X-ray Tube and Generator – Basic principles and construction

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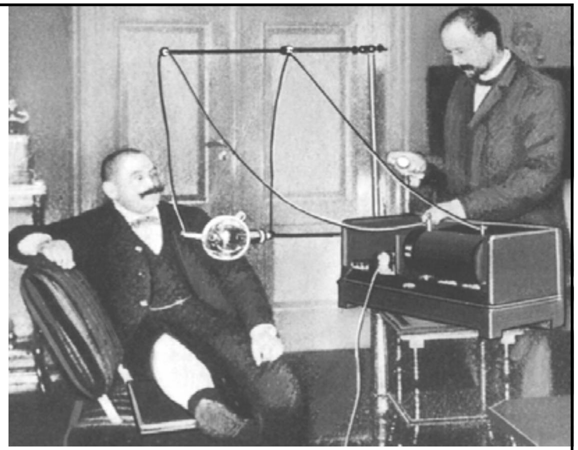


H.V. X-ray Generator ⇨ X-ray Tube → X-ray entrance Spectrum → Object Patient → X-ray exit Spectrum → X-ray stand (detector)

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)

COLLECTIVE DOSE TO THE POPULATION OF U.K. FROM DIAGNOSTIC MEDICAL RADIOLOGY (man Sv)

Medical X-rays (excl. CT)	15500
Computed tomography (estimated)	500
Dental X-ray	200
Nuclear medicine	950
TOTAL (man Sv) : 17150	

Data for mid-1980

NRPB, 1989

Estimated annual collective dose to UK population from Diagnostic Radiology for 1990 is approx. 20,000 manSv. On the basis of risk estimate this could be responsible for up to 700 cancer deaths/year ! Safety in Diagnostic Radiology, IPEM, 1995

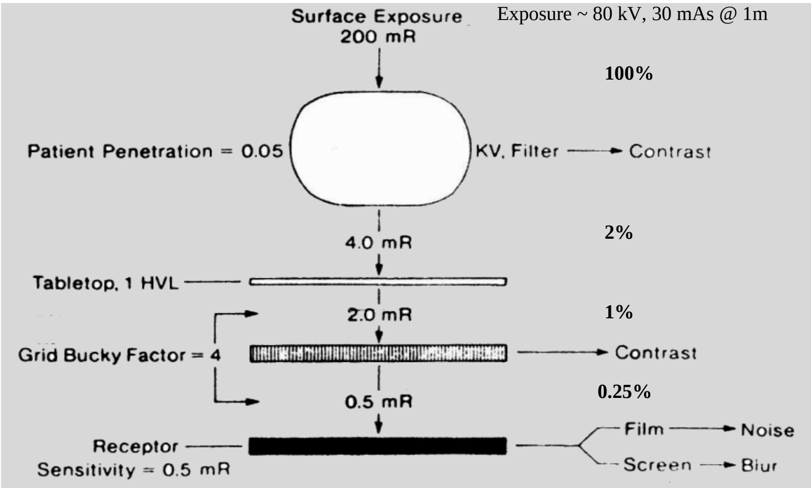
Approximately 90% of the total collective dose to UK population from man-made radiation sources arises from Diagnostic Radiology Safety in Diagnostic Radiology, IPEM, 1995

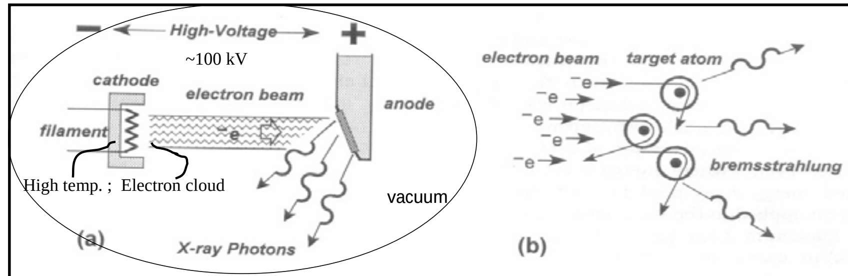
In most industrialised countries there are between 300 and 900 X-ray examinations for every 1000 inhabitants every year. Over half of these are chest examinations (these figures does not include dental X-ray examinations or mass screening programs).

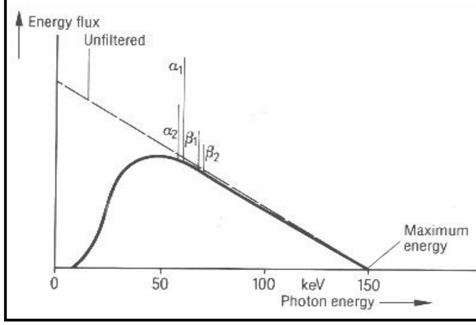
Doses varies widely from hospital to hospital, even in the same country, sometimes by a factor of 100.

