DEVELOPMENT OF ADVANCED QUANTUM-BEAM SOURCES AND THEIR APPLICATIONS AS SOPHISTICATED IMAGING TOOLS

By

K.YAMADA[1], R.KURODA[1], H.TOYOKAWA[1], H.IKEURA-SEKIGUCHI[1], M.YASUMOTO[1], N.SEI[1], H.OGAWA[1], M.KOIKE[1], R.SUZUKI[1], F.SAKAI[2], K.MORI[3], H.MORI[4], N.FUKUYAMA[4], E.SATO[5]

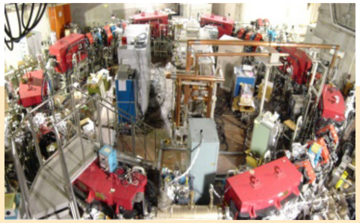
[1]National Institute of Advanced Industrial Science and Technology (AIST)
[2]Sumitomo Heavy Industries, Ltd.(SHI)
[3] Ibaraki Prefectural University of Health Sciences
[4]Tokai University, School of Medicine
[5]Iwate Medical University

The ICFA workshop "Compton Sources for X/gamma Rays: Physics and Applications", 7-12 September 2008, Hotel Porto Conte, Alghero, Italy.

QUANTUM-BEAMS AS IMAGING TOOLS AT AIST

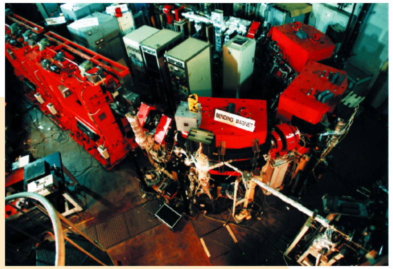
- Laser Compton X/gamma-rays
  - # S-band compact linac based system (10 – 40 keV) ⇦ Presentation by R. Kuroda
    Fine and low dose X-ray imaging in biology and medicine
  - # Storage-ring based system (1 – 40 MeV) ⇦ Presentation by H. Toyokawa
    Non-destructive inspection of industrial products composed of high-density materials
- Free Electron Lasers
  - # UV beam line in operation (300 – 198 nm)
    Imaging of surface chemical phenomena using photoelectric effects
  - # IR beam line in commissioning (1 – 10 μm)
    Imaging of surface chemical phenomena using molecular vibration
    Generation of intra-cavity laser Compton X rays
- Slow positron beams
  - # S-band linac based system
    Characterization of thin films containing defects and pores in atomic - nanometer scales
    Defect-sensitive positron microscopy

AIST ACCELERATOR FACILITIES



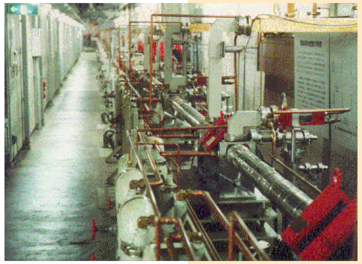
800 MeV STORAGE RING "TERAS"

for SR application and R&D of new quantum beam sources



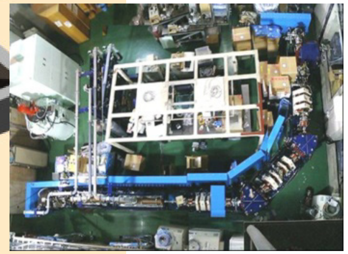
400 MeV STORAGE RING "NIJI-IV"

for FEL



400 MeV S-band LINAC

for injector



S-band COMPACT LINAC

for quasi-monochromatic X-ray generation

600MeV STORAGE RING "NIJI-II"

for SR processing

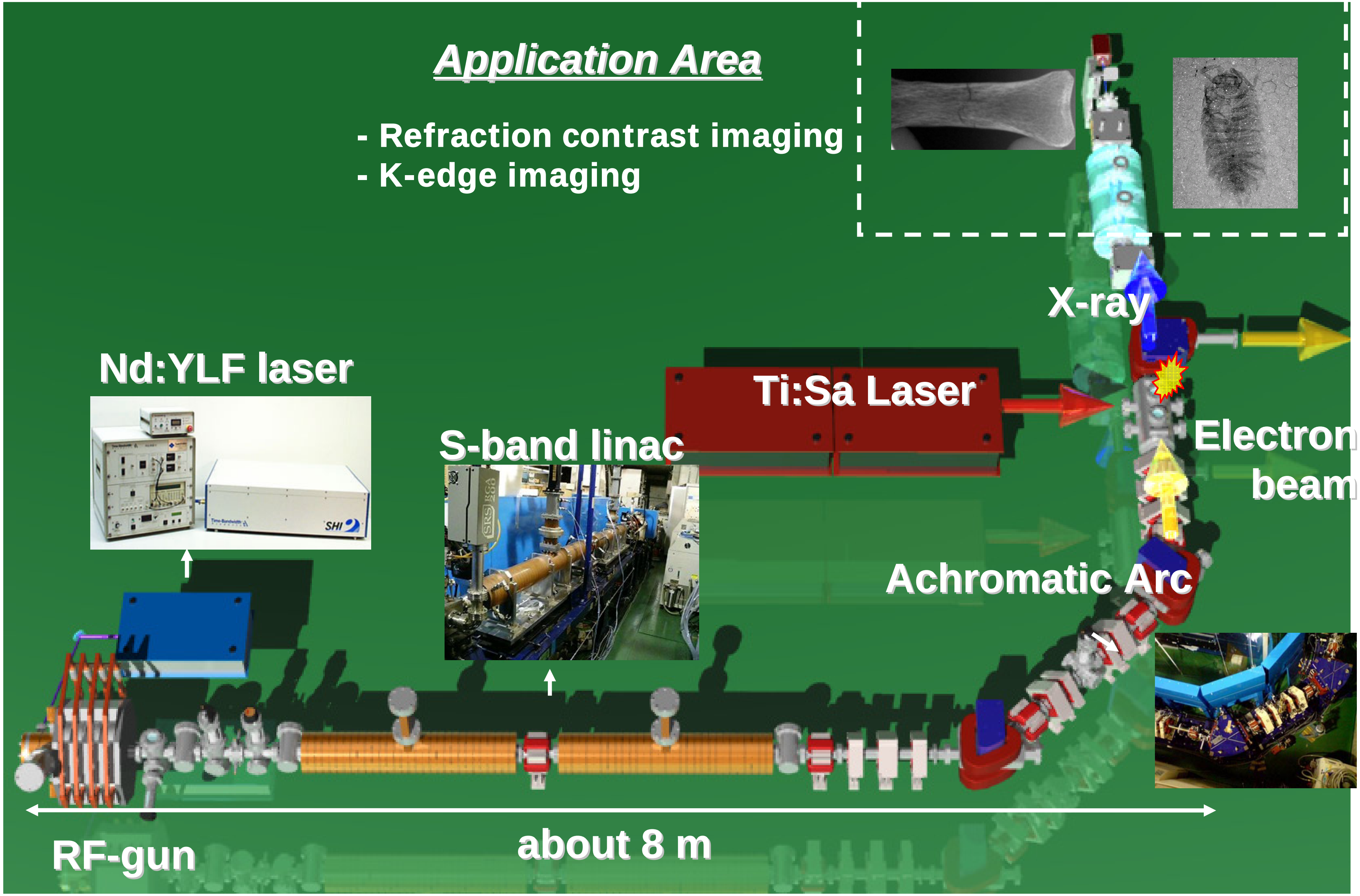
SLOW POSITRON FACILITY

for characterization of solid surface layers

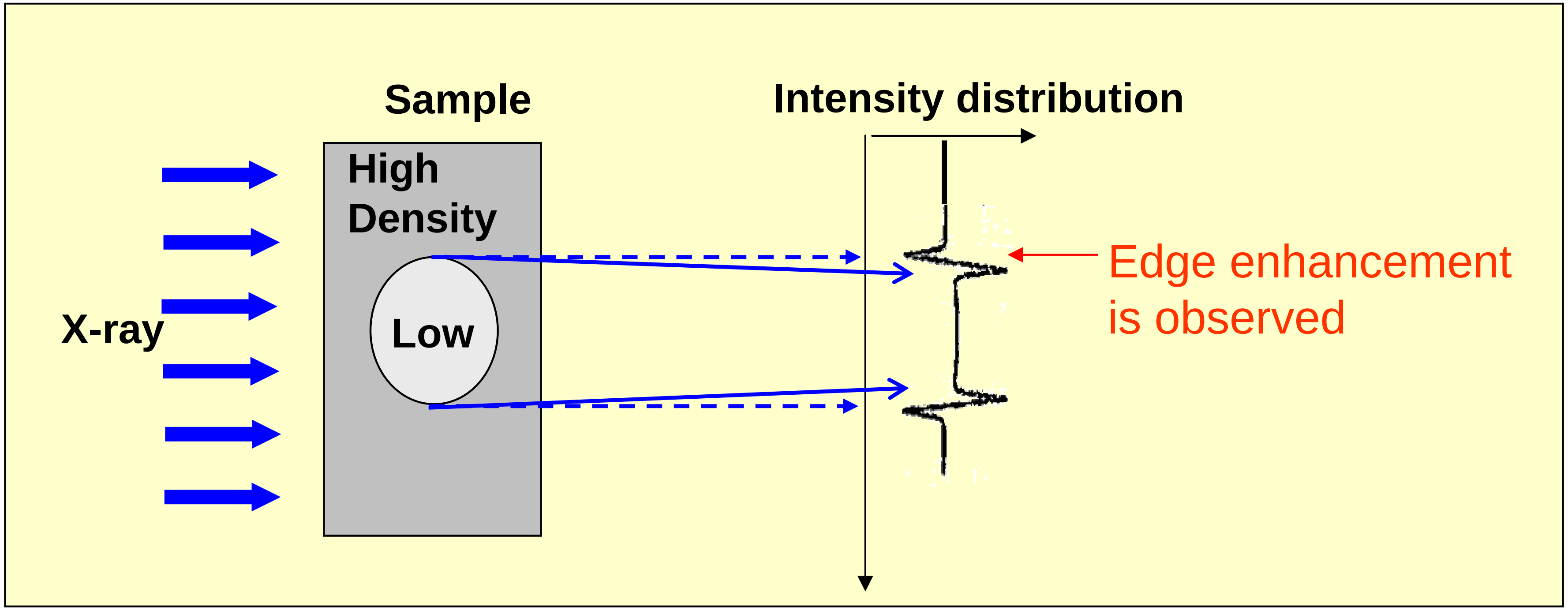
Imaging by Compton X-rays

AIST

S-BAND COMPACT LINAC BASED COMPTON X-RAY SOURCE



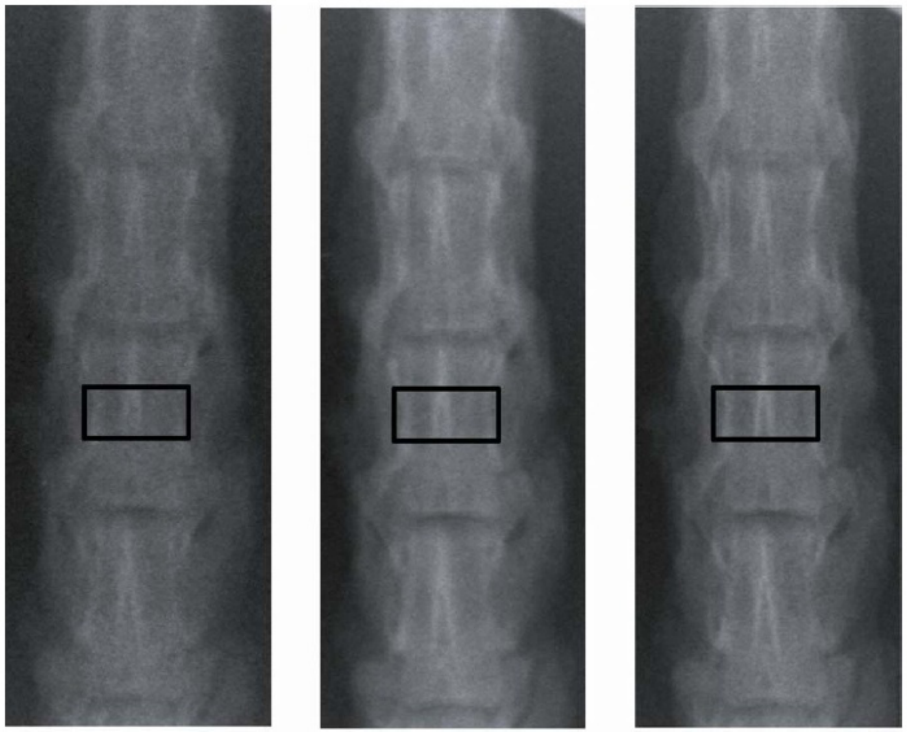
REFRACTION CONTRAST IMAGING OF BIOLOGICAL SPECIMEN



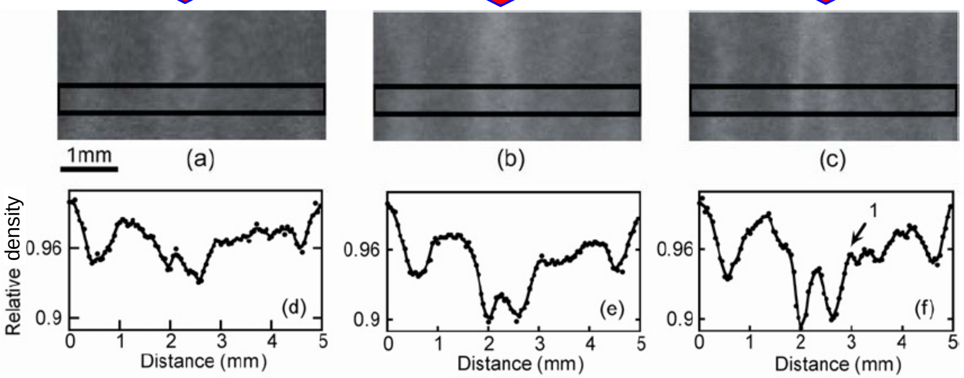
- **X-ray refraction due to phase shift enhances the contrast around the region boundary even in almost transparent materials.**
- **Partial spatial-coherence in X-rays is required.**

