X-ray Tomography

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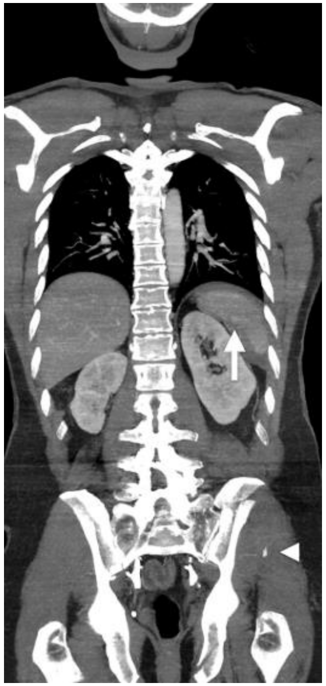
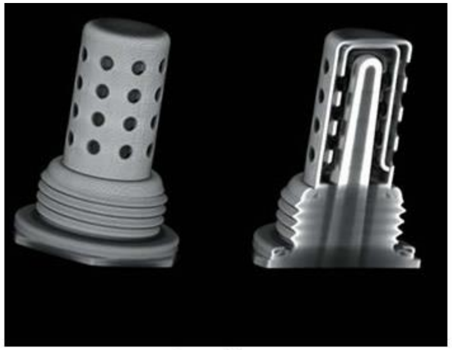
Physical Inspection and AttacKs on ElectronicS (PHIKS)

X-ray Scanning

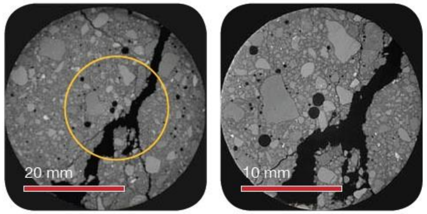
Non Destructive Testing

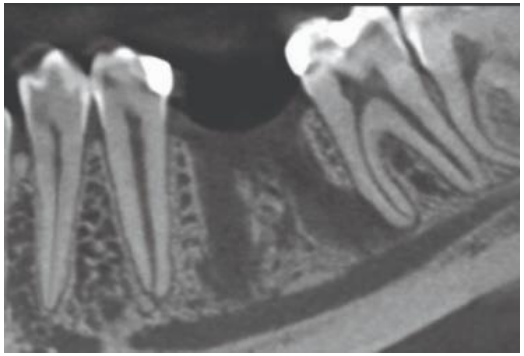
- Medical applications
- Automobile industry
- Aerospace inspection
- Oil and gas
- Batteries
- Electronics

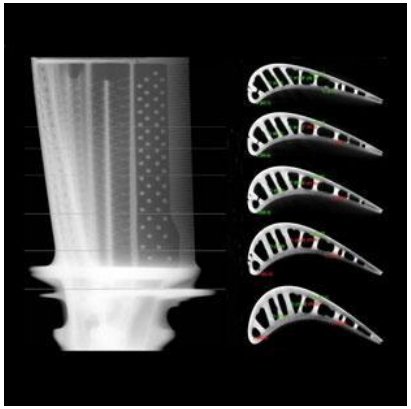


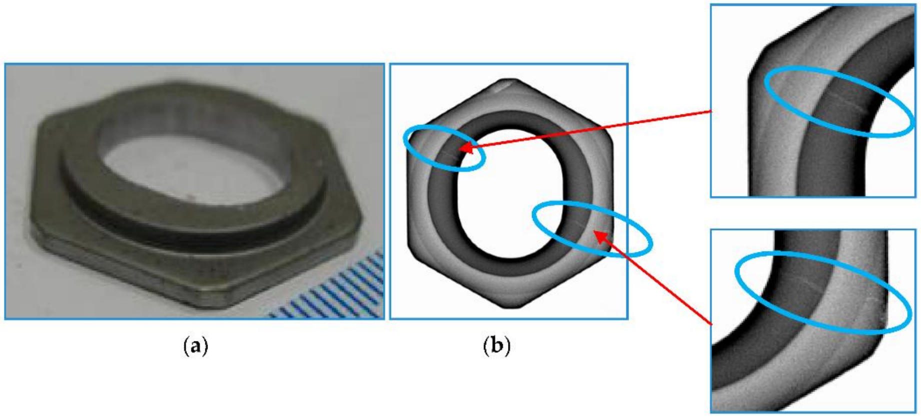


Oxygen Sensor









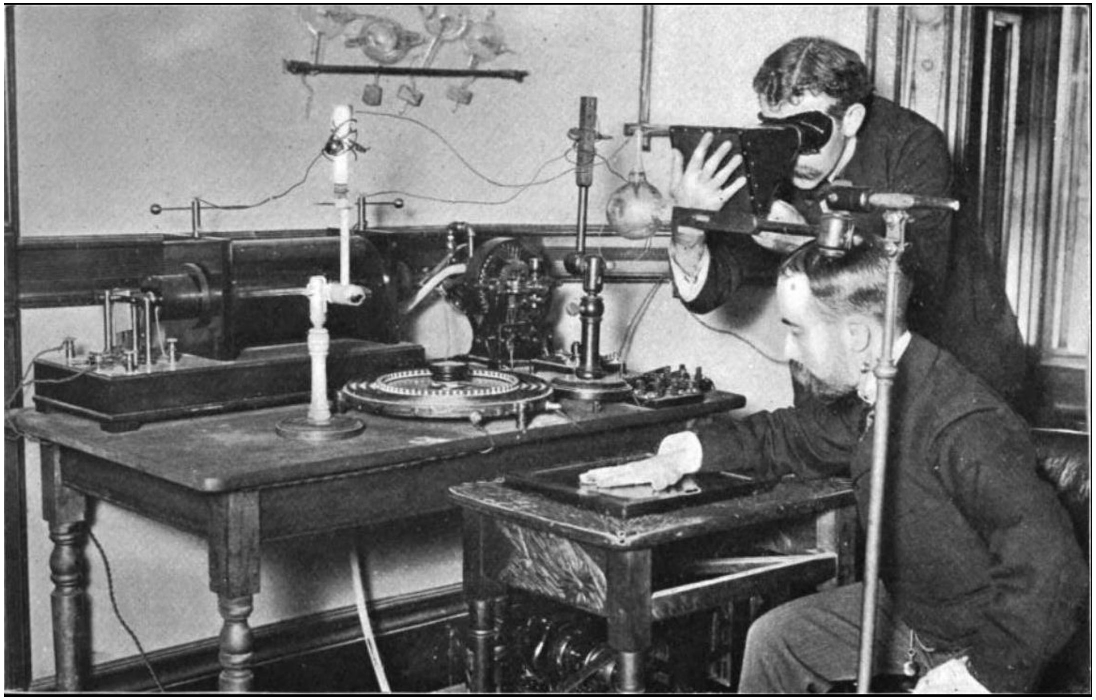
(a) (b)

Taxonomy of Defects

- **Defects**
  - **Physical**
    - **Exterior**
      - Packaging/ Shipping
        - D1: Invalid Lot Code
        - D2: Invalid OEM Shipping Labels
        - D3: Invalid OEM Packaging
        - D4: No ESD Bags for ESD Sensitive Devices
        - D5: Missing/ Forged Paperwork
        - D6: Multiple Date Codes within a Lot
        - D7: Part Orientation within Packaging
        - D8: Missing/ incorrect MSD Indicators
      - Leads/Balls/ Columns
        - D9: Dents
        - D10: Re-tinned
        - D11: Incorrect Dimensions
        - D12: Wrong Materials
        - D13: Contamination
        - D14: Oxidation/ Corrosion
        - D15: Color Variations
        - D16: Tooling Marks
        - D17: Misaligned/ missing Balls/ Columns
        - D18: Distorted/ Non-uniform Balls/Columns
      - Package
        - D19: Invalid Lot/Date/ Country Code
        - D20: Sanding / Grinding Marks
        - D21: Markings
        - D22: Burned Markings
        - D23:Ghost Markings
        - D24: Color Variations/Fade
        - D25: Improper Textures
        - D26: Extraneous Markings
        - D27: Dirty Cavities
        - D28: Incorrect Dimensions/ Weight
        - D29: High Fine/Gross Leak (Hermetic)
        - D30: Package Mold Variations
        - D31: Corrosion
        - D32: Contamination
        - D33: Package Damage
    - **Interior**
      - Bond Wires
        - D34: Missing Wires
        - D35: Poor Connection
        - D36: Broken Wires
        - D37: Poor/ Inconsistent Lead Dress
        - D38: Double Wire Bonds
      - Die
        - D39: Missing Die
        - D40: Wrong Die
        - D41: Delamination
        - D42: Gross Cracks
        - D43: Improper Die Markings
        - D44: Die Damage/ Extraneous Markings
  - **Electrical**
    - **Parametric**
      - D45: Transistor V_{th} Variation
      - D46: TDDB
      - D47: Resistive Open / Short
      - D48: Out-of-spec Leakage Current
      - D49: Out-of-spec. Transient Current
      - D50: Incorrect Temp. Profile
      - D51: Delay Defects
    - **Manufacturing**
      - Process
        - D52: Missing Contact Windows
        - D53: Misaligned Window
        - D54: Oxide Break-down
        - D55: Parasitic Transistors
      - Material
        - D56: Fine Cracks
        - D57: Crystal Imperfection
        - D58: Surface Impurities
        - D59: Improper Materials (Seals, Epoxies, Dielectrics, etc)
      - Package
        - D60: Surface Passivation and Corrosion
        - D61: Contact Degradation
        - D62: Seal Leaks
        - D63: Electromigration
        - D64: Mechanical Interfaces: Intermetallic Growth
        - D65: Mechanical Interfaces: Fatigue

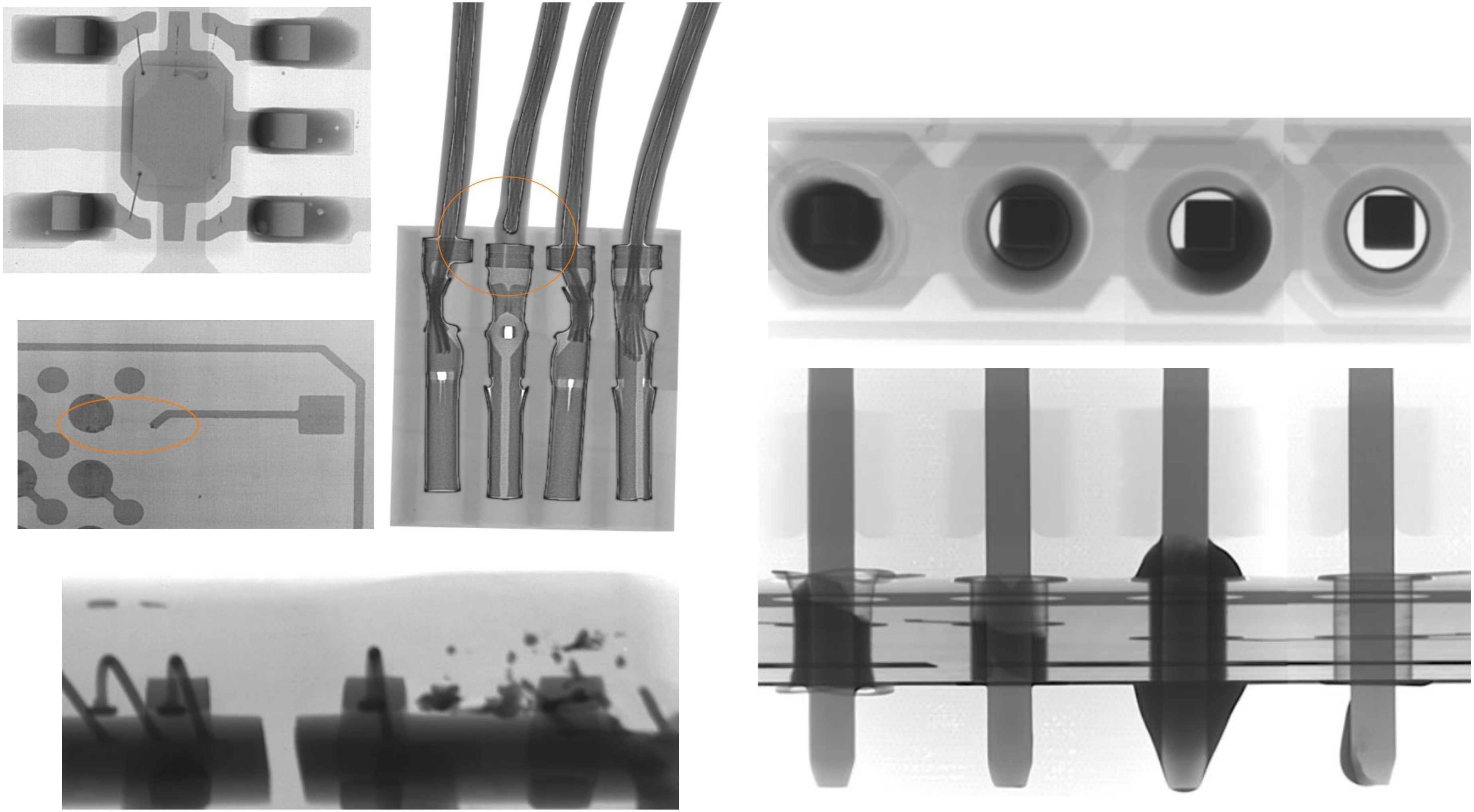
X-rays Discovery

First X-ray image by German physicist, Wilhelm Rontgen, 1895



- First X-ray image application for medical purposes
- No precautions against radiation exposure were taken

2D X-ray Inspection

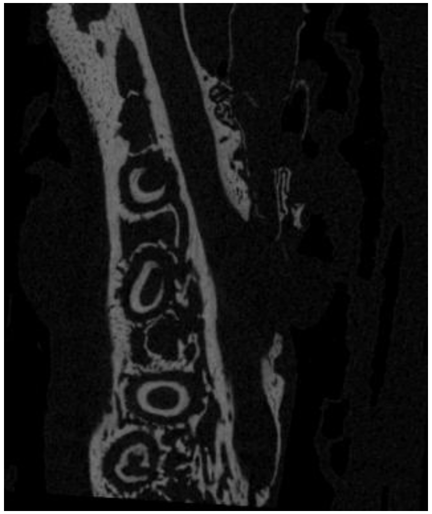


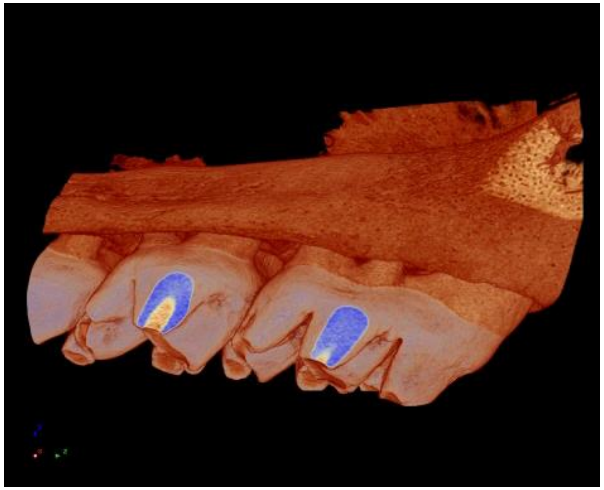
What is X-ray Computed Tomography?

