of x-rays
   B. Increased amount of characteristic radiation produced
   C. Increased amount of bremsstrahlung radiation produced
   D. More efficient heat dissipation

11. More than 99% of the energy applied to an x-ray tube is converted into:
   A. bremsstrahlung radiation.
   B. characteristic radiation.
   C. secondary radiation.
   D. heat.

12.Which of the following are the types of radiation produced at the anode?
   A. Thermionic emission and heat
   B. Electromagnetic and thermal
   C. Characteristic and bremsstrahlung
   D. Remnant and scatter

13. What type of radiation is produced by the sudden slowing and direction change of the electron stream as kinetic energy is converted to other energy forms?
   A. Characteristic radiation
   B. Scatter radiation
   C. Bremsstrahlung radiation
   D. Thermionic emission

14. What type of radiation is formed within the target atoms as a result of interactions with an inner-shell electron?
   A. Characteristic radiation
   B. Scatter radiation
   C. Bremsstrahlung radiation
   D. Thermionic emission