X-ray Tube and Generator –

Basic principles and construction

Dr Slavik Tabakov

King's College London

H.V. X-ray Generator → X-ray Tube → X-ray entrance Spectrum → Object Patient → X-ray exit Spectrum → X-ray stand (detector)

OBJECTIVES

- Production of X-rays
- X-ray tube construction
- Anode - types, efficiency
- X-ray tube working characteristics
- Intensity of X-ray beam, housing and filtration
- Classical X-ray generator (block diagram)
- Medium frequency X-ray generator (block diagram)
- Principle of radiographic contrast formation
- X-ray film and film/screen combination
- Mammographic contrast and X-ray tubes
- Various radiographic contrasts (definitions)

Table 2. Annual exposure of the UK population from all sources of radiation.

Source	Percentage
Natural	
Radon gas	50
Gamma rays from rocks and soil	14
Radionuclides in food and drink[a]	11.5
Cosmic rays	10
Artificial	
Medical x-rays	13
Nuclear medicine	1
Occupational[b]	0.3
Fallout from nuclear weapons tests	0.2
Nuclear discharges[c]	<0.1
Consumer products	<0.1

[a] Mainly potassium-40.
[b] About 80% from natural sources.
[c] About 20% from natural activity.

In most industrialised countries there are between 300 and 900 X-ray examinations for every 1000 inhabitants every year. Over half of these are chest examinations (these figures does not include dental X-ray examinations or mass screening programs).

Doses varies widely from hospital to hospital, even in the same country, sometimes by a factor of 100.

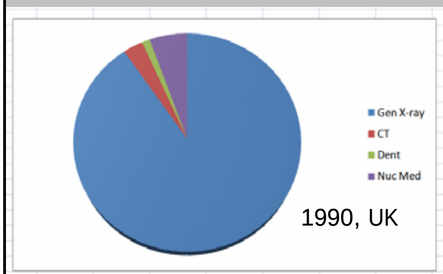
Radiation and You, EU, Luxembourg 1990

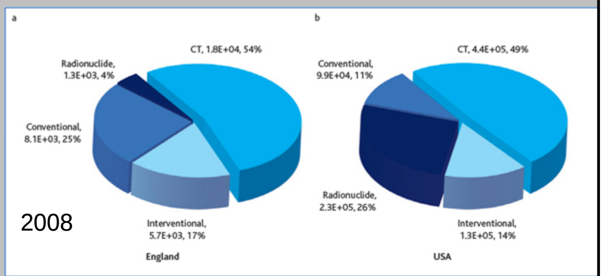
Approximately 90% of the total collective dose to UK population from man-made radiation sources arises from Diagnostic Radiology

Safety in Diagnostic Radiology, IPEM, 1995

Patient radiation doses from diagnostic radiology, D Hart, 1996

Collective dose to population from Diagnostic Radiology

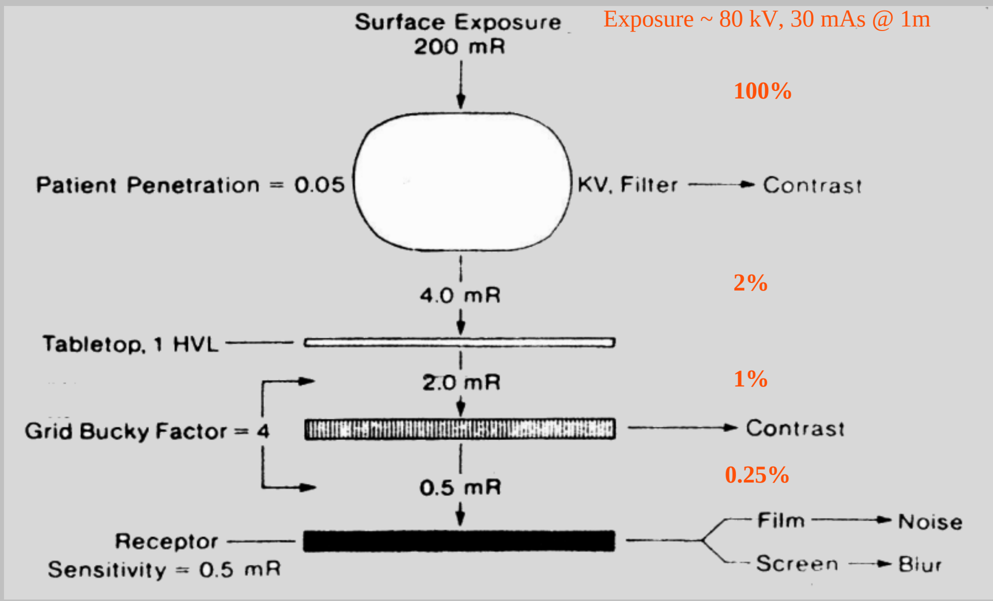


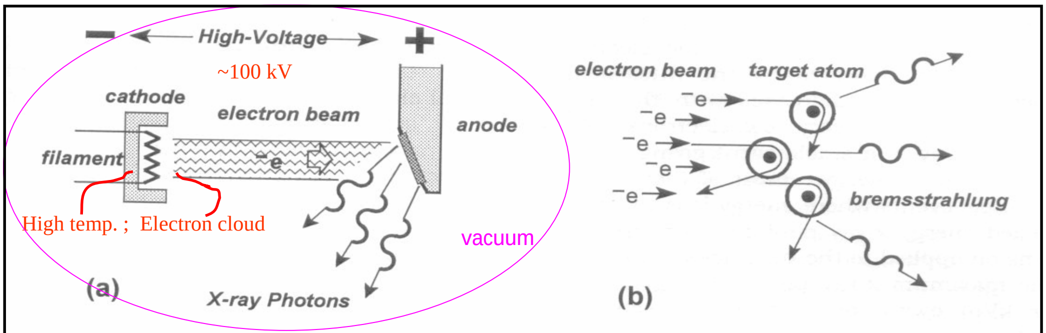


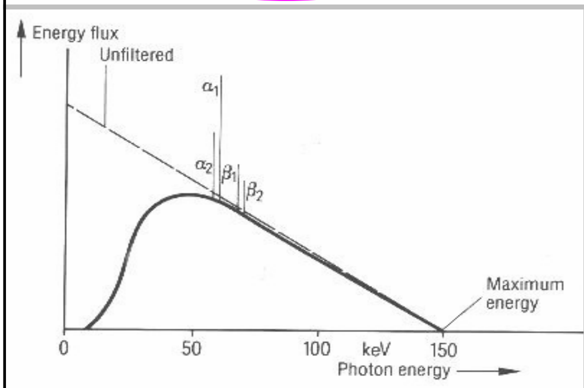
Estimated annual collective dose to UK population from Diagnostic Radiology (approx. figures):
1989 - 17,000 manSv;
1999 - 20,000 manSv (risk estimate approx. 700 cancer deaths/year);
2008 - 25,000 manSv