1. **“Scan”**
A set of x-ray “projection” images are taken over a rotation of the imaging axis of 180 or 360 degrees

2. **“Reconstruction”**
The“projection” images are processed by the filtered Feldkamp cone-beam method to create the stack of crossection slices

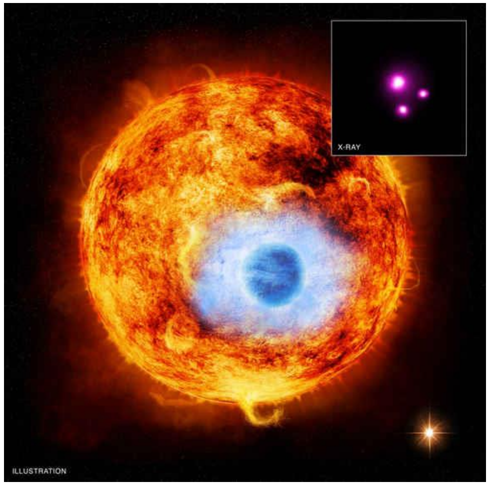
3. **“Analysis and visualisation”**
The reconstructed crossection slices are processed into 3d models for morphometric measurements and virtual visual inspection

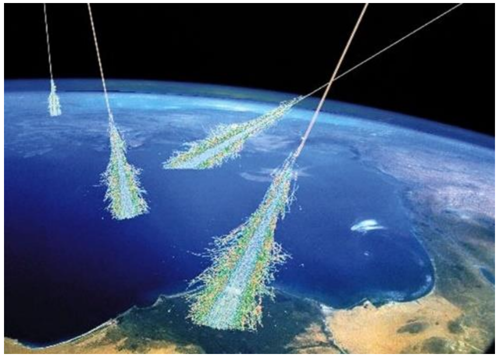




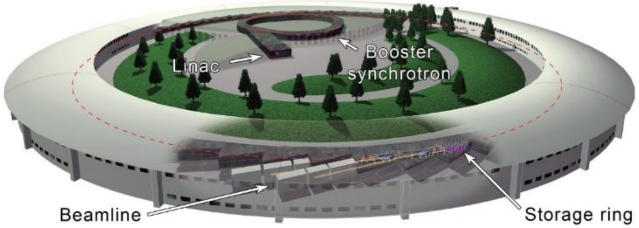
How are X-rays Produced?

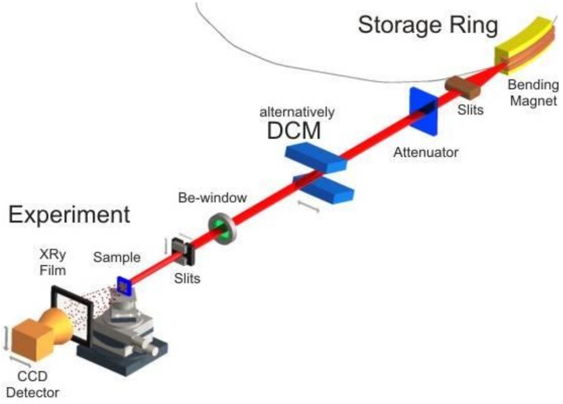
Cosmic Events



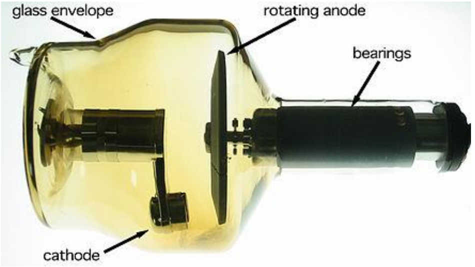


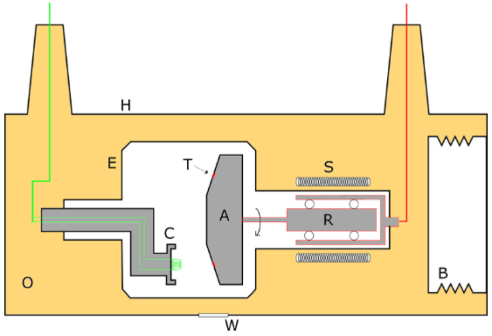
Synchrotron





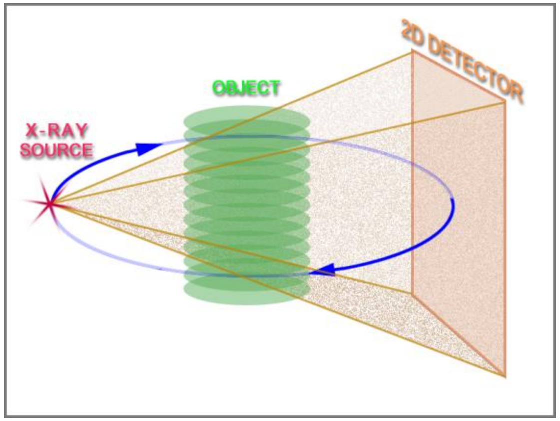
Laboratory

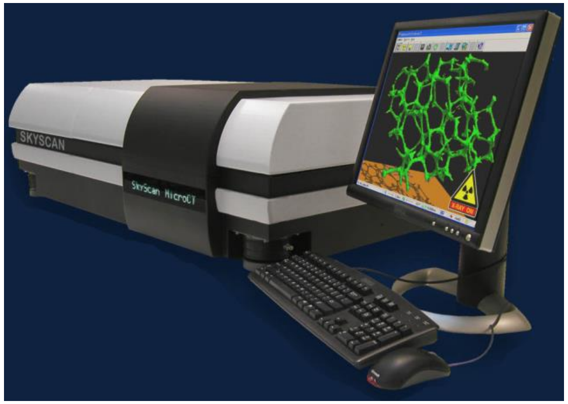




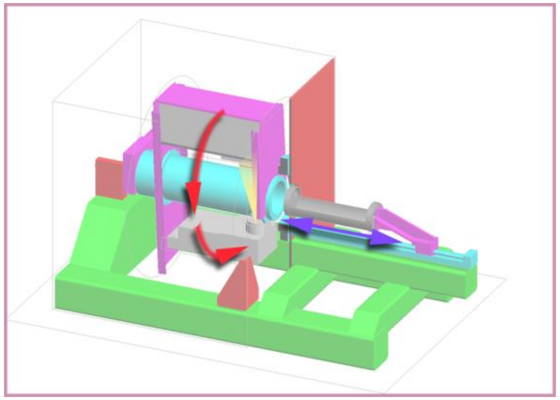
in vivo and *ex vivo* Methods

In the **“*ex vivo*”** scanner type, the sample rotates on a stage around a vertical axis, allowing angular projection images over 360 degrees



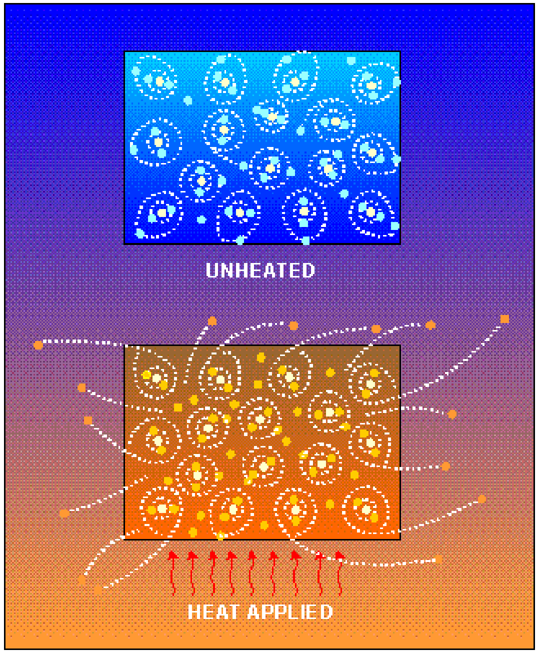


In the **“*in vivo*”** scanner type, the sample – e.g. a live mouse or rat – lies still on a horizontal bed, while x-ray source and camera rotate around the sample bed, over 360 degrees



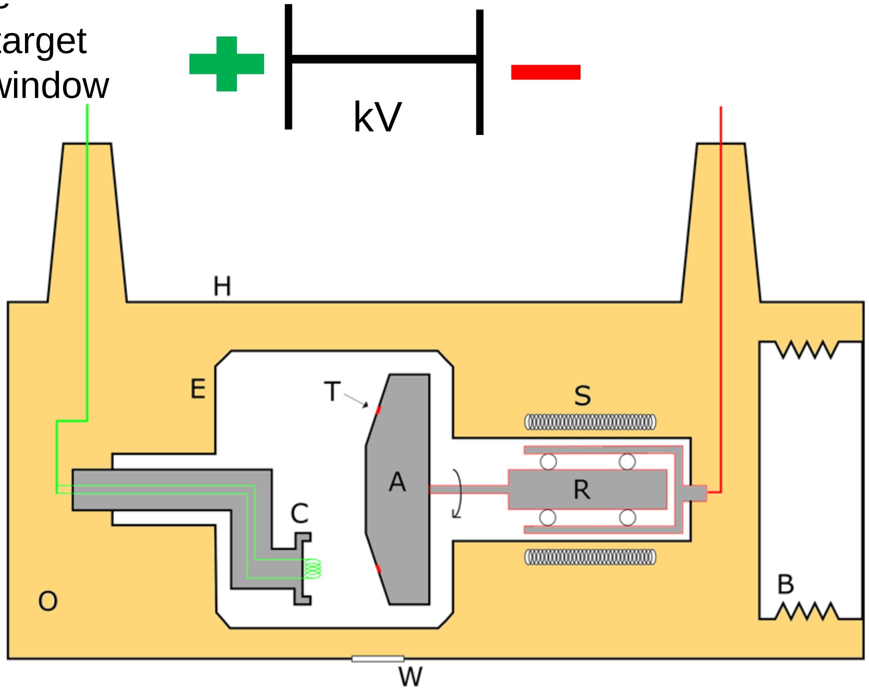
How are X-rays Produced?

X-ray Emission



Thermionic Emission:
Filament is heated until the electrons can escape

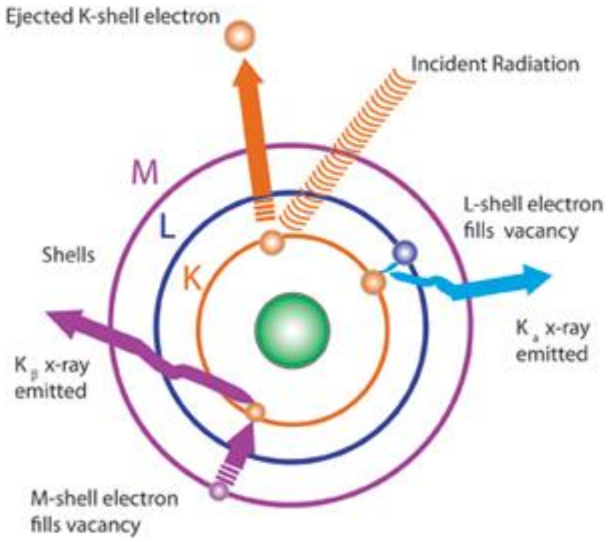
- Simplified rotating anode tube schematic
- A: Anode
- C: cathode
- T: Anode target
- W: X-ray window

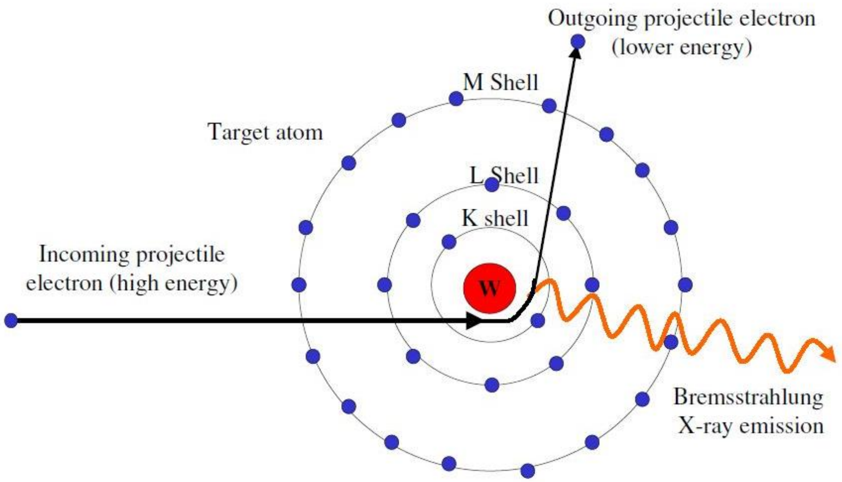


- Filament is Tungsten
- Target typically Tungsten (Alt: Cu, Mo, Ag)
- Window is Beryllium allows X-rays out but keeps chamber under vacuum
- Inefficient process ~1% converted to X-rays

X-ray Spectrum

X-ray Spectrum





Characteristic X-rays
(Specific X-rays)

