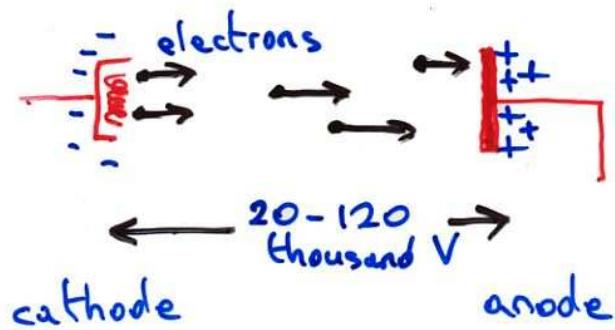


X-ray circuits (ch 9 of text)

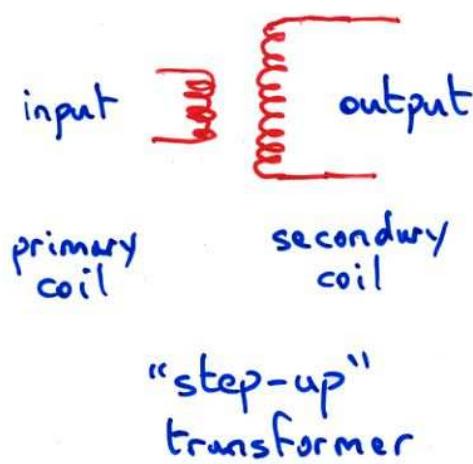
Overview: take mains power, convert to high-voltage DC for electron acceleration
use some power to heat filament at cathode to release electrons



Electricity is used to:

- heat filament at cathode
- accelerate electrons to high energies
- rotate anode
- control and monitoring

Voltage conversion achieved using transformers:



"step-down"
transformer

NB/ current through primary must vary with time
to create (varying) current in secondary

The ratio of voltages is determined by the turns ratio:

$$\frac{V_{sec}}{V_{prim}} = \frac{N_{sec}}{N_{prim}}$$

(assuming 100% efficiency)

turns ratio

↑ "output" or "secondary" voltage ↑ "input" or "primary" voltage

e.g. primary has 500 turns, secondary has 400,000.

What is the turns ratio? $\frac{400,000}{500} = 800$

The input voltage is 200V. What is the output voltage?

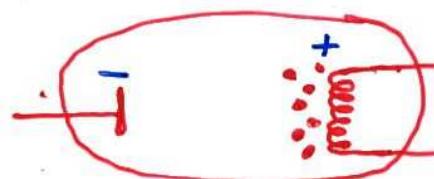
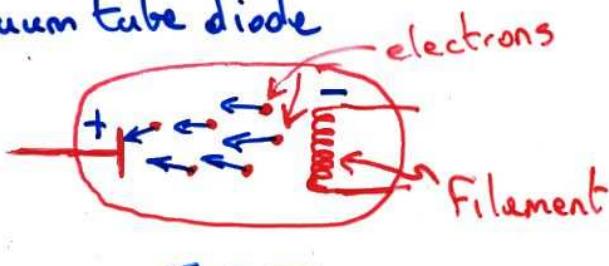
$$800 \times 200V = 160,000V$$

Rectification

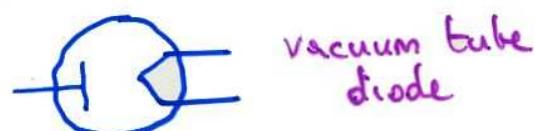
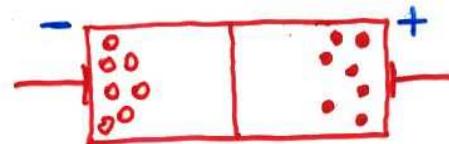
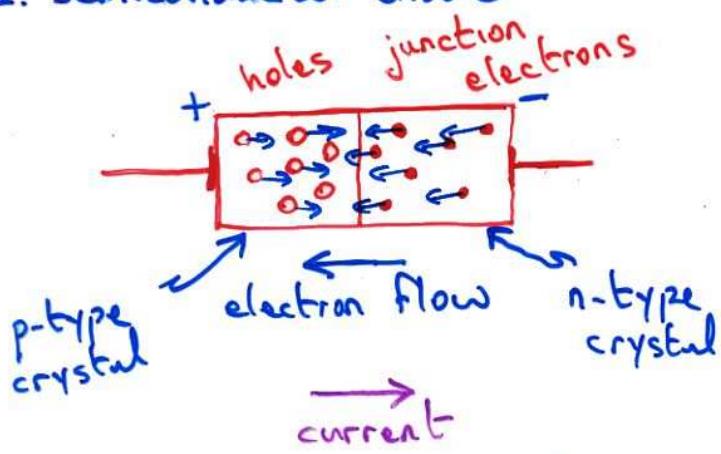
- convert alternating current to direct current
 - ↑ alternates flow direction
 - ↑ flows in 1 direction only
- ideally can supply constant DC voltage to the cathode-anode pair (\Rightarrow X-rays steady)