Radiation and You, EU, Luxembourg 1990

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

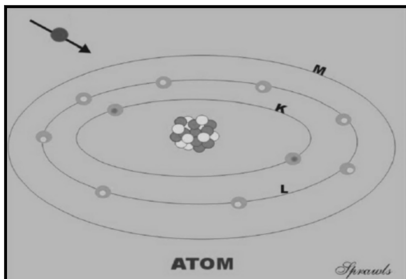


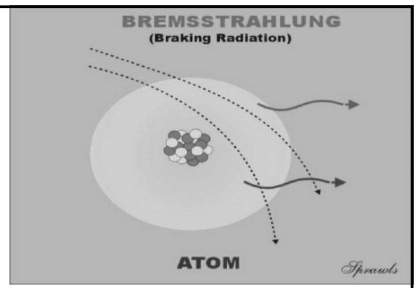




Production of X-rays and Bremsstrahlung (stopping radiation) – thermal electron emission in vacuum (10^{-6} mbar) and target bombardment

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:

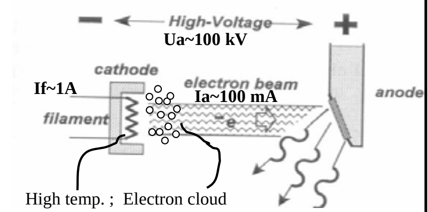
e vs **A**

~ 10^{15}

Richardson equation:

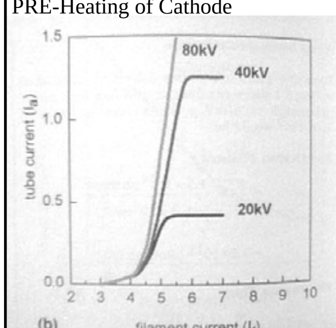
$$J_0 = A_0 . T^2 . e^{-w/kT}$$, where

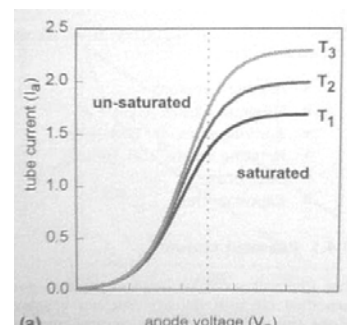
J_0 - density of the emission current ;
T - temperature of the emitter (in K);
k and w - constants (k-Boltzmann constant, w- work function, for W = 4.5 eV)
A_0 - constant depending of the material of the emitter (for W = 60 A.cm^{-2}K^{-2})



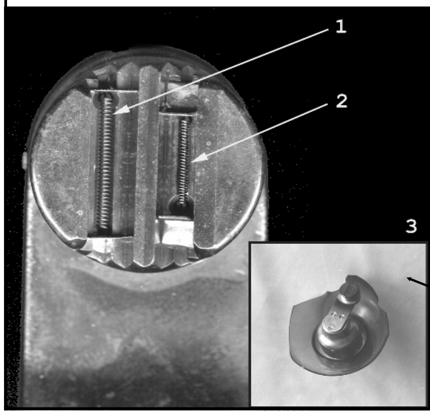
Space charge effect -
X-ray tube function characteristics

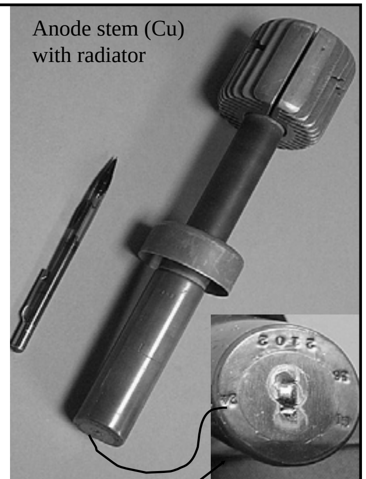
PRE-Heating of Cathode





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



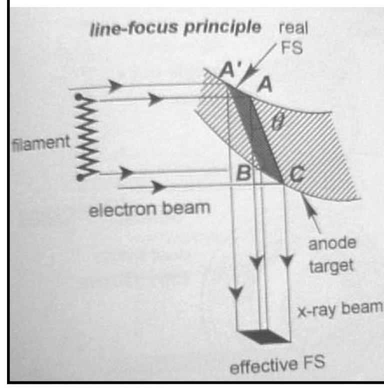


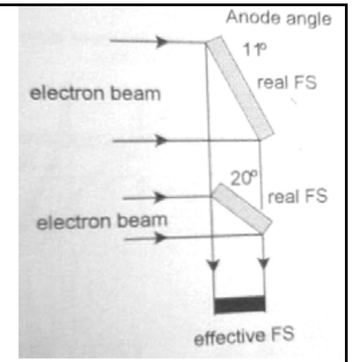
Cathode assembly
(inside broken Tube)