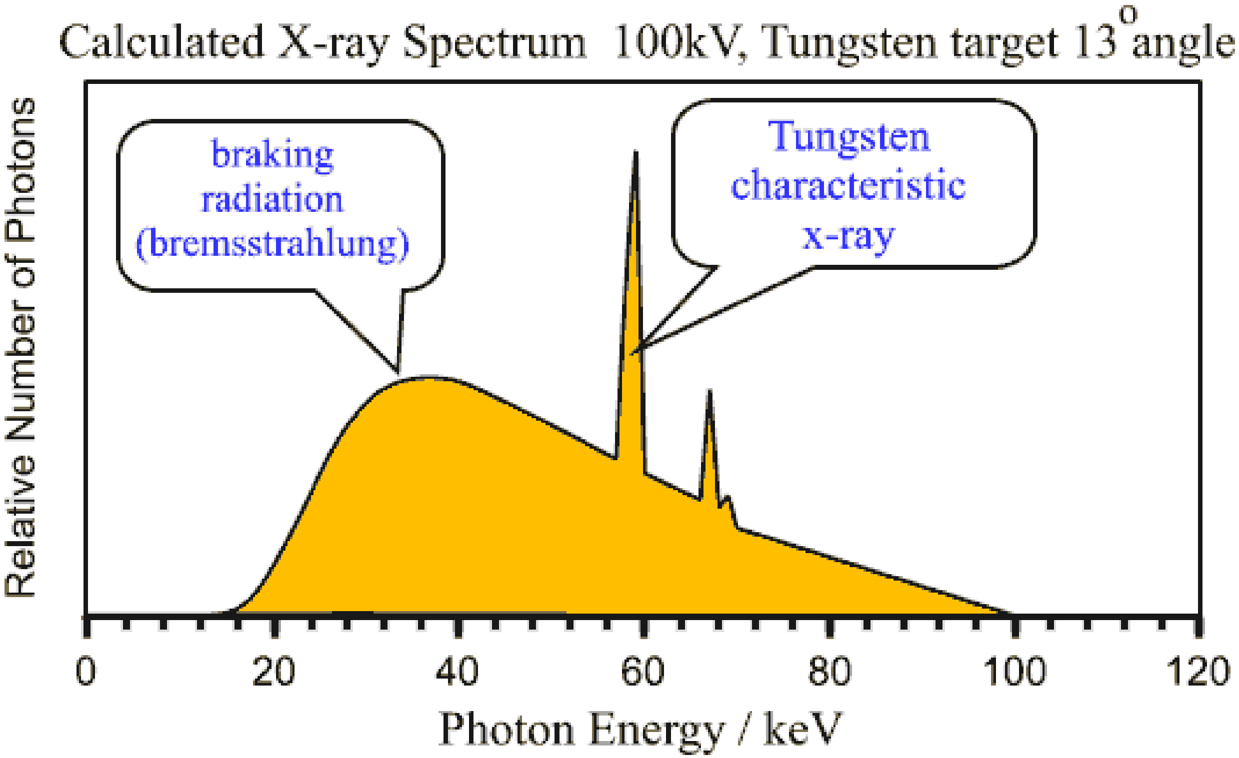
Bremsstrahlung X-rays
(Continuous X-rays)

X-rays are produced in 2 ways: Characteristic X-rays (Shell Electron Emission) and Bremsstrahlung X-rays (Incoming Electron Deflection)

X-ray Spectrum

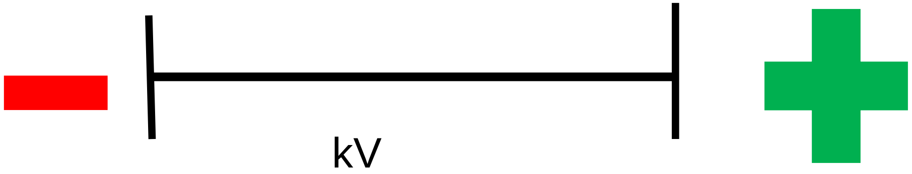
- **Monochromatic** beam (single energy X-ray). XPS,
- In reality, laboratory X-ray systems are normally a **polychromatic** beam (a range of energy spectrum),
- Various components of the energy spectrum are not attenuated uniformly when passing through an object.

- The lower energy component of X-ray spectrum is more easily attenuated or even completely adsorbed when traveling through a dense part and causes beam hardening defects.

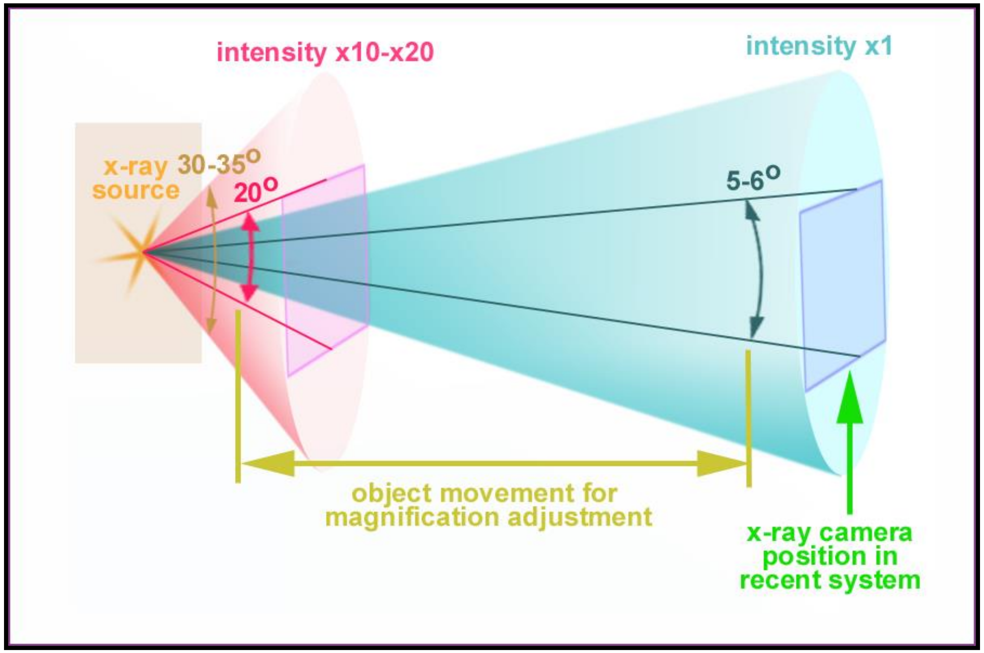


X-ray Propagation

X-ray Power



- Total power defined by wattage on target
- P = I*V (Watt = Amps * Volts)
- 10 W = (100uA) * (100kV)

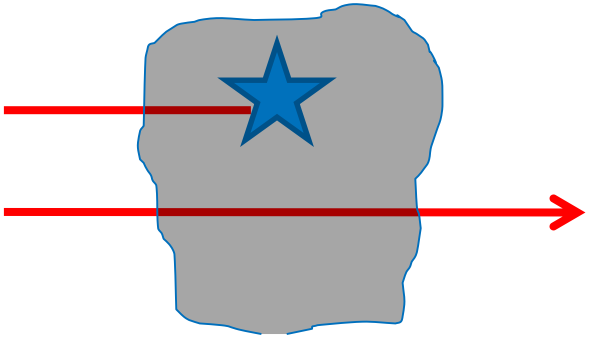


X-ray flux can be thought of like a *flow* of light.

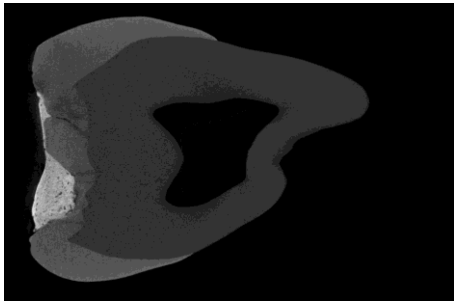
X-ray interaction with Matter

- X-rays, like light, are **electromagnetic radiation** but with higher photon energy – and they transmit through materials allowing internal imaging.

- Xray imaging requires **partial absorption** – some x-rays absorbed, some transmitted



- Another requirement for imaging of internal structure by x-rays is **differential absorption**, that is, different parts of the object having significantly different x-ray absorption – to give CONTRAST



X-ray interaction with Matter

Attenuation of X-rays

$$I = I_o * \exp(-\mu\, x)$$

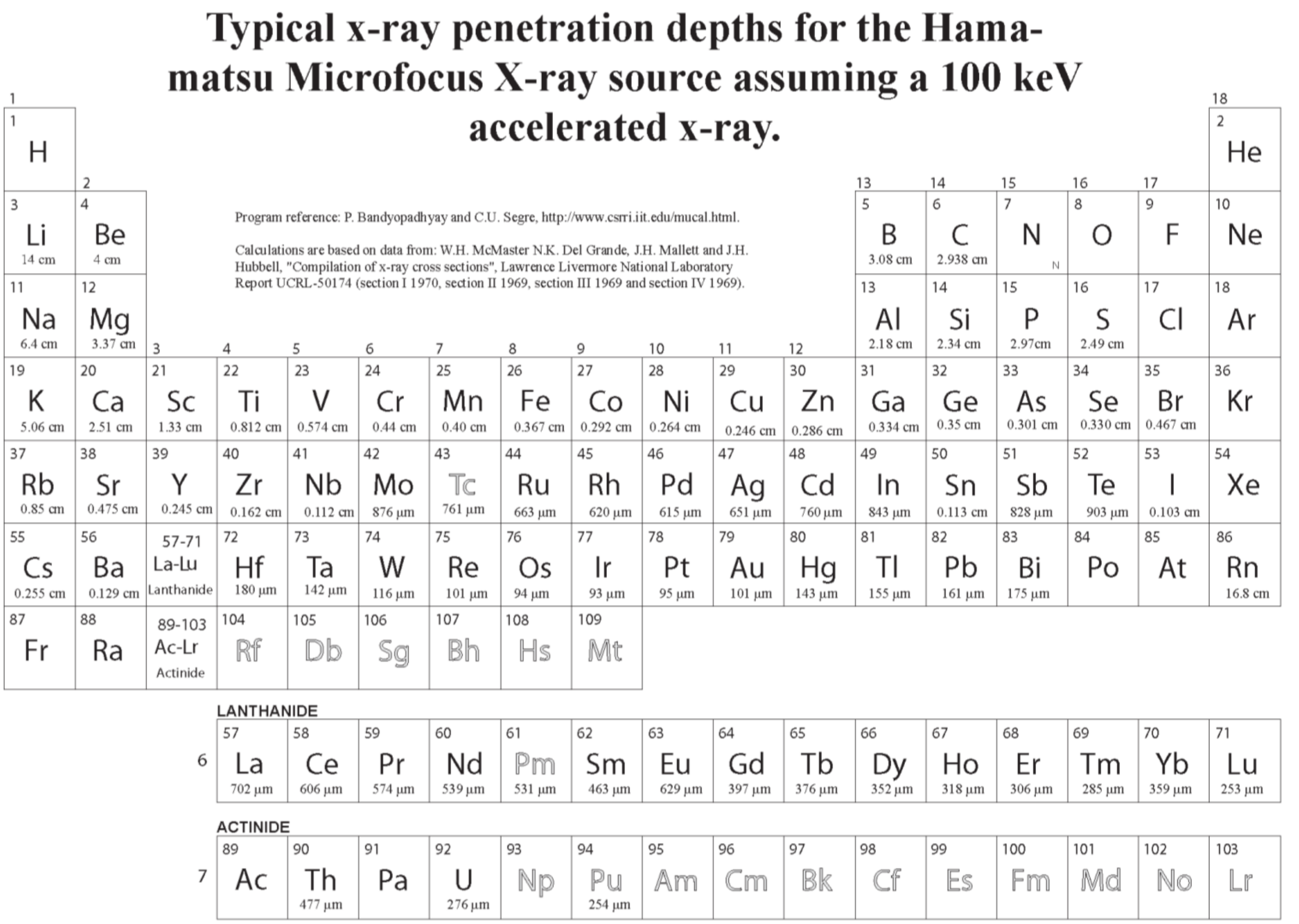
Where:

I_o = intensity of the unattenuated beam

x = the thickness of (homogenous) material (cm)

μ = linear attenuation coefficient (cm^{-1})

Penetration Depth Guidelines



Typical x-ray penetration depths for the Hamamatsu Microfocus X-ray source assuming a 100 keV accelerated x-ray.

Program reference: P. Bandyopadhyay and C.U. Segre, http://www.csrri.iit.edu/mucal.html.

Calculations are based on data from: W.H. McMaster N.K. Del Grande, J.H. Mallett and J.H. Hubbell, "Compilation of x-ray cross sections", Lawrence Livermore National Laboratory Report UCRL-50174 (section I 1970, section II 1969, section III 1969 and section IV 1969).