Safety in Diagnostic Radiology, IPEM, 1995; UK population dose from medical X-ray examinations , D. Hart , B. F. Wall, 2002; Considerations for Radioactive Substances Regulation under the Radioactive Substances Act 1993 at nuclear sites in England and Wales, 2008

Distribution of X-ray dose from the Tube through the Patient to the X-ray film

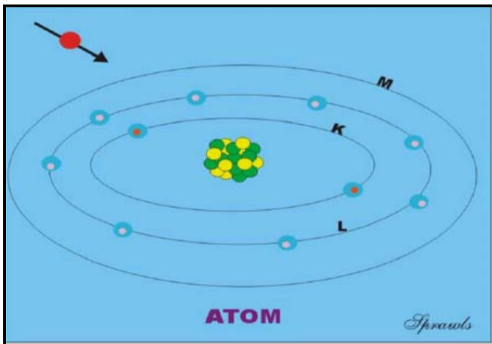


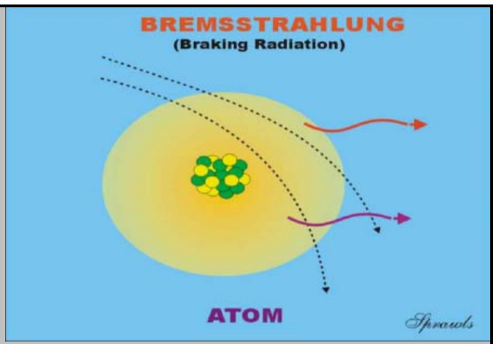




Production of X-rays and Bremsstrahlung (stopping radiation) – thermal electron emission in vacuum (10^{-6} mbar) and target bombardment

White X-ray spectrum (gamma quanta with all energies) and its final view (after tube filtration)





Imaginary model	Real (approximate)	Scaled-up approx. model (linear)
Electron radius	10^{-15} m	1 mm
Nucleus radius	10^{-14} m	10 mm
Atom radius	10^{-10} m	100 000 mm (100 m)
Inter-atom dist in crystal	10^{-10} m	100 m

Volume ratio:

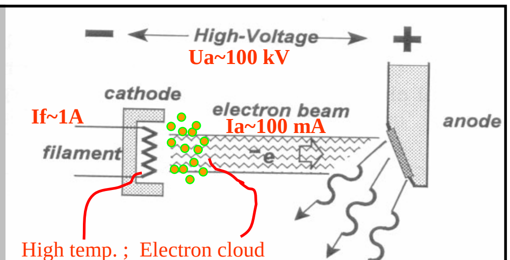
e vs **A**

~ 10^{15}

Richardson equation:

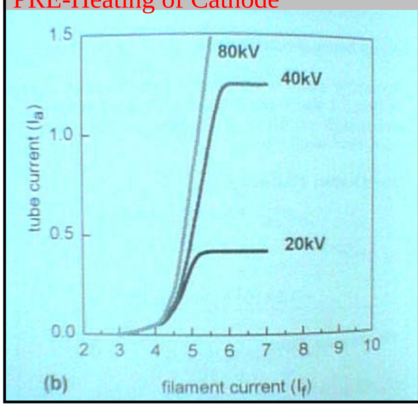
$$J_0 = A_0 . T^2 . e^{-w/kT}$$, where

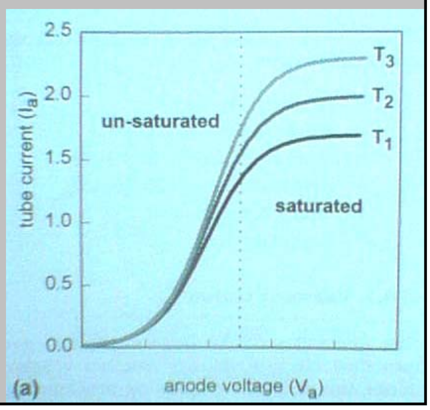
J_0 - density of the emission current ;
T - temperature of the emitter (in K);
k and w - constants (k-Boltzmann constant, w- work function, for W = 4.5 eV)
A_0 - constant depending of the material of the emitter (for W = 60 $A.cm^{-2}K^{-2}$)



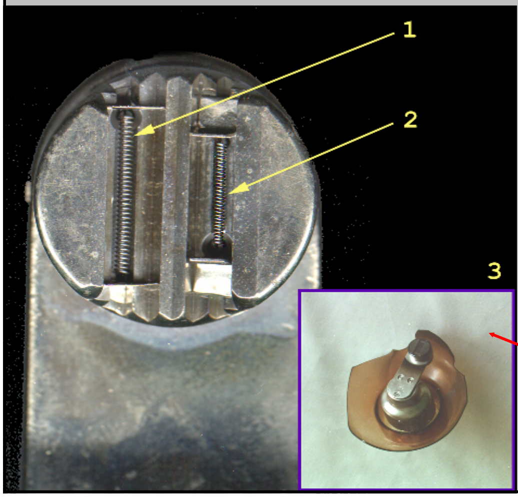
PRE-Heating of Cathode

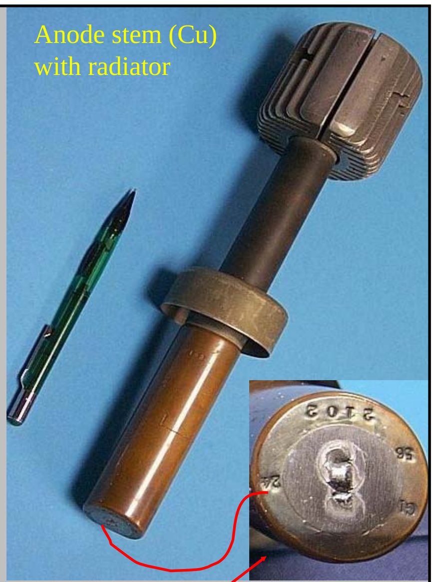
Space charge effect -
X-ray tube function characteristics





Cathode – W wire filament (~10x0.2 mm)
Anode – W plate (melting at 3370°C)
Construction: stationary and rotation



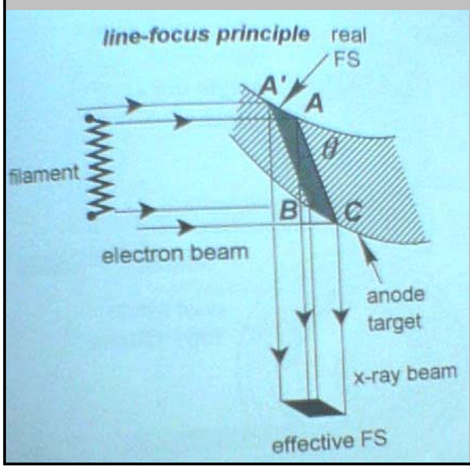


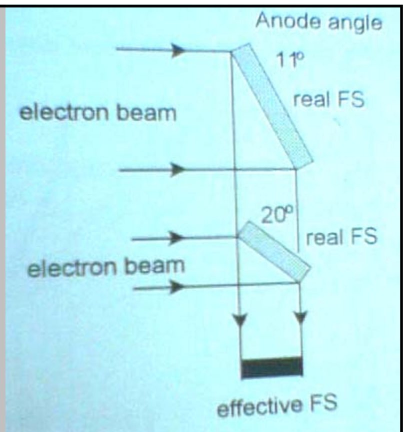
Cathode assembly
(inside broken Tube)