Melted tungsten
at anode target

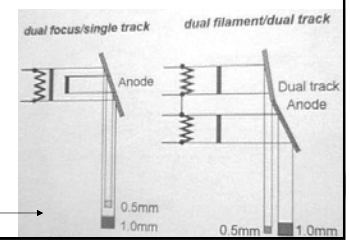
ANODE: X-ray tube focal spot -

Line focus principle

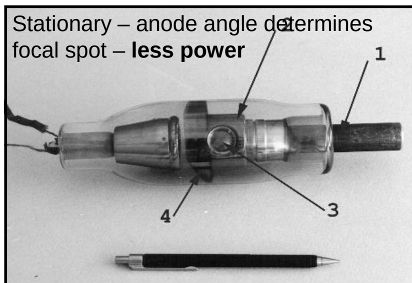


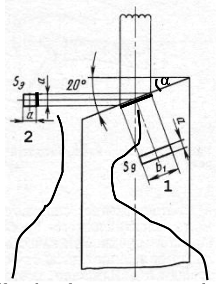


Dual focus X-ray tube



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



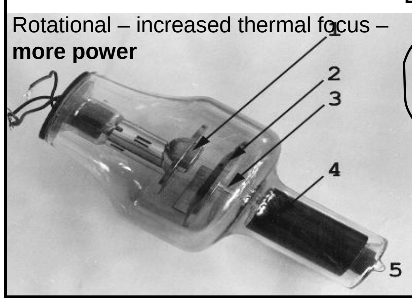


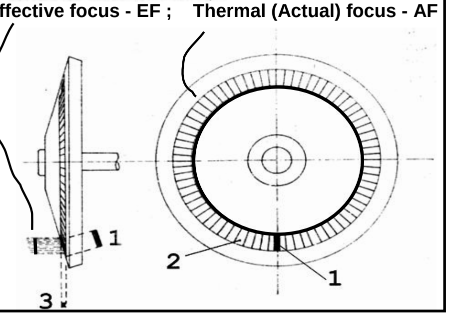
Anode angle

EF = sin α . AF

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

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



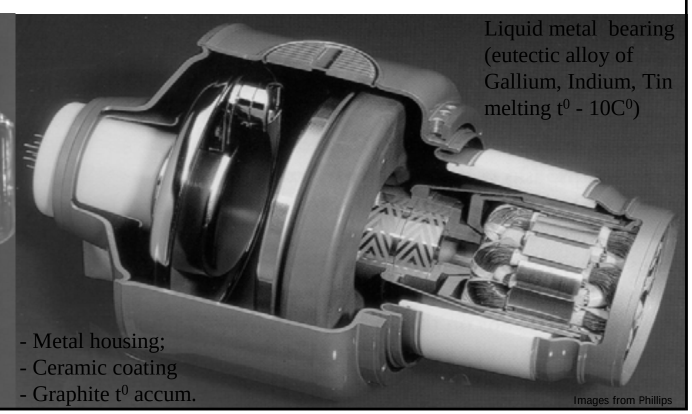


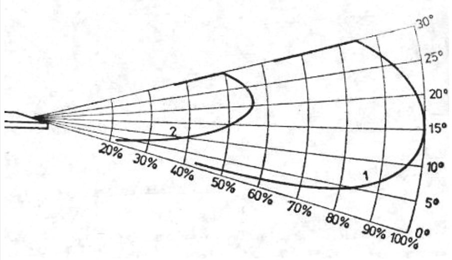
Metal X-ray tube with liquid metal bearing (‘aqua planning’ groove)

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.):





X-ray Intensity distribution:

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

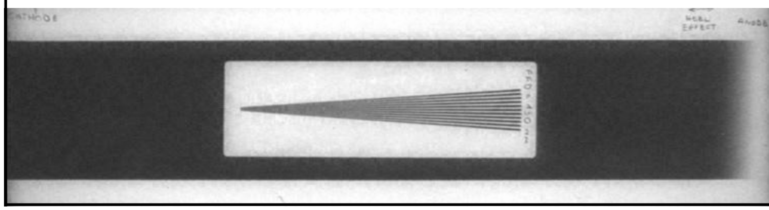
-The overall output intensity decreases with ageing of Tube

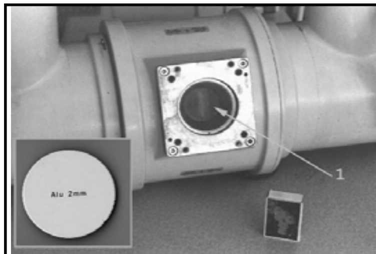
- Decreased intensity at Anode site (Heel effect) – it is more obvious with old Tubes

Intensity of X-ray radiation : **W ~ I.U².Z**

Anode efficiency η **~ k.U.Z** (Z-anode atom. No.)

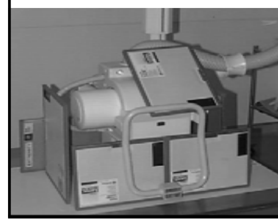
(intensity per energy unit - η = **W/I.U**)

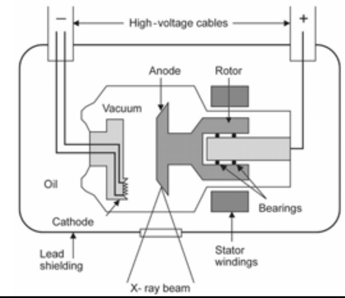




X-ray Tube Housing – Insulating Oil; Output window; Pb lining; Leakage radiation

Tube leakage radiation measurement

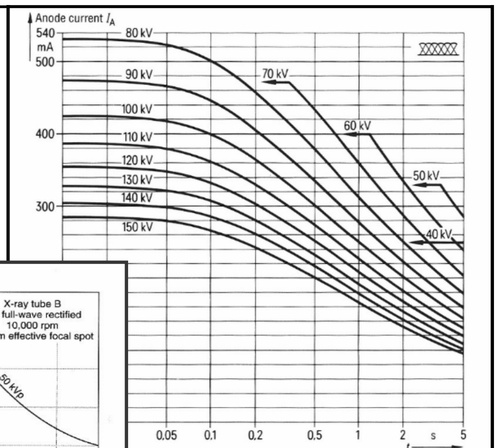


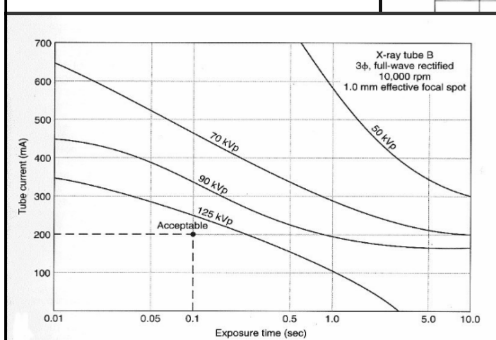


Tube and Housing cooling & T° protection

Max. power of the tube:
P=kV.mA (100x300=30kW)