	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18
1	1 H																	2 He
2	3 Li 14 cm	4 Be 4 cm											5 B 3.08 cm	6 C 2.938 cm	7 N N	8 O	9 F	10 Ne
3	11 Na 6.4 cm	12 Mg 3.37 cm											13 Al 2.18 cm	14 Si 2.34 cm	15 P 2.97cm	16 S 2.49 cm	17 Cl	18 Ar
4	19 K 5.06 cm	20 Ca 2.51 cm	21 Sc 1.33 cm	22 Ti 0.812 cm	23 V 0.574 cm	24 Cr 0.44 cm	25 Mn 0.40 cm	26 Fe 0.367 cm	27 Co 0.292 cm	28 Ni 0.264 cm	29 Cu 0.246 cm	30 Zn 0.286 cm	31 Ga 0.334 cm	32 Ge 0.35 cm	33 As 0.301 cm	34 Se 0.330 cm	35 Br 0.467 cm	36 Kr
5	37 Rb 0.85 cm	38 Sr 0.475 cm	39 Y 0.245 cm	40 Zr 0.162 cm	41 Nb 0.112 cm	42 Mo 876 µm	43 Tc 761 µm	44 Ru 663 µm	45 Rh 620 µm	46 Pd 615 µm	47 Ag 651 µm	48 Cd 760 µm	49 In 843 µm	50 Sn 0.113 cm	51 Sb 828 µm	52 Te 903 µm	53 I 0.103 cm	54 Xe
6	55 Cs 0.255 cm	56 Ba 0.129 cm	57-71 La-Lu Lanthanide	72 Hf 180 µm	73 Ta 142 µm	74 W 116 µm	75 Re 101 µm	76 Os 94 µm	77 Ir 93 µm	78 Pt 95 µm	79 Au 101 µm	80 Hg 143 µm	81 Tl 155 µm	82 Pb 161 µm	83 Bi 175 µm	84 Po	85 At	86 Rn 16.8 cm
7	87 Fr	88 Ra	89-103 Ac-Lr Actinide	104 Rf	105 Db	106 Sg	107 Bh	108 Hs	109 Mt									

LANTHANIDE

6	57 La 702 µm	58 Ce 606 µm	59 Pr 574 µm	60 Nd 539 µm	61 Pm 531 µm	62 Sm 463 µm	63 Eu 629 µm	64 Gd 397 µm	65 Tb 376 µm	66 Dy 352 µm	67 Ho 318 µm	68 Er 306 µm	69 Tm 285 µm	70 Yb 359 µm	71 Lu 253 µm

ACTINIDE

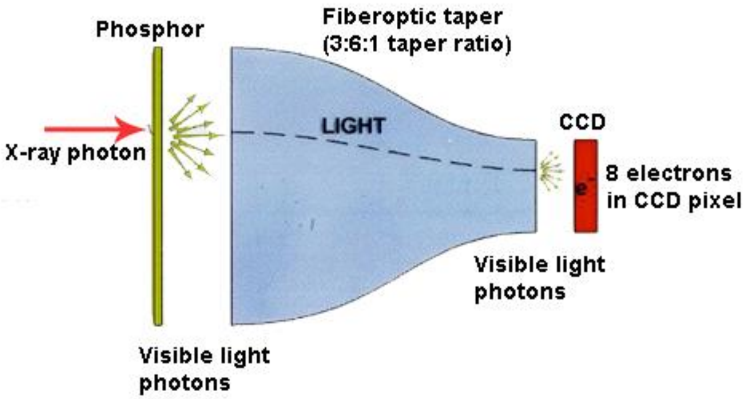
7	89 Ac	90 Th 477 µm	91 Pa	92 U 276 µm	93 Np	94 Pu 254 µm	95 Am	96 Cm	97 Bk	98 Cf	99 Es	100 Fm	101 Md	102 No	103 Lr

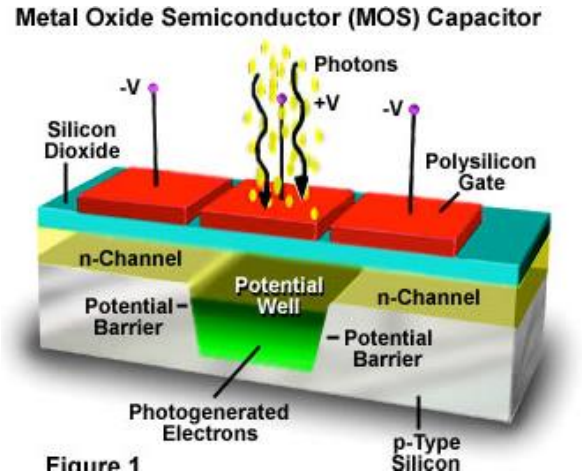
Table courtesy of B. Patterson, Los Alamos National Laboratory.

To be used only as a rough guide. These values do not represent limits only an estimate of the thickness of material needed to obtain ~33% transmission

X-ray Image Detection

Scintillators and Detectors





Scintillators convert X-ray photons into white light that can be imaged by the detector (CCD or CMOS),

Detectors convert white light into electrical charge which is read out through the camera as pixel value.

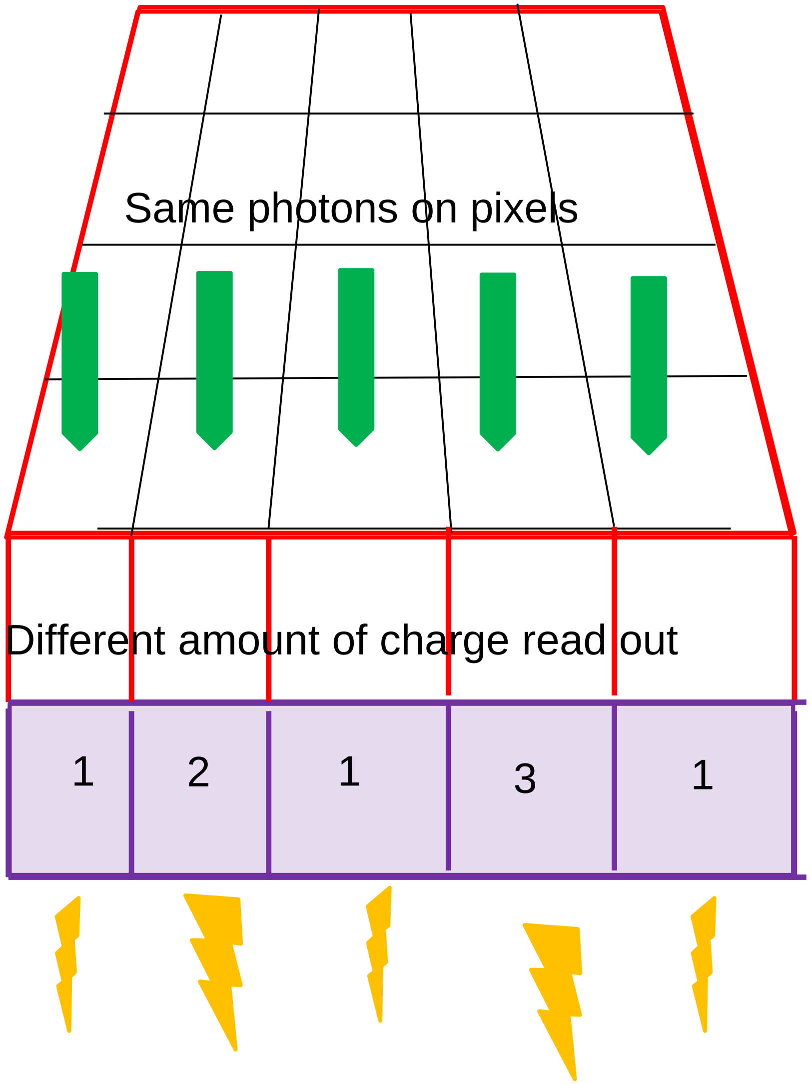
X-ray Image Detection

Pixel Readout Noise

Each pixel has readout noise.

Readout noise occurs from fluctuation in the amplification of digitizing the analog signal.

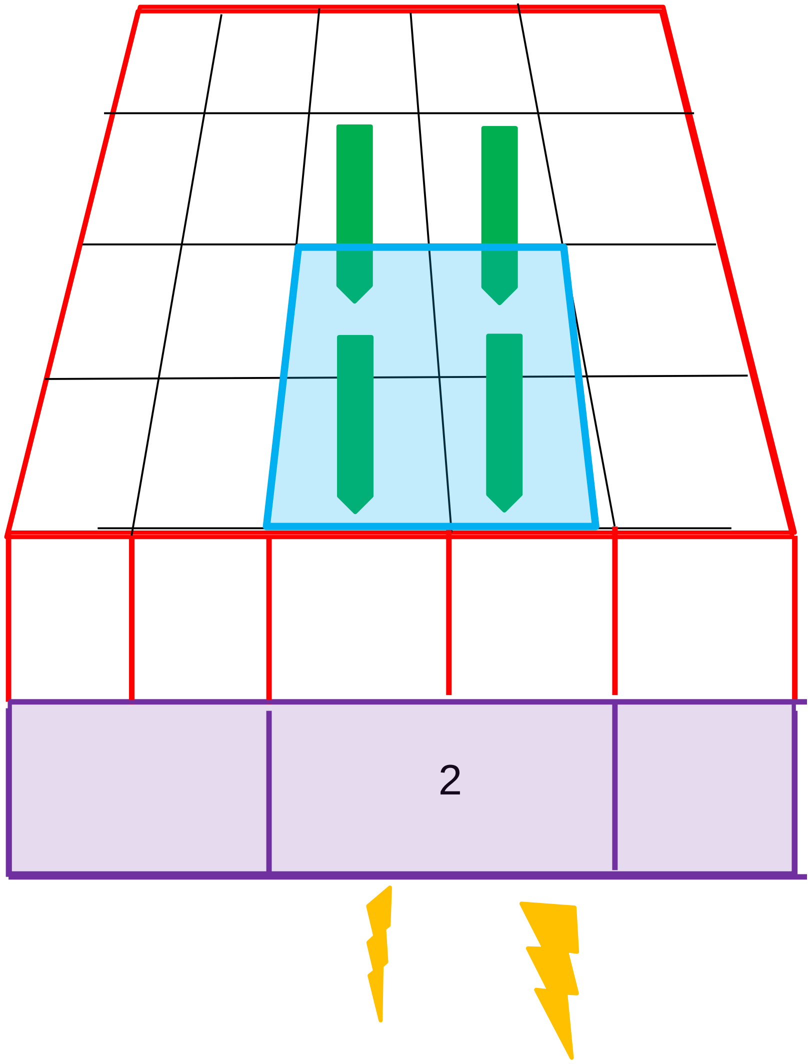
(i.e. even though same amount of charge is put on each pixel, the Analog-to-Digial Units (ADU) is not the same.



X-ray Image Detection

Reduce Readout Noise

By binning the pixel, it reduces readout noise, in case of 2 x 2 binning, because it is signal from 4 pixel with 1 readout, so the contribution is much less.

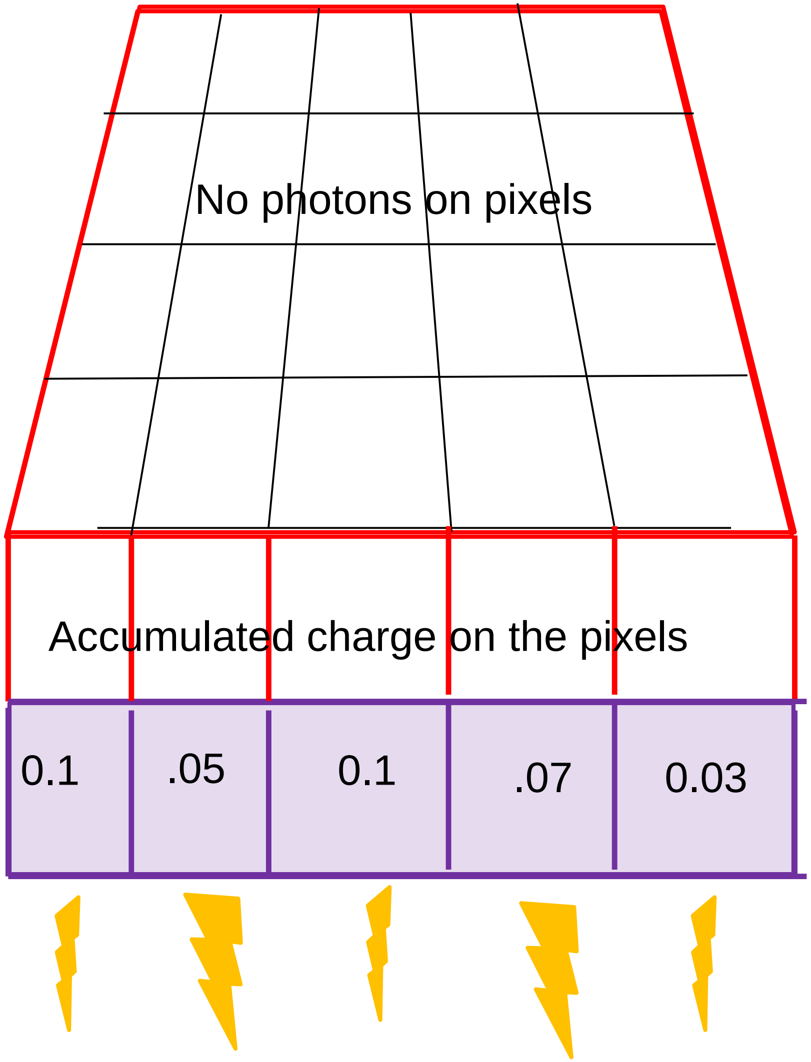


X-ray Image Detection

Dark Current

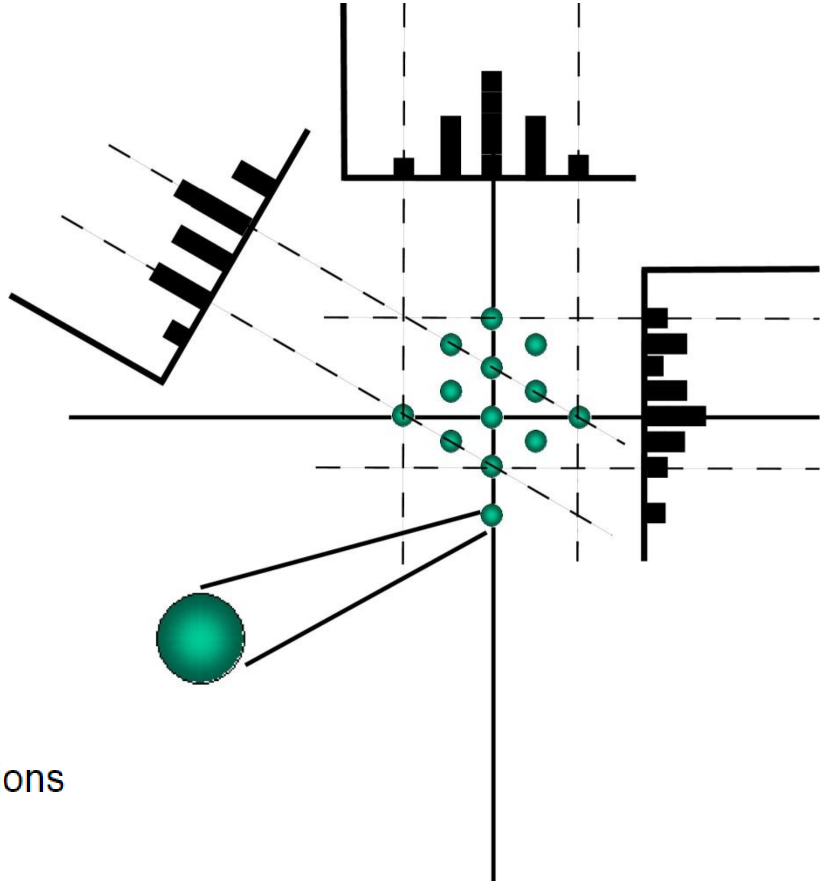
Dark current is accumulated charge on the detector in the absence of light.