Melted tungsten
at anode target

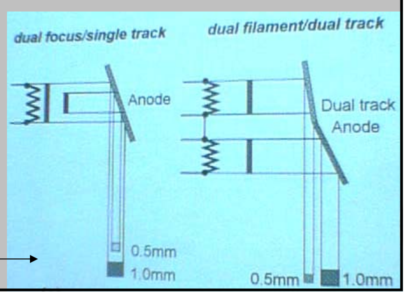
ANODE: X-ray tube focal spot -

Line focus principle

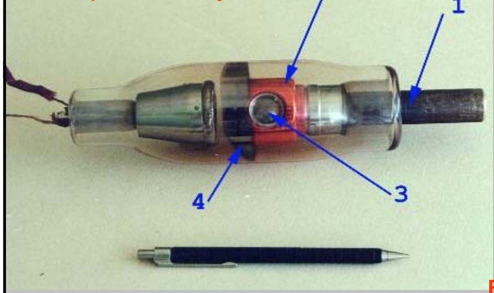




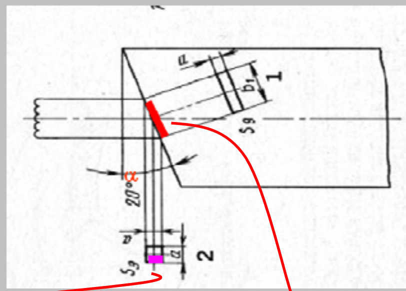
Dual focus X-ray tube



Stationary – anode angle determines focal spot – **less power**

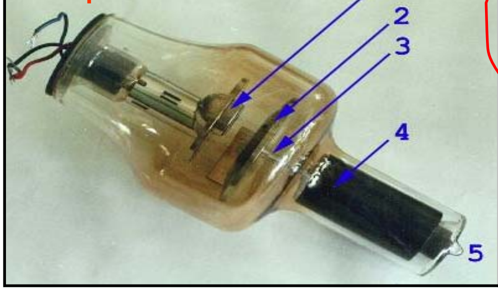


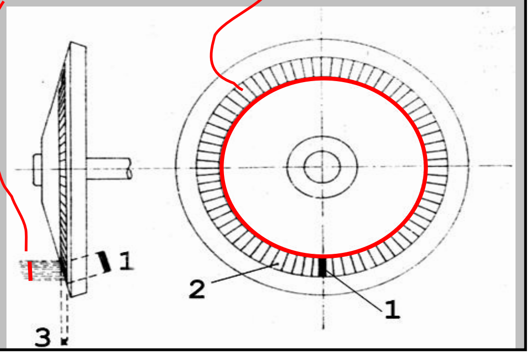
Anode angle: EF = sin α . AF

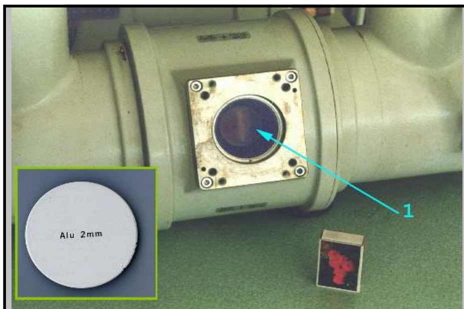


Effective focus - EF ; Thermal (Actual) focus - AF

Rotational – increased thermal focus – **more power**

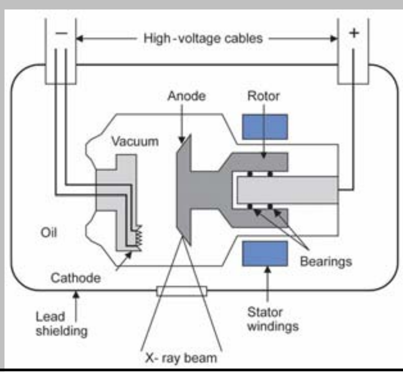






X-ray Tube Housing – Insulating Oil; Output window; Pb lining; Leakage radiation

Tube leakage radiation measurement



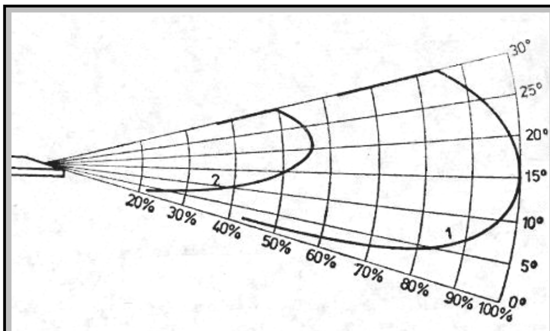
Tube and Housing cooling & T° protection

Metal X-ray tube with liquid metal bearing ('aqua planning' groove)

Anode heat - storage and dissipation (cooling)

$$P_{max} \sim f^{3/2}.D^{1/2}.n^{1/2} / \sin \alpha$$

The maximal power of the rotating anode(**P_{max}**) depends from the effective focal spot size (**f**); the diameter of the target track (**D**); the angle of the anode (**α**); and the speed of rotation (**n** - r.p.m.):



Intensity of X-ray radiation : **$W \sim I.U^2.Z$**

Anode efficiency **$\eta \sim k.U.Z$** (Z-anode atom. No.)

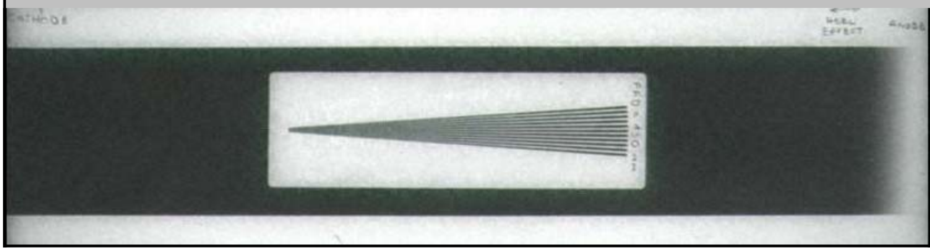
(intensity per energy unit - **$\eta = W/I.U$**)

X-ray Intensity distribution:

-In all directions inside the Tube housing (only a fraction of X-rays used – output dose)

-The overall output intensity decreases with ageing of Tube

- Decreased intensity at Anode site (Heel effect) – it is more obvious with old Tubes