REFRACTION CONTRAST IMAGING: SAMPLE #1

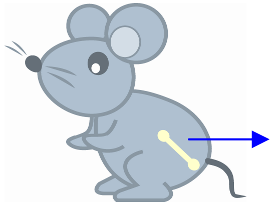
Accumulating Time: 30 min (18,000 pulses)



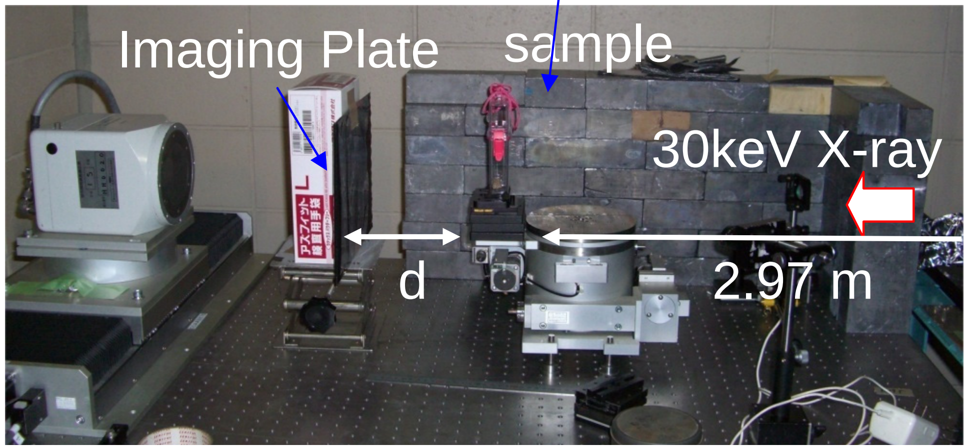
expansion

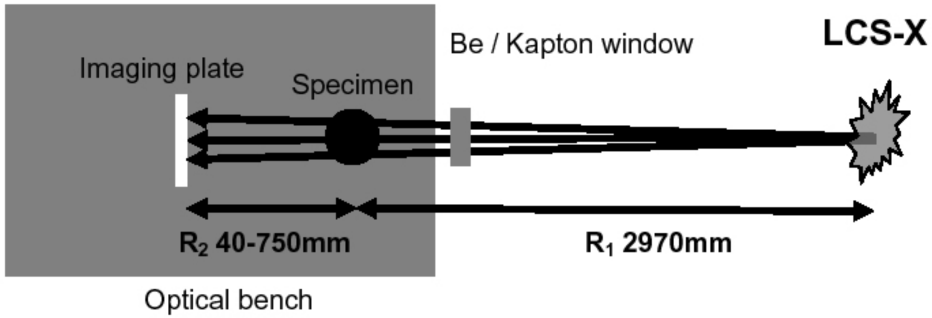


d = 40mm 200mm 750mm



Lumbar vertebra





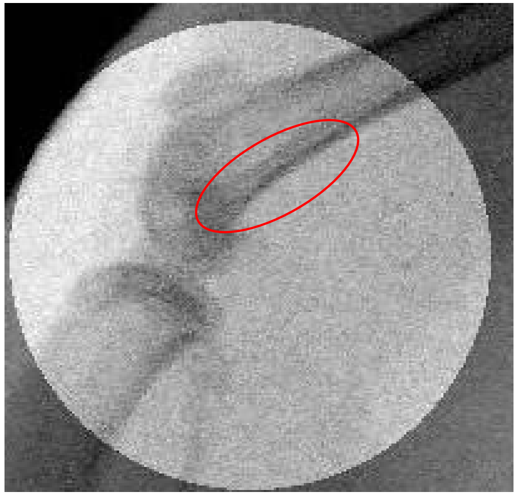
Contrast enhancement obseved with increasing distance

H. Ikeura-Sekiguchi et al., *Applied Physics Letters*, 92, 131107 (2008)

DIAGNOSIS OF OSTEOPOROSIS

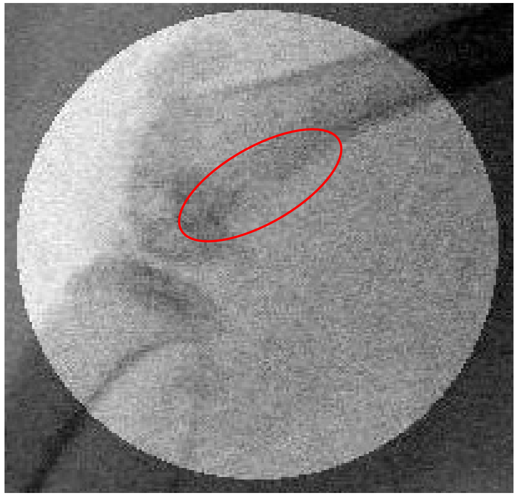
Sample: Hind limbs of Normal mouse & OVX mouse

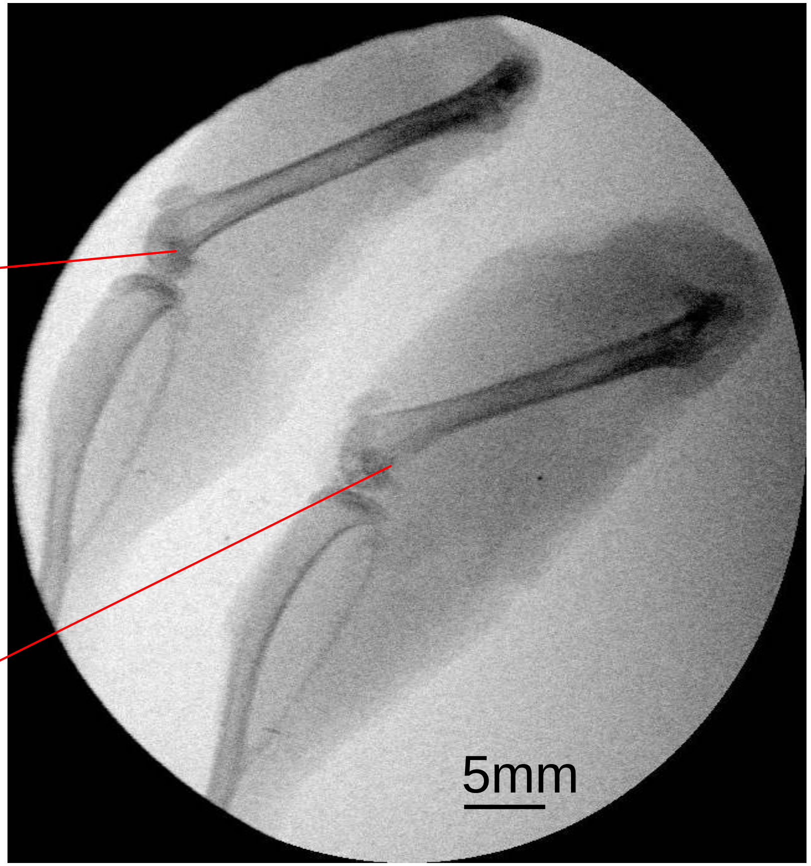
OVX: ovary-extracted

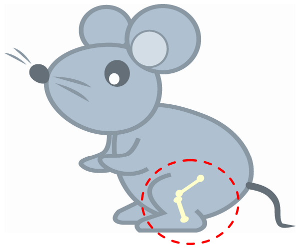


Normal

OVX







Observed at 20 cm from the sample

Bone erosion observed in case of the OVX mouse

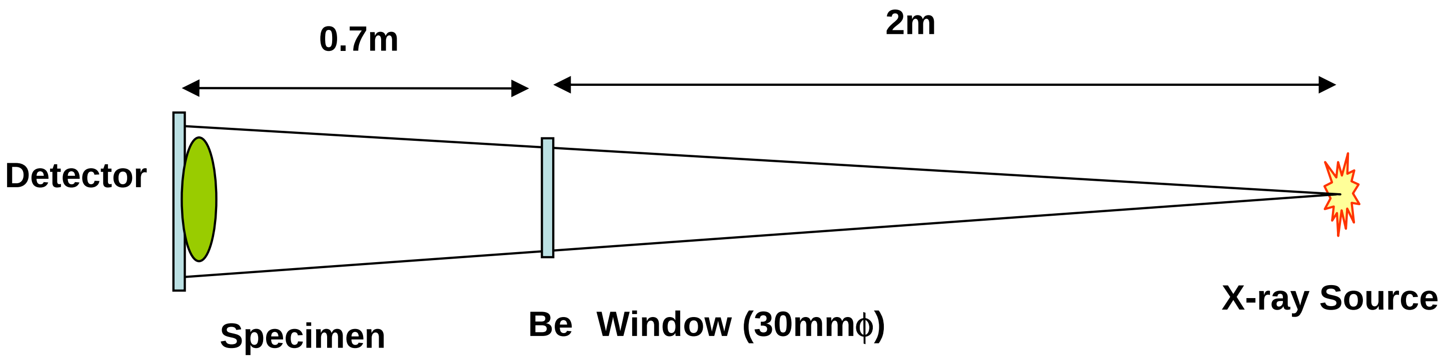
→ ***A symptom of osteoporosis ?***

K-EDGE IMAGING FOR ANGIOGRAPHY

Goal:
- Diagnosis of arterioles (very thin blood vessels) in patients, such as diabetic

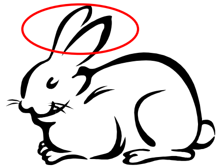
Samples:
- Rabbit ears with iodinated and barium contrast media

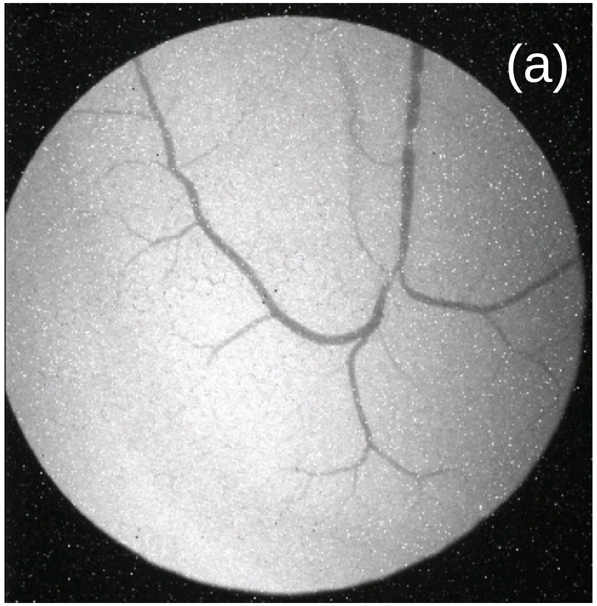
Detectors:
- Cooled X-ray CCD
- Imaging Plate
- HARP camera with X-ray image intensifier