rectifier - high-voltage ^{device} component that allows current to flow in only one direction
 - uses diodes

1. vacuum tube diode



2. semiconductor diode

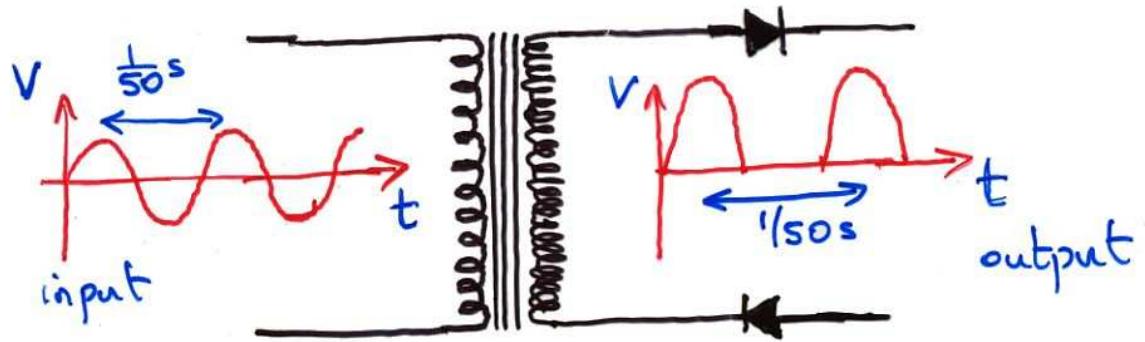


vacuum tube
diode

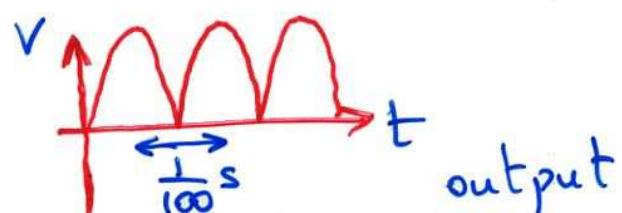
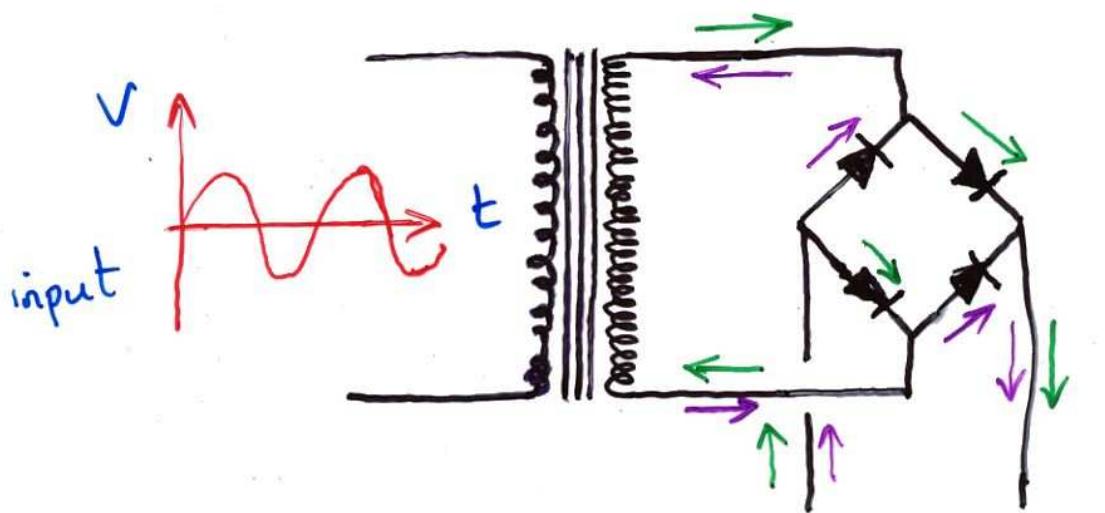


semiconductor
diode

yes!
no!



