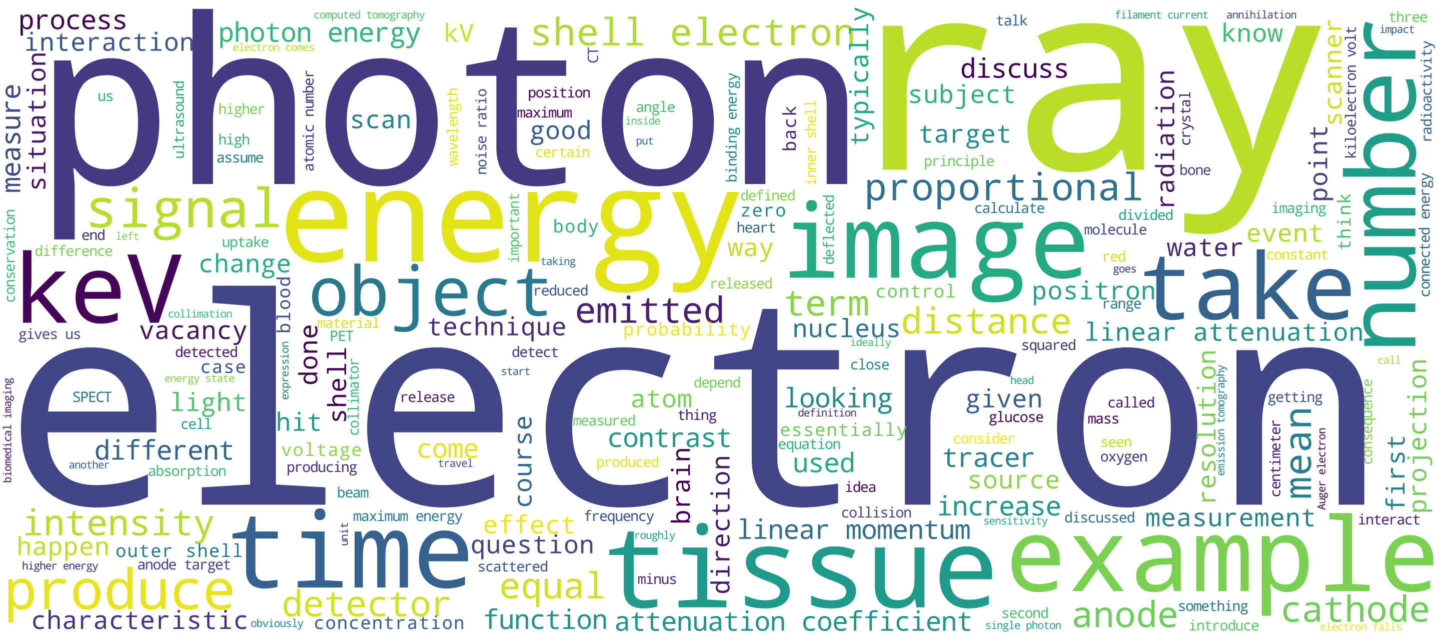
2.4 Generation of medical x-rays

Fundamentals of Biomedical Imaging

Prof. Rolf Gruetter



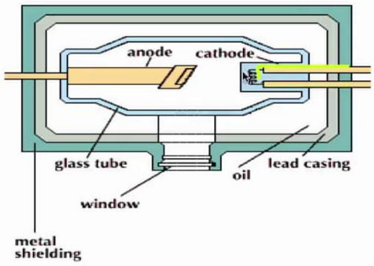
Search MOOC

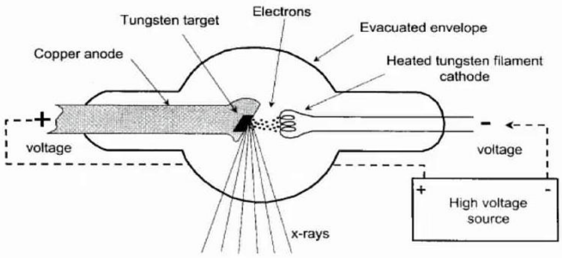
Video

2-4. How are x-rays generated (scheme) ?

Negatively charged cathode = electron source

- Electrical current (filament current) heats up the cathode (why is that necessary ?)
- Electrons are liberated and accelerated by electric field (Energy of $e^- = q\Delta V$)





2-16

Now, I want to briefly talk about the process of generating x-rays. It's very schematic what I will introduce here, I'm mainly keen on discussing two major effects that we have, two major experimental parameters that are under the control of the experiment. And so, we are having here a negatively charged cathode, that's the source of the electrons. We have a filament here and we use an electrical current that runs through the filament, here in green, that is heating up the cathode. So why is this necessary? Why do we need a current here? Well, think about it, we are in the end-- what we want to do is we want to produce x-rays and the x-rays, the production, is been done as we'll see shortly by the release of electrons from the cathode. If we heat up the cathode, we increase the connected energy of the electrons and therefore the probability that an electron is being released. Then, what happens between the cathode and anode, the electrons are accelerated by the electric field, the energy of the electron its charged times the voltage difference between cathode and anode, so that gives us the electron-volts, here is the charge, this is a fairly high charge negative here, positive here, so the electrons are being emitted from the cathode and attracted towards the anode.