FLAT FIELDS



Computed Tomography Reconstruction

Ideal Case of Uniform Attenuating Sphere

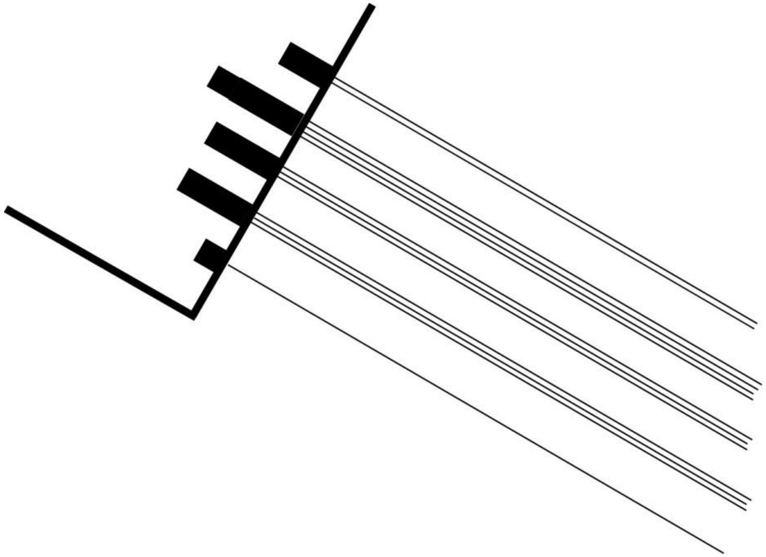


Assumptions:

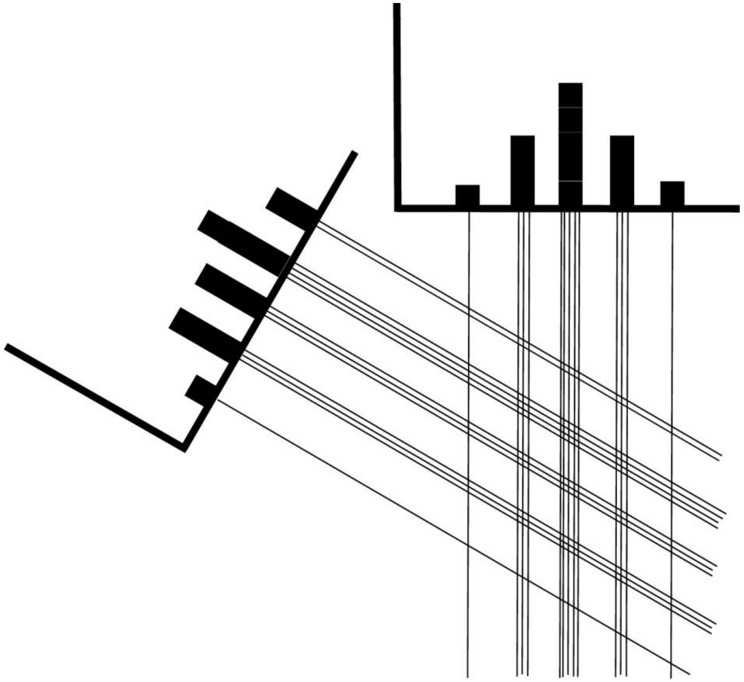
- Ideal Geometry
- Low Noise
- Sufficient number of projections

Computed Tomography Reconstruction

Ideal Case of Uniform Attenuating Sphere



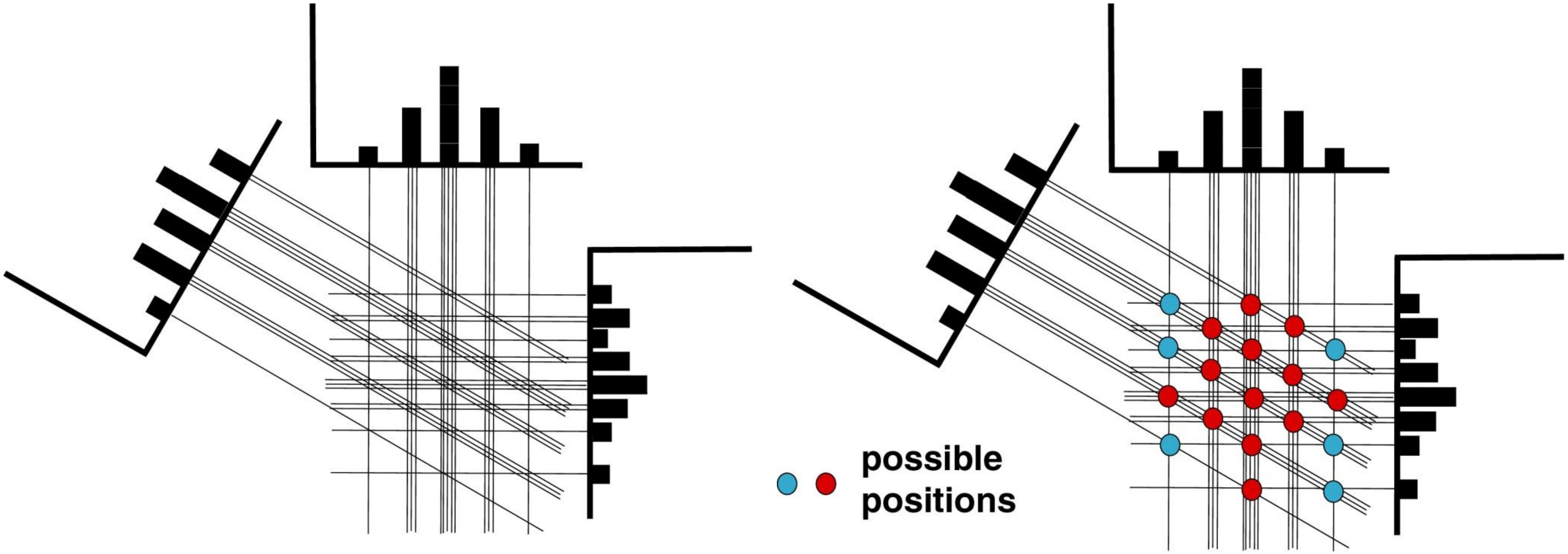
First Projection



Second Projection

Computed Tomography Reconstruction

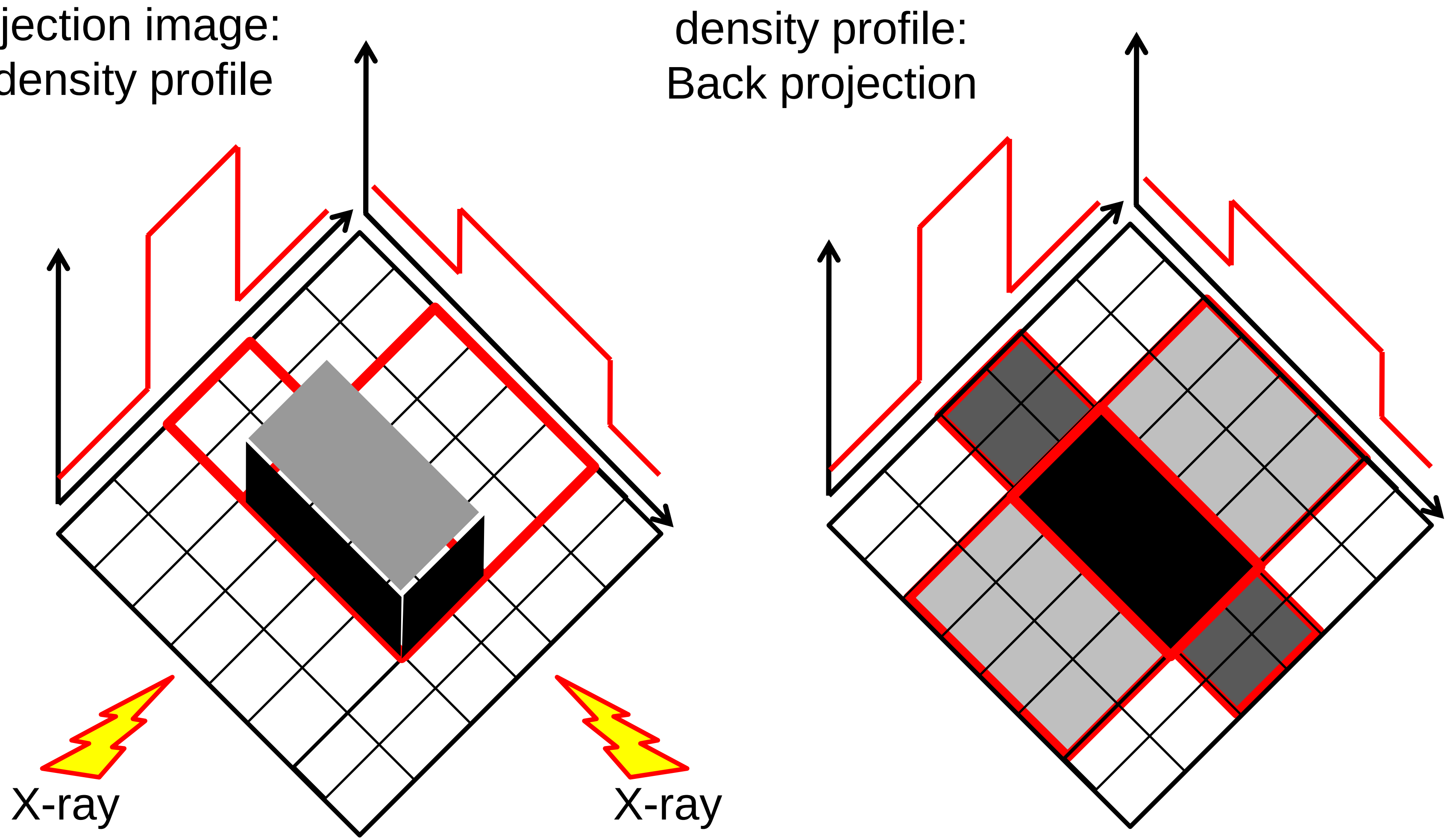
Ideal Case of Uniform Attenuating Sphere



First Projection

Second Projection

Reconstruction: back projection

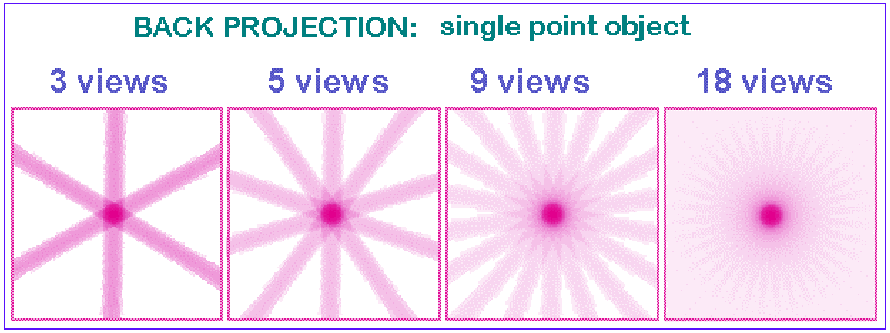


Computed Tomography Reconstruction

Backprojection

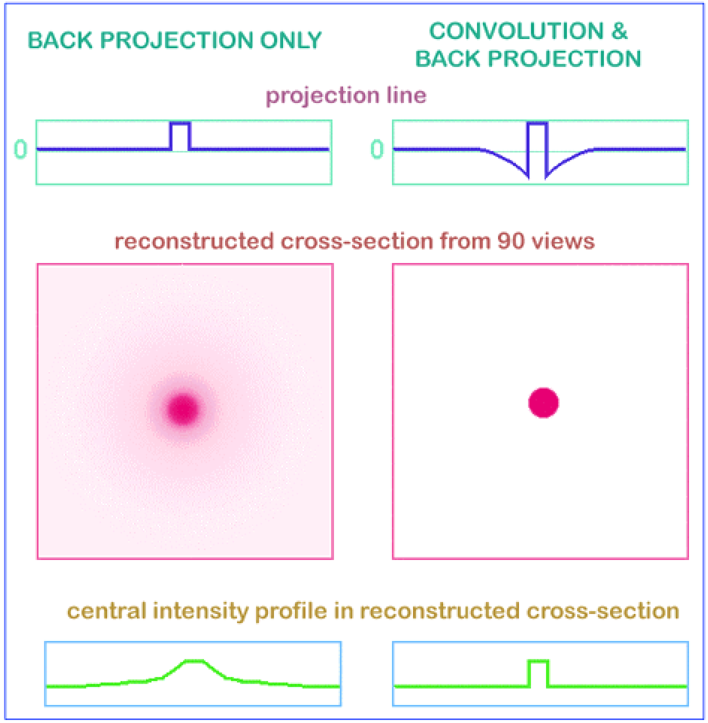
Modified Feldkemp Backprojection (NRECON SERVER)

INSTARECON: Proprietary that makes use of oversampling in the center to speed reconstruction up