half-wave rectification
- inefficient



full-wave rectification
- efficient, but output has large voltage fluctuations

⇒ X-rays fluctuate

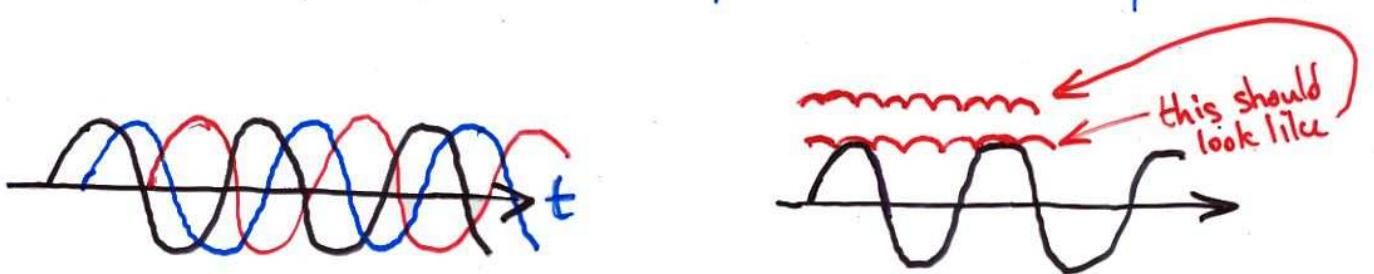
[an X-ray pulse every $\frac{1}{100}$ sec]

low $V \Rightarrow$ low X-ray flux, (also lower energy X-rays)

⇒ exposure takes longer

Three-phase power

- generate three sinusoidal wave forms out of phase with each other
- Fully rectified \Rightarrow 6 overlapping pulses per cycle ~~rather~~
(cf 2 non-overlapping pulses)
 \Rightarrow smoother production of X-rays



Jiggle of voltage after rectification is called ripple, expressed as $\frac{V_{\max} - V_{\min}}{V_{\max}} = \frac{\Delta V}{V_{\max}}$

single phase, fully rectified 100%

three-phase, fully rectified
six pulse 13%

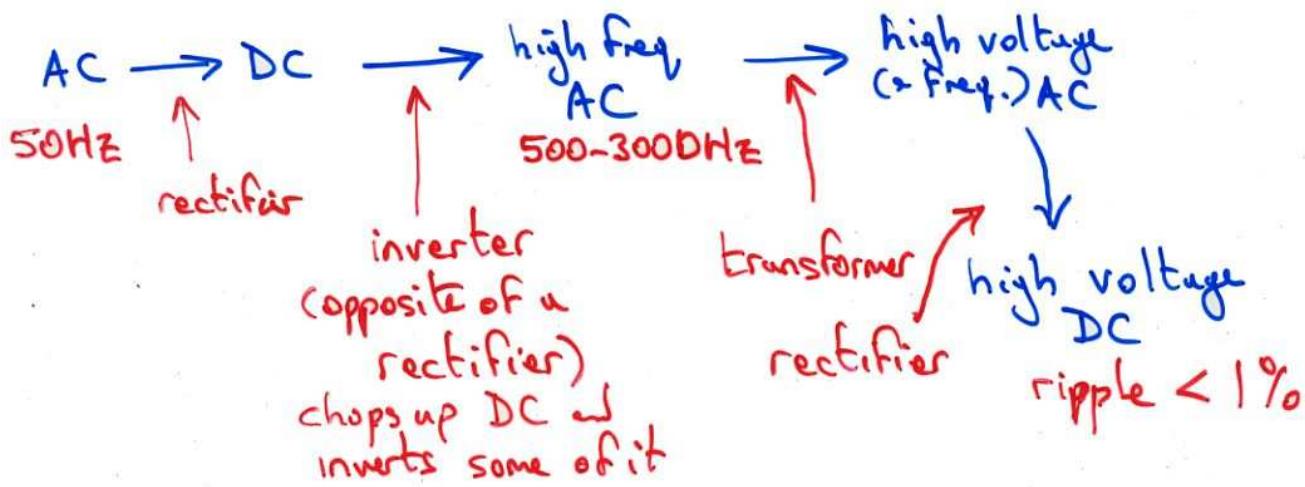
three-phase, fully rectified
twelve pulse 4%