Notes

Summary

0m 03s

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2-4. How are x-rays generated (scheme) ?

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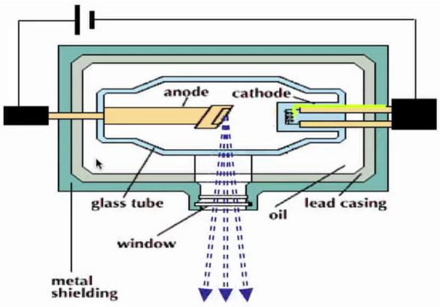
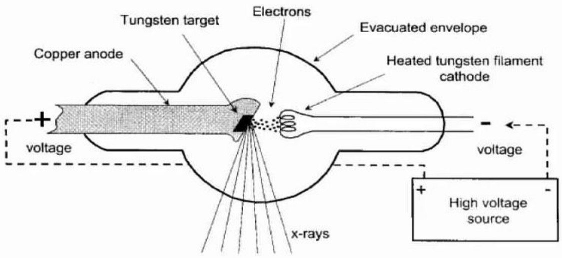


Anode = metal target (tungsten)
- accelerated electrons hit anode ⇒ generate X-rays
  - (tube current with voltage difference up to 150 kV)

Intensity of beam = Power/Area
1. Number of X-rays (proportional to tube current)
2. Energy of X-rays $h\nu$ (proportional to voltage)



2-16

So, in the anode we have a target and this is a metal target typically it's Tungsten, we'll discuss in a short while why-- So, they heat the anode and then it's the voltage between cathode and anode is up to 150 kiloelectron volts (keV)-- up to 150 kilovolts (kV). So, this electrons as they interacted with the target here the metal target, they will produce x-rays. And this x-rays are then emitted and used for imaging. Now, in this animation that you see here, let's not be fooled, the x-rays that are produced in the anode target they go in all sorts of directions, while we have metal shielding of the x-ray tube here, we are just leaving a window open here, so it's only through that window that the x-rays can penetrate and produce a beam of x-rays in the direction. Typically, the intensity of the beam is expressed as power per area, it is proportional, the beam is proportional to the number of x-rays, the number of x-rays is proportional to the number of electrons that hit the target, and the number of electrons that hit the target, the anode here, is proportional to the current in the cathode, so the filament current. The energy of the x-rays is somehow related to the voltage difference between anode and cathode, here and here.

Notes

Summary

1m 35s

2-4. How are x-rays generated (scheme) ?

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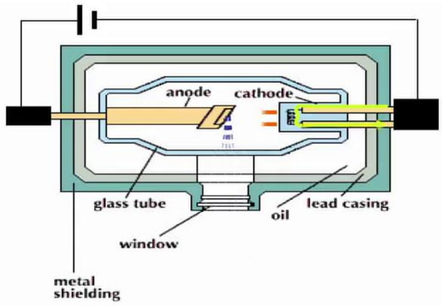
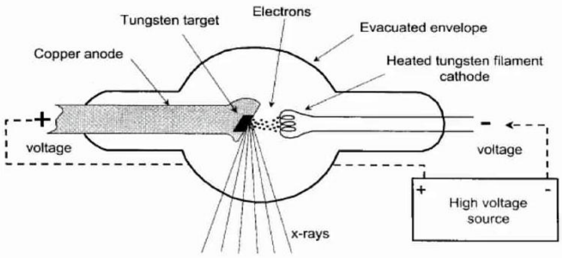