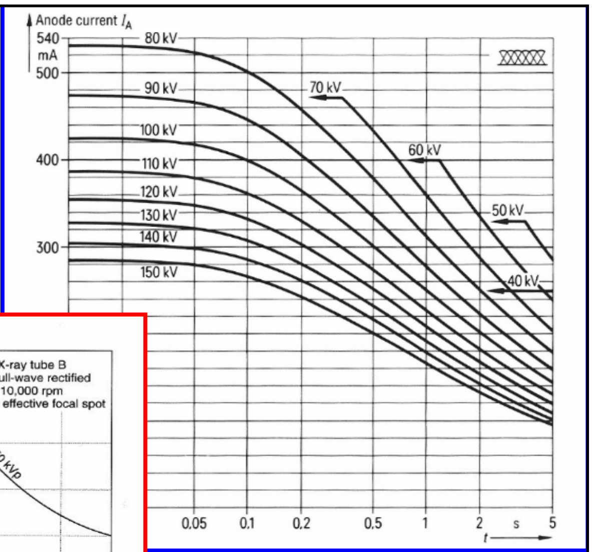
Max. power of the tube:

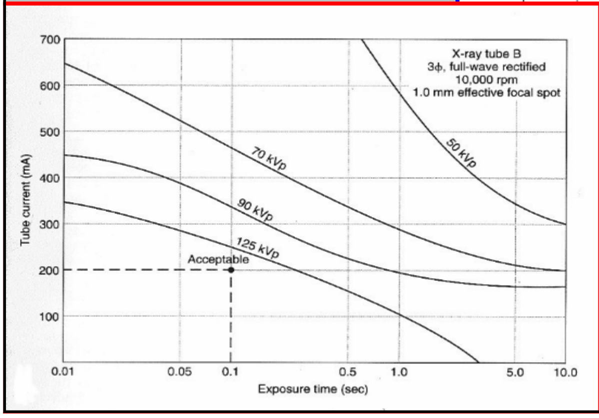
P=kV.mA (100x300=30kW)

Max anode heat capacity

HU=kV.mAs (100x1000=100kHU)

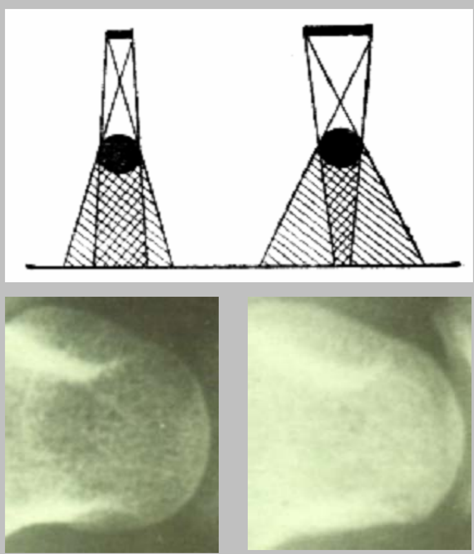
1HU=1.4 Joules





X-ray Tube characteristics:
Using of single exp. chart

Fine focus and Large focus effects



X-ray image resolution depends on the size of the X-ray tube focal spot (effective focus)

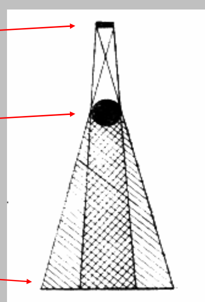
Fine (~ 0.5mm) or Broad (~1mm)

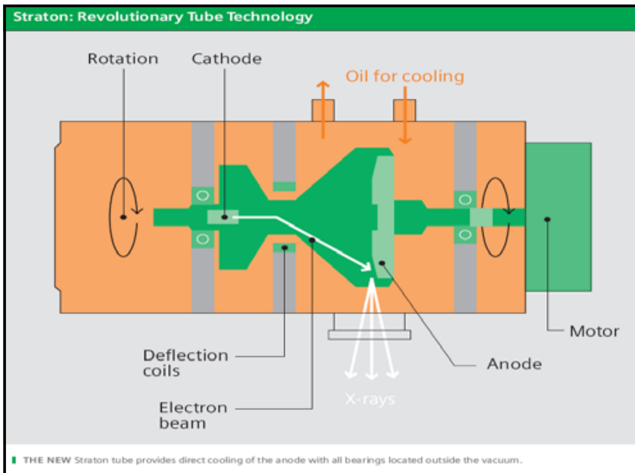
The BF smears the contours of the imaged objects (this increases with the increase of object-to-film distance)

Focus

Object

Film

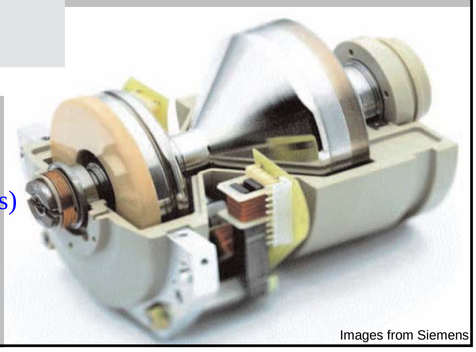




The new Straton tube

1. New construction;
2. Focused and deflected beam of thermal e-;
3. The whole tube+anode assembly rotates;
4. Bearings outside
5. Modulated output

Superb e- focusing + heat dissipation (cooling) =
small focal spot (better spatial resolution) +
high X-ray tube power (penetration &long exposures)



Images from Siemens

X-ray H.V. Generator

- Basic circuits of classical High Voltage X-ray Generator

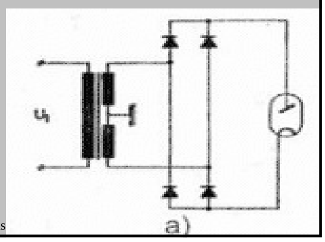
- kVp waveforms and ripple

- New Medium frequency X-ray Generator

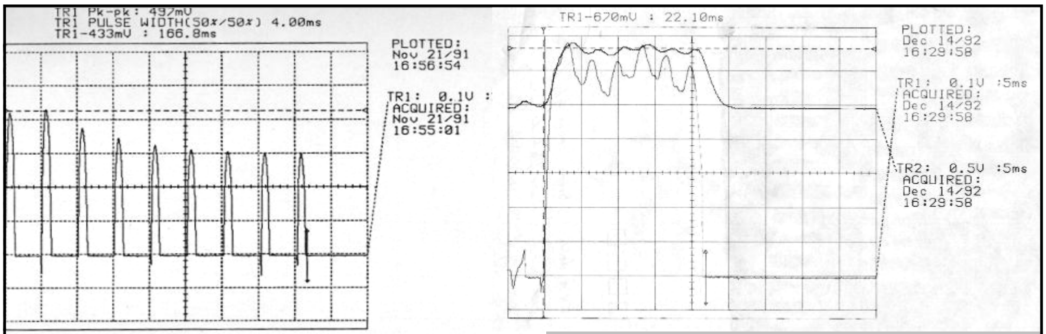
- Basic circuits of medium frequency X-ray Generator