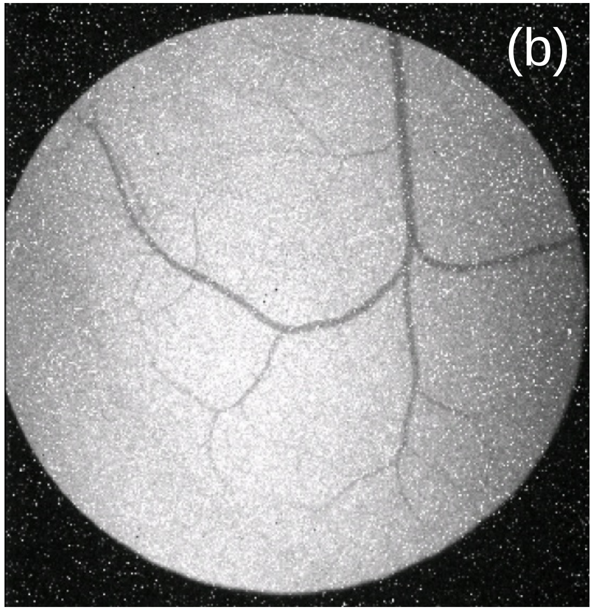
K-EDGE IMAGING FOR ANGIOGRAPHY IN ACCUMULATION MODE

Sample: Rabbit ears

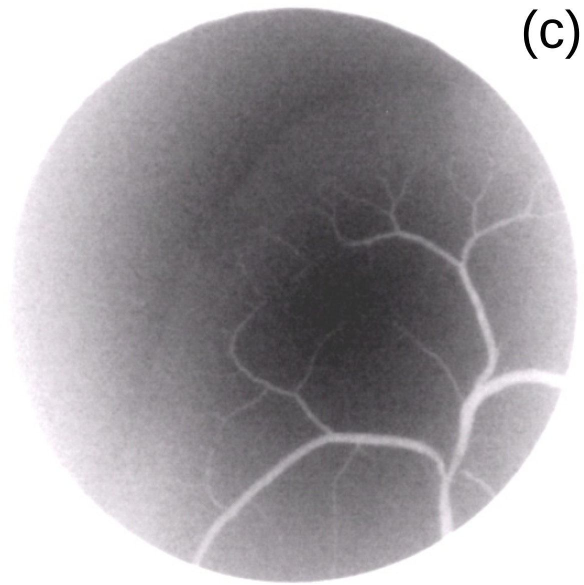




- Cooled X-ray CCD
- Iodinated contrast medium
- 33 keV
- 30-min. accumulation
- 5th thin vascular branch observed



- Cooled X-ray CCD
- Barium contrast medium
- 37 keV
- 5-min. accumulation
- No remarkable difference from the use of iodinated contrast medium

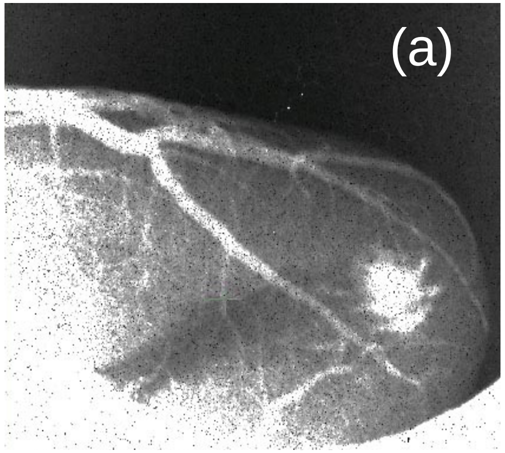


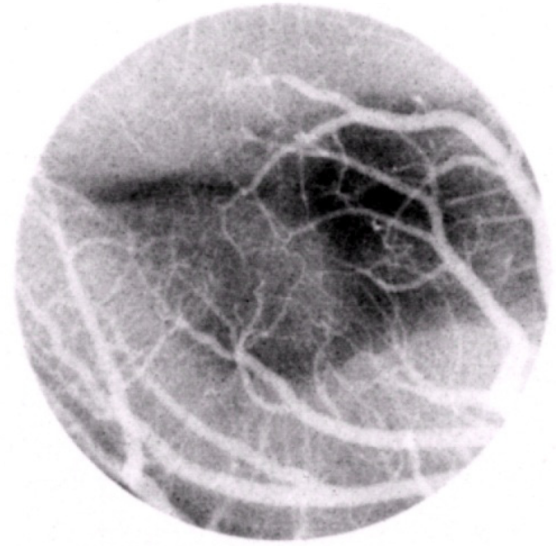
- Imaging Plate
- Iodinated contrast medium
- 33 keV
- 10-min. accumulation
- 7th thin vascular branch observed

Achieved spatial resolution reached about 80μm both for CCD and IP, the detector resolution.

K-EDGE IMAGING FOR ANGIOGRAPHY IN ACCUMULATION MODE

Sample: Canine heart





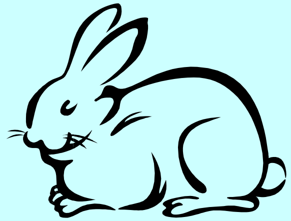
-Cooled X-ray CCD
-Iodinated contrast medium
-33 keV
-30-min. accumulation
-3rd vascular branch observed

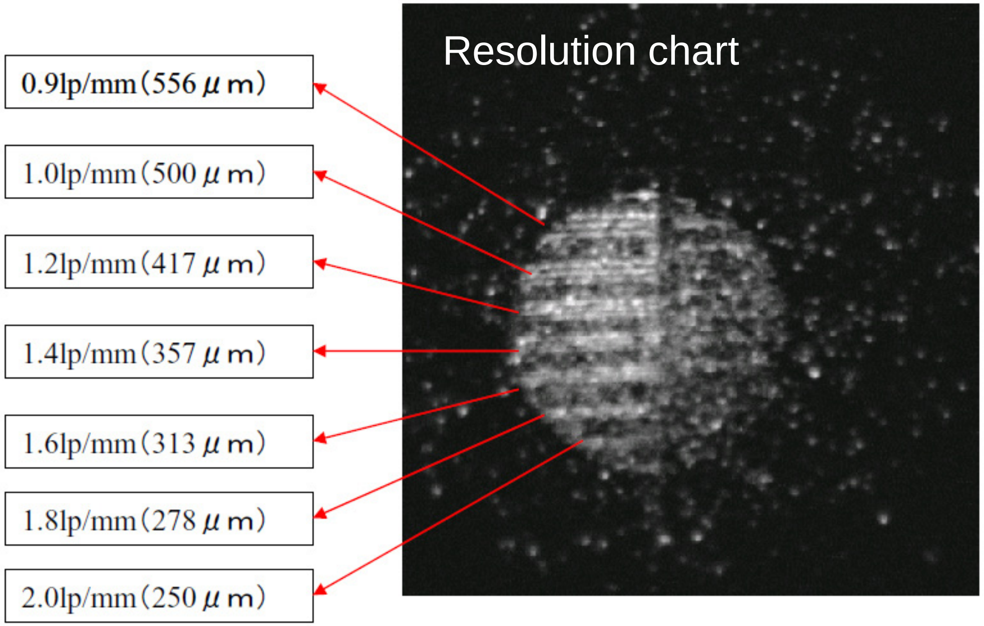
-Imaging Plate
-Iodinated contrast medium
-33 keV
-10-min. accumulation
-108-μm thin vascular branch observed

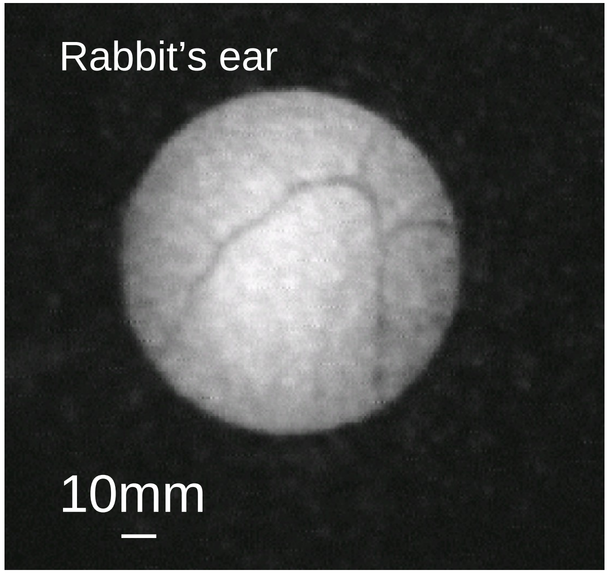
Spatial resolutions was 108 μm even for IP due to thickness of the specimen. More Compton-photon flux required.

K-EDGE IMAGING FOR ANGIOGRAPHY IN REAL-TIME MODE

Detector: HARP camera with X-ray image intensifier
Samples: Resolution chart
Rabbit's ear with iodinated contrast medium
Duration of X-rays: 3 ps (rms) / shot







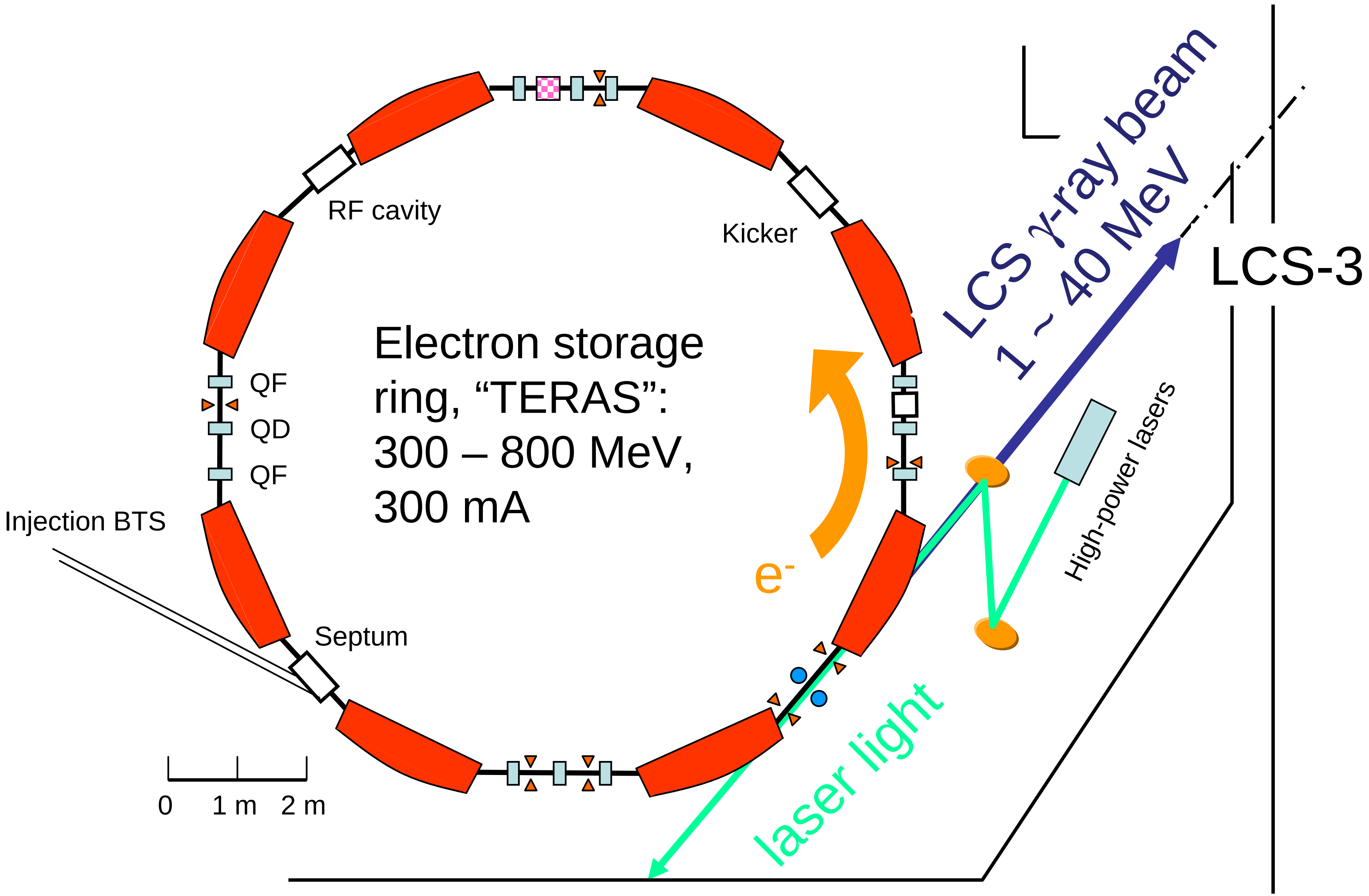
- 33 keV
- 1-shot mode
- 250-μm resolution achieved (125-μm in 10-shot accumulation)

- Iodinated contrast media
- 33 keV
- 10-shot mode (1-sec. accumulation)
- 3rd vascular branch (480 μm in bore) observed

At present the resolution of real-time K-edge imaging is insufficient and an enhancement of X-ray flux will be required.
Flat-panel detector will be more suitable due to its higher resolution.