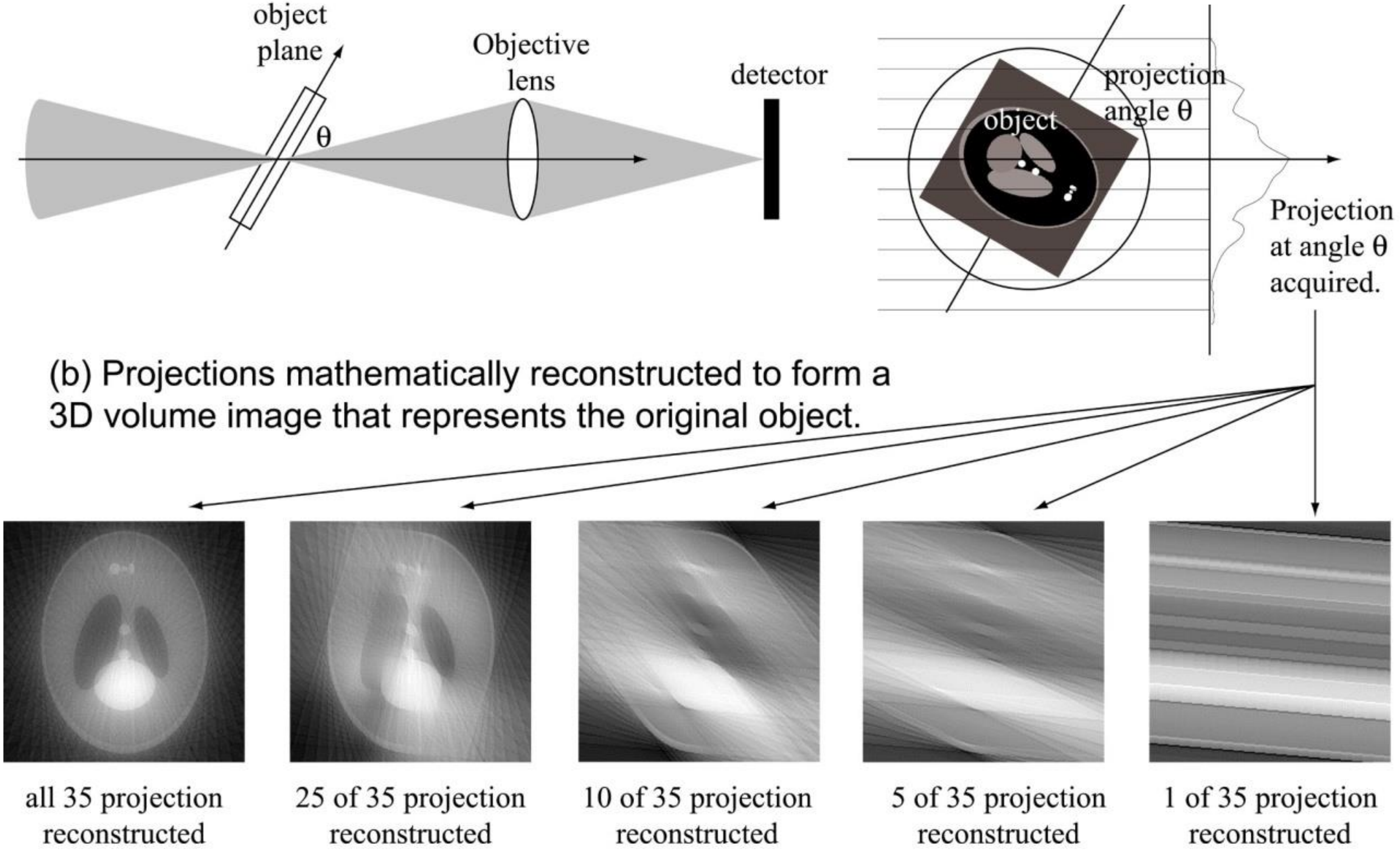
Convolution

Applies a sharpening correction to the results of back-projection



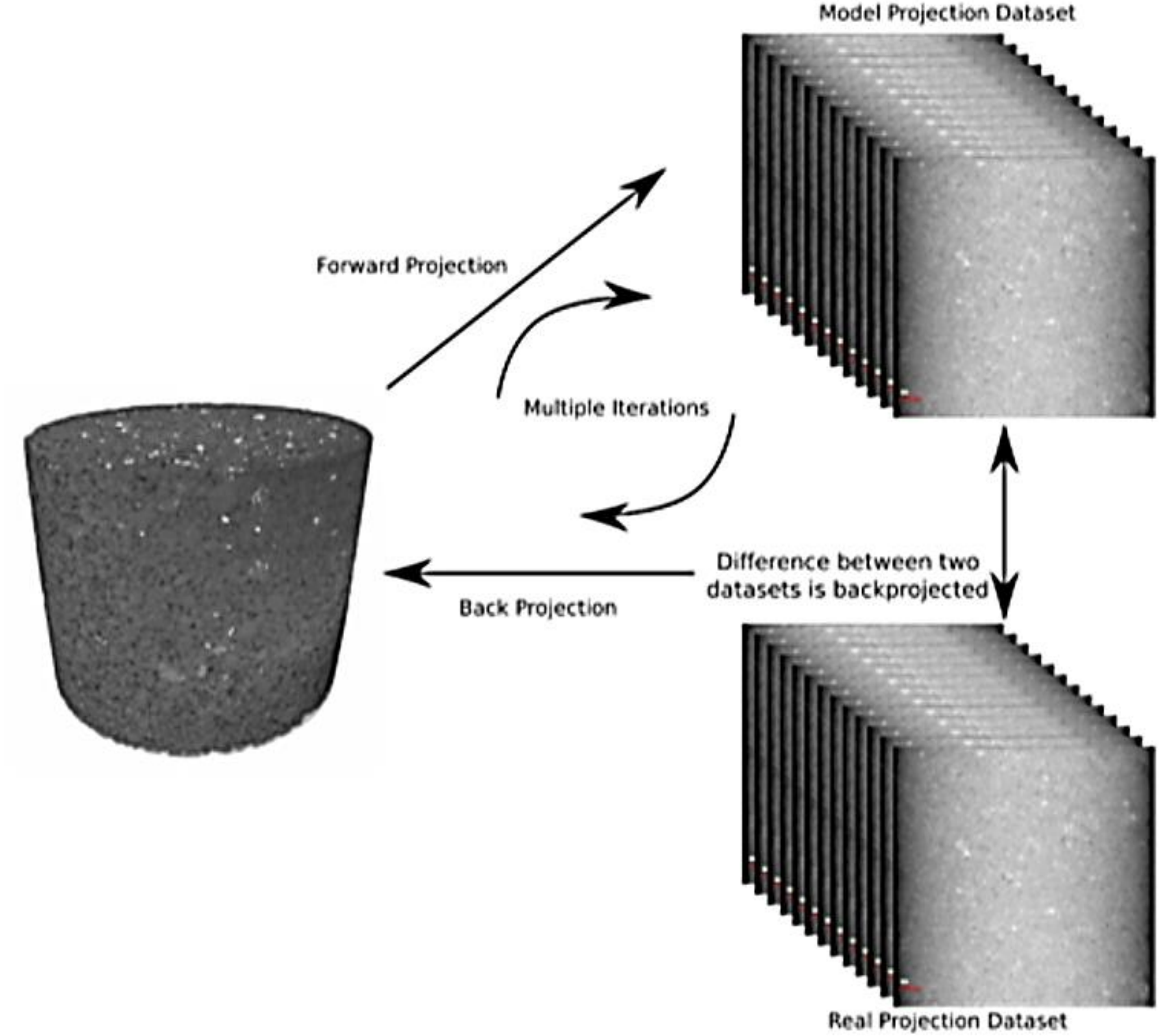
Computed Tomography Reconstruction

(a) Object imaged at various angles to obtain tomographic projections

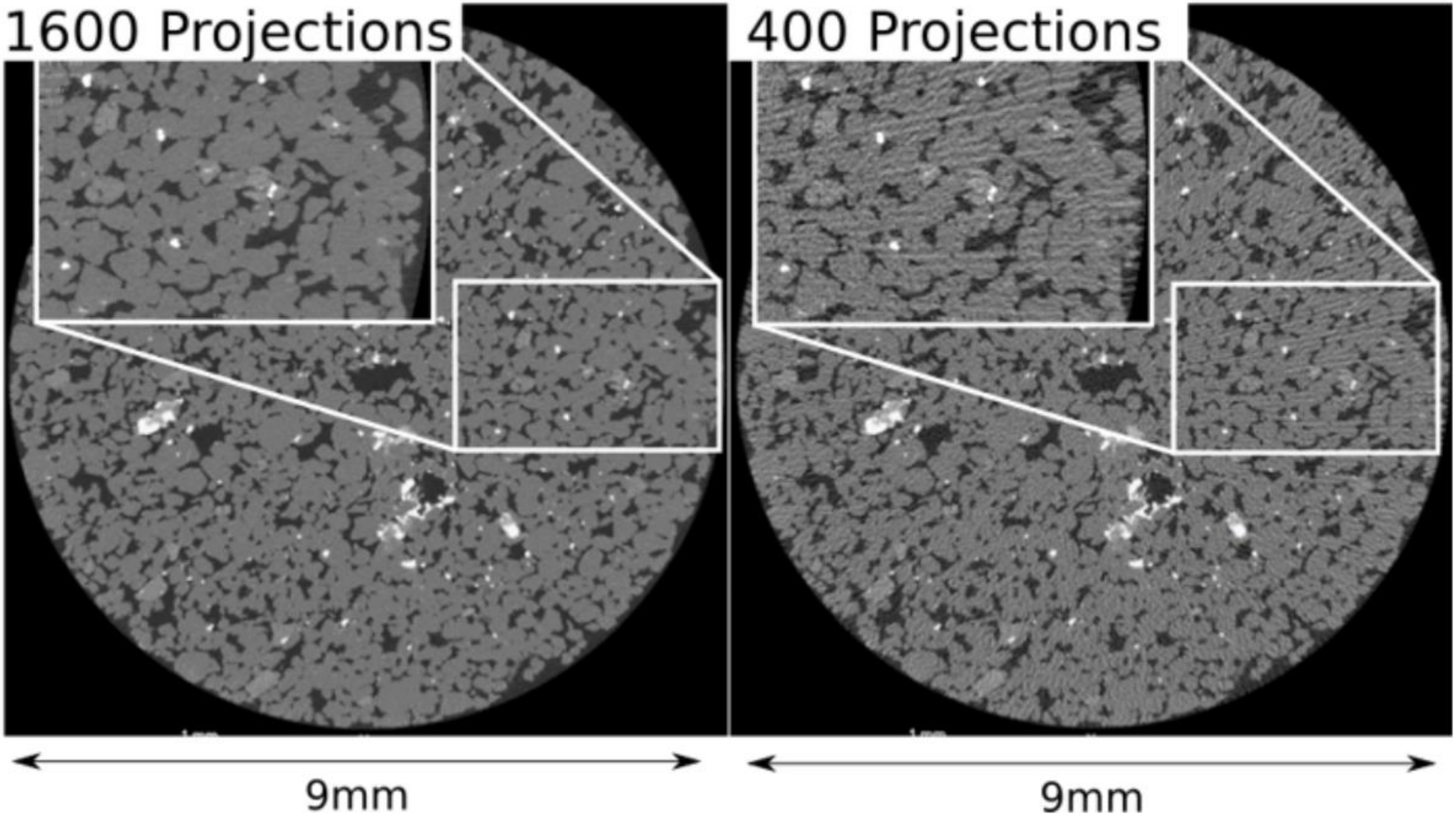


(b) Projections mathematically reconstructed to form a 3D volume image that represents the original object.