Intensity of beam = Power/Area

1. Number of X-rays (proportional to tube current)
2. Energy of X-rays hν (proportional to voltage)



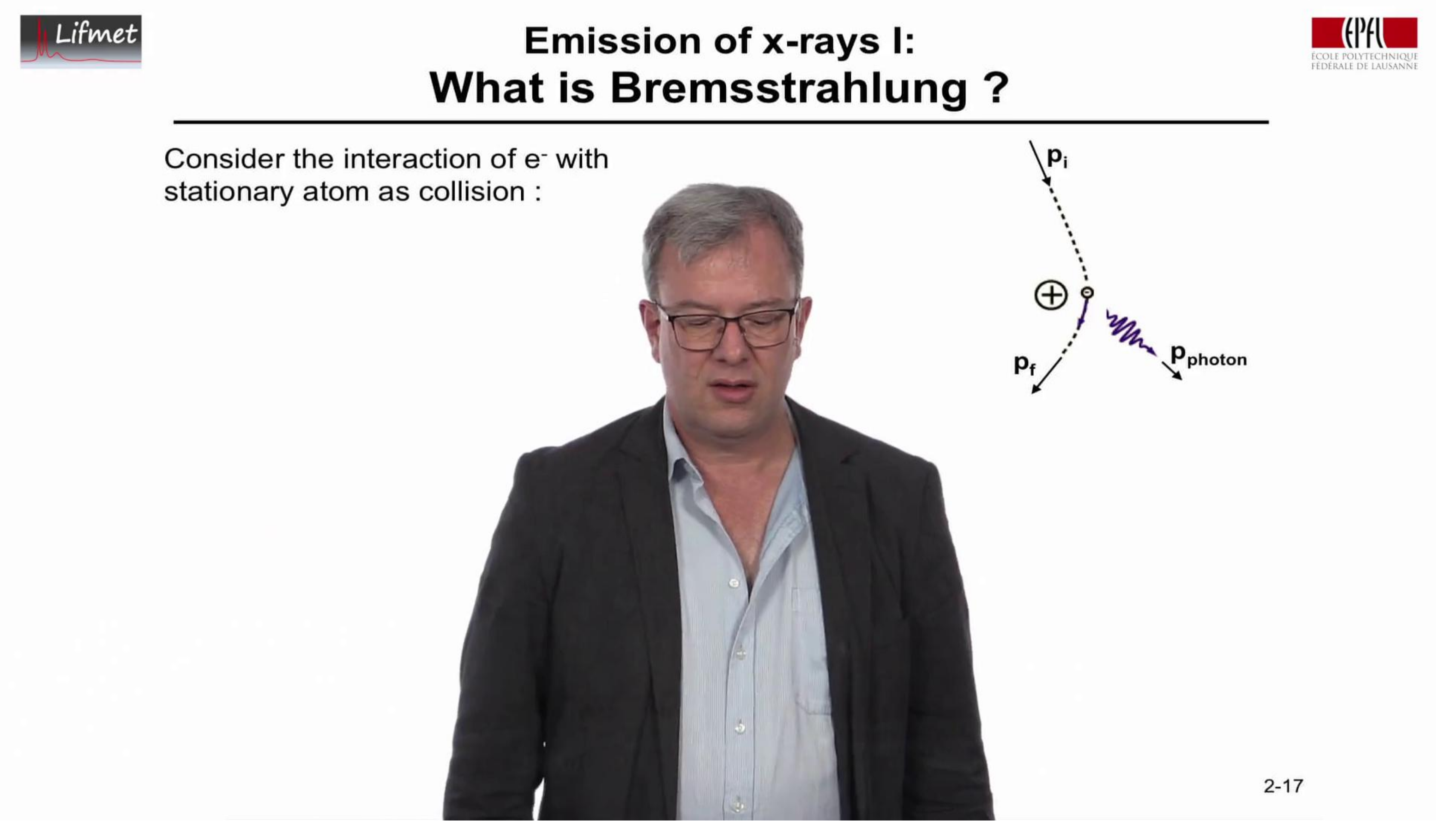
2-16

If we have 150 kV, then we produce electrons with an energy that hit the target of 150 keV. If we use only 50 kV, then, the energy of the electrons as they hit the Tungsten target is 50 keV. So this are the two things that we can control, we can control the filament current and so increase the tube current that is increasing the number of electrons and therefore the number of photons per second that are being emitted and with the voltage between the cathode and the anode we control the maximum energy of the photons that are being emitted, that is we control the energy of the electrons when they hit target. Here is just a scheme showing the same thing again, we have the filament current, we have the anode target the voltage between here and the whole thing is an tube in the vacuum, otherwise the electrons will never see their target.