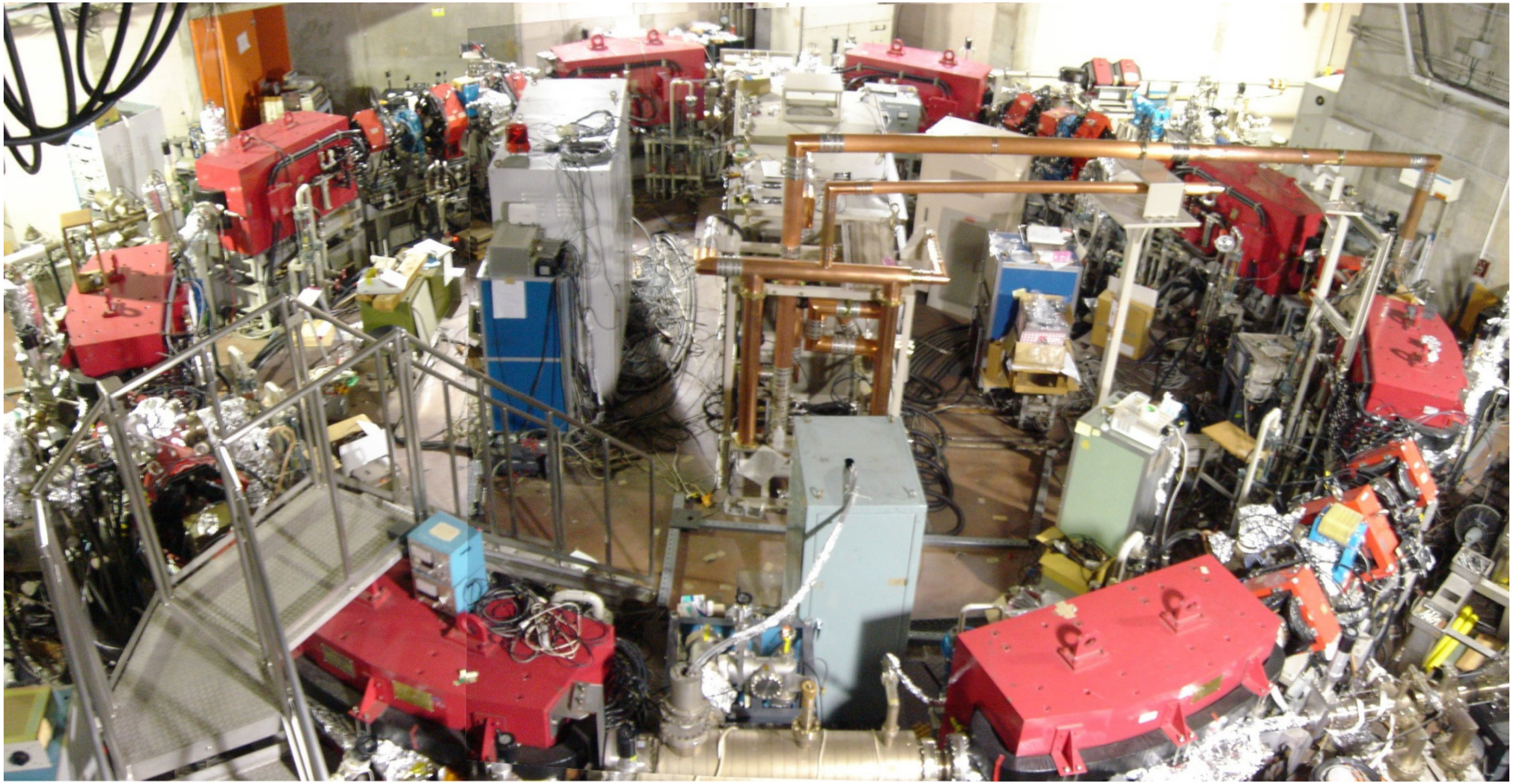
Imaging by Compton γ-rays

STORAGE-RING BASED LASER COMPTON γ-RAY SOURCE



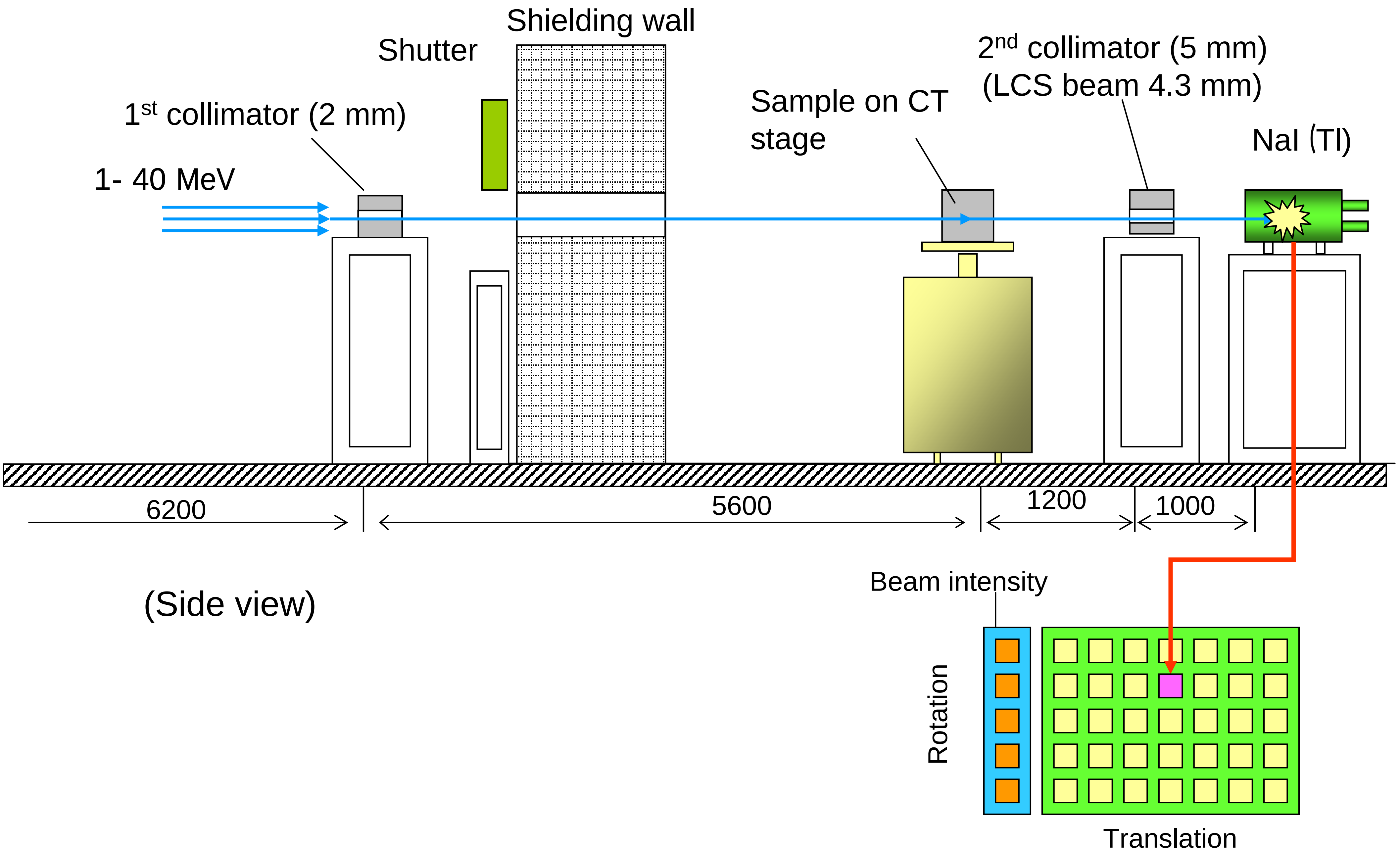
AIST

PHOTOGRAPH OF TERAS



Location: Tsukuba, Japan (AIST)	Operation frequency: 172 MHz
Energy: 300 ~ 800 MeV	Natural emittance: 600 nm rad
Current: 300 mA	Harmonics: 18
Construction year: 1981	Life (1/e): 8 hours
Circumference: 30 m	Critical energy: 490 eV

SCHEMATIC VIEW OF THE LASER-COMPTON GAMMA-RAY BEAM LINE



ATTENUATION OF GAMMA PHOTONS IN MATERIALS

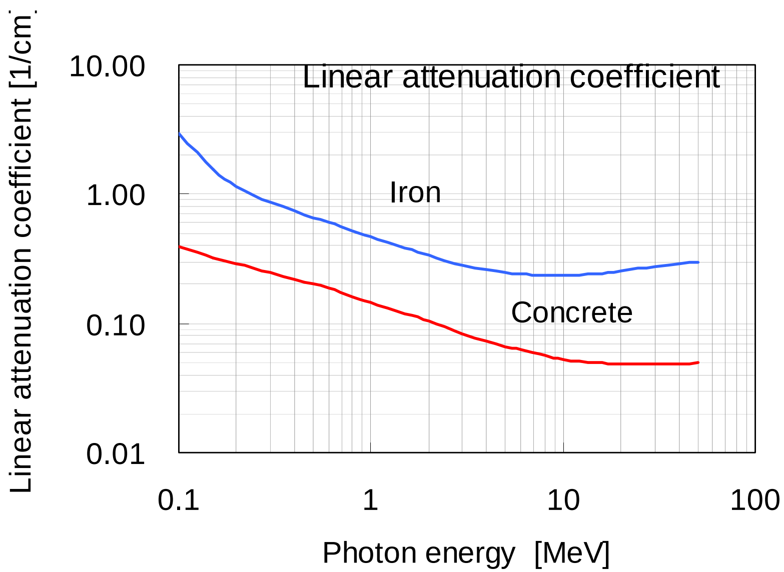
$$\frac{dI}{dx} = -\sigma N I, \quad \sigma \approx \sigma_c + \sigma_p$$

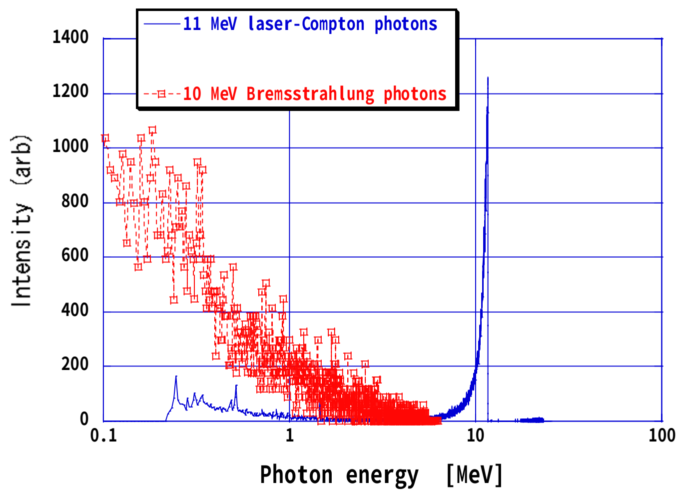
$$I = I_0 e^{-\mu x}, \quad \mu = \sigma N$$

μ : linear attenuation coefficient
σ: total cross section
σ_c: Compton scattering cross section
σ_p: pair-creation cross section
N : Atomic number density

Compton gamma-ray CT gives correct spatial distribution of μ with a good contrast resolution.

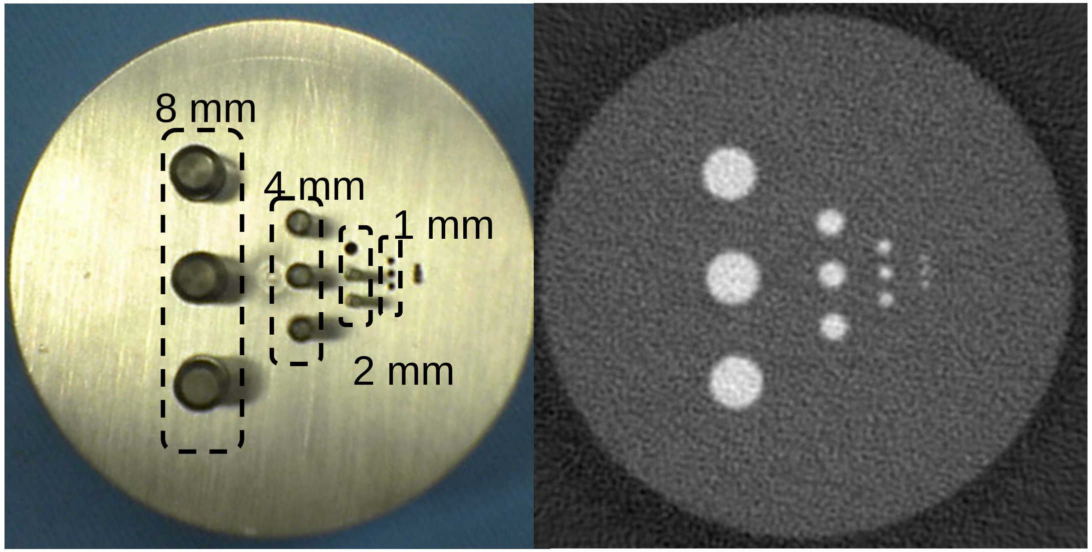
Berger M.J. et al., XCOM: Photon Cross Sections Database, *NIST Standard Reference Database 8 (XGAM)*