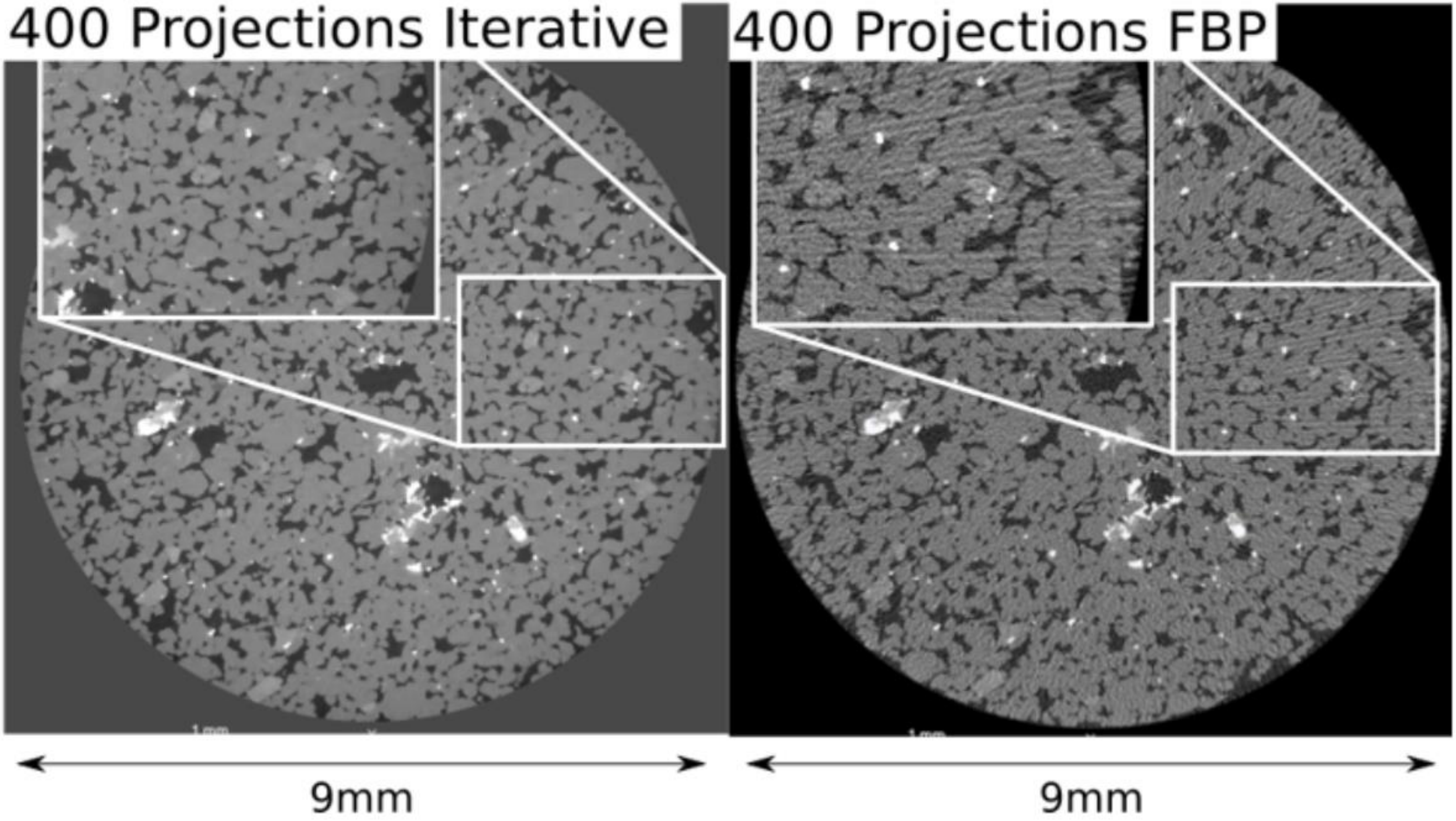
Iterative Reconstruction



Back Projection



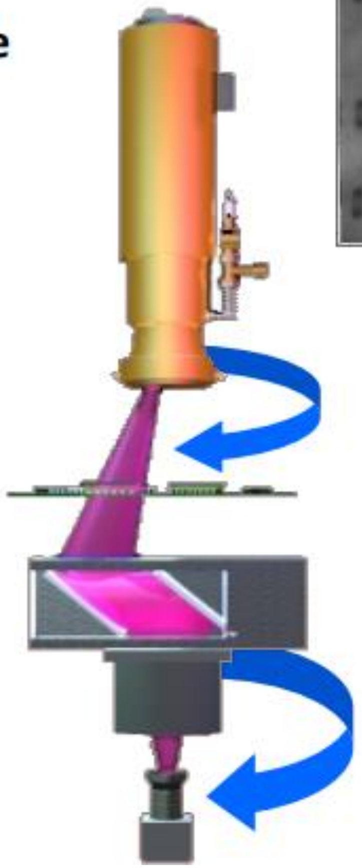
BP vs. Iterative Reconstruction



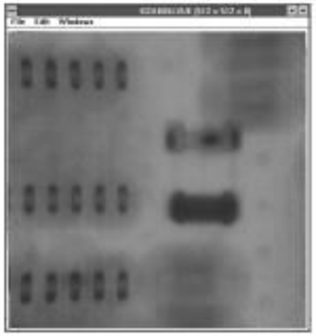
X-ray Laminography

Mechanical Image Integration

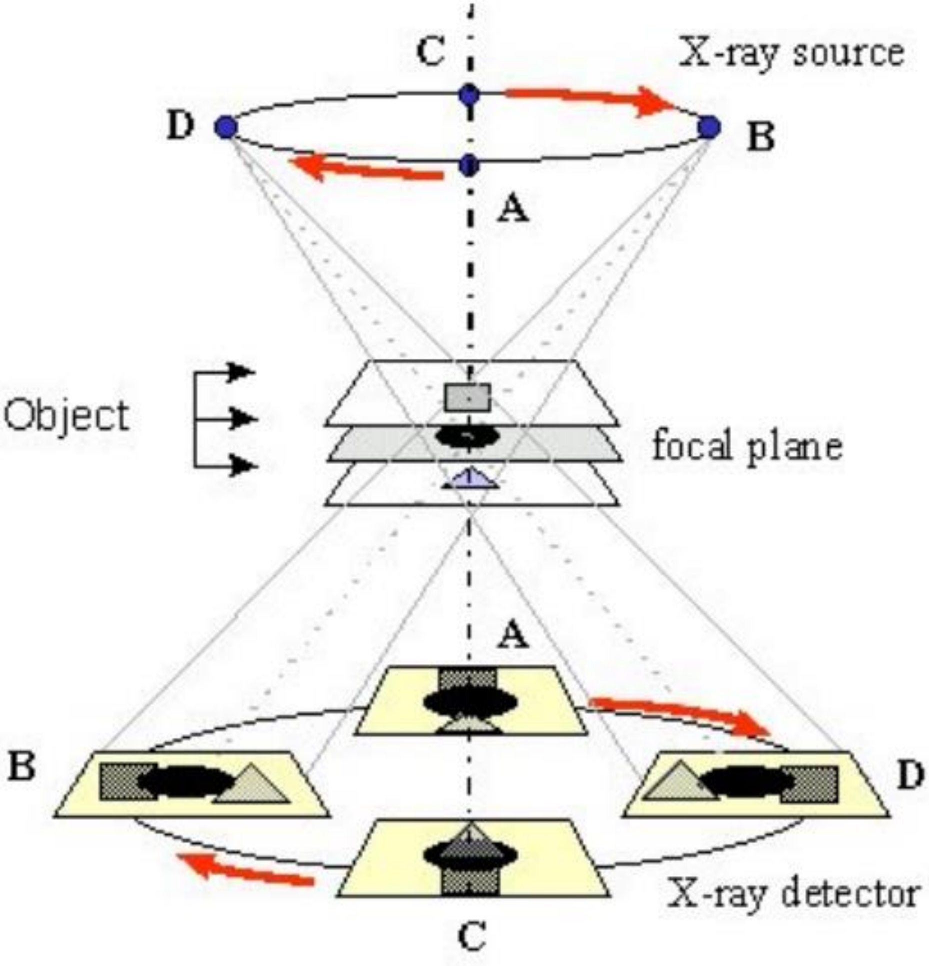
Generate
Off-axis
X-rays



Rotating
Detector

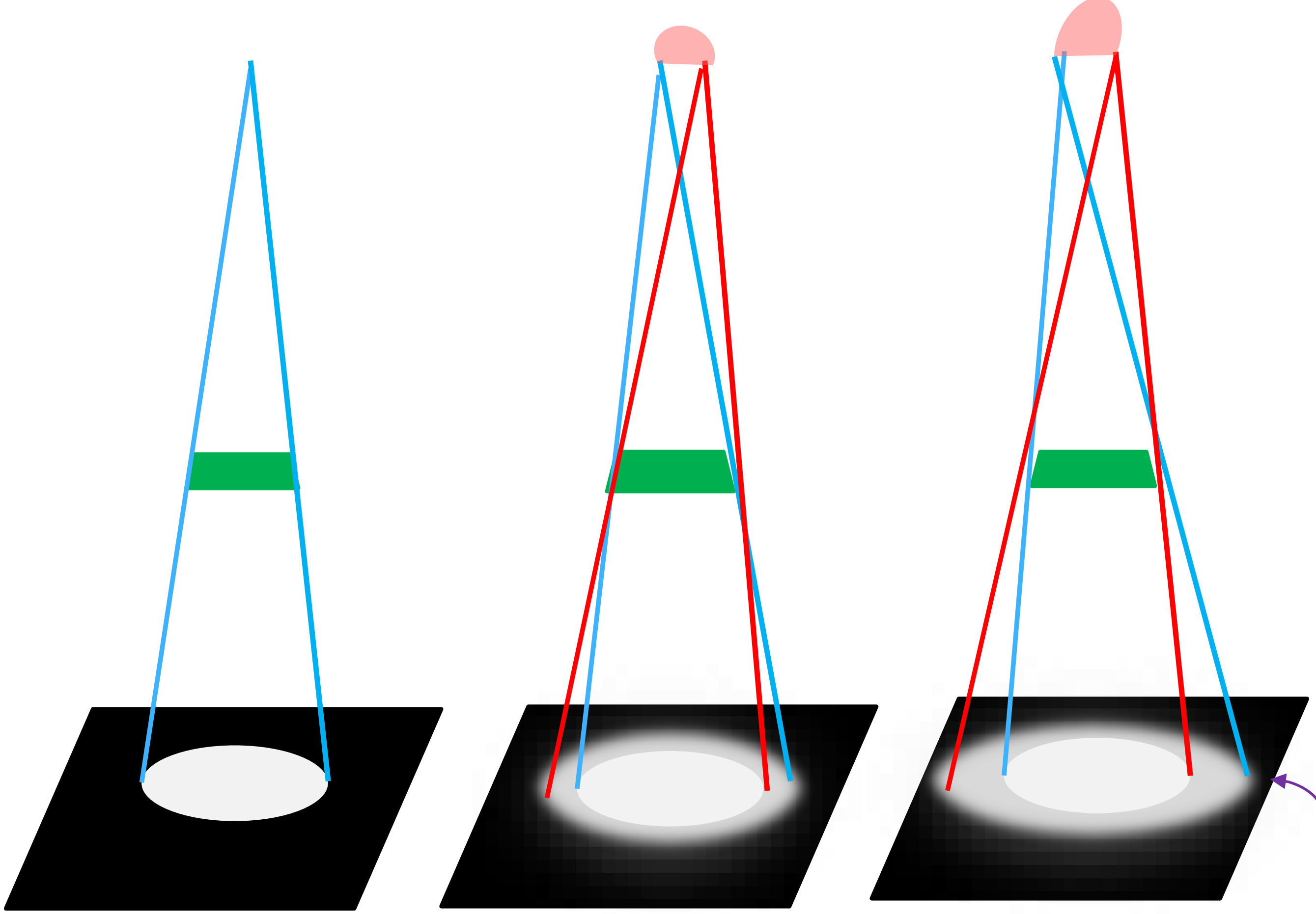


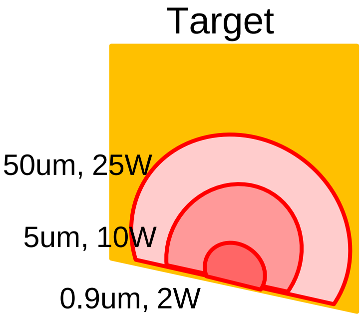
Principle of Laminography



Geometrical Magnification

X-ray Spot Size



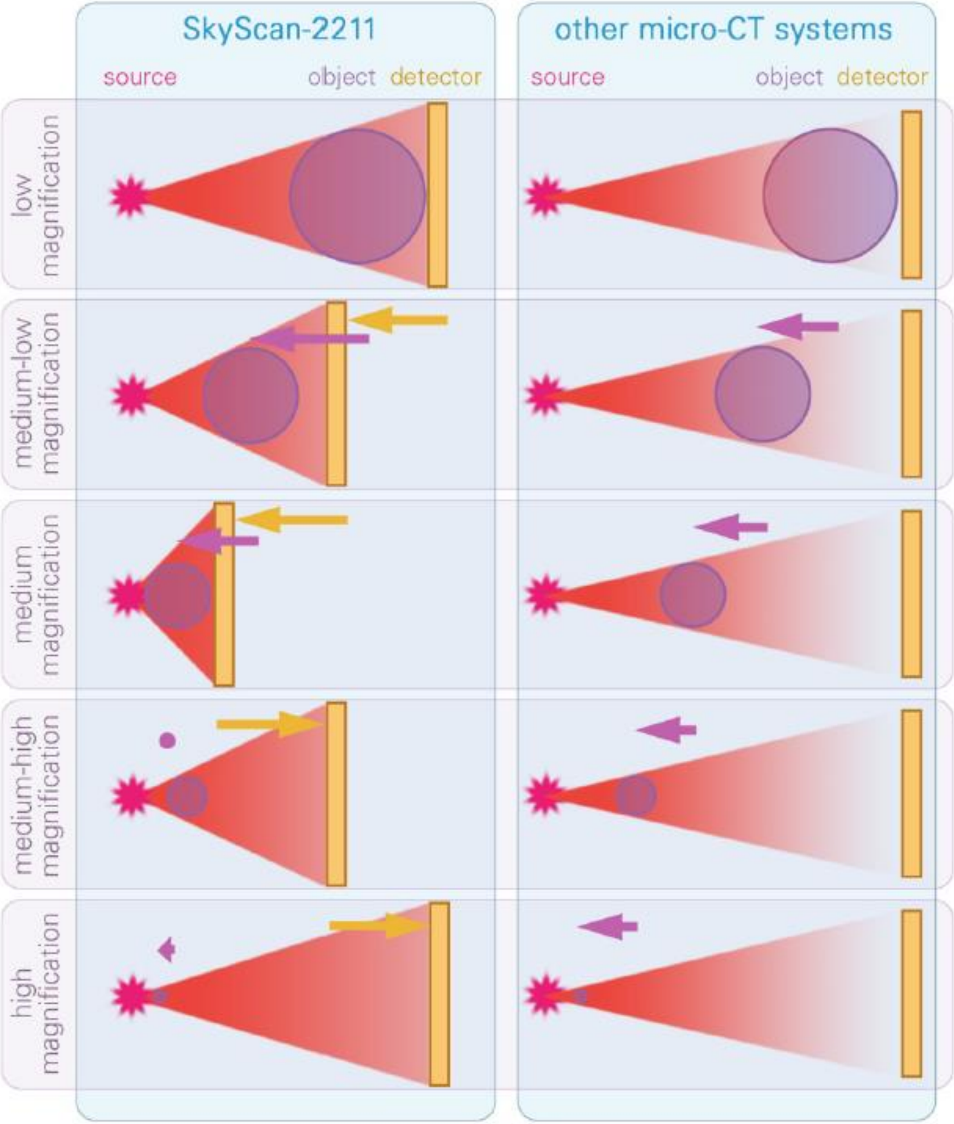


The smaller the spot size, the harder it is to get more X-ray power out.