Notes

Summary

3m 05s

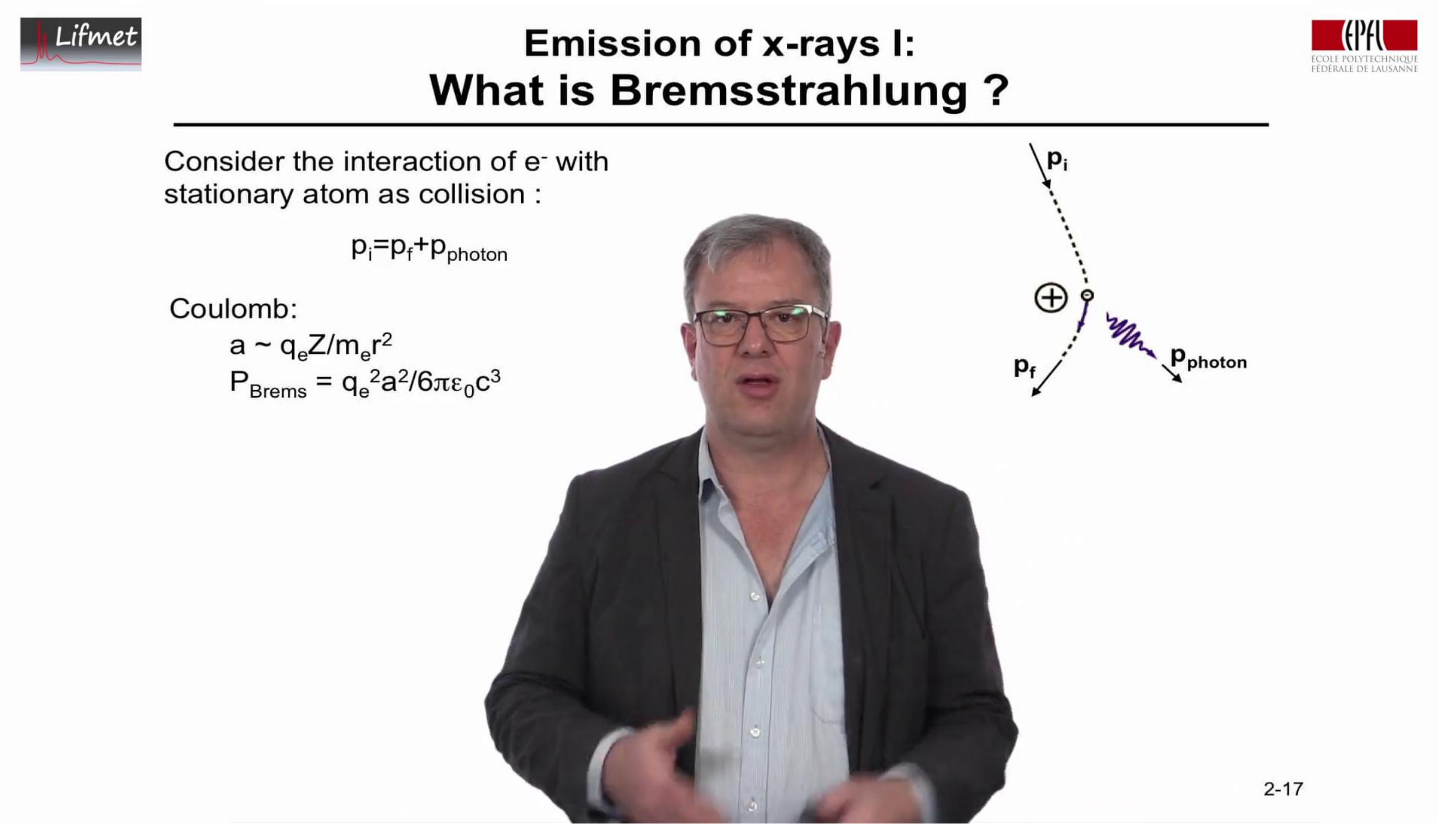


Now, ideally I said the electrons have an energy of 150 keV and ideally this will produce x-rays of energy for each photon, for each electron that hits the target of 150 keV. That would be the ideal case, but this is not the reality and we are going to have to look at the emissions of x-rays generated in the x-ray tube, and we are going to look at the interaction of the electron with the stationary atom. We'll look at this as a collision so we have a nucleus here, we have the electrons as it comes in, it is attracted by Coulomb force, so it changes direction. Now, when it changes direction we have, we can look at this as a collision, we have at the beginning, we have the atom stationary we have the electron with a certain linear momentum, it leaves after it has passed by the nucleus with another momentum, but now as it has been deflected, the momentum has changed. In conservation of linear momentum as a collision, requires that there is another object with a linear momentum that is involved in this collision and that's the emission of a photon. So, we have conservation of linear momentum and initial linear momentum of the electron as equal to the final momentum of the electron plus the momentum of the photon.

Notes

Summary

4m 08s



Now, if you look at Coulomb, I'm just going to talk here, Coulomb basically says, the Coulomb force says that the electron is subjected to an acceleration which is proportional to the charge of the electron, *Qe*, proportional to the atomic numbers, *Z*, the number of photons and nucleus, divided by the mass the electron and the distance to the nucleus. So the acceleration of the electron that is in changing linear momentum can not, a priori, have the need to be defined, we won't be getting 150 keV. It depends on where the electron is deflected with a nucleus, how close this interaction is, by how much is it deflected, etc... So, we do not, a priori, know what this distance are, so, we will not get a fixed acceleration so we'll not get a fixed photon energy, we'll get a mixed of photon energy. The way you can imagine this is, the electron comes to the target the anode target, it's deflected, releases a photon then a few micrometers later or a few atoms later, it interacts with the next nucleus and it's deflected again and it releases again a photon, and so on, and so on. So there is a subsequent release of the photon until an electron essentially comes to rest, but not a single photon, in general, has been released.

Notes

Summary

5m 38s

Emission of x-rays I:
What is Bremsstrahlung ?

Consider the interaction of e^- with stationary atom as collision :

$$p_i = p_f + p_{photon}$$

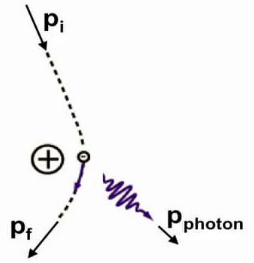
Coulomb:

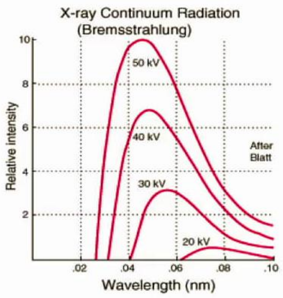
$a \sim q_e Z / m_e r^2$

$P_{Brems} = q_e^2 a^2 / 6\pi\varepsilon_0 c^3$

No info on directionality of radiation

(but maximum energy is defined, how?)