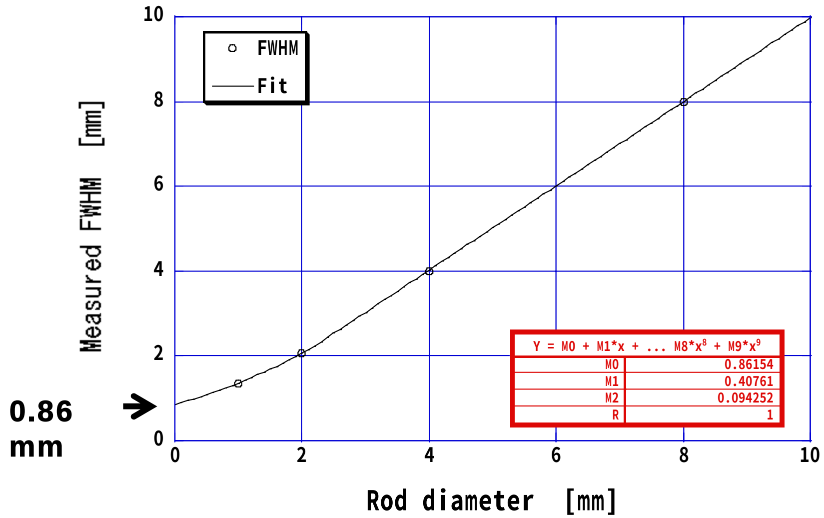
ESTIMATION OF SPATIAL RESOLUTION

Aluminum phantom with stainless rods

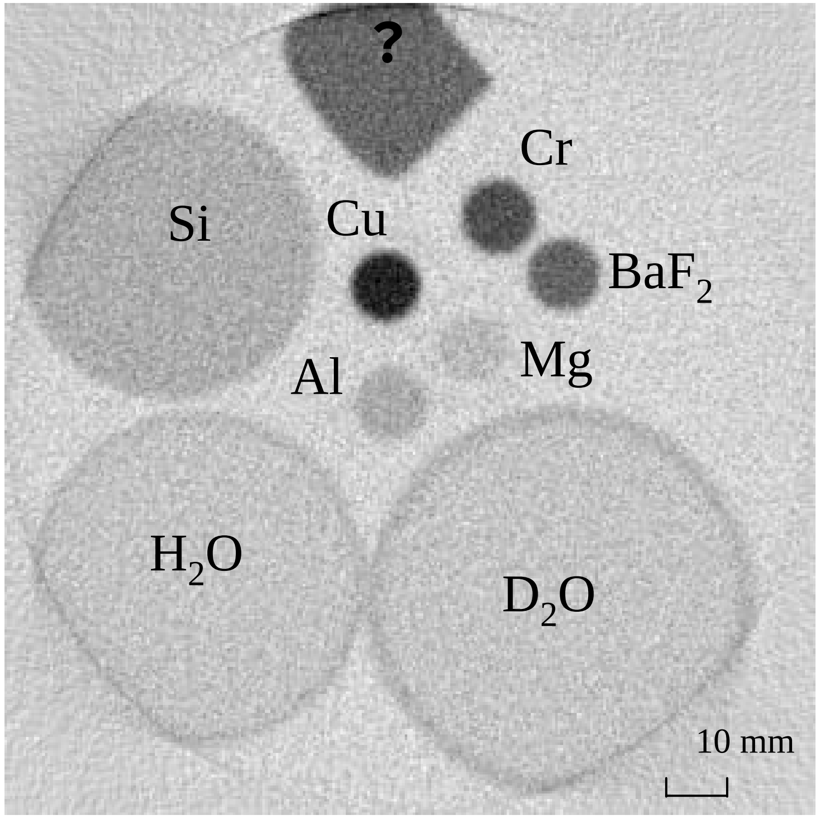


(a) photograph (b) CT image

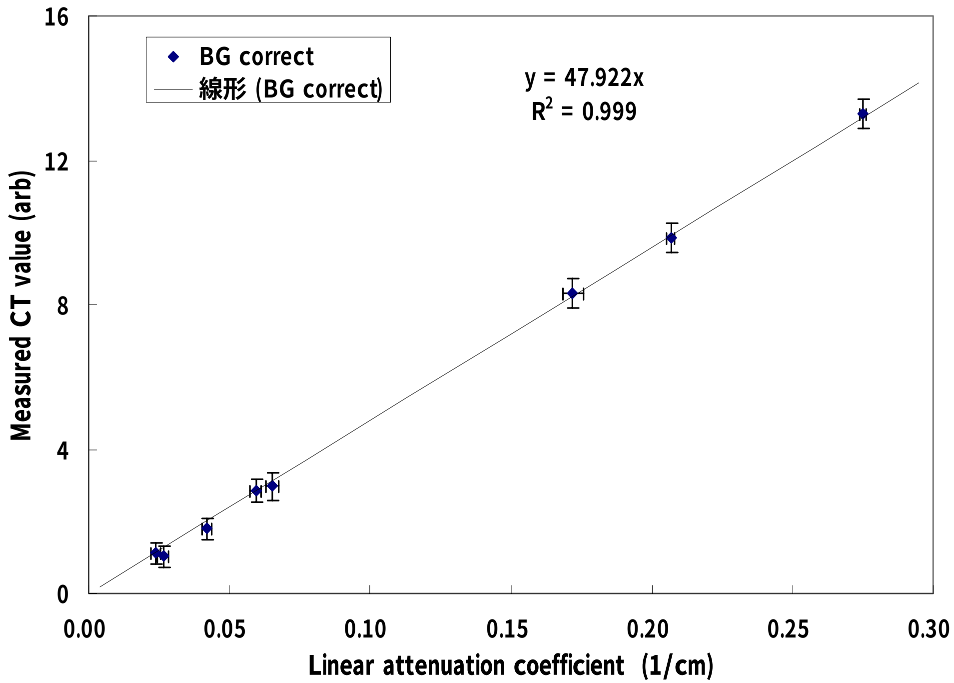
Rod thickness measured from the CT image



ESTIMATION OF CONTRAST RESOLUTION



Sample materials

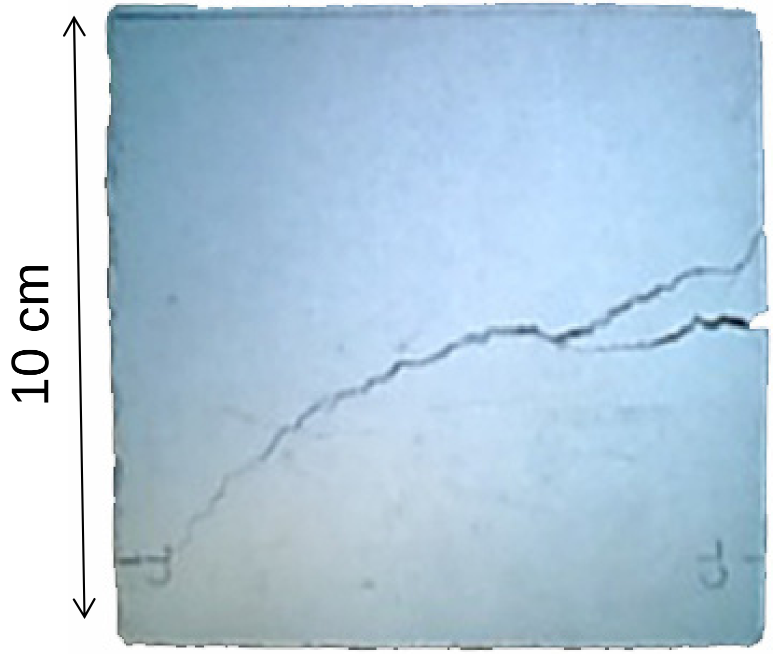


Silicon rod (Si), 28.08 amu, 99.9999%, [D40xL100], Specific gravity (s.g.) = 2.33
Deuterium oxide (D_2O), MERECK Art. 3428, 99.9%, [100ml, o.d.=53] , s.g. = 1.1056
Barium fluoride (BaF_2), molecular mass=175.32, [o.d.=10mm], s.g. = 4.89
Water (H_2O), [o.d.=46mm], s.g. = 1
Magnesium (Mg), NILACO, 99.95%, [D9.5xL100] , s.g. = 1.738
Copper (Cu), NILACO, 99.999%, [D9.5xL100], s.g. = 8.92
Aluminum (Al), NILACO, 99.999%, [D9.5xL100], s.g. = 2.70

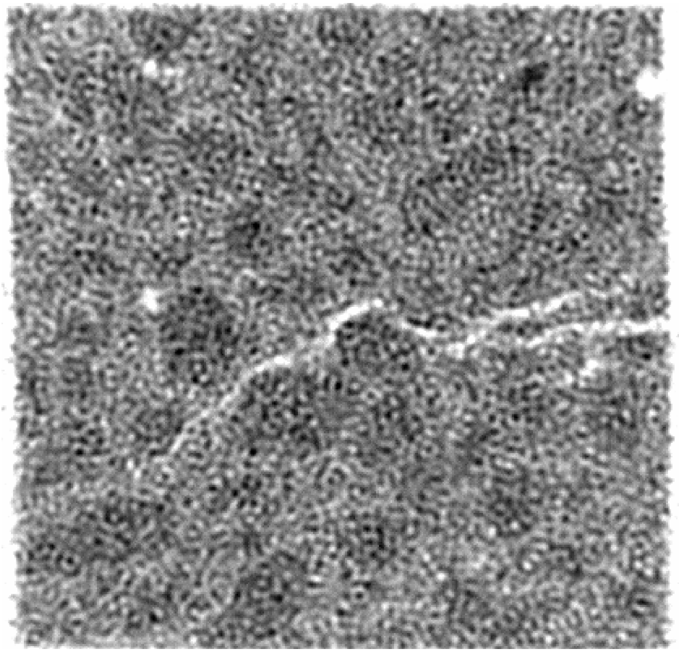
Contrast resolution: 3% for copper (0.275 cm^{-1})

TYPICAL CT IMAGE OF A CRACKED CONCRETE BLOCK

Photograph of the surface

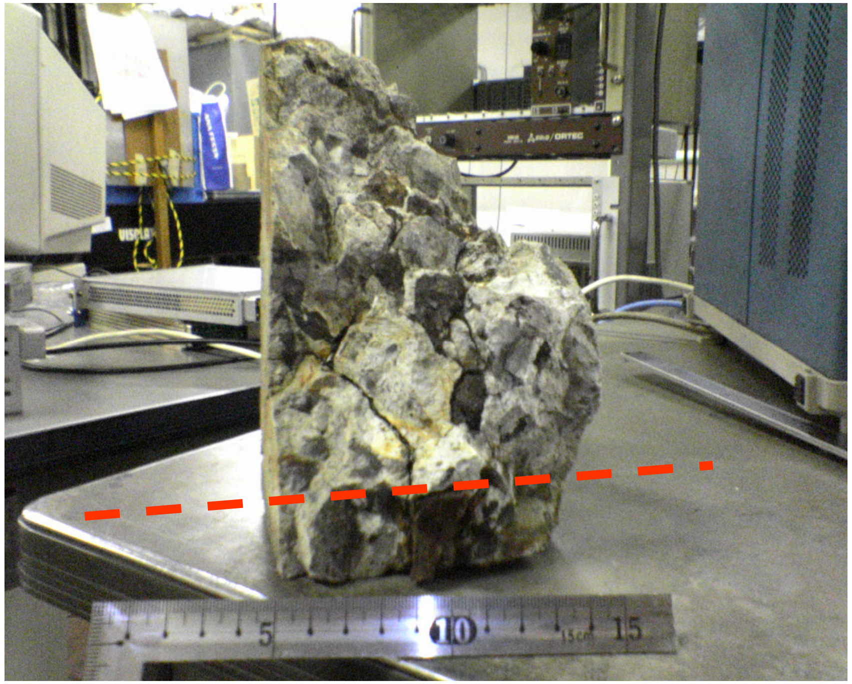


CT image



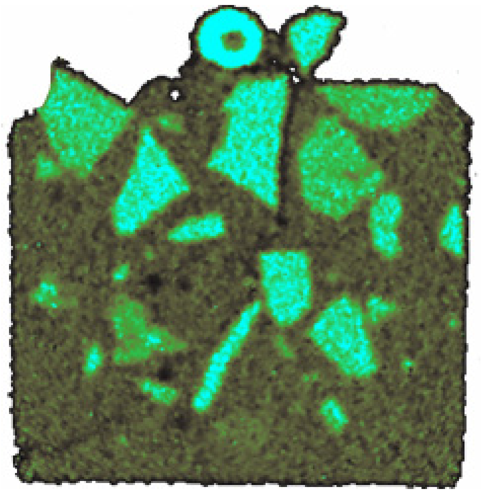
- Gamma-ray of 10 keV.
- Cross section at 5 mm under the surface.
- Coarse aggregates and mortar are well distinguished.
- Crack runs in the mortar area avoiding coarse aggregates.
- The finest crack width recognizable is 0.2 ~ 0.3 mm.

