Diffraction Enhanced Imaging and Other Biomedical Applications of NSLS-II

Z. Zhong
National Synchrotron Light Source, Brookhaven National Lab

Collaborators:

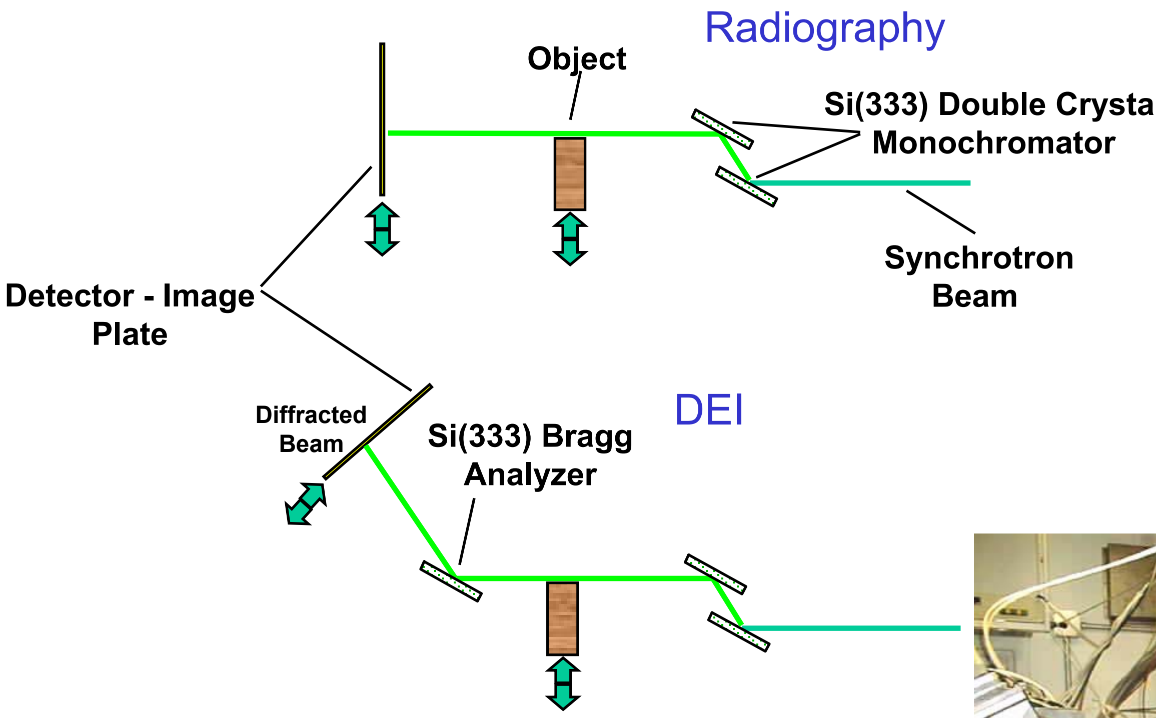
D. Chapman[2], D. Connor[3], A. Dilmanian[6], M. Hasnah[2], M. Kiss[3], J. Li[4], C. Muehleman[4], O. Oltulu[2], C. Parham[5], E. Pisano[5], D. Sayers[3]

2. Illinois Institute of Technology/University of Saskachewen
3. Dept. Physics, North Carolina State University
4. Rush-Presbyterian-St. Luke's Medical Center
5. Dept. Radiology, University of North Carolina, Chapel Hil
6. Medical Dept., Brookhaven National Lab

Background

- Diffraction Enhanced Imaging (DEI) was developed, in 1995 at the NSLS, to explore the use of synchrotron radiation for mammography.
- Used for mammography research since 1995 -> Chris Parham's talk.
- Dedicated facility built at X15A in 1998.
- US Patent issued in 1999.
- Cartilage imaging since 1999 -> Carol Muehleman's talk.
- Other facilities, Daresbury, Elettra, ESRF, HASYLAB, KEK, Spring8, have also developed DEI capability ... Most more advanced than NSLS.
- Canadian Light Source, being built at Saskatoon, plans for DEI/Medical Imaging facility.