2-17

So, we have from this laws, we have neither the information of the directionality of radiation, nor on the photon energy that it's been released. So, but we do know a maximum value for the energy of the photon that has been released. How is this defined? Well, the definition here is this, we have the electron comes in with the connected energy of 150 keV and let's assume, it is by whatever process in the anode target, it's immediately stopped. Then the energy of the electron is converted into the energy of the photon and that equals to the energy of the electron, if you have 150 kV at the anode cathode, the energy of the electron 150 keV by conservation of energy the maximum photon energy is 150 keV. So, this effect of that the electron is subsequently decelerated, loses its connected energy, this is a braking effect on the electron and the term for this, that has been used, is Bremsstrahlung, it's a German term which basically means braking radiation. Why it's German? Well this is historical, until 1945 Germany was a leading country in physics so, that's why we are with German terms.

Notes

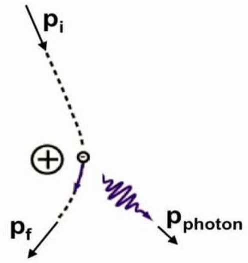
Summary

7m 11s

Emission of x-rays I:
What is Bremsstrahlung ?

Consider the interaction of e^- with stationary atom as collision :

$p_i = p_f + p_{photon}$



Coulomb:

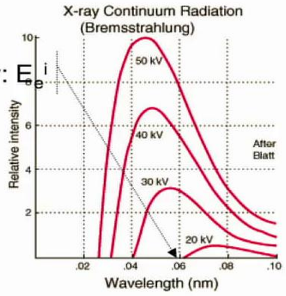
$a \sim q_e Z / m_e r^2$

$P_{Brems} = q_e^2 a^2 / 6\pi\varepsilon_0 c^3$

No info on directionality of radiation

(but maximum energy is defined, how?)

Max. Energy: $E_{e^-}^i$



Decreasing energy

Elastic scattering:

Probability ~ Z^2/E_{e-}^2

Inelastic scattering: γ release

Probability ~ Z^2

High Z: Tungsten is a good target

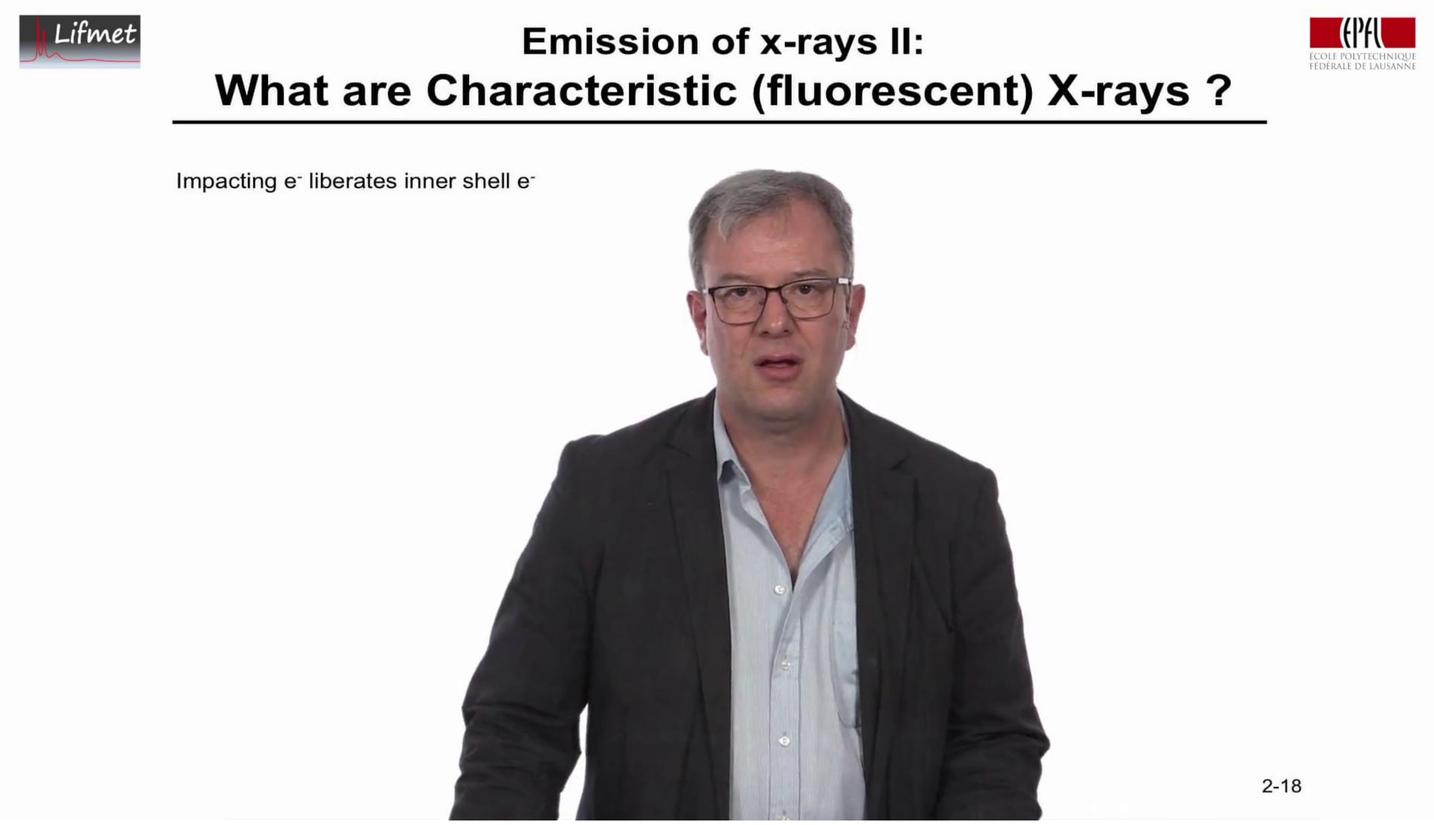
2-17

So, if you now look at the relative intensity of this Bremsstrahlung as a function wavelength, then we have decreasing energy to the right, so the highest energy is on the left, and as we can see here, the maximum energy for a voltage of 50 kV is 50 keV, this is the maximum energy that we have here. As we decrease the voltage, to 40 kV the maximum energy is reduced, we can not go higher than that maximum energy of 40 keV, we got 30 kV we are now here, and finally 20 kV. So we have this spectrum of focal energy for a giving wavelength that's giving energy, and this is what is called the Bremsstrahlung continuum. Now, we have the *elastic scattering*, I don't want to talk too much about it, we have, the probability is proportional to Z, the atomic number squared divided by the energy of the electrons squared, and then we have *inelastic scaterring*, there the probability is proportional Z^2 inelastic scaterring, meaning that we have the electron which is releasing a photon. So what does this mean if it is proportional to Z^2? It means to generate as much Hertz-electron as many photons. Hertz-electron, we want to use a material with high Z and this is, the explanation here is why Tungsten is a good target, it has a high atomic number a high number of photons in the nucleus.