AN EXAMPLE OF COMPTON GAMMA-RAY CT



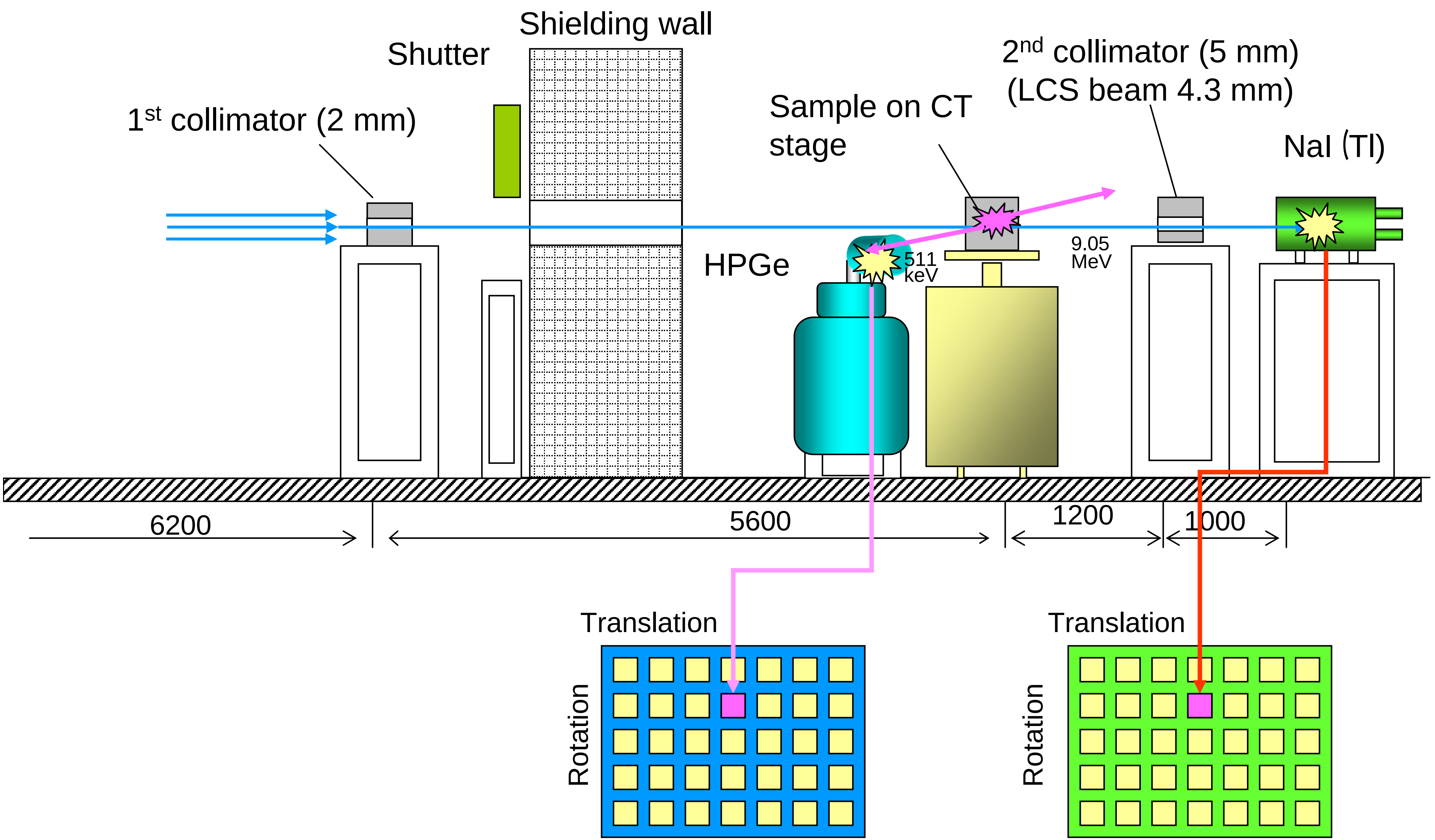
Bottom view

An old concrete fragment used for radiation shielding, containing iron ores and a rebar for reinforcement.

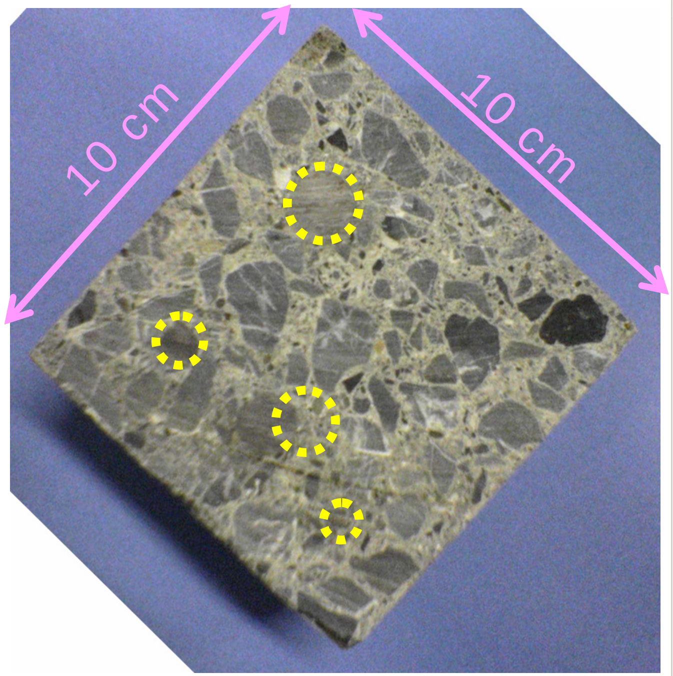


CT image

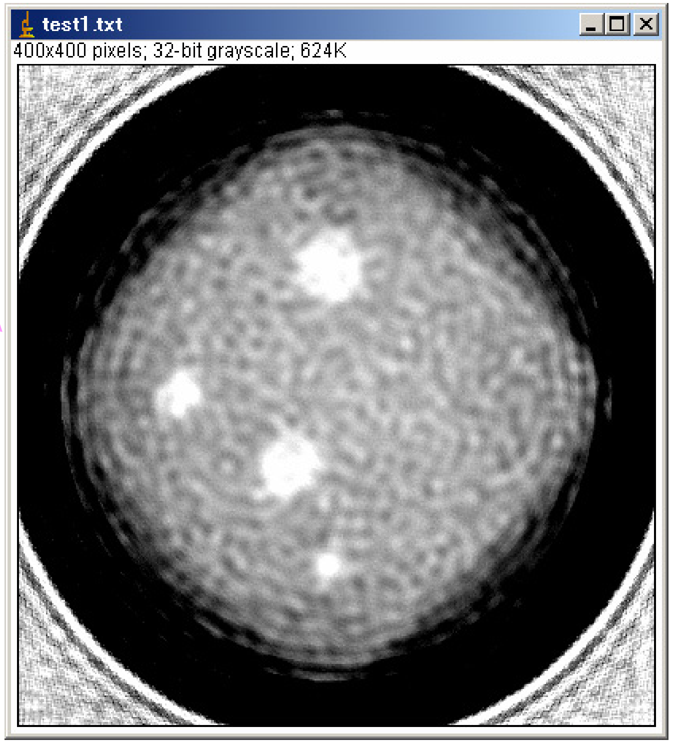
A TRIAL OF CT IMAGING USING POSITRON-ANNIHILATION GAMMA RAYS



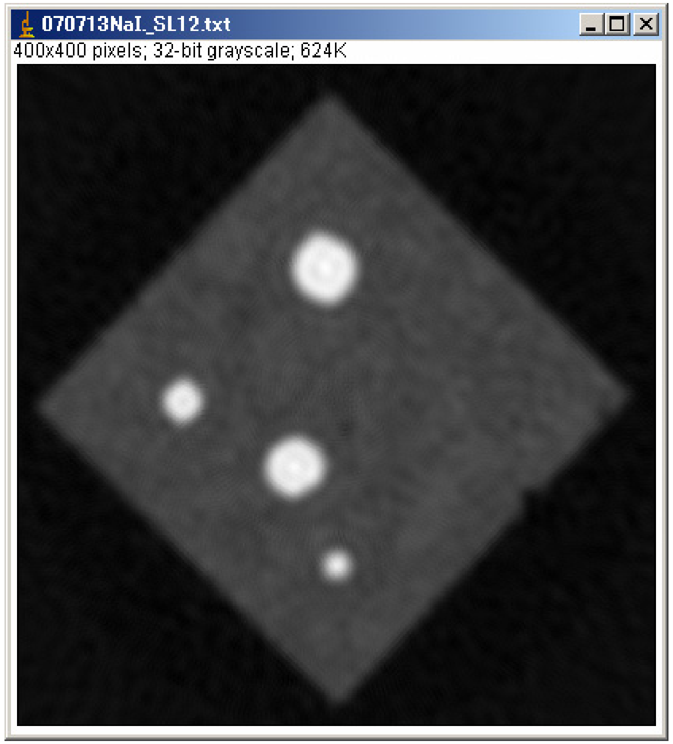
DUAL-ENERGY CT USING POSITRON-ANNIHILATION GAMMA RAYS AND COMPTON GAMMA RAYS



Reinforced concrete cube with 10-cm edges. (Dashed circles indicate the rebars' positions.)



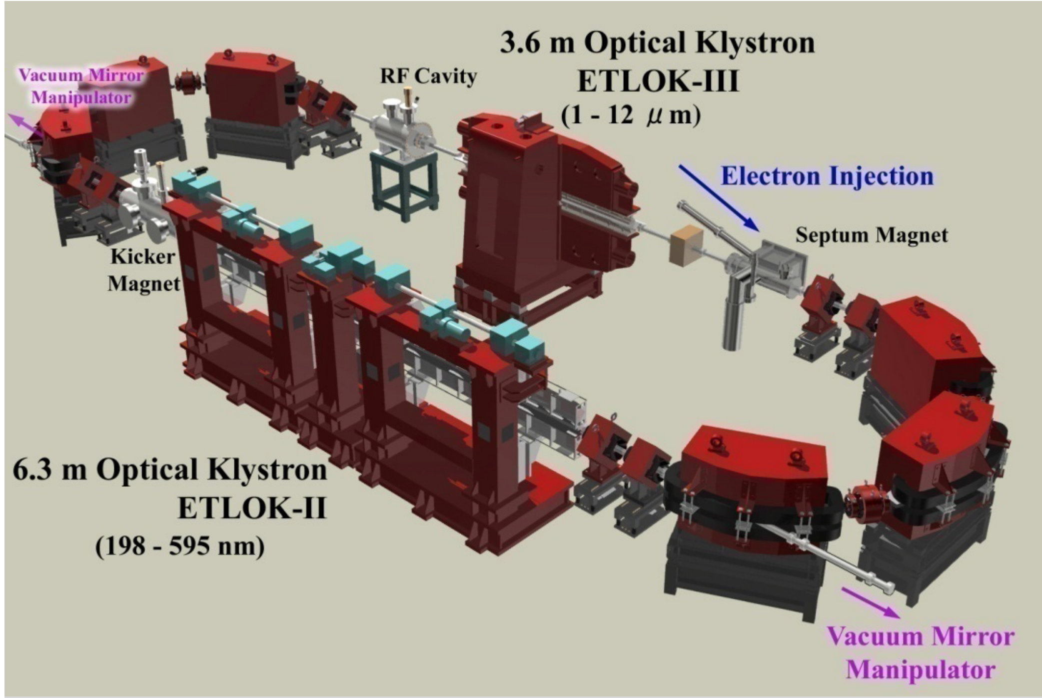
CT with 511-keV annihilation gamma-rays



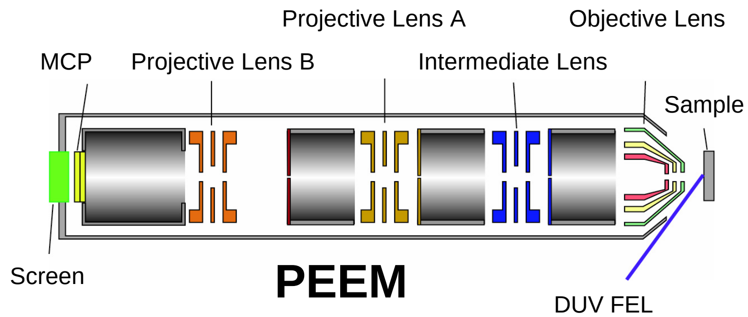
CT with 9.05-MeV transmitted gamma-rays

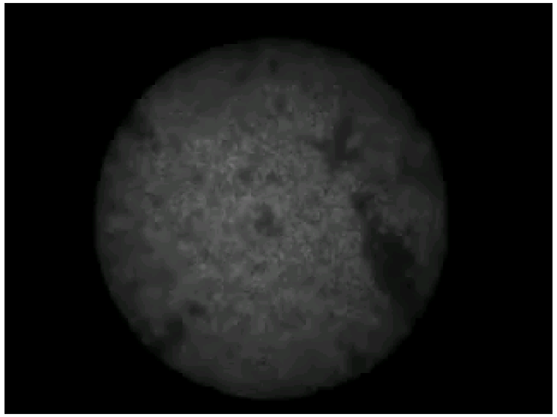
Imaging by Free Electron lasers

NIJI-IV STORAGE-RING FREE-ELECTRON LASER FOR IMAGING OF SURFACE CHEMICAL PHENOMENA



Circumference	29.6 m
Lattice	TBA
Electron energy	240 – 450 MeV
RF frequency	162.17 MHz
Betatron tune H	2.291
Betatron tune V	1.214
M compaction factor	0.089
Natural emittance	6.5×10^{-8} m rad
Natural bunch length	50 ps
Energy spread	2.6×10^{-4}

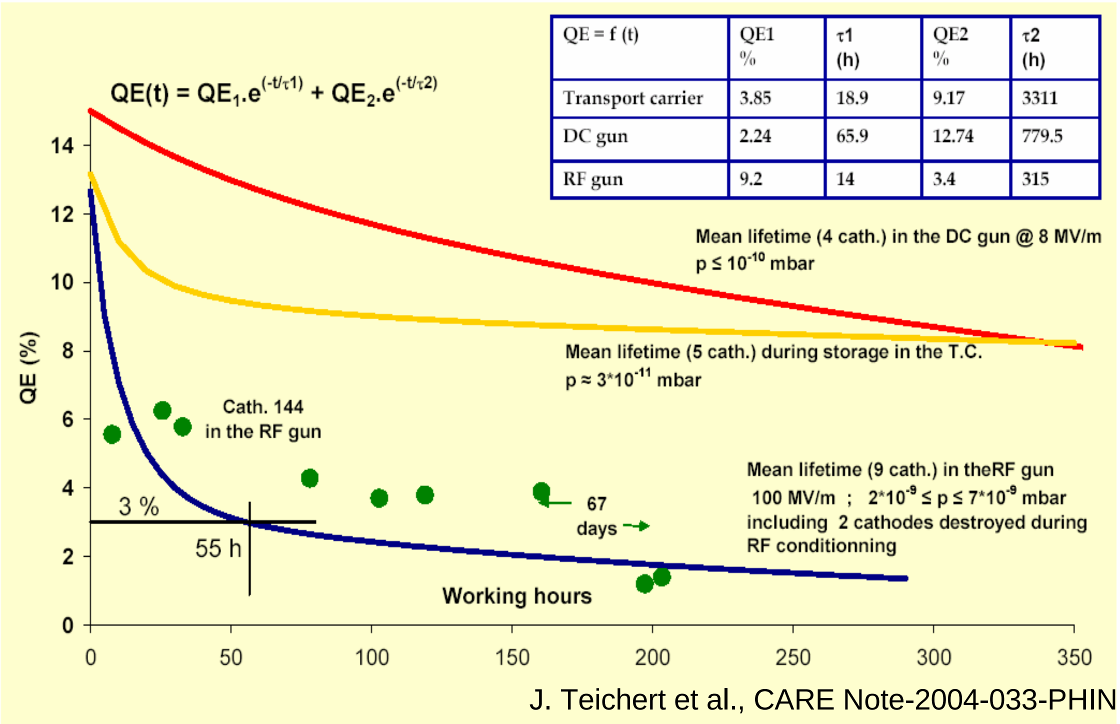




- Substrate: Pd(111)
- Temperature: 360K
- Reactant:
  Mixture of CO (5×10^{-6} Pa)
  and O_2 (4×10^{-5} Pa)
- Field of view: 200 μm^{ϕ}

Surface chemical reaction observed by PEEM with DUV-FEL as an excitation source

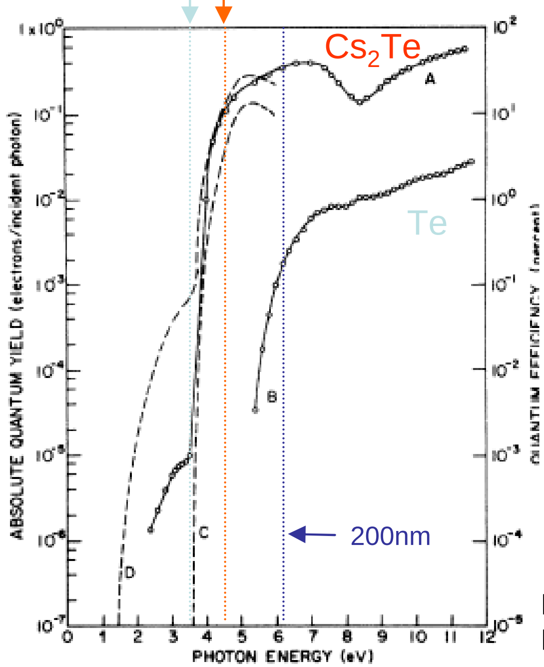
OBSERVATION OF Cs-Te PHOTOCATHODE BY PEEM WITH DUV-FELs



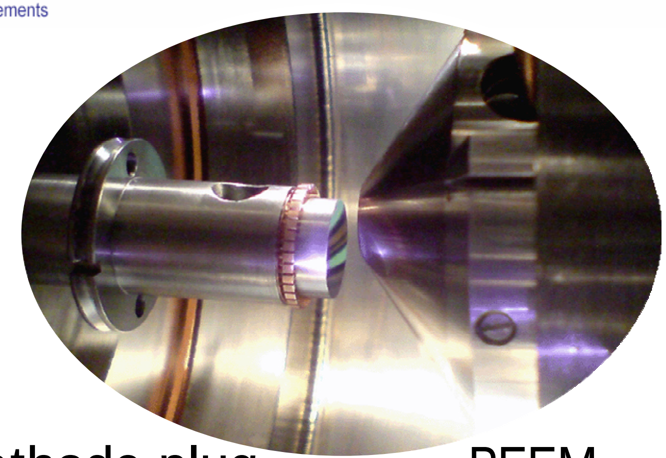
QE = f (t)	QE1 %	τ1 (h)	QE2 %	τ2 (h)
Transport carrier	3.85	18.9	9.17	3311
DC gun	2.24	65.9	12.74	779.5
RF gun	9.2	14	3.4	315

J. Teichert et al., CARE Note-2004-033-PHIN.

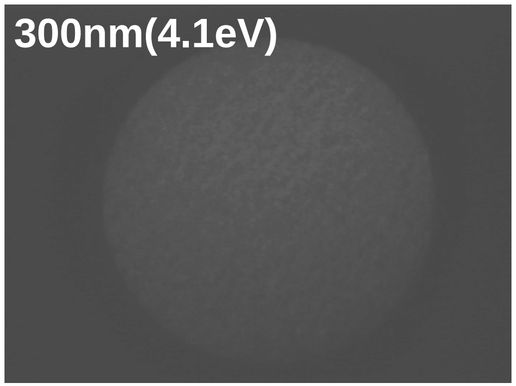
CERN measurements



R.A.Powell et al.; PRB8(1973)3987.



Cs_2Te cathode plug PEEM



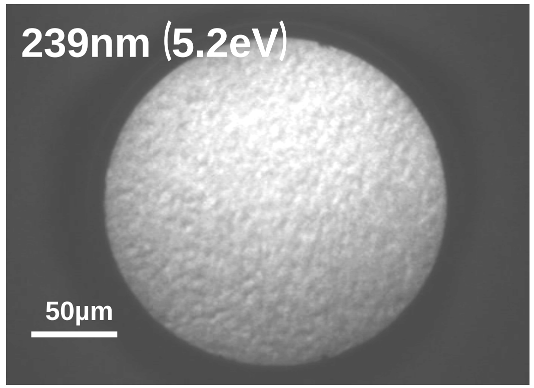
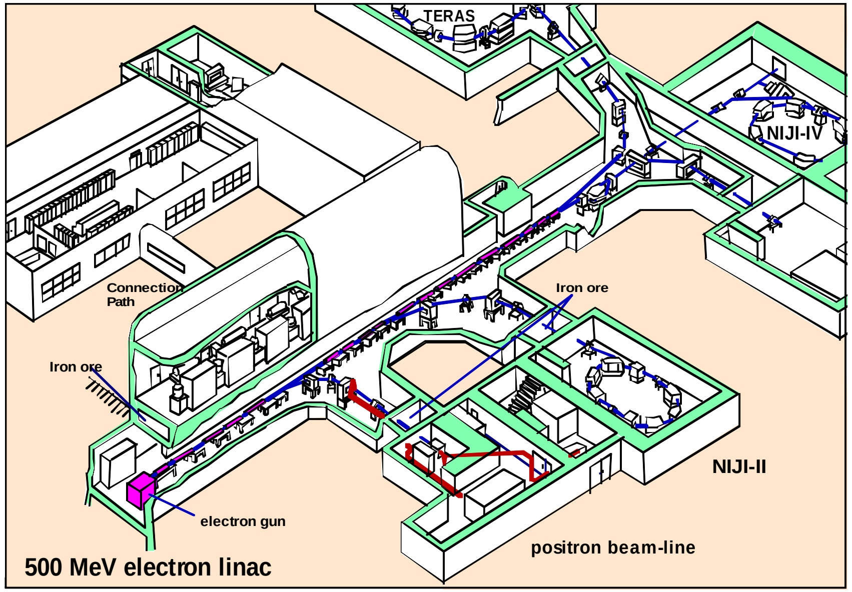


Photo-excitation by a Hg-Xe lamp

Imaging by Slow Positron Beams

THIN-FILM CHARACTERIZATION WITH PULSED SLOW POSITRON BEAMS



Pulsed slow e+ beams

- Intensity: 10^8 e^+/s (max)
- Initial Energy: ~5 eV

◎**PALS**(Positron Annihilation Lifetime Spectroscopy),

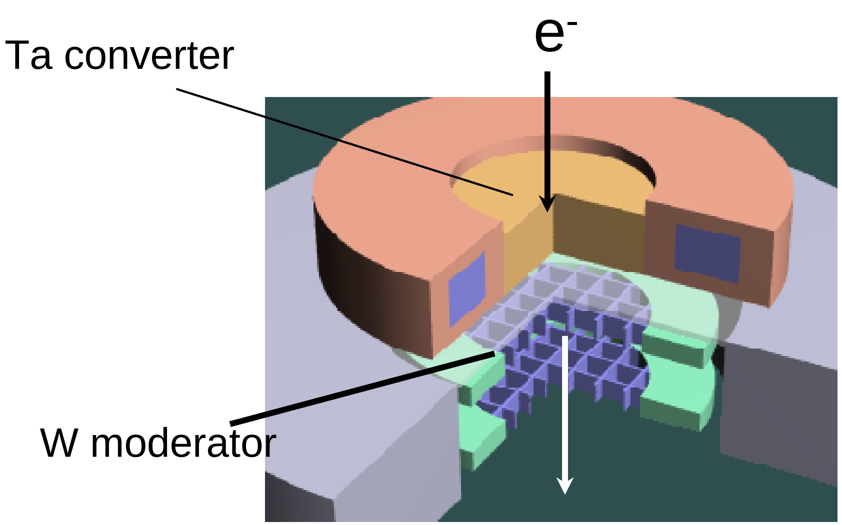
Pore-size measurement in atomic - nm scale.

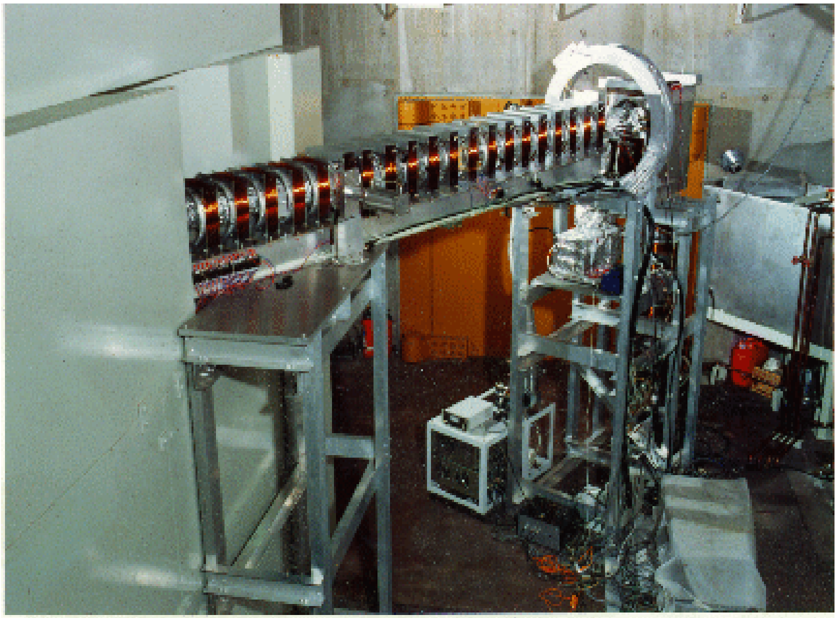
◎**AMOC**(Age-Momentum Correlation)

Defect and impurity identification.

◎**PAES** (Positron annihilation induced Auger Electron Spectroscopy)

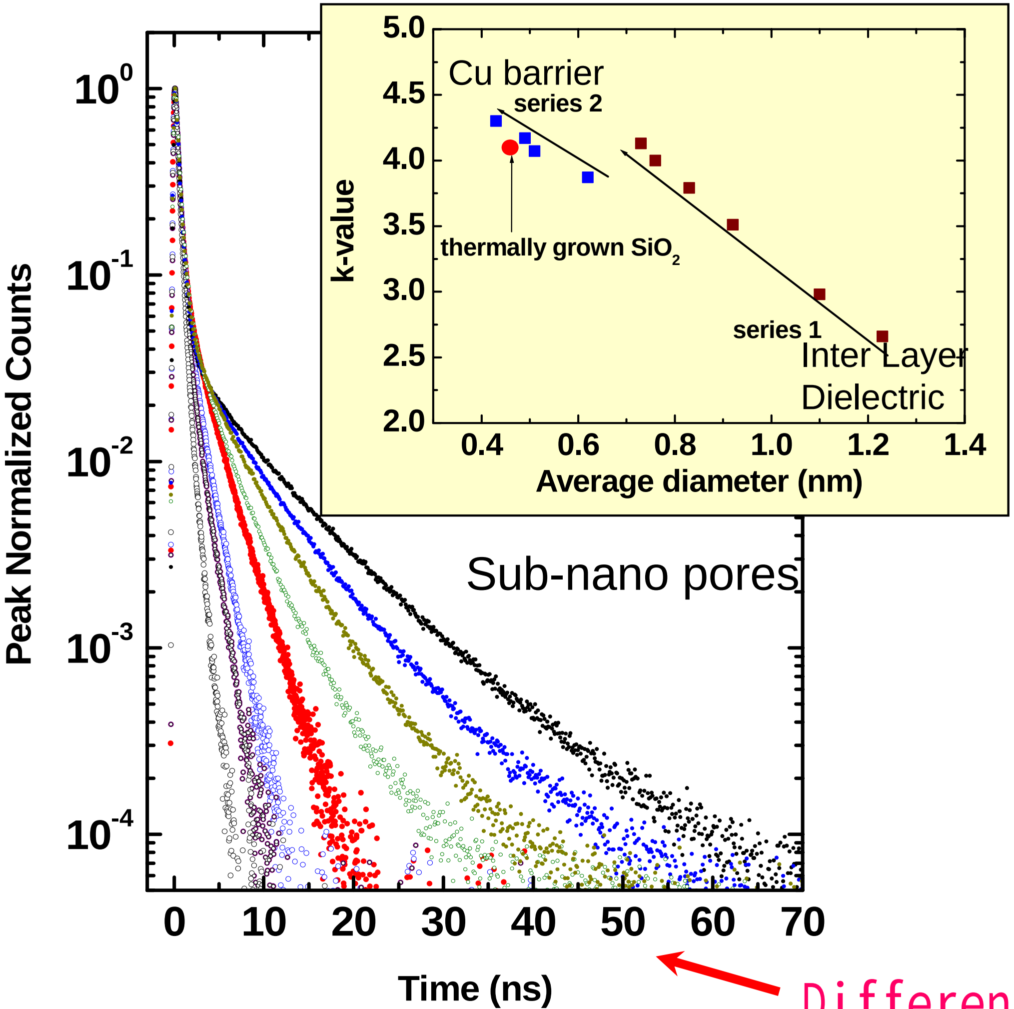
Surface characterization.



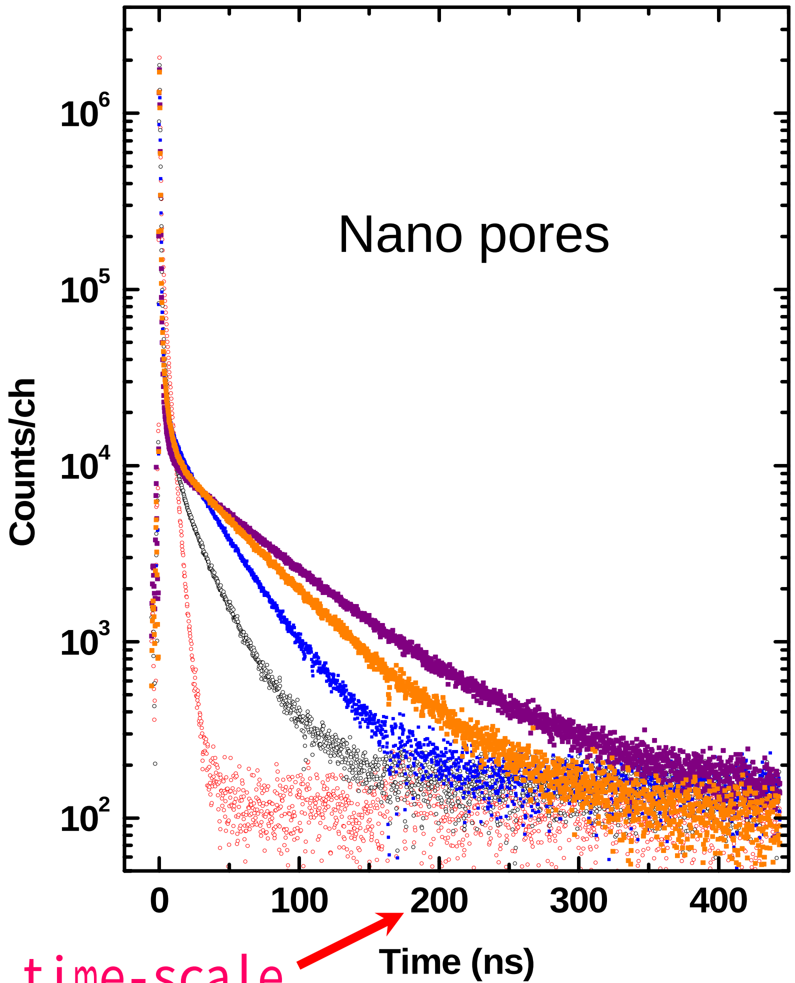


POSITRON LIFETIME SPECTRA OF LOW-k FILMS FOR NEXT GENERATION LSI

PECVD grown films



Spin-on-dielectric (SOD)

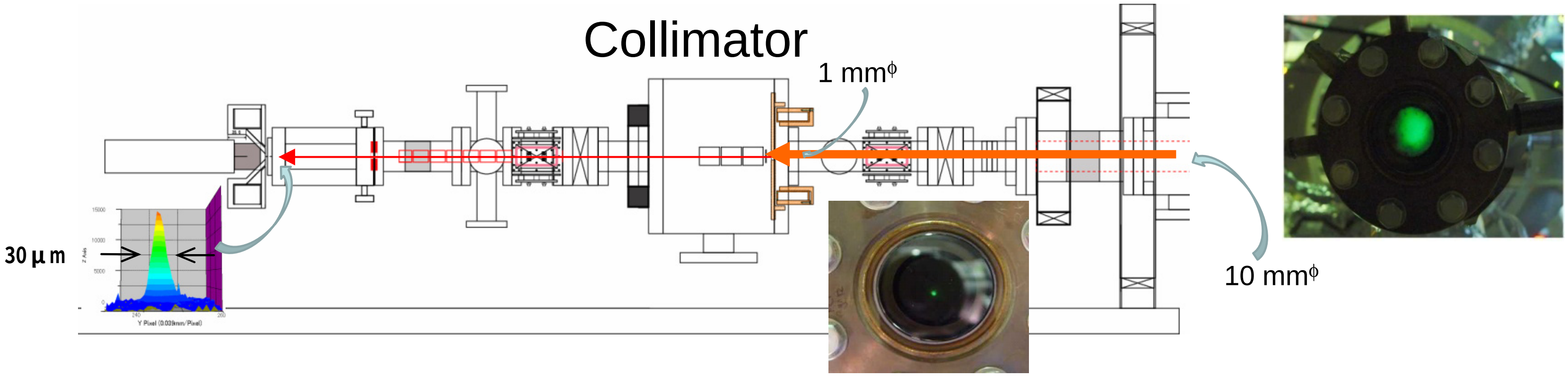


Different time-scale

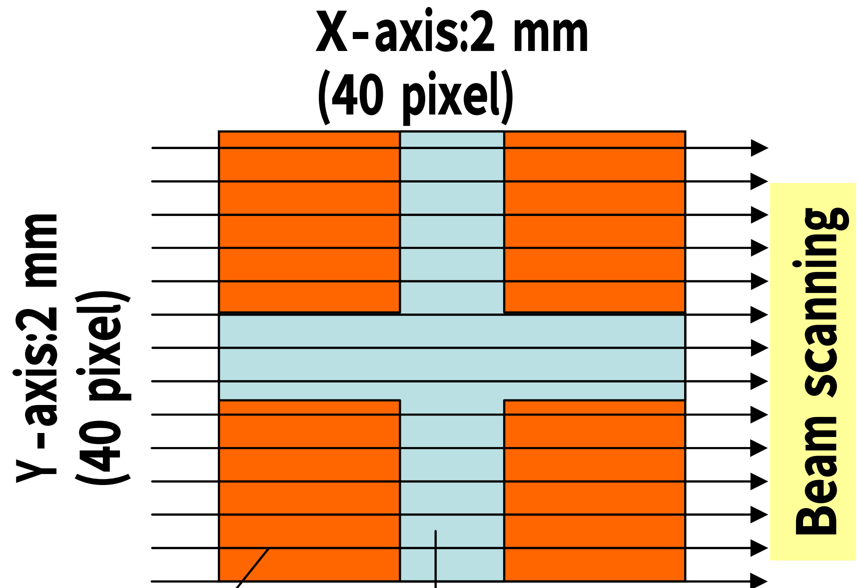
PECVD grown films generally have smaller pores than SOD grown films

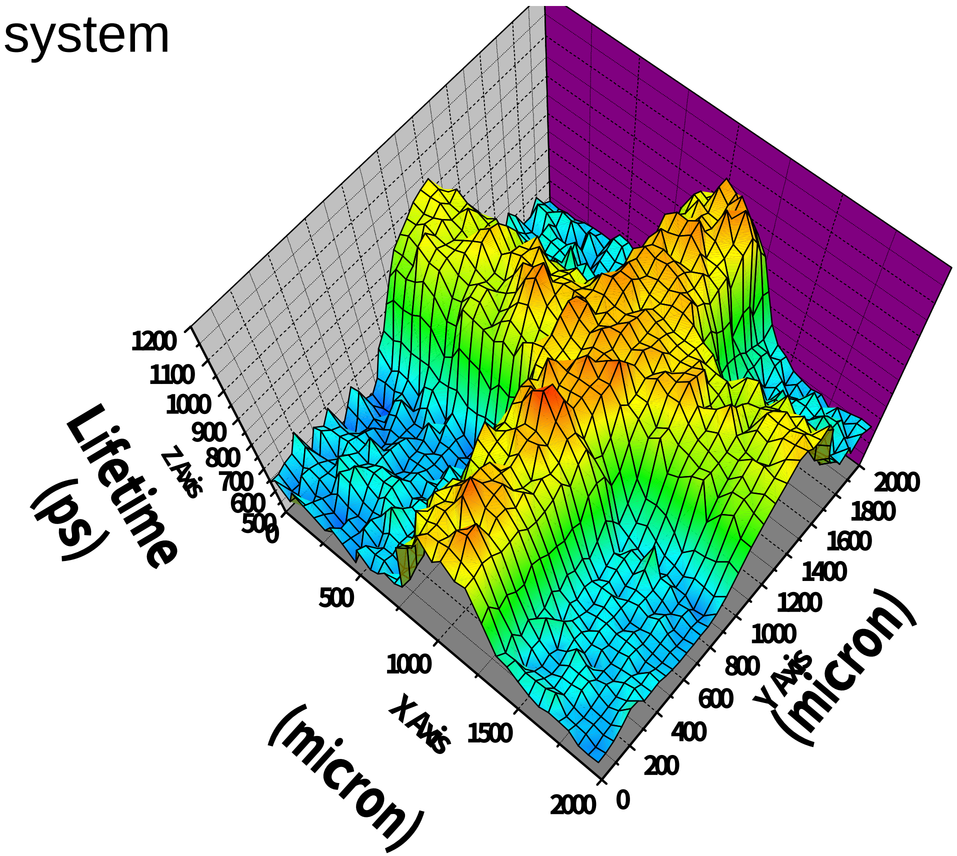
⇒Higher mechanical strength

IMAGING OF DEFECT DISTRIBUTION WITH POSITRON PROBE MICRO ANALYZER



Positron-beam focusing system





N^+ -irradiated SiO_2 substrate

SUMMARY

- Quantum-beams developed at AIST accelerator facities were applied as imaging tools to clarify various features in materials.
- Compton X-rays based on a compact linac were very usuful for refraction contrast imaging in biological specimen and K-edge imaging for microangiography.
- Compton gamma-rays indicated a good performance as high-energy photon sources for non-destructive inspection in both transmission and positron annihilation modes.
- FEL excited photoelectron emission microscope may reveal the degradation mechanisms of Cs-Te photocathode used in the RF gun.
- Positron micro probe successfully realized the defect-distribution imaging.