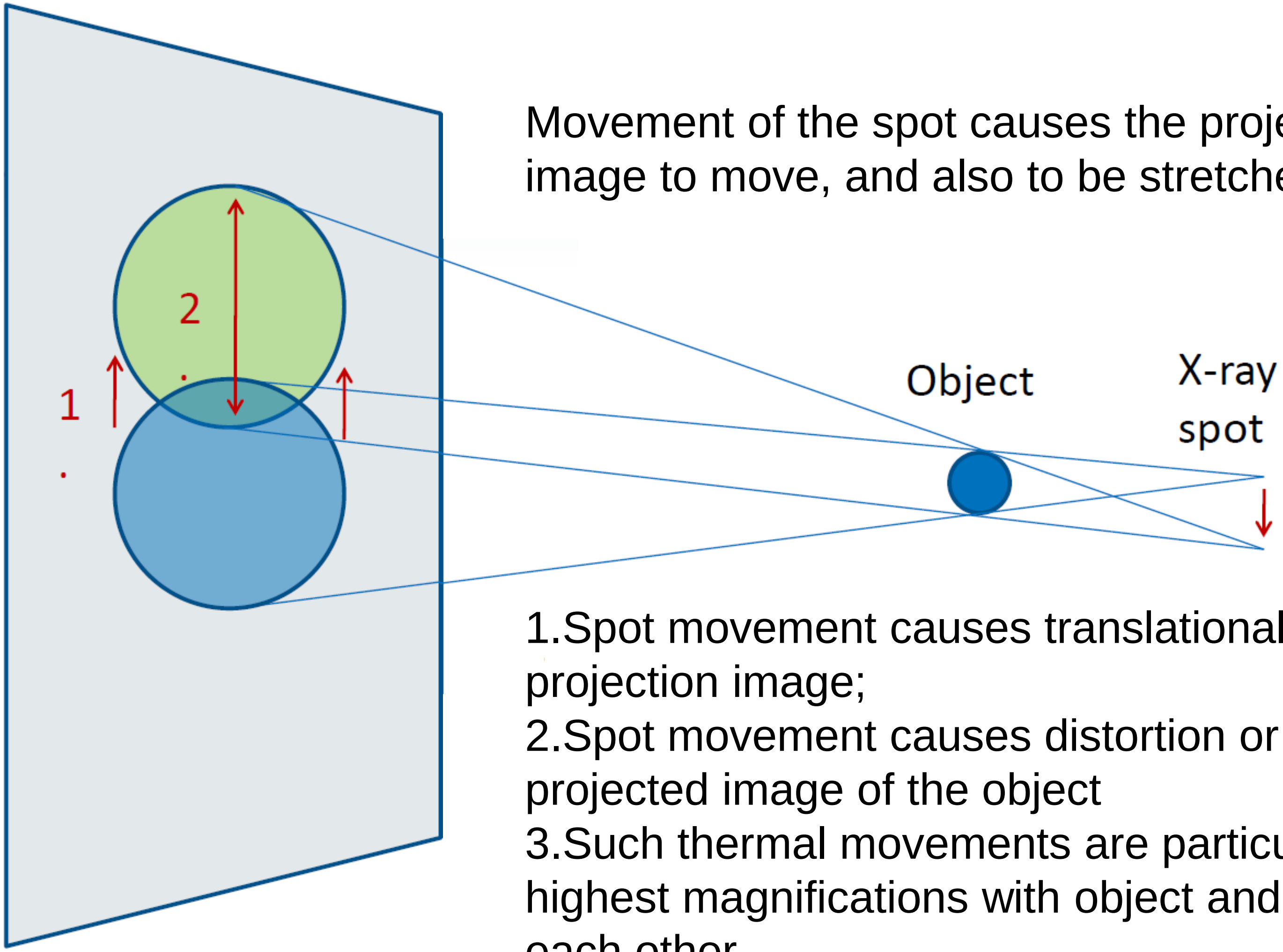
Or vice versa, the more power applied to the source, the larger the spot size is.

Penumbra Blurring

Geometrical Magnification



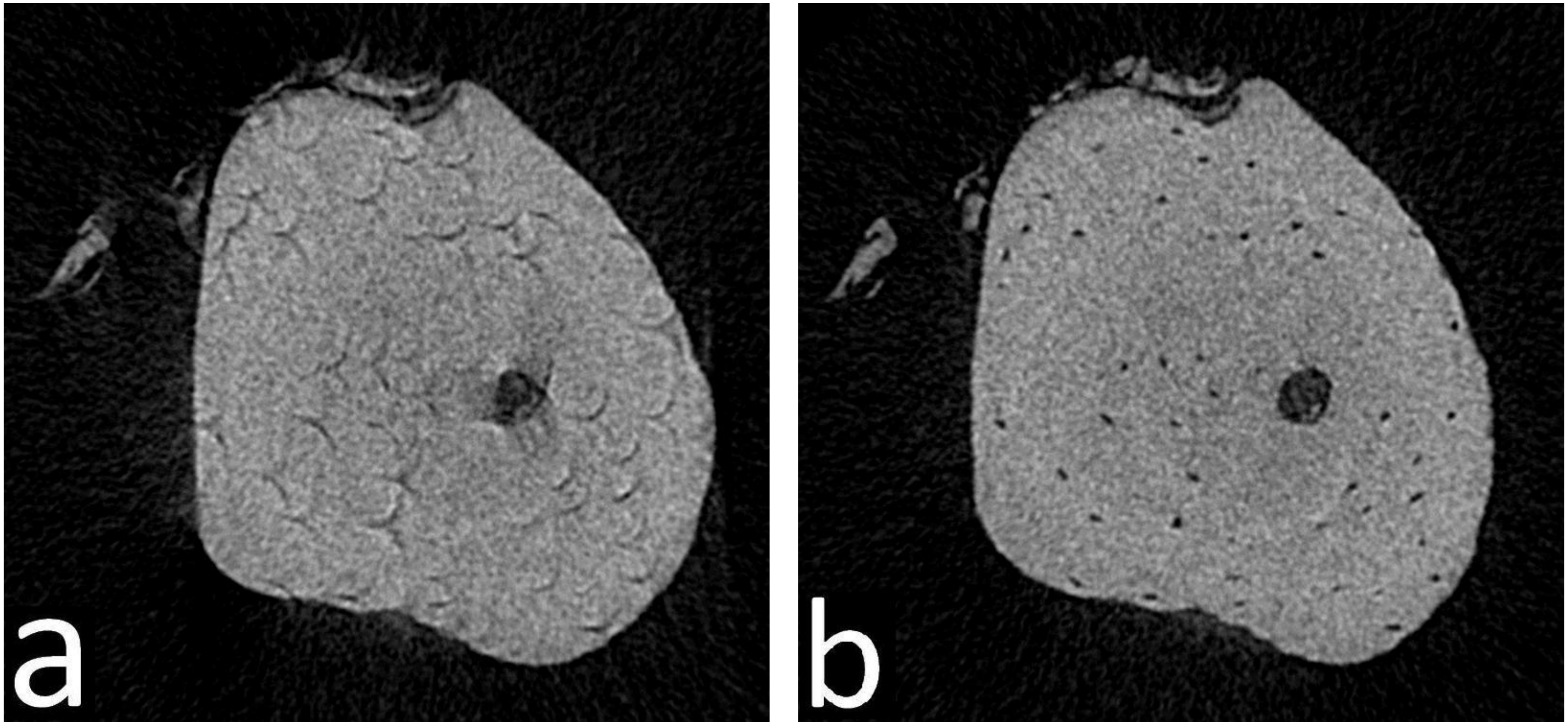
Alignment Correction



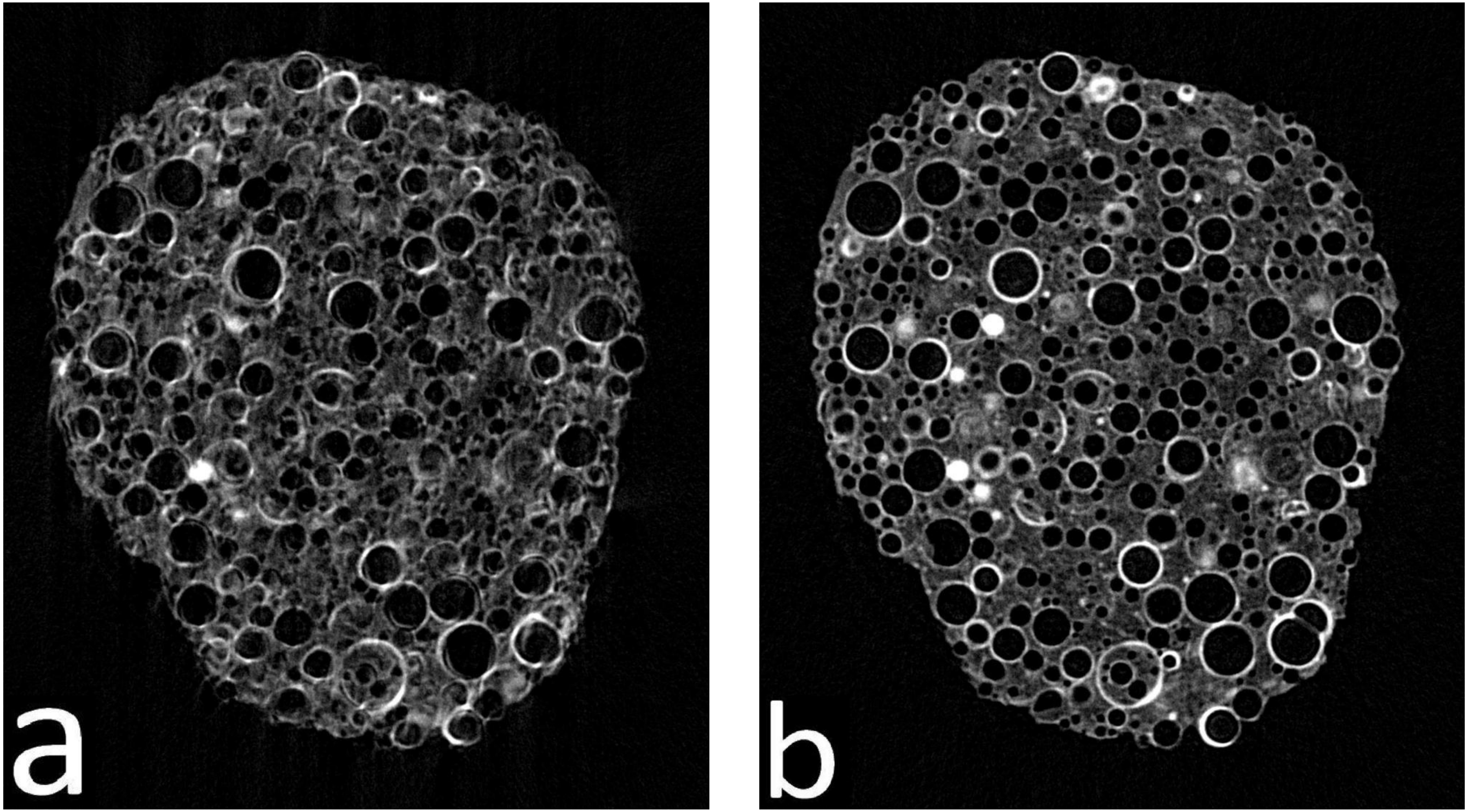
Movement of the spot causes the projection image to move, and also to be stretched

1.Spot movement causes translational movement of the projection image;
2.Spot movement causes distortion or stretching of the projected image of the object
3.Such thermal movements are particularly severe at the highest magnifications with object and source very close to each other.

Alignment Correction

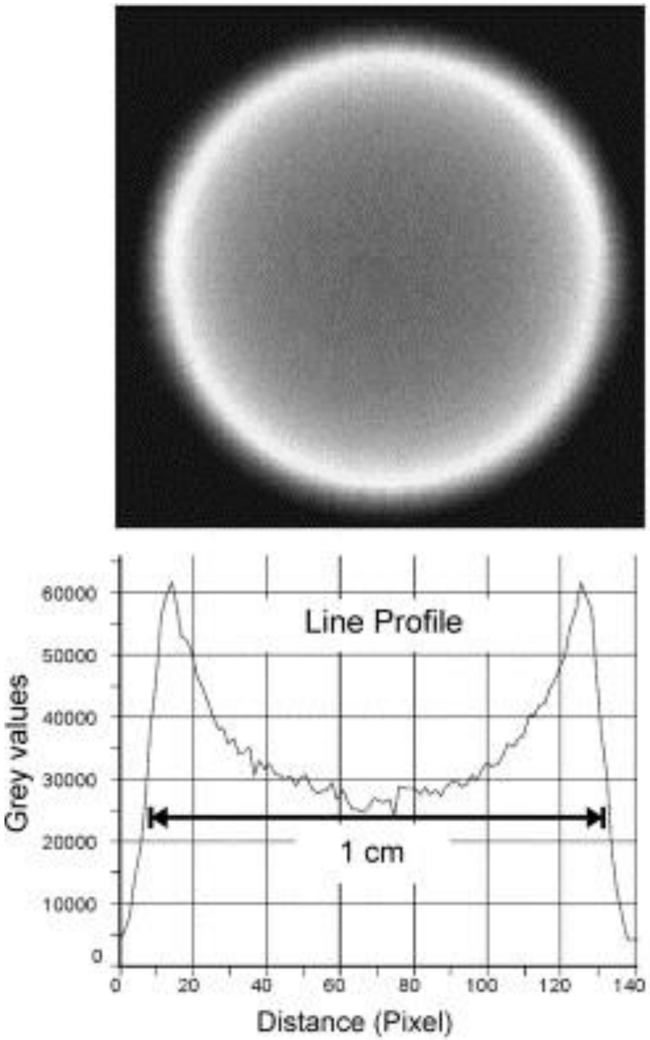


Alignment Correction

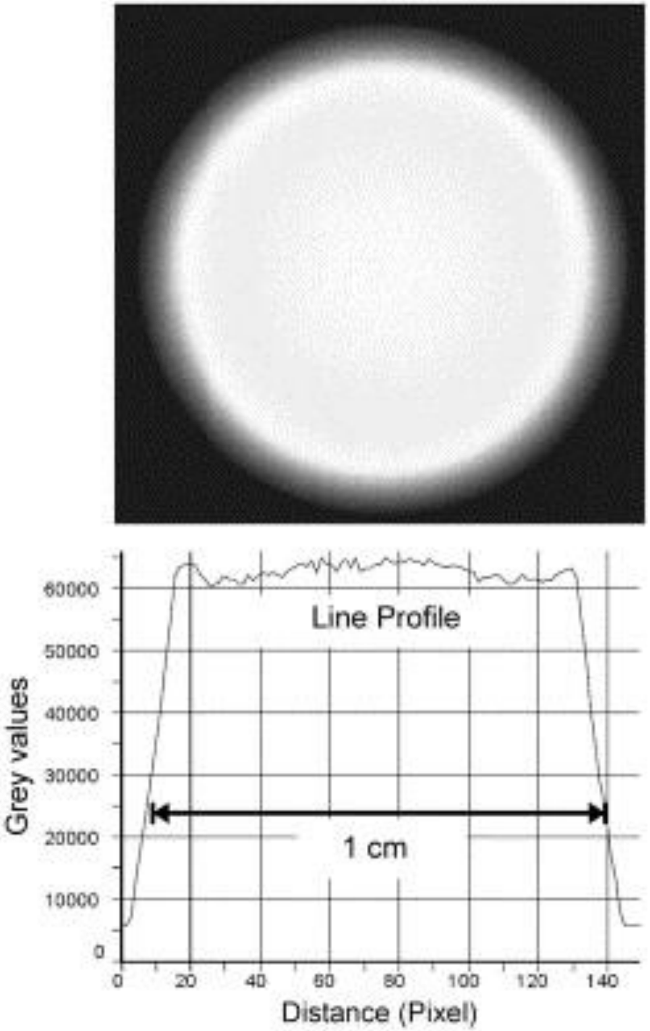


Beam Hardening Correction

Before



After



X-ray Scanners

Zeiss

Skyscan

Nikon

Nikon

Nordson

Creative Electron