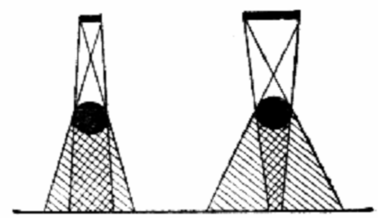
Max anode heat capacity
HU=kV.mAs (100x1000=100kHU)
1HU=1.4 Joules

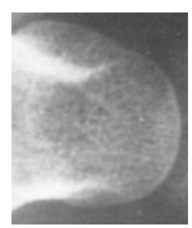


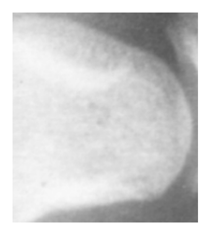


X-ray Tube characteristics:
Using of single exp. chart

Fine focus and Large focus effects







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

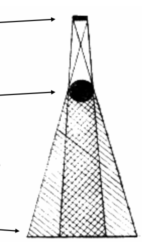
Fine (~ 0.5mm) or Broad (~1mm)

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

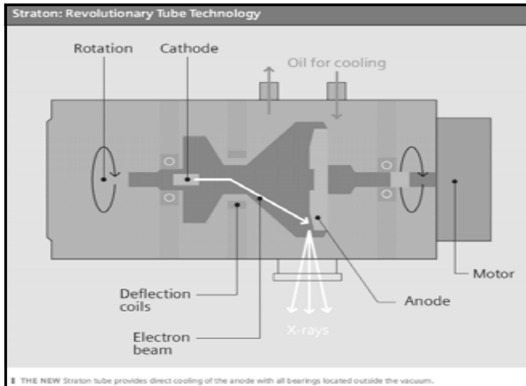
Focus

Object

Film



The new Straton tube



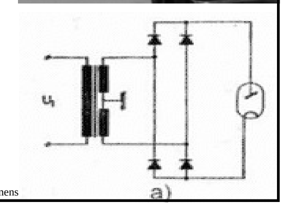
1. New construction;
2. Focused and deflected beam of thermal e-;
3. The whole tube+anode assembly rotates;
4. Bearings outside
5. Modulated output

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

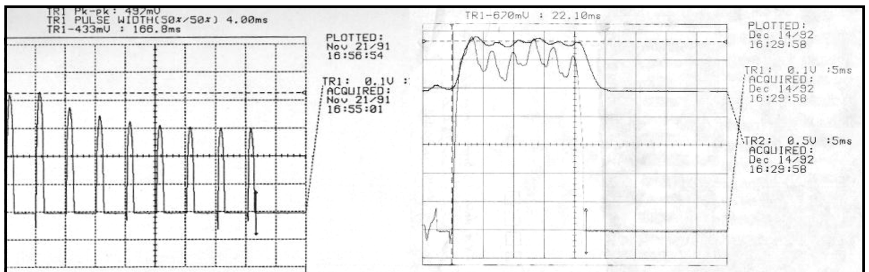
Images from Siemens

X-ray H.V. Generator

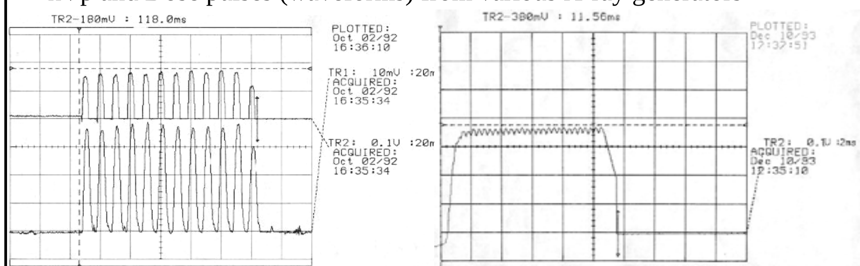
- Basic circuits of classical High Voltage X-ray Generator
- kVp waveforms and ripple
- New Medium frequency X-ray Generator
- Basic circuits of medium frequency X-ray Generator
- kVp Control and diagnostic use
- Automatic Exposure Control