Notes

Summary

8m 38s

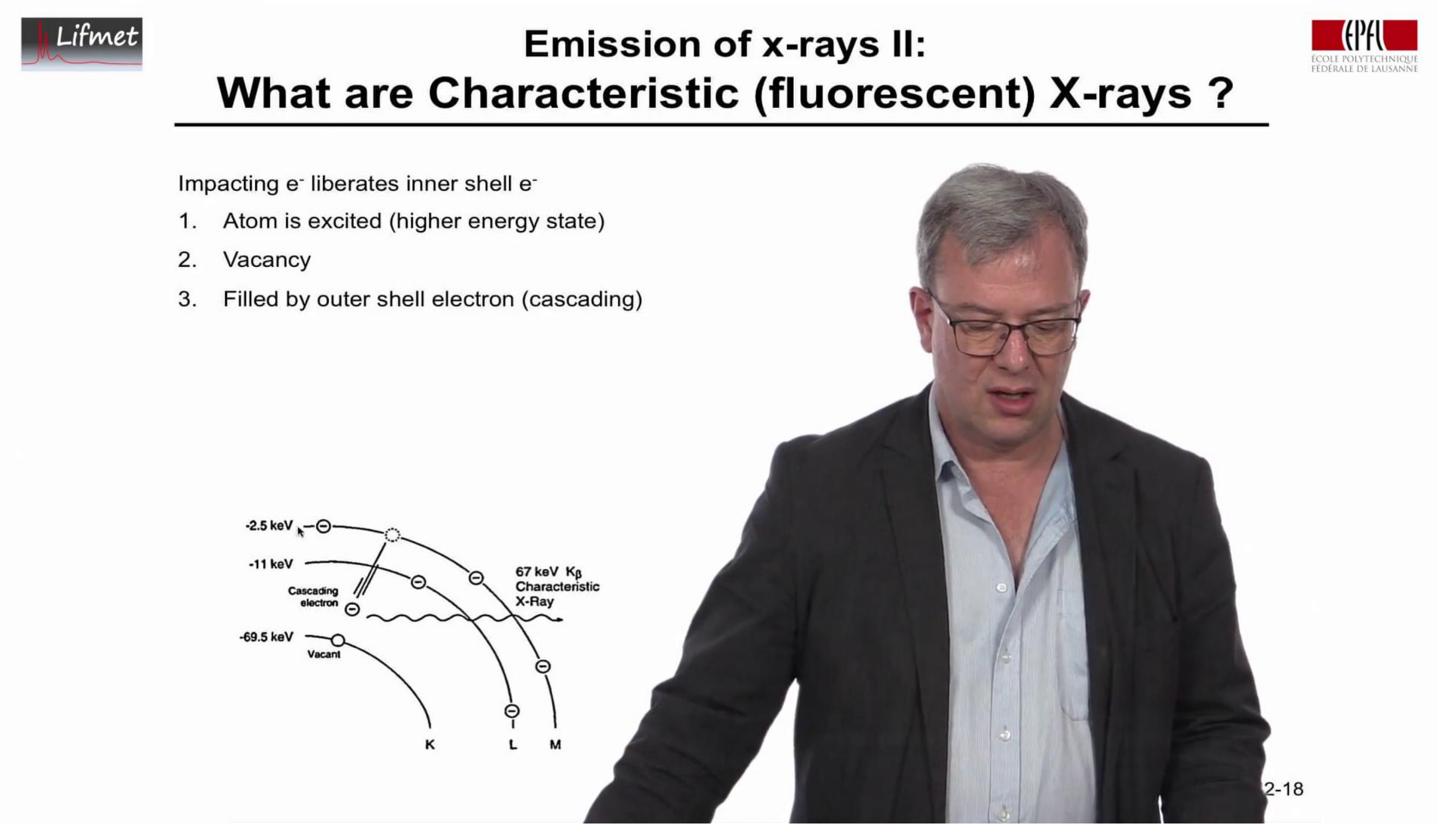


So far, we've talked about the Bremsstralhung continuum we've explained why this braking of the electrons in the tissue is not deterministic in defining a precise x-ray energy, and there is another effect that I need to discuss here, that characterize the x-ray spectrum and this is the question of what are the characteristics of these fluorescent x-rays. The mechanism that we are looking at this, we have the electron that interacts with the atom and here the interaction is reminiscent of playing billiard. Think of the electrons that comes in like a billiard ball, it hits another electron like another billiard ball, that inner shell electron is then bumped out of its shell and leaves the atom.

Notes

Summary

10m 21s



What does this mean now that the atom is excited, it is in a higher energy state, it's no longer has in the K-shell its electron, so it is a higher energy state, in other words, we have a vacancy in the K-shell, for example, so to recap, the electron comes in, bumps the K-shell electron out of the K-shell, creates a vacancy, so there is a spot to be filled and here is the process that happens, that this inner shell electron is vacancy here, at this point, is being replenish by an outer shell electron, That's called cascading, so it can be not just one, but here is the case of one, we have created this vacancy by a collision, the electron is missing, the atom has a higher energy state so, it wants to go back to its ground state, so an outer shell electron here from the M-shell falls down into the K-shell here and as it does so, it will release a photon whose energy is exactly the difference in binding energy. Here we have 2.5 keV of binding in the M-shell, we have 69.7 keV in the K-shell the difference in energy is giving off as a single photon that's the characteristic x-ray and this will have, and you can do the math here, is exactly 67 keV K-shell x-ray.

Notes

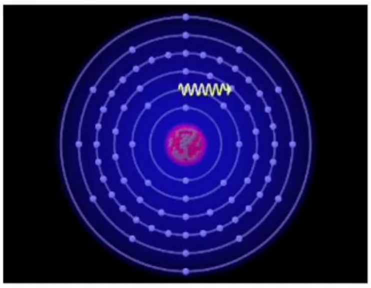
Summary

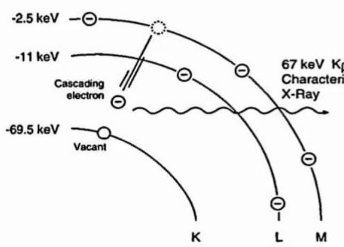
11m 08s

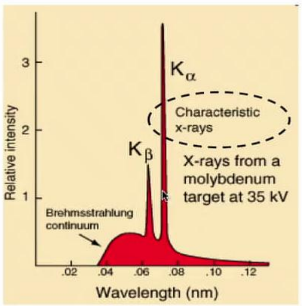
Emission of x-rays II:
What are Characteristic (fluorescent) X-rays ?

Impacting e^- liberates inner shell e^-

1. Atom is excited (higher energy state)
2. Vacancy
3. Filled by outer shell electron (cascading)
4. Emission of characteristic x-ray