less ripple \Rightarrow higher radiation quantity and quality

High frequency AC

at higher frequencies

- transformers more efficient, so can be made much more compact and lighter.
- convert to DC with much less ripple: improves image quality at lower doses
- now common.



kV_p selector - determines voltage for e⁻ acceleration by controlling voltage input to step-up transformer
peak

mA selector - determines tube current by controlling input voltage to step-down transformer whose output drives the filament.

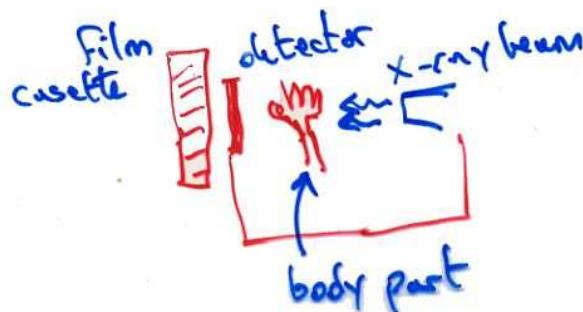
Timing circuits - cut off high voltage applied to tube after a certain exposure time

1. Automatic exposure control (AEC)

- monitors radⁿ striking film and turns off x-ray production when exposure is sufficient
- usually 3 detectors (ionisation chambers, scintillators, or solid-state detectors), select 1, 2 or 3 of them depending on geometry
- must be calibrated for a given film/screen combination
- detectors have to be correctly positioned
- can adjust to modify overall exposure, i.e. density of exposed film
- set mA & time, or mAs

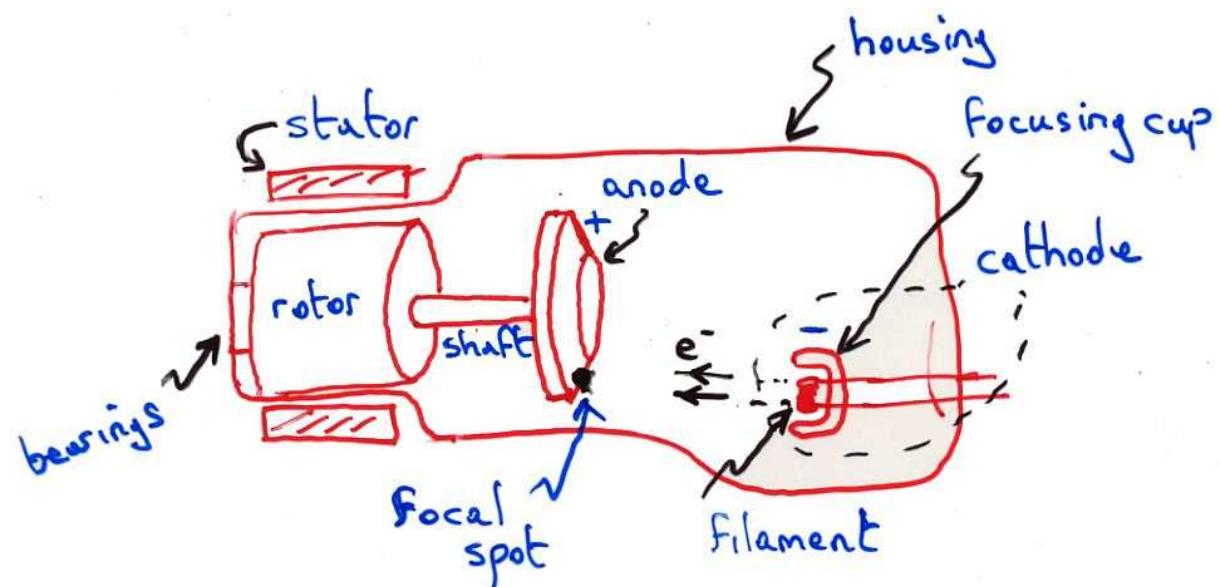
2. Backup timer

- terminates exposure (typically after 5 sec)
- in case AEC does not work (e.g. misalignment)
- prevents tube failure
- avoids x-raying the patient more than they need.