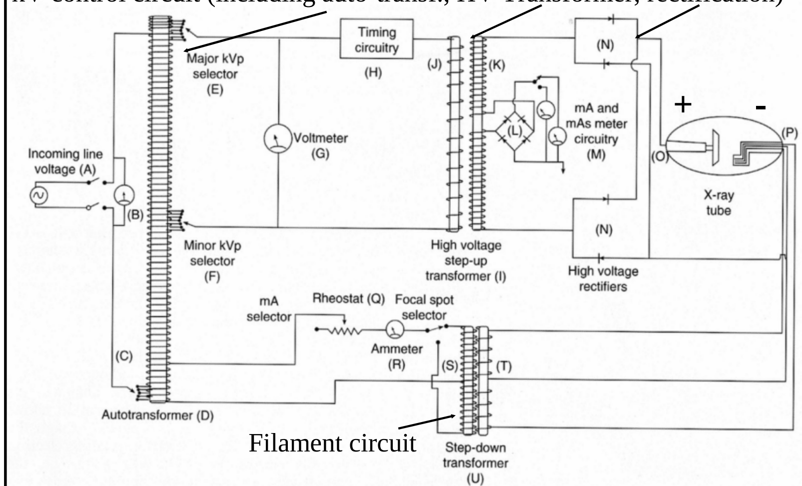
Images from www.emerald2.net and Siemens



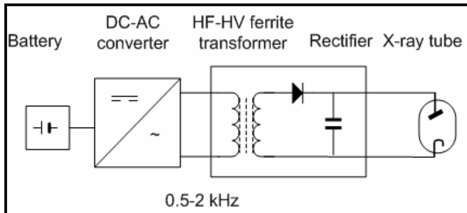
kVp and Dose pulses (waveforms) from various X-ray generators



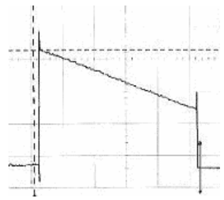
kV control circuit (including auto-transf., HV Transformer, rectification)



Basic diagram of Classical X-ray Generator with the Tube

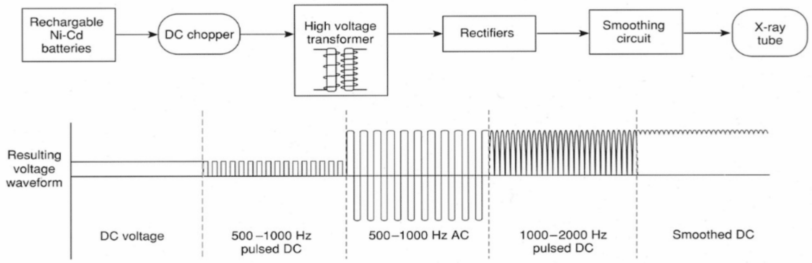


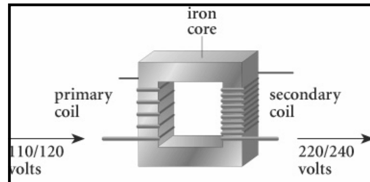
Capacity discharge X-ray Generator



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

(small HV transformer; frequency varies kV)





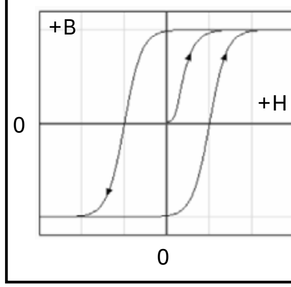
U / f ~ A . n

voltage U with frequency f

A - cross section of the transform core;

n – ratio of transformer windings (transformer ratio);

The High Voltage Transformer



B = μ H

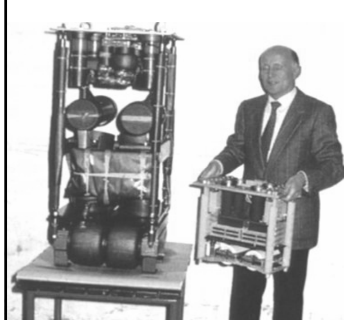
magnetic flux density - B (T)

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

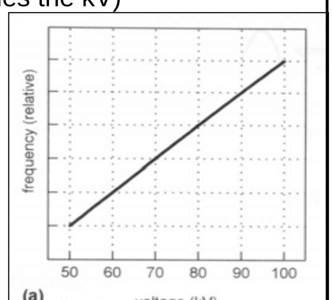


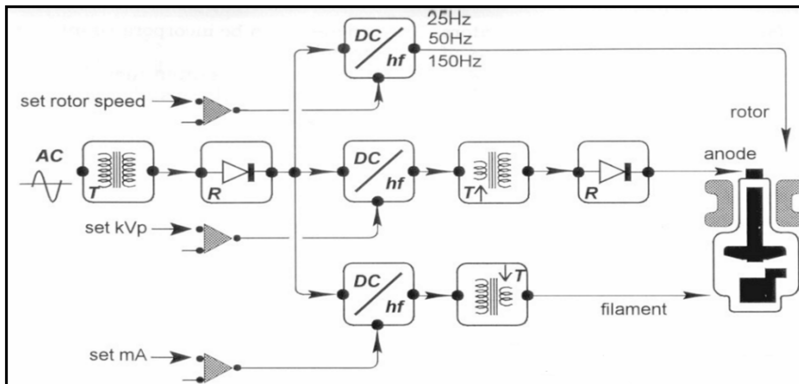
U / f ~ A . n

A . n – is constants for a transformer,

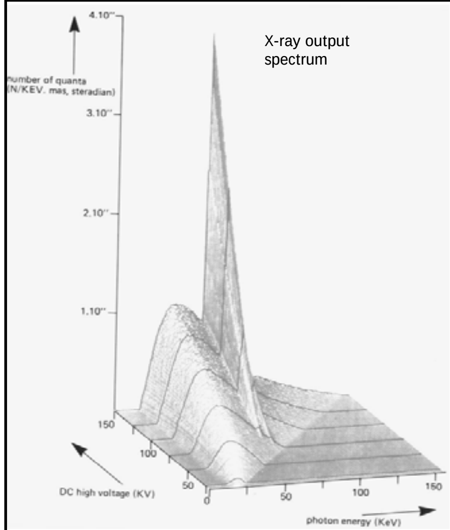
hence **U ~ c.f**

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)