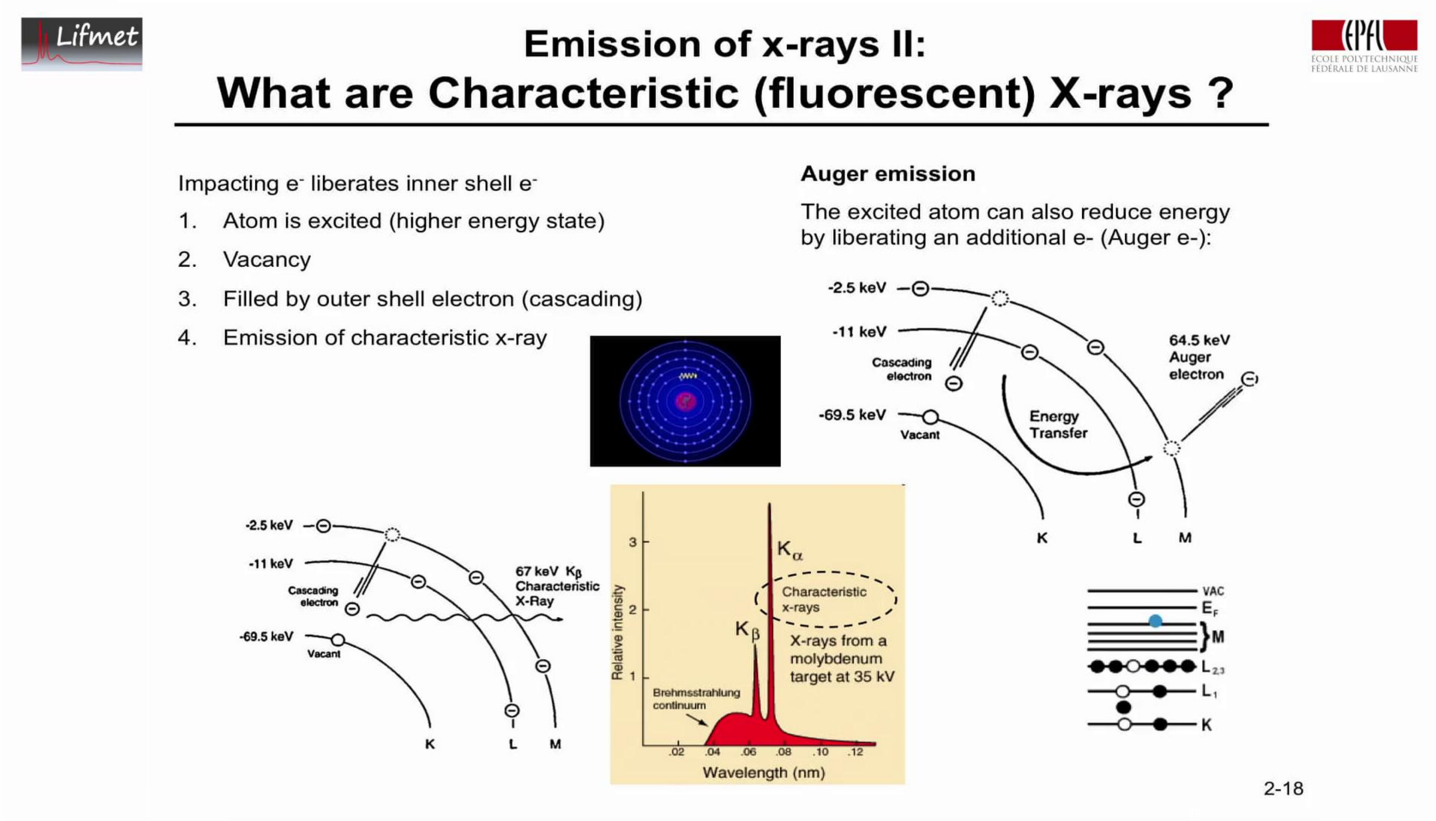
2-18

Now looking here, this is graphically illustrated here, we have the electron that impacts the K-shell electron so, it plays billiard, the two electrons leave the atom and then you see that the outer shell electron falls into the K-shell and as it does so, it releases the characteristic x-ray with a very defined frequency. So, as a consequence if we look at the relative intensity of the emitted x-rays from a target, here is the molybdenum target, bombarded with electrons with energy exposed to 35 kV, we have the Bramsstrahlung continuum that we've discussed in the preceding slide, and then we have these characteristics x-rays spikes here, as pointed out here, the energy difference between the energy levels is very precise, so this will produce a very precise photon and this are those characteristics or fluorescent x-rays that are added to the spectrum of the x-rays that are being produced.

Notes

Summary

12m 35s



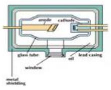
Now, there is one effect that I'd like to discuss, I've just mention here, this is Auger emission. So if you have an excited atom here, on the beginning we have the vacancy, we have the excited atom. Now, instead of producing a cascading electron falling down when the electron falls down into the inner shell, and producing a photon, instead of producing a photon this can also result in an emitted electron. So, the energy instead of being transferred here to a photon, it's here transferred to an outer shell electron and this produces an Auger electron. So we have seen here, this is 67 keV energy difference, which produces 67 keV characteristic x-ray and here we're having an Auger electron from the M-shell at 64.5 keV. It's reduced because we have to take into account that the binding energy has to be overcome, so it will have connected energy of 64.5 keV. This is Auger emission and that electron, of course, will then, diffuse and interact with the Tungsten target. And as if it were an electron coming from the outside at 64.5 keV. So, here is the process in this animation, the Auger process illustrated, we have here initial state, we have the *Incident electron* that produces the vacancy here, in the K-shell, as the electron falls into the K-shell and an L-shell electron here is emitted, as a Auger electron.

Notes

Summary

13m 43s

Credits



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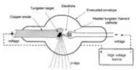
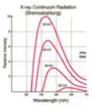
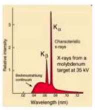
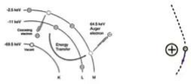
http://hanialtanbour.com/electronic/theori/156.htm



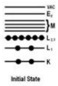
“The Essential Physics of Medical Imaging”
Fig. 5-1, from Jerrold T. Bushberg, J. Anthony Seibert, Edwin M. Leidholt, John M. Boone

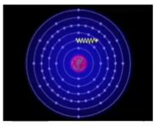
X-Rays
http://www.wikiradiography.net/page/Characteristics+and+Production+of+X-rays



“The Essential Physics of Medical Imaging”
Fig. 2-6, from Jerrold T. Bushberg, J. Anthony Seibert, Edwin M. Leidholt, John M. Boone



Surface structure determination
http://leung.uwaterloo.ca/MNS/102/Lectures%202007/SSNT-4-Surface%20Structure%20Determination%20Techniques%20I.htm



K X-Ray Production *(video extract)*
https://youtu.be/n9FkLBaktEY

Now, this concludes the introduction of the generation of x-rays, and in the next week we will discuss the interaction of x-rays with tissue, the principal modes will be discussed, we'll introduce some important relationships and as well, include a small primary on x-rays safety considerations and protection procedures.

Notes

Summary

15m 29s