- kVp Control and diagnostic use

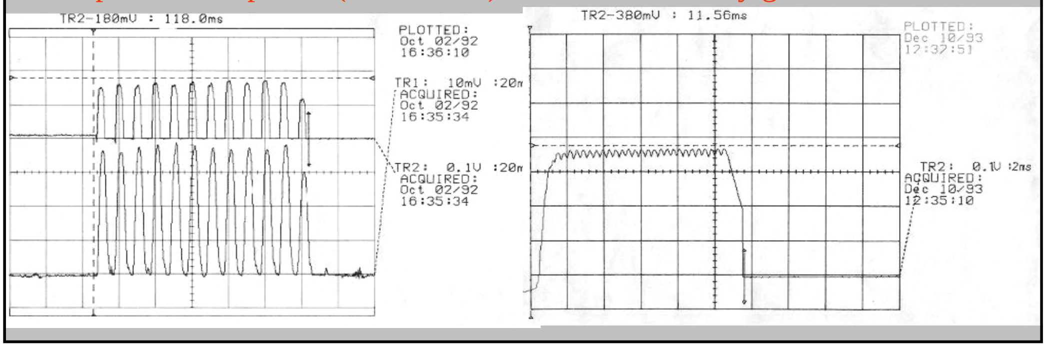
- Automatic Exposure Control



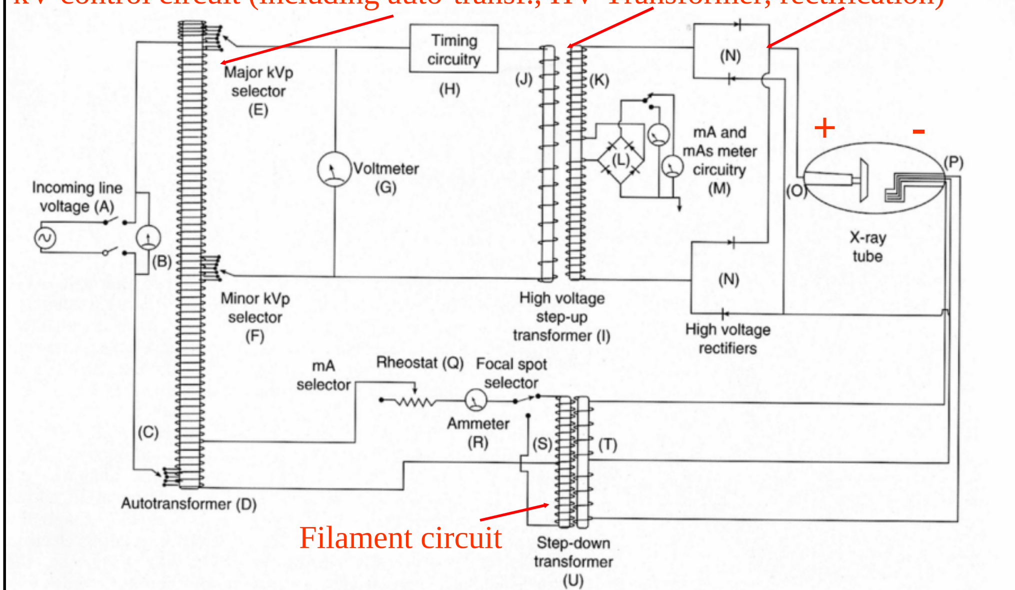
Images from www.emerald2.net and Siemens



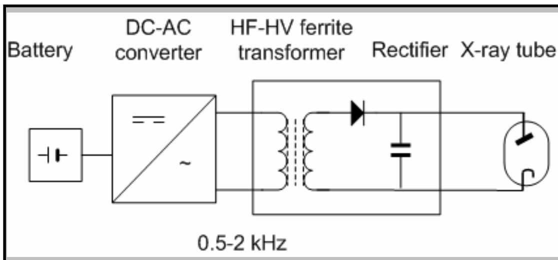
kVp and Dose pulses (waveforms) from various X-ray generators



kV control circuit (including auto-transf., HV Transformer, rectification)

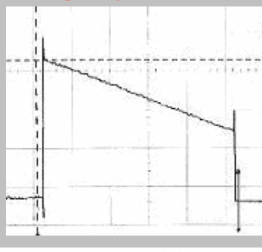


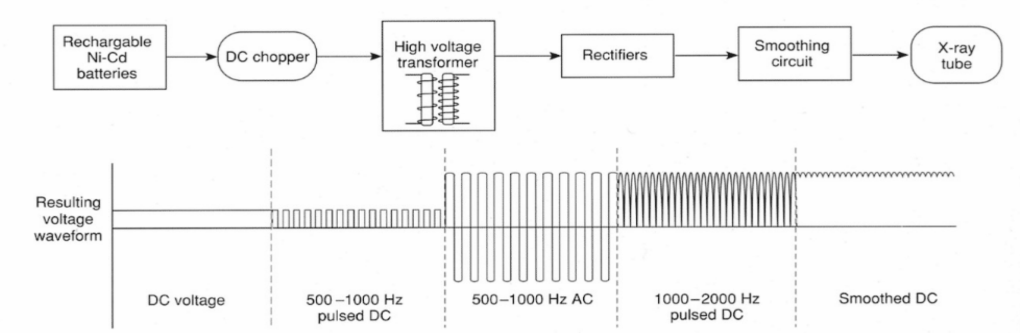
Basic diagram of Classical X-ray Generator with the Tube

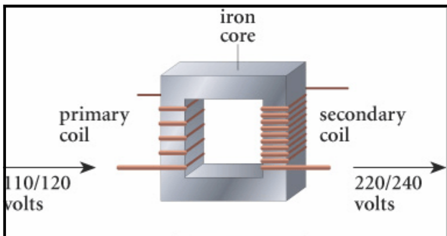


Contemporary medium-frequency (high-frequency) X-ray Generator

(small HV transformer; frequency varies kV)







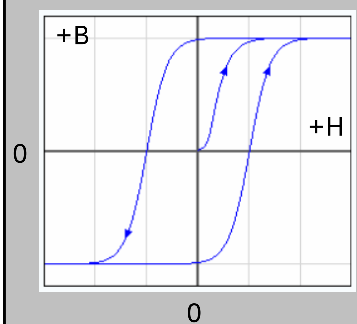
U / f ~ A . n

voltage U with frequency f

A - cross section of the transform core;

n - number of transformer windings (transformer ratio);

The High Voltage Transformer



$$B = \mu H$$

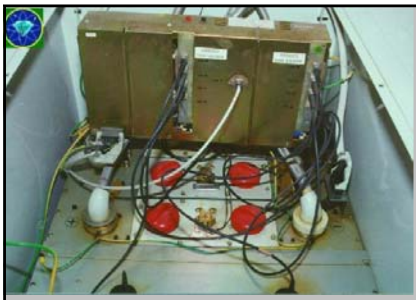
magnetic flux density - B (T)

magnetic field strength - H (A/m)