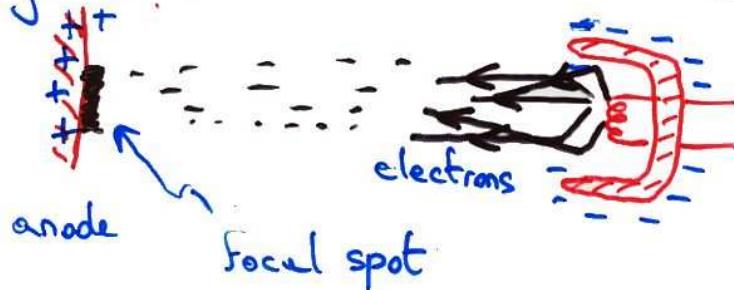
X-ray tubes (ch 10)

- housing is glass or metal, surrounded by oil
metal preferred as glass picks up a tungsten coating
 - ↳ electrical insulation
 - ↳ cooling
- evacuated (i.e. no air)
air slows electrons
- shielded except at window
standard is < 100 mR/hour at 1m, except from window
- interior contains cathode
filaments (large + small)
anode, shaft and rotor



Cathode

- large and small filaments sit in focussing cup



- Filament is heated to high temperature to "boil off" electrons: thermionic emission

- Filament = tungsten coil

- heating controlled by the filament current, 2-5A

NB tube current, or projectile electron current, is called the milliamperes, mA (50-800mA), and is proportional to # of e^- striking anode per second, so is prop. to X-ray production rate

- tube current depends on rate e^- boil off filament, which is controlled by the filament current

- X-ray intensity is limited by heating of anode at focal spot. Small spot is good for imaging but bad for the anode at high tube current.

small filament \Rightarrow small spot. Less intense X-ray beam
but better imaging $< 1\text{mm}$

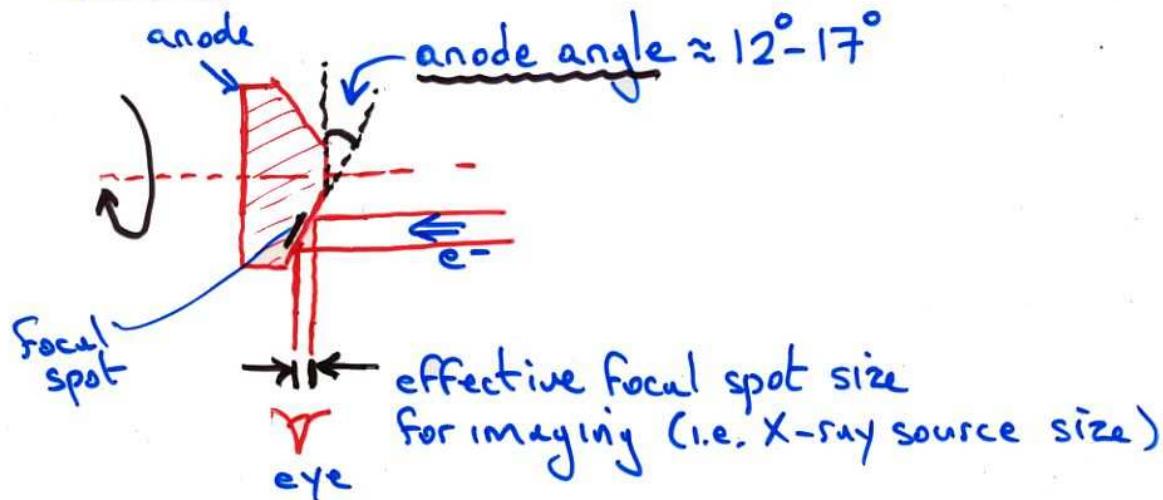
large filament \Rightarrow large spot. More intense beam, worse imaging.
 $1-3\text{mm}$