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)

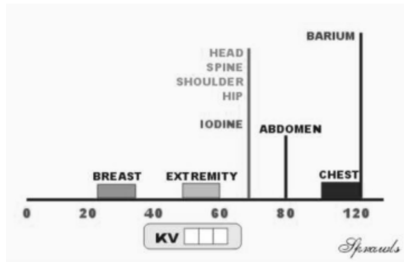
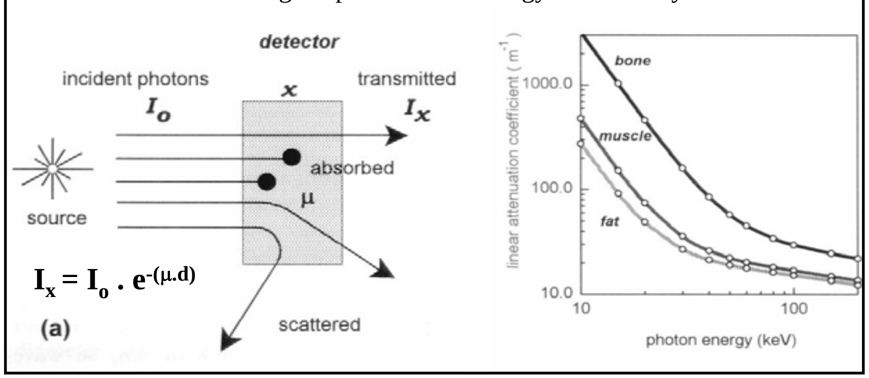


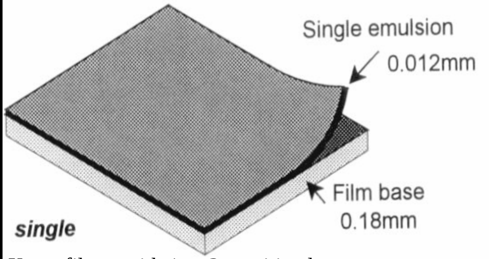
Image from Siemens and www.sprawls.com

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.

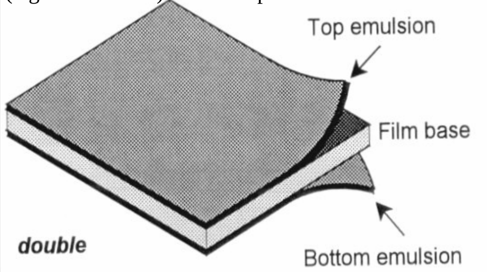
The contrast of the image depends on the energy of the X-ray beam.



$$\mathbf{I_x = I_o \cdot e^{-(\mu.d)}}$$



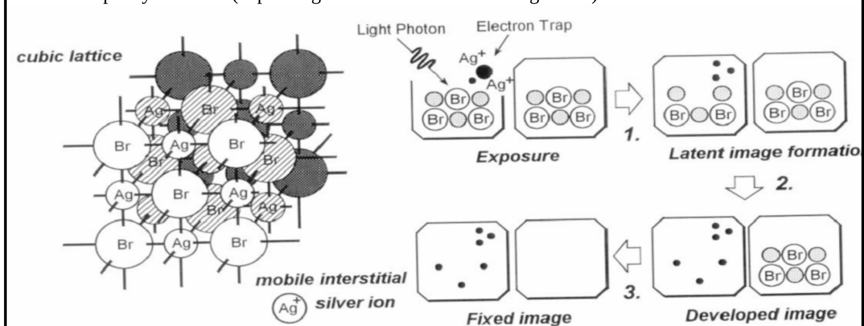
X-ray film – with 1 or 2 sensitive layers (AgBr emulsions) over transparent base

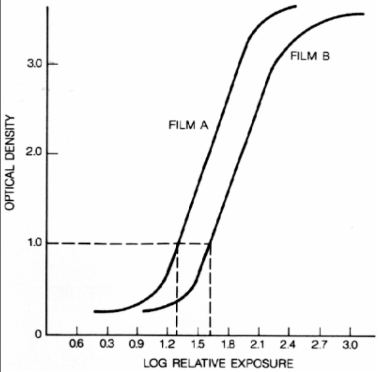


The film is exposed to both X-rays and light inside the cassette

Photoemulsion: The lattice Ag and Br atoms are fixed. The individual silver hallide crystals within the emulsion contain: 1. interstitial +Ag ions (mobile) and 2. electron traps (usually silver sulfide).

Light (X-ray) photon excites a Bromine atom (and it looses an e-). These free e- are trapped into crystal defects (traps). The (+) Silver ions are attracted into these (–) defects, where they are neutralised and become Ag atoms (sensitised grains). The combination of areas in the film with different number of sensitised grains forms a LATENT IMAGE. During the process of film development the sensitised grains are stabilised (the exposed AgBr crystals are reduced to stable Ag atoms). During the next process of film fixing the remaining un-sensitised grains (which had not been exposed to light photons) are removed and washed out. The final visible image contains areas with various opacity/darkness (depending on the concentration of Ag atoms).