magnetic permeability - μ

Ferrites - low hysteresis loss, high permeability, work at high frequencies

New High (Medium) Frequency Transformers use 1-20 kHz

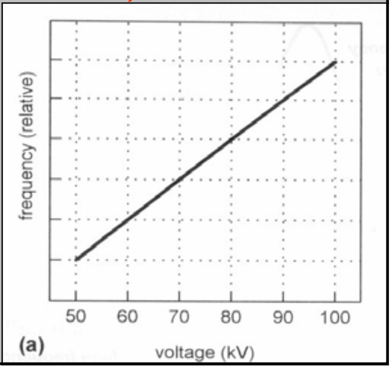


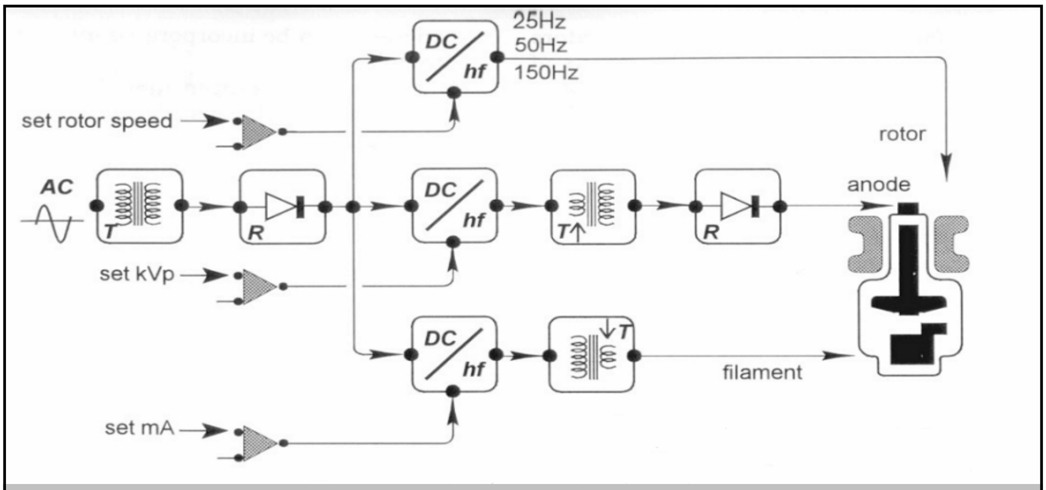
U / f ~ A . n

A . n – is constants for a transformer,

hence **U ~ c.f**

New ferrite core for HV transformer:
(smaller transformer size; electronics;
frequency varies the kV)





Block-diagram of modern computer-controlled
medium frequency X-ray Generator (~20 kHz)

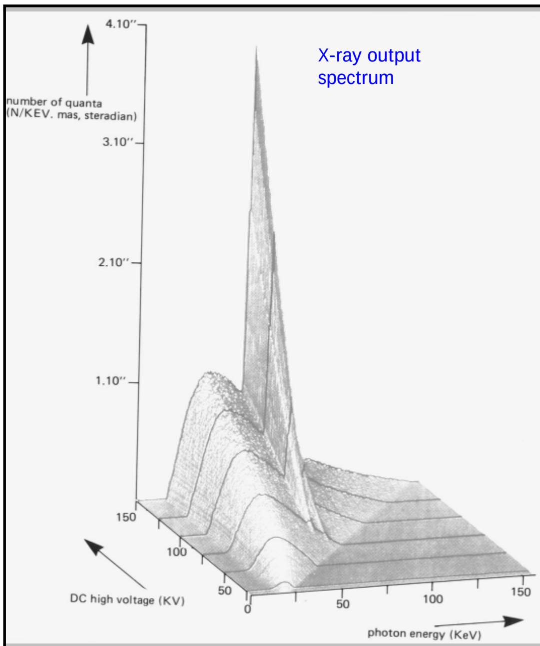


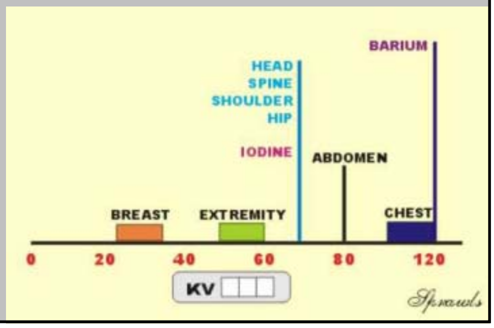
Image from Siemens and www.sprawls.com

X-ray tube:

- Focal spot (spatial resolution; power)
- Total filtration at tube output (pat. dose)
- Tube housing (leakage radiation)

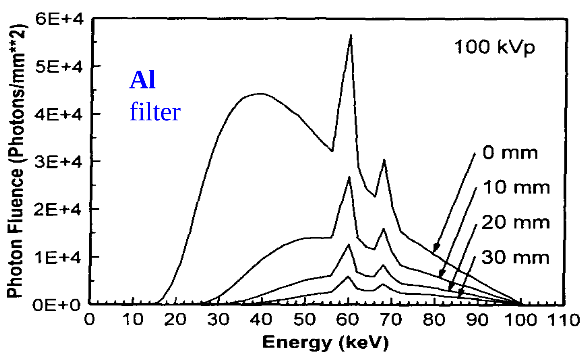
X-ray Generator:

- kV control (image contrast, **pat. dose**[2])
- mA control (image brightness, pat.dose)
- Time (msec) control (img bright., pat. dose)



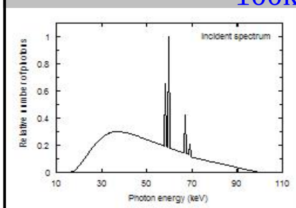
Spectrum and Filtration

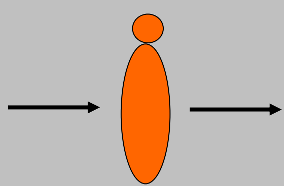
1. Reducing low energy quanta (hence reducing dose absorbed in patient)
2. Increasing X-ray mean energy (penetration)
3. Usually Aluminium, but shaping the X-ray spectrum using K-edge is specially useful in mammography

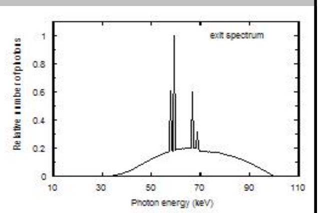


Handbook of Medical Imaging:Volume 1 Physics and Psychophysics by Beutel, Kundel and Van Metter

Incident and exit spectrum in radiography
100kVp W target with 2.5mm Al filter

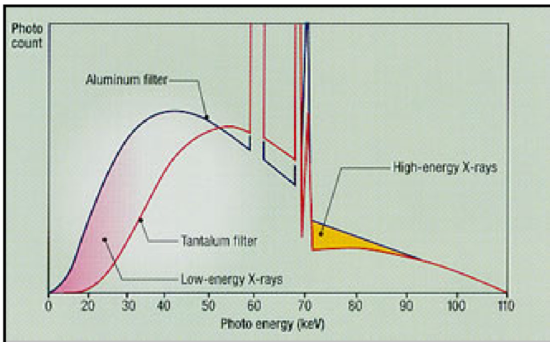






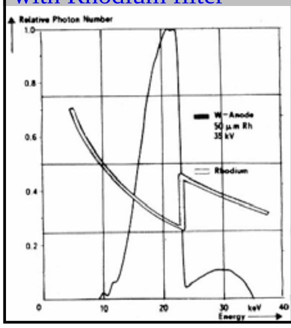
Images from Handbook of Medical Imaging and L.Martinez Lectures

Filtration with use of K-edge



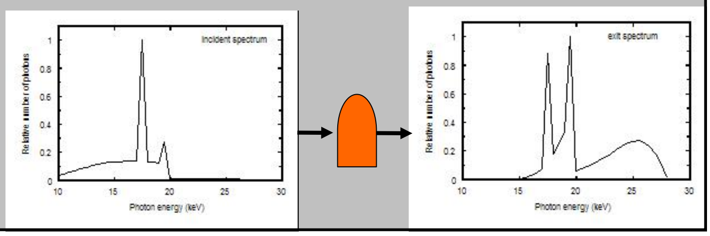
1. Tantalum filter (Toshiba) cuts out the low energy X-ray components and also the high-energy X-ray components that cause scattered radiation. This leads to reduced dose (~30%) and improved signal/noise.