(Select size manually, or autoselection based on mA)

The focal spot

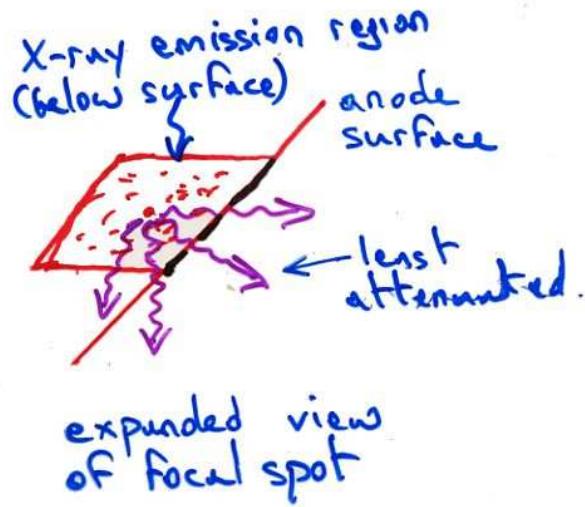
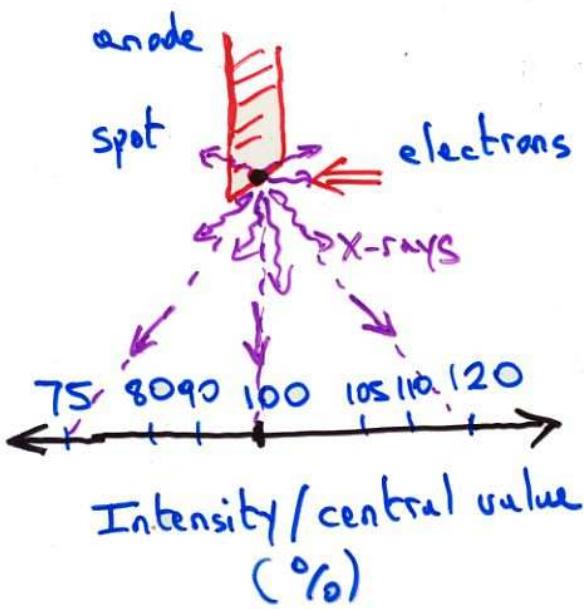
1. Line Focus principle

- use geometry to get a small effective spot size but a larger dissipation area by angling the anodes surface



2. The heel effect

- X-rays are produced below the anode surface
 \Rightarrow X-rays not isotropic because of attenuation in the anode $\sim 40\%$ variation



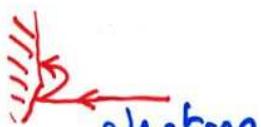
Heel effect \Rightarrow imaging field has varying X-ray intensity across it \Rightarrow density variation in image

- smaller anode angle
 - larger field size
 - shorter source-to-image distance
- } all make it worse

Can exploit this by putting thicker bit of body part on the cathode side of the tube.

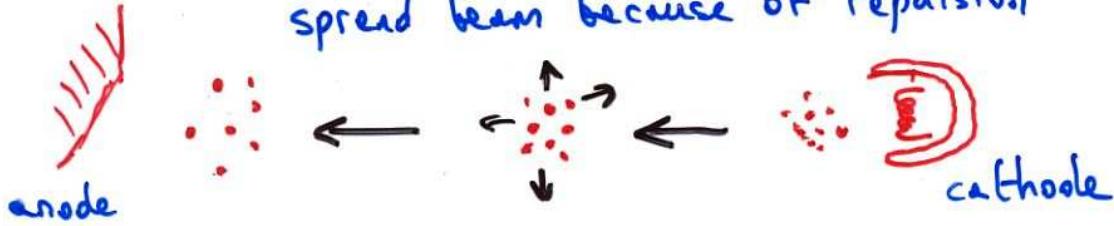
3. Off-focus radiation

- electrons hitting anode outside of focal spot also create X-rays
- would blur image, but attenuated by tube housing and collimator near window