X-ray film characteristics:

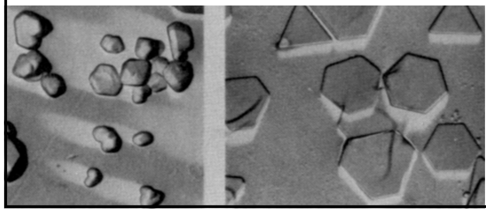
-Exposure latitude (dynamic range);

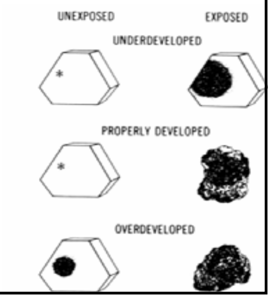
-Resolution (grain size)

-Sensitivity (film speed)

Cassette intensifying screen influence

Development process influence



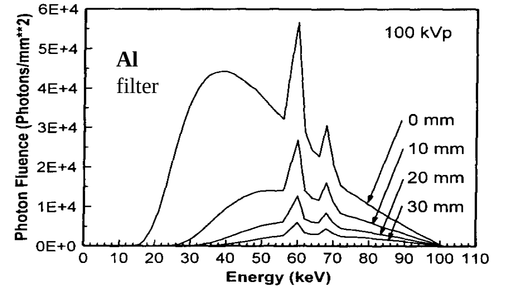


Spectrum and Filtration

1. Reducing low energy quanta (hence reducing dose absorbed in patient)

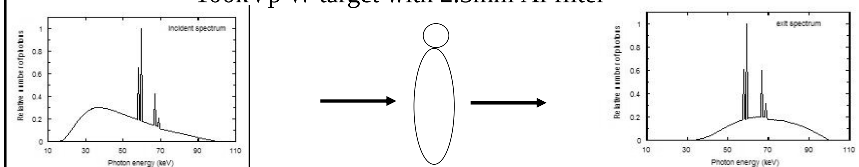
2. Increasing X-ray mean energy (penetration)

3. Usually Aluminium, but shaping the X-ray spectrum using K-edge is specially useful in mammography

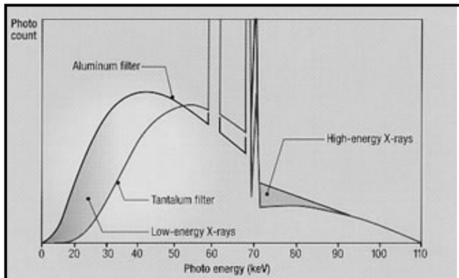


Handbook of Medical Imaging:Volume 1 Physics and Psychophysics by Beutel, Kundel and Van Metter

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



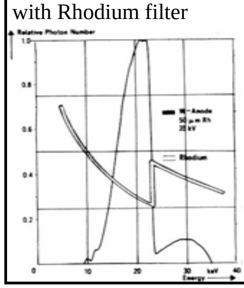
Images from Handbook of Medical Imaging and L.Martinez Lectures



Filtration with use of K-edge

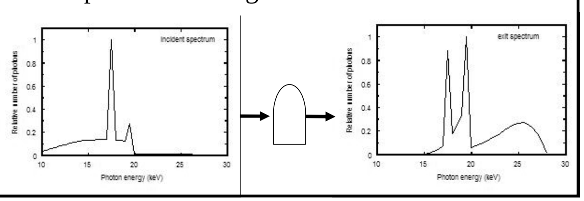
1. Tantalum filter (Toshiba) cuts out the low energy X-ray components and also the high-energy X-ray components that cause scattered radiation. This leads to reduced dose (~30%) and improved signal/noise.

2. Mammo Tungsten anode with Rhodium filter



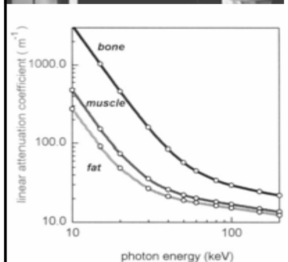
Images from:
http://www.toshibamedical.co.jp/tmd/english/products/xray/cardiovascular/xray5.html
and Tompson, Hattaway, Hall, Dowd "Principles of Imaging Science and Protection"

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



Basic Principles of Mammography

➔X-ray mammo spectrum, tube positioning and breast compression



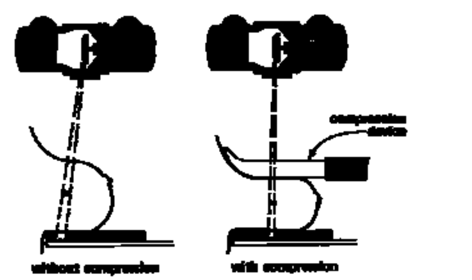
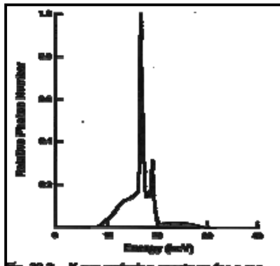
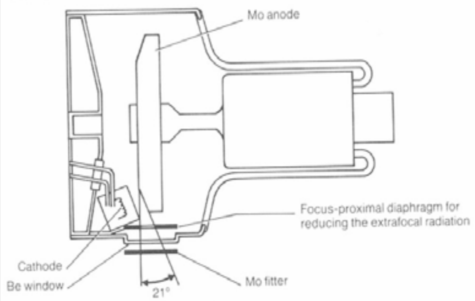


Fig. 20-8. Use of compression in mammography has three advantages: uniform image receptor exposure, reduced focal-spot blur, and reduced absorption and scatter.