2. Mammo Tungsten anode with Rhodium filter



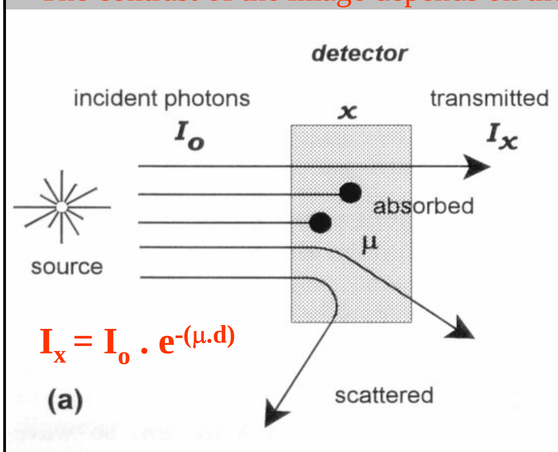
Images from:
http://www.toshibamedical.co.jp/tmd/english/products/xray/cardiovascular/xray5.html
and Tompson, Hattaway, Hall, Dowd "Principles of Imaging Science and Protection"

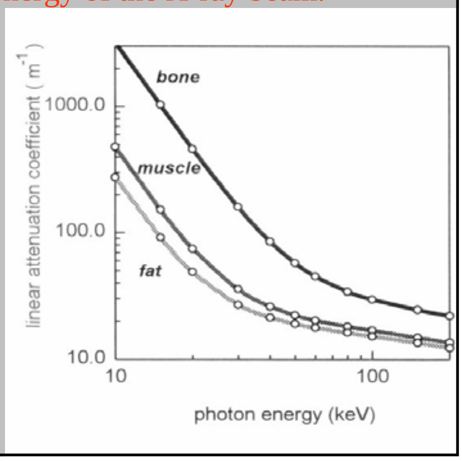
3. Incident and exit spectrum in mammography
28kVp Mo anode target with 0.03mm Mo filter

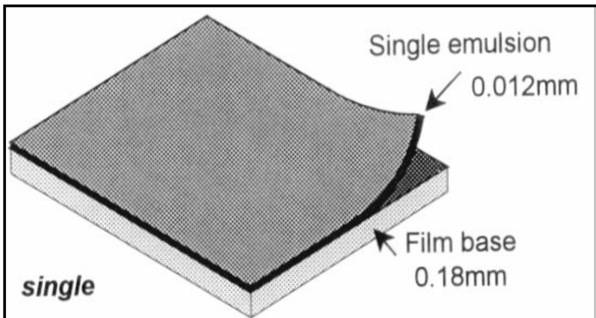


The X-ray source radiation $\mathbf{I_o}$ passes through the object (the body) and is modulated by the body tissues $^{(\mu.d)}$ on its way. This modulated radiation beam $\mathbf{I_x}$ interacts with the detector, where the modulated radiation is transformed into modulated light – the X-ray image.

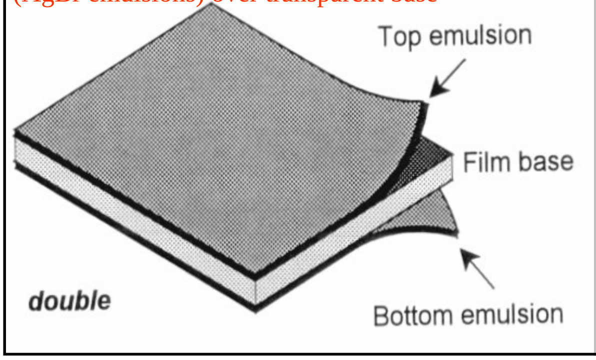
The contrast of the image depends on the energy of the X-ray beam.



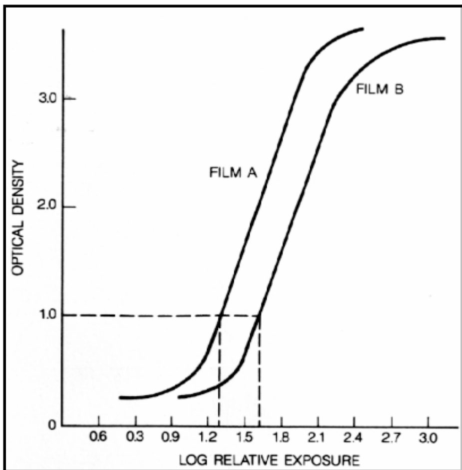




X-ray film – with 1 or 2 sensitive layers (AgBr emulsions) over transparent base



The film is exposed to both X-rays and light inside the cassette



X-ray film characteristics:

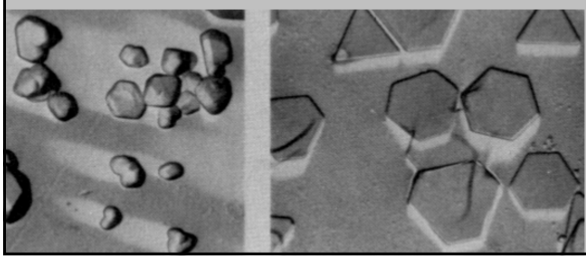
-Exposure latitude (dynamic range);

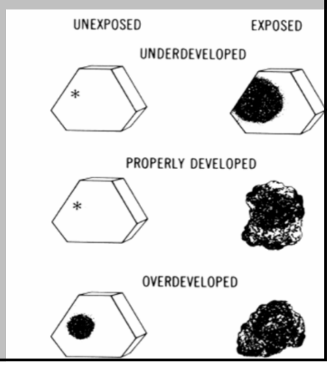
-Resolution (grain size)

-Sensitivity (film speed)