4. Blooming of focal spot

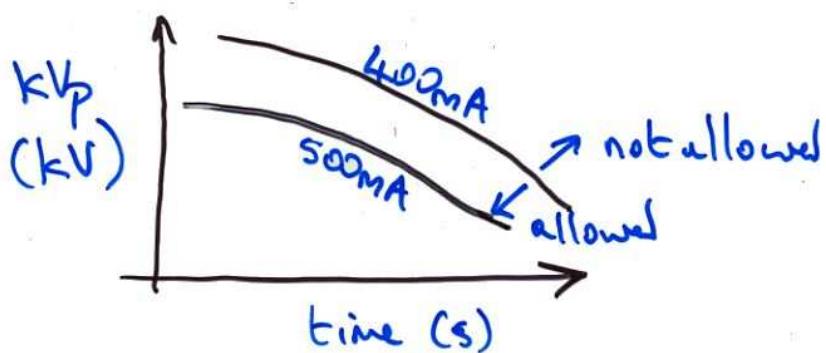
- at high mA, electron number high enough to spread beam because of repulsion



- only significant for low kVp & high mA
chosen together

Tube max. heat load is specified in HU. Exceed this and get into trouble! melting, cracking

Heat limit curves are more precise - show what combinations of kVp, mA & s are allowed.



- also depends on spot size, as a larger spot helps
- modern equipment will forbid settings that would damage tube in one exposure but multiple exposures can still overload it!
- sometimes have an anode heat monitor

Warm-up procedures

- avoid thermal expansion problems
anode-cracking, filament failure, bearing damage

- e.g. two 70kVp - 100mA - 2s exposures

↑ ↑ ↑
low low long

- should be done if idle for \geq 2 hours

Heating of the anode

~99% of KE of incoming electrons converted into heat

∴ total heat deposited during an exposure, heat load

$$= \frac{\# \text{ of } e^- \text{ arriving}}{\text{unit time}} \times \frac{\text{exposure time}}{\text{time}} \times \frac{\text{energy per electron}}{\text{electron}}$$

$$= \frac{\text{charge arriving}}{\text{per unit time}} \times \frac{\text{exposure time}}{\text{time}} \times \frac{\text{energy per unit charge}}{\text{unit charge}}$$

$$= \frac{\text{current}}{\text{C/s}} \times \frac{\text{exposure time}}{\text{s}} \times \frac{\text{potential difference}}{\text{J/C}}$$

$$\text{Heat unit, HU} = \text{Fudge} \times kV_p \times mA \times \text{seconds}$$

kilovoltage tube current
 peak voltage in kV in mA

exposure time in seconds

accounts for % variation in voltage (ripple)	less ripple	1	single-phase (full wave)
		1.35	three-phase, six pulse
		1.41	three-phase, twelve pulse or high frequency circuit

e.g. single-phase $\left. \begin{array}{l} 100 \text{ kVp} \\ 200 \text{ mA} \\ 0.1 \text{ s} \end{array} \right\} \text{heat load} = 100 \times 200 \times 0.1 = 2000 \text{ HU}$

With the same settings, but a high freq. circuit

$$\text{heat load} = 1.41 \times 2000 = 2820 \text{ HU.}$$

- grid-controlled tubes are used for very short exposures
 apply voltage to trap e^- near filament,
 switch on & off to make bursts of x-rays

Anode

- when electrons are stopped at the focal spot,
 $\approx 99\%$ of KE \rightarrow heat $\leftarrow T$ rises to $\approx 3000^\circ C$
 $\approx 1\% \dots \rightarrow X\text{-rays}$ during an exposure
 6-15cm across
- anode is disc-shaped, rotates at 3600 rpm or more to disperse heat deposited at spot, and is made of Tungsten-based alloy (melts at $3400^\circ C$)
 x-ray efficiency larger for large Z , so Tungsten is good on that basis too.
- anode, shaft + rotor spin at 3600 rpm during exposure
 ↑
 molybdenum (low heat conductivity)
 rotor bearings can fail due to heat
- spun by an induction motor
 ↑ allows vacuum to be maintained
 stators - electromagnets fixed on outside of housing