➔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

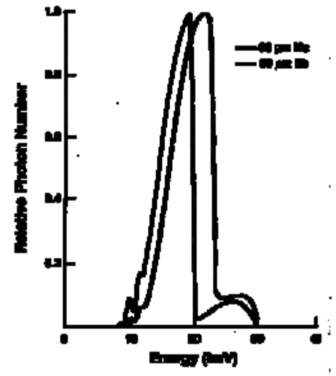
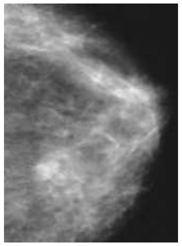
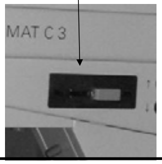
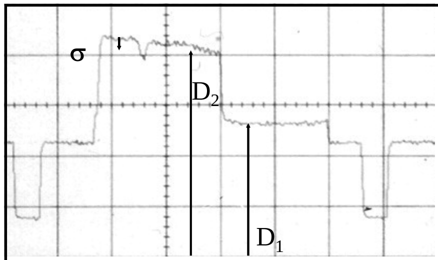
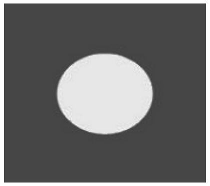


Fig. 28-4. The emission spectra from a tungsten target filtered by molybdenum or rhodium.









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

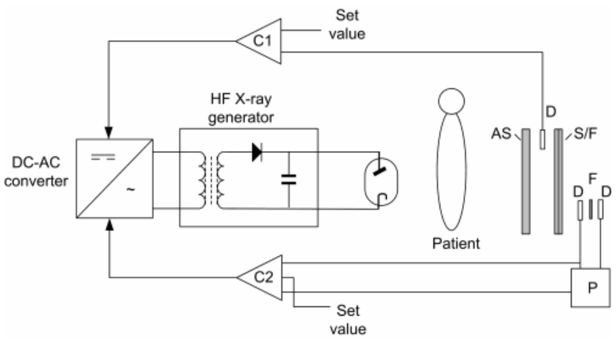
$\gamma = [D_2 - D_1]/[\log E_2 - \log E_1]$

Subject Contrast $\Delta C = I_2 - I_1$

Visual contrast

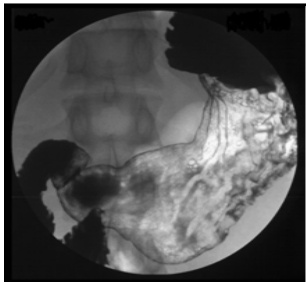
$\Delta C = \log I_2 - \log I_1$

Automatic Exposure Control (AEC) system

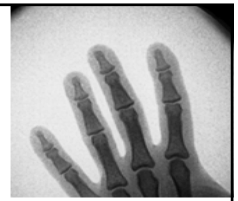


Block diagram showing two typical AEC types.

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



Anatomical X-ray contrast >>



Artificial X-ray contrast:
(various contrast agents)

<<< Barium-based (ex.stomach)

Iodine-based >>>
(ex.heart/vessels)

<<< Interventional
Radiology

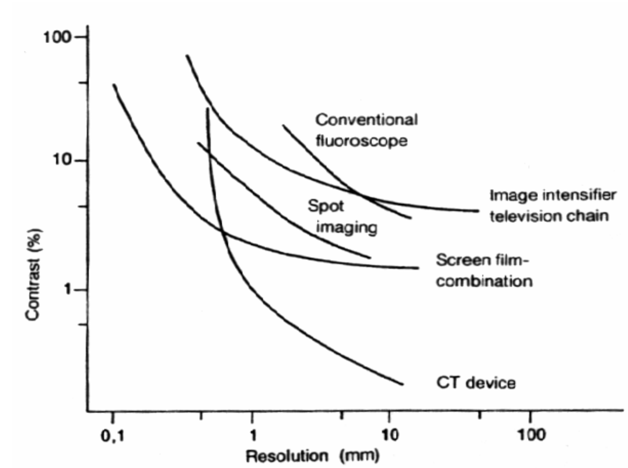
Contrast and Resolution of various X-ray detectors and methods

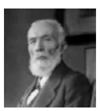
Contrast:

1. CT
2. Film
3. Fluo

Resolution:

1. Film
2. Fluo
3. CT





PHILIPS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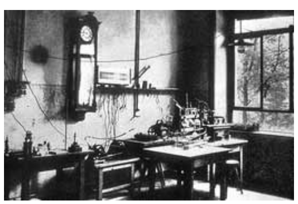
The history of
X-ray imaging


_William Crookes



Wilhelm Conrad Rontgen,
University of Wurzburg,
Nobel Prize No.1, 1901

_November 8, 1895

Philip Lenard,
University of Heidelberg ,
Nobel Prize 1905