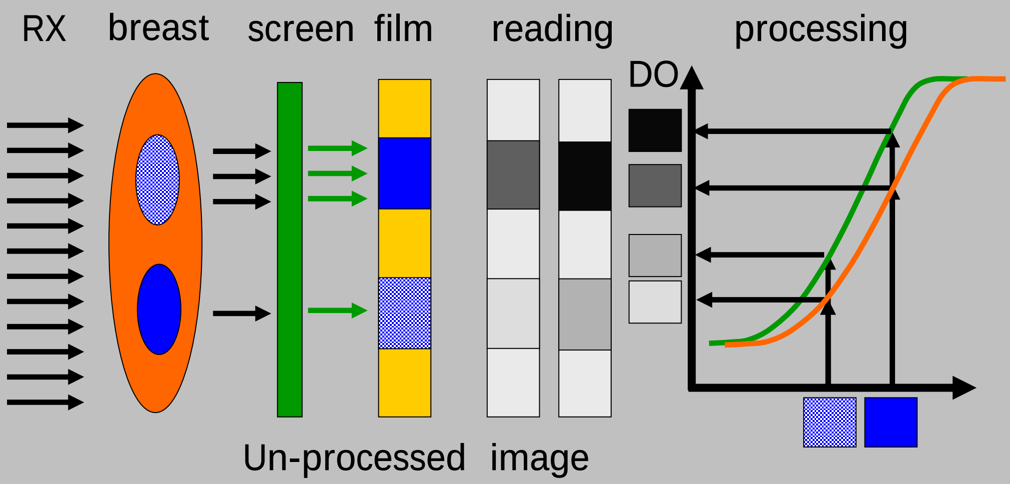
Cassette intensifying screen influence

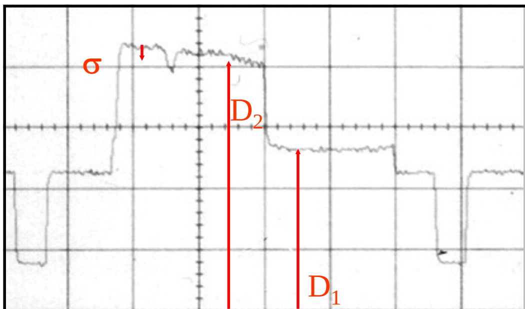
Development process influence

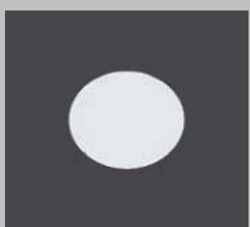




Influence of the characteristic curve







I – Intensity

D – Density

E - Exposure

Signal-to-Noise Ratio: SNR

$\Delta C = [D_2 - D_1]/\ \sigma$

Radiographic contrast

$\Delta C = [D_2 - D_1]/D_1$

Film contrast

$\gamma = [D_2 - D_1]/[\log E_2 - \log E_1]$

Subject Contrast $\Delta C = I_2 - I_1$

Visual contrast

$\Delta C = \log I_2 - \log I_1$

Basic Principles of Mammography

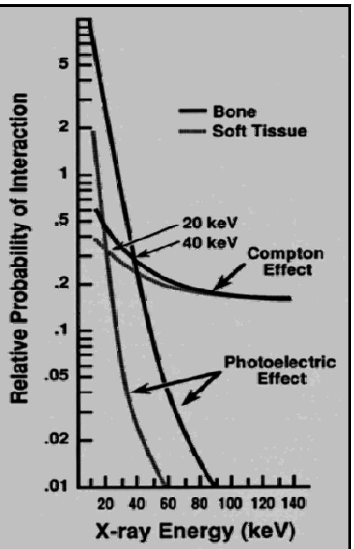
➔Use of low kV due to the type of imaged tissue

Photoelectric absorption :

$$\tau_m \approx 8(Z_{eff}\lambda)^3$$

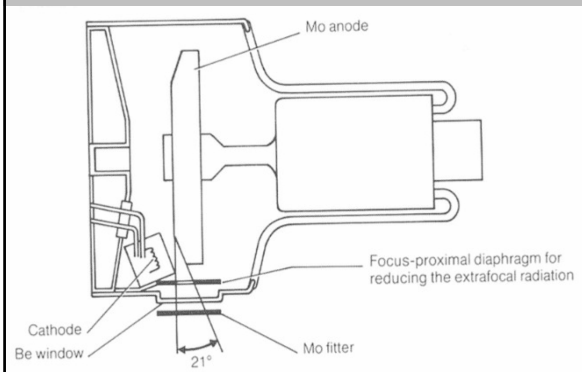
Total absorption = Photoelectric + Compton:

$$\mu = \sigma + \tau \approx \rho[0.2 + 8(Z_{eff}\lambda)^3]$$



➔Some specific parameters of mammographic X-ray equipment

Parameter	
X-ray Generator	**Medium frequency or at least 3 phase (~ 5 kW)**
X-ray tube Anode + added filtration	**Mo/ 30 µm Mo Rh/ 50 µm Rh W / 60 µm Mo W / 50 µm Rh**
Focal spot	**Small 0.1- 0.3 mm Large 0.4-0.6 mm**
kV	**20-35 kV, steps – 0.5-1 kV**



X-ray spectrum from W anode with 0.06 mm Mo or 0.05 mm Rh filtration– 30 kV

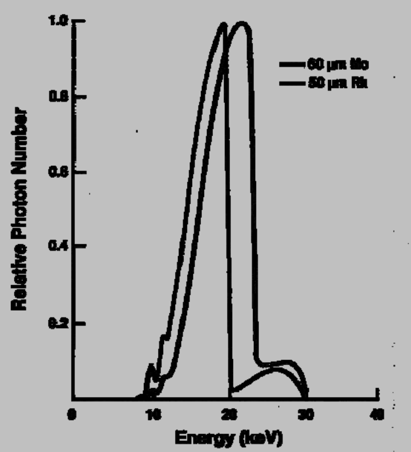
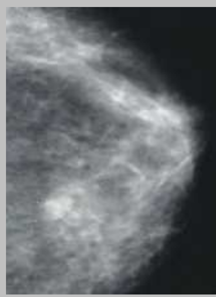
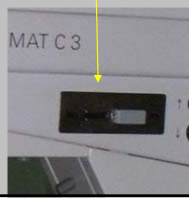
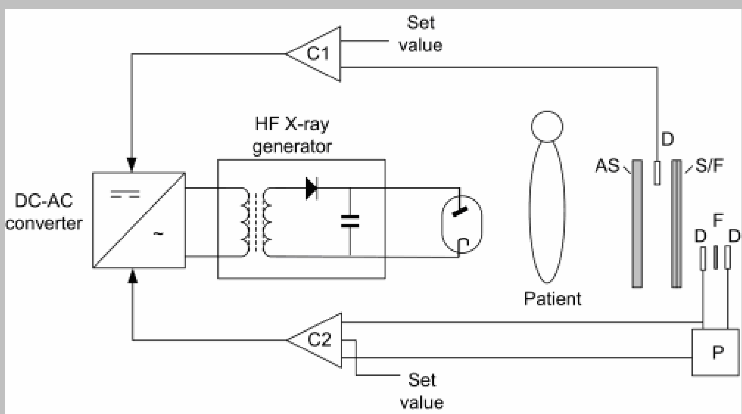


Fig. 20-4. The emission spectra from a tungsten target filtered by molybdenum or rhodium.





Automatic Exposure Control (AEC) system



Block diagram showing two typical AEC types.

C1 – used for chest radiography and C2 used for mammography.