Synchrotron Radiography and DEI

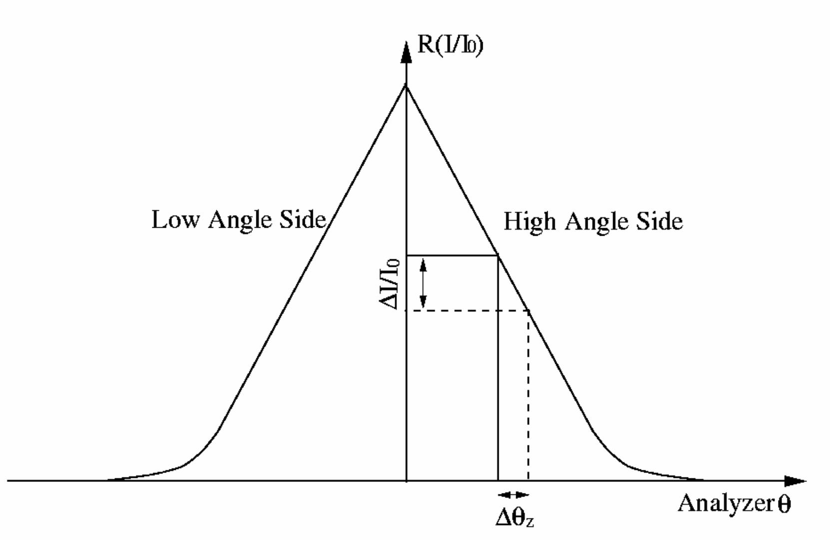


Experimental Setup at NSLS X15A

X-rays are analyzed in angle, using perfect silicon crystal, after passing through object.

How does DEI work?

• DEI utilizes the small range of angles (a few microradians) over which a perfect crystal reflects X-rays.
• The analyser functions as an extremely narrow slit.
• If the analyser angle is set half way on the rocking curve ($\theta_B \pm \Delta\theta_D/2$), rays that are deviated in the object will be reflected with either a greater or lower efficiency than 0.5.
• The steep slope of the rocking curve acts as a angle-intensity converter and reveals X-ray *refraction* which carry different information to conventional absorption images.



D. Chapman, W. Thomlinson, et. al., *Phys. Med. Biol.*, **42** (1997) 2015-2025

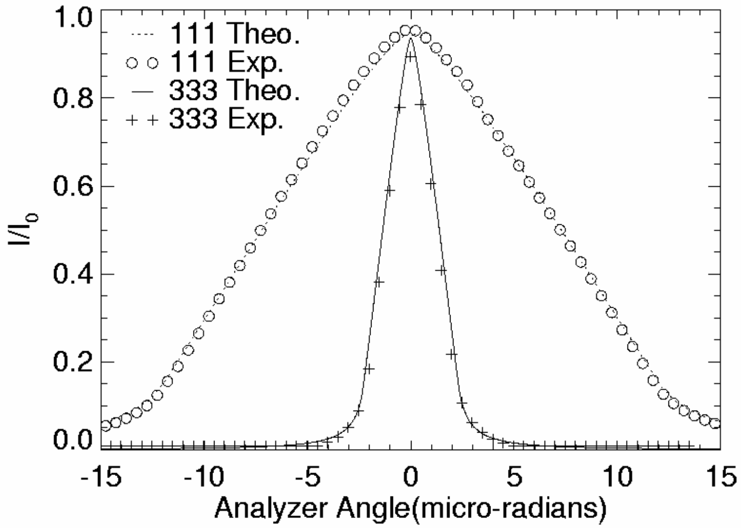
Refraction

- Variations of ρ and/or t in the sample causes x-ray refraction
- Refractive angle is comparable to the Si (333) Darwin width

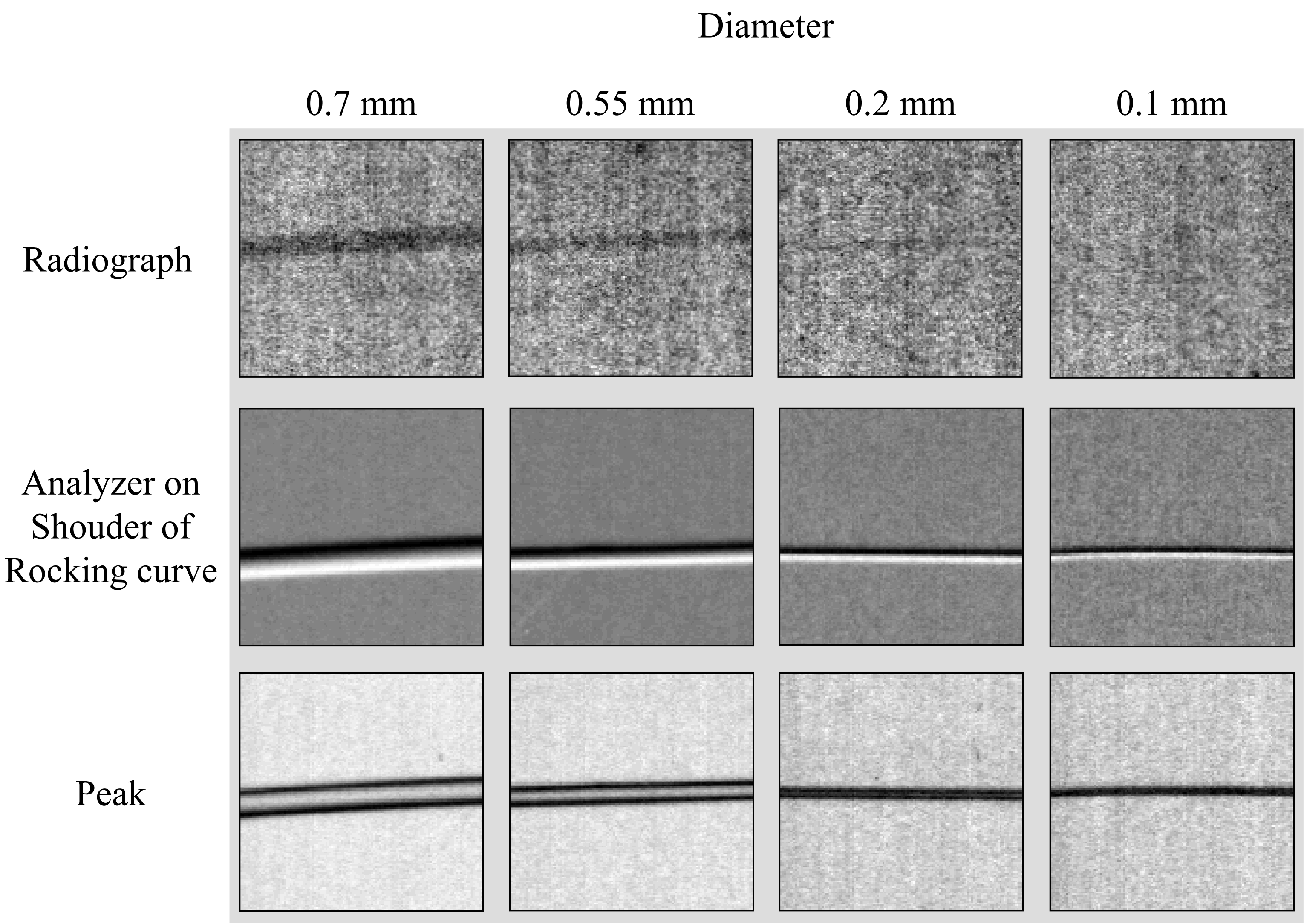
$$1 - n \cong \frac{N_e r_e \lambda^2}{2\pi} \cong 1.5 \rho \lambda^2 \times 10^{-6}$$

$$\delta_z \cong 1.5 \times 10^{-6} \lambda^2 \frac{\partial(\rho t)}{\partial z} \cong \mu\text{radians}$$

$$\omega_D \cong 2 \frac{r_0 \lambda^2 |F_H|}{\pi V_C} \frac{1}{\sin 2\theta_B} \cong \mu\text{radians}$$



Refraction contrast in Nylon fiber

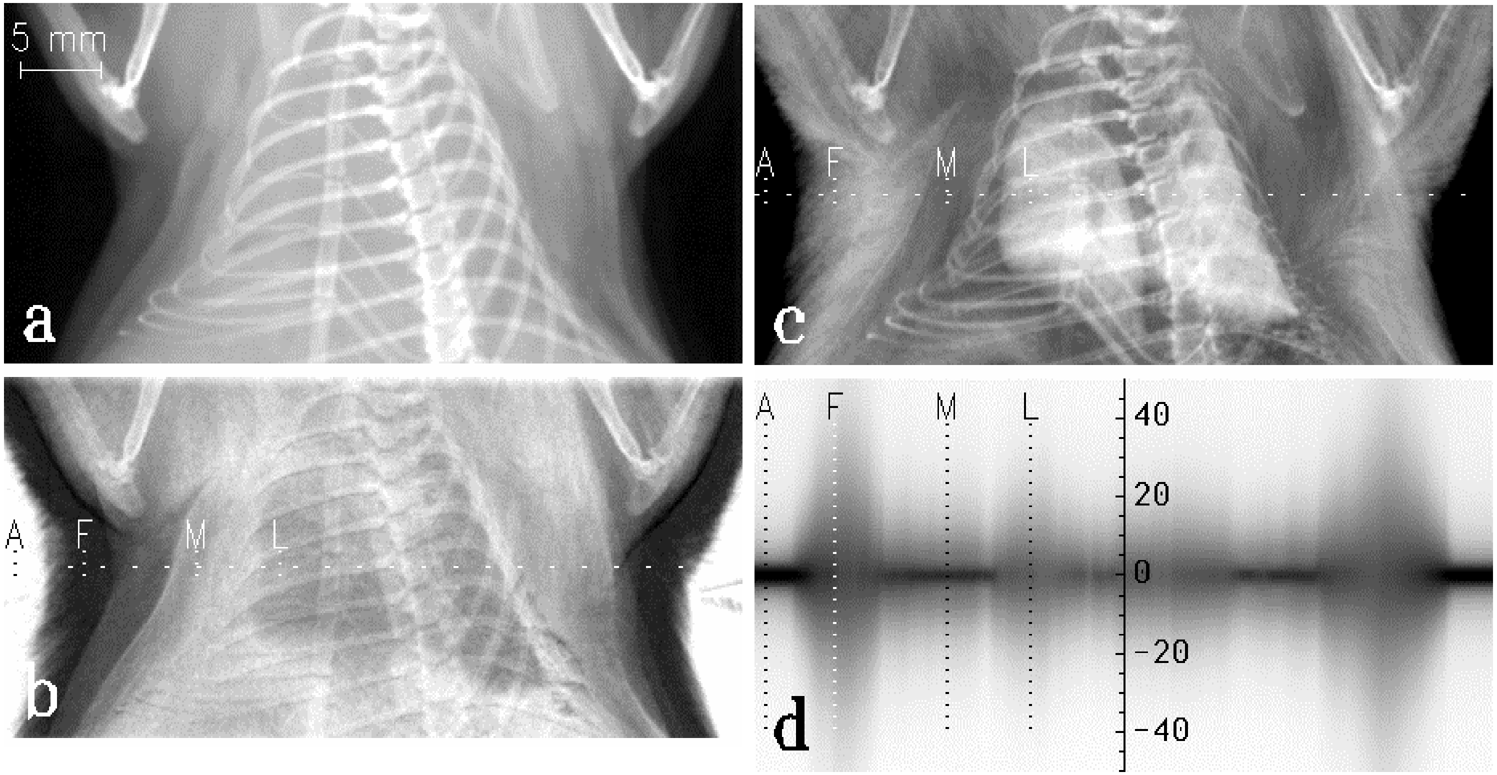


Nylon fiber simulates density variation in soft tissue

Extinction Contrast in Mouse Lung

Radiograph

DEI with analyzer on peak, the lungs have more contrast than bones



DEI at +3 micro-radians
Note reversed lung contrast

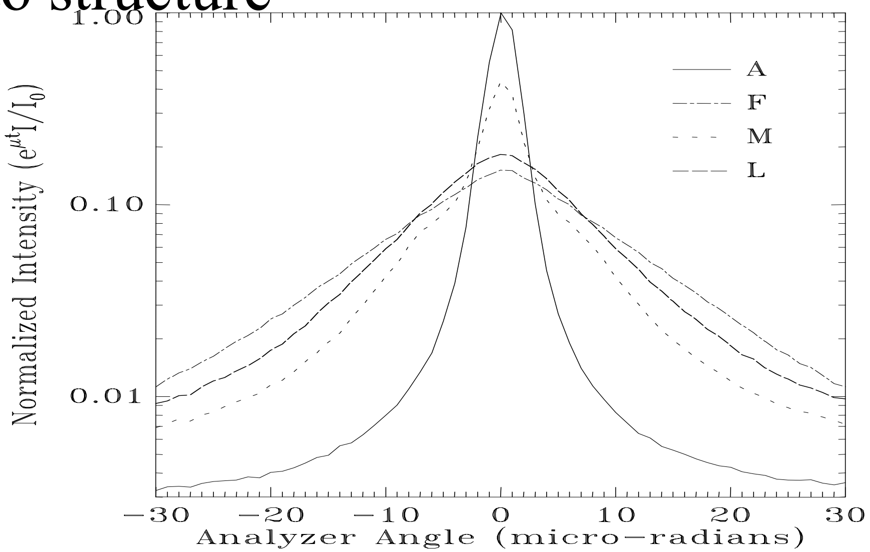
Rocking curves

- Lungs have small absorption contrast
- Large extinction contrast is due to the porous structure of alveoli

Z. Zhong et. al., *Nucl. Instrum. Meth. in Phys. Res. A.* **450** (2000) 556-567

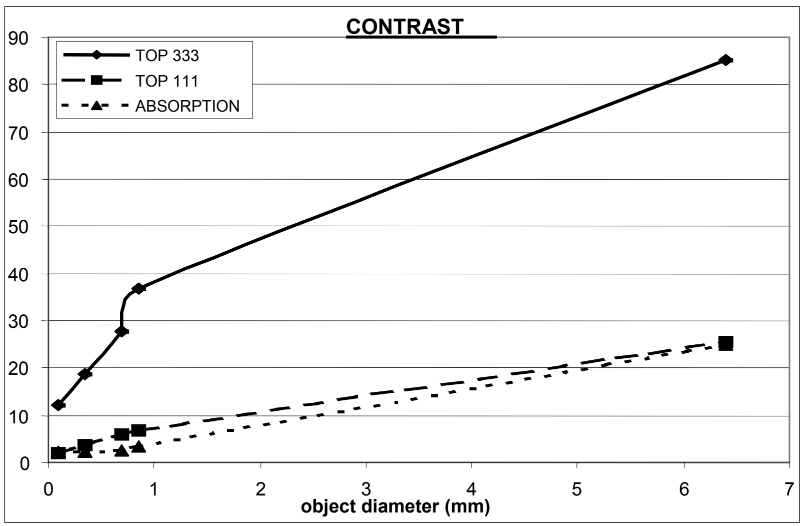
DEI Sources of Contrast

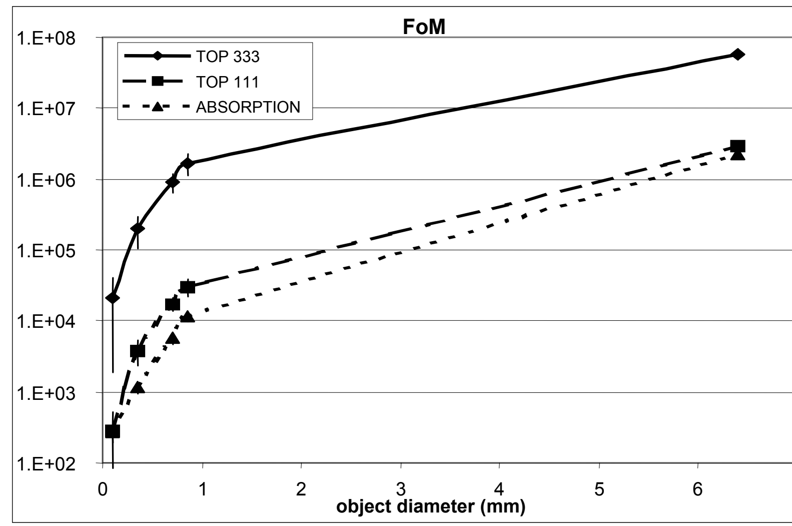
- Normal Absorption - same as from conventional radiography
- Refraction Contrast - sensitive to refractive index gradients at the imaging energy
  - Characterized by a shift in peak position of the rocking curve
  - Edge enhancement without computer processing the image
- Extinction Contrast – Characterized by broadening of rocking curve - sensitive to structure



DEI shines at smaller feature size

- Normal Absorption - Proportional to object size.
- Refraction Contrast – Roughly the same regardless of object size, limited only by the resolution of the detector





$$SNR = \frac{ACN_1}{\sigma(AN_1)}$$

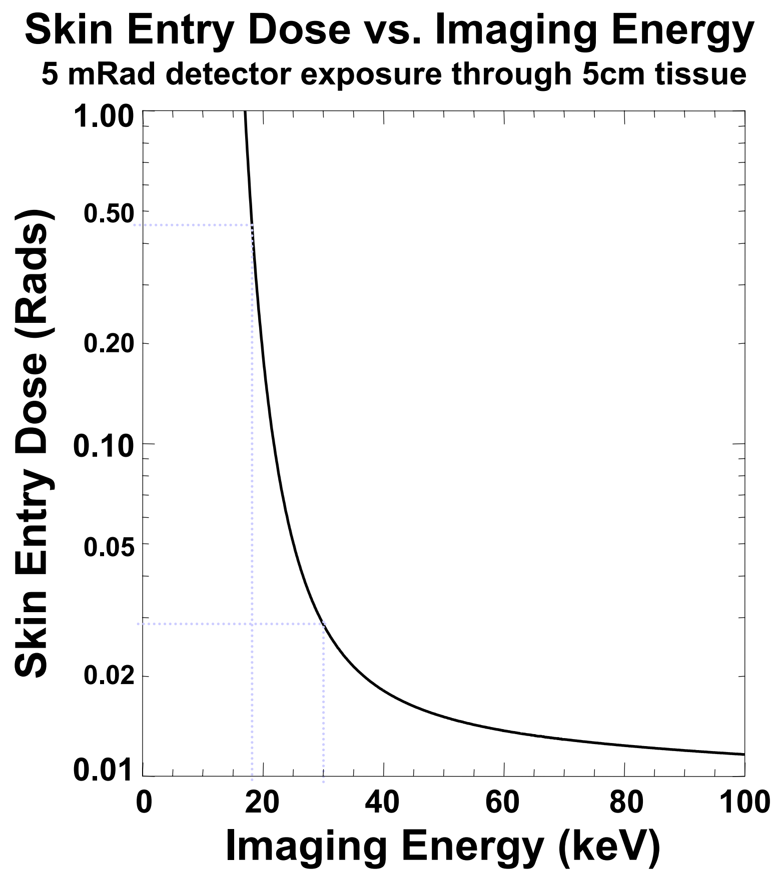
$$FoM = \frac{SNR^2}{dose}$$

L. Rigon, Z. Zhong, et. al., *Proc. SPIE 4632: Physics of Medical Imaging* (2002)

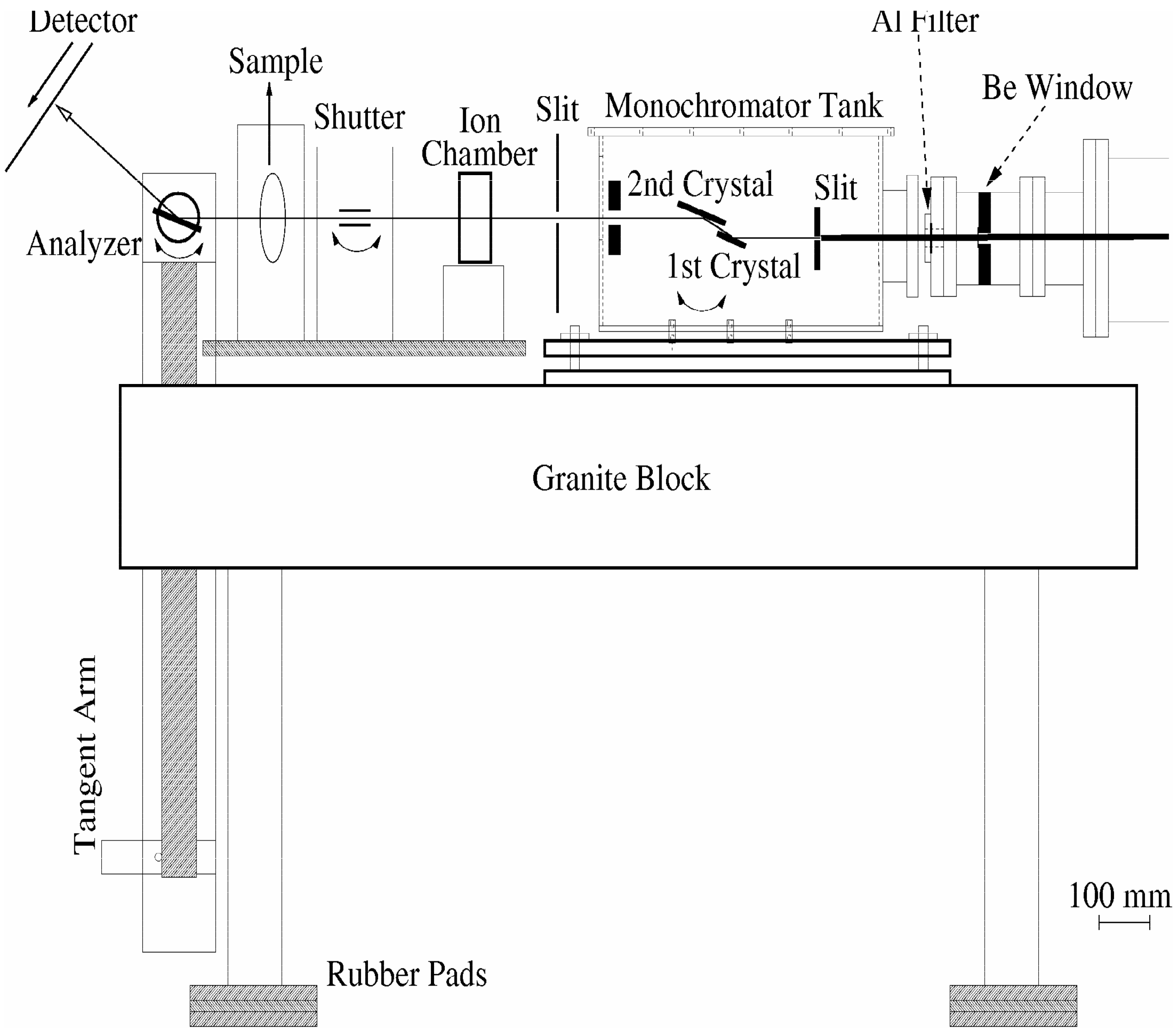
DEI does not rely on absorption (=dose)

- DEI can be implemented at near zero dose by utilizing higher-energy x-rays.

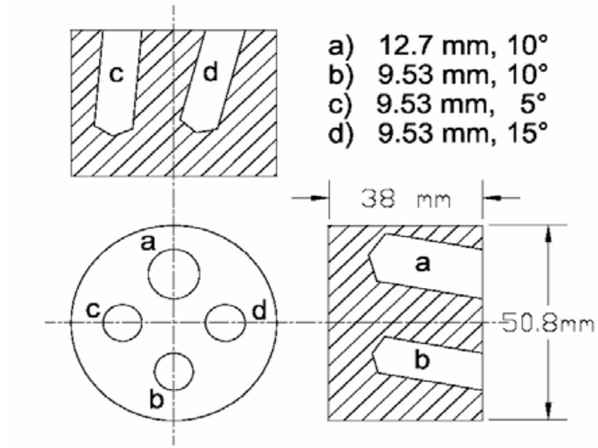
- 5 mRads exposure to detector
  - @18keV @ 30keV
  - 2.65×10^{7} 7.85×10^{7} photons / pixel onto detector
  - 0.010 0.175 transmission factor through 5cm thick tissue
  - 2.65×10^{9} 4.49×10^{8} photons / pixel at front surface of tissue
  - 0.450 0.029 Rads skin entry dose
- 15.5 x smaller dose at 30keV compared to 18keV



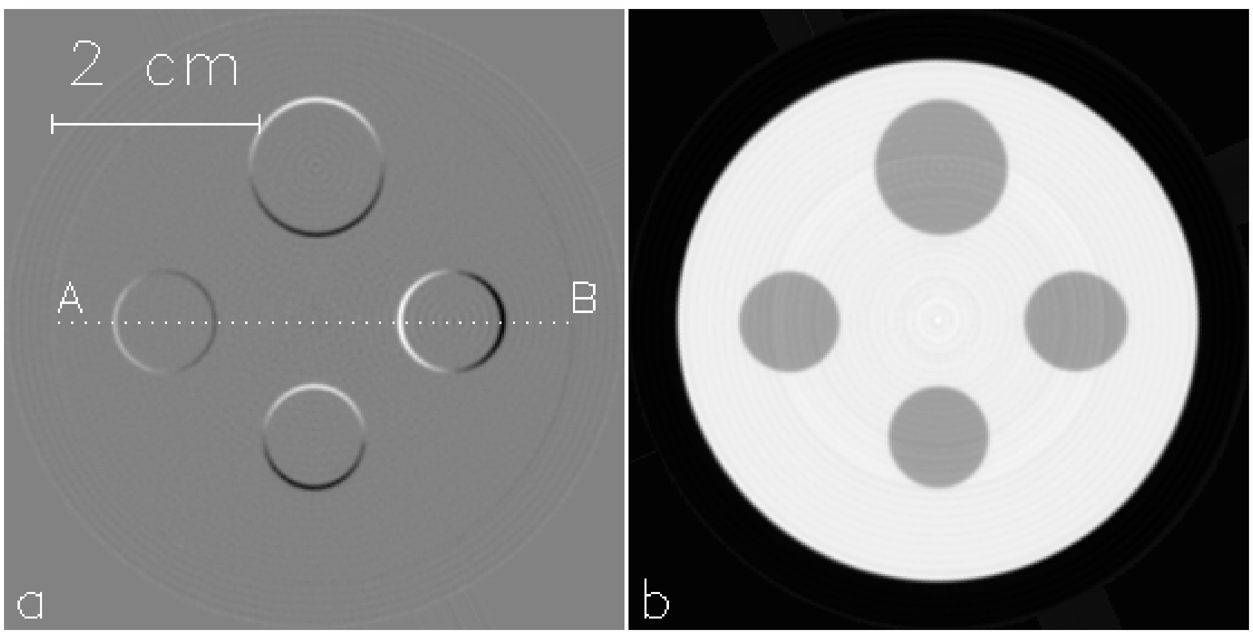
DEI Setup at NSLS X15A



Compatibility with CT



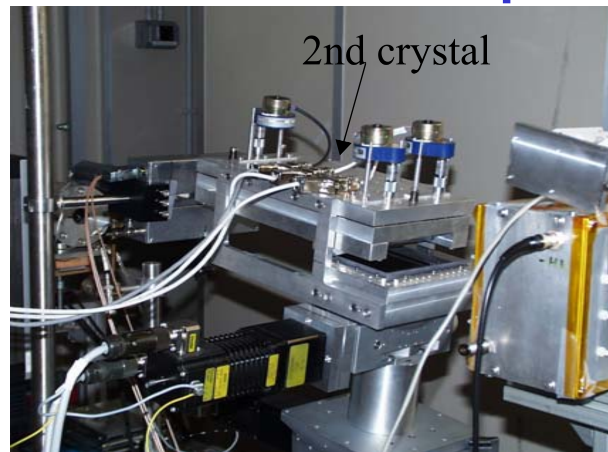
- The DEI CT projection sets of the “refraction image” and the “apparent absorption image” are complete
- Filtered back-projection can be used

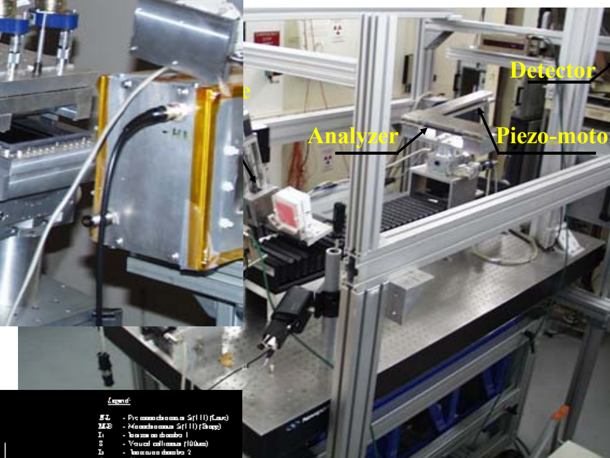


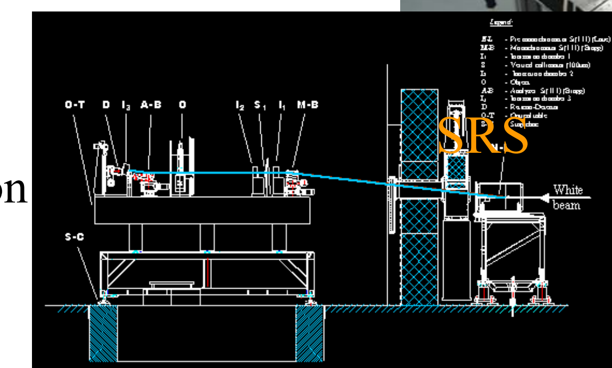
A. Dilmanian, Z. Zhong, et. al., Phys. Med. Bio. 45 (2000) 933-946.

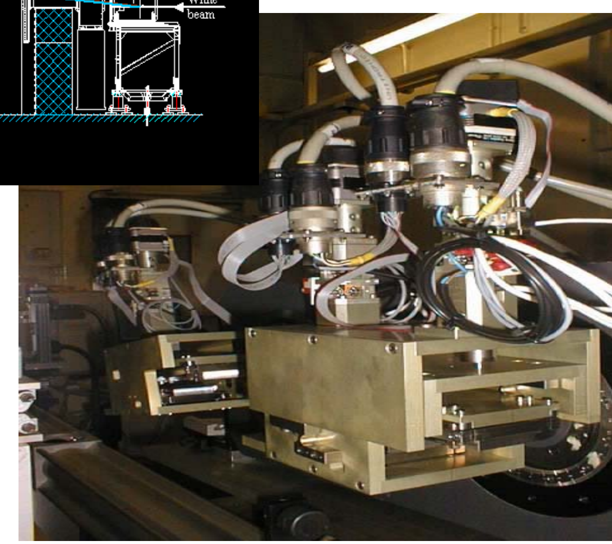
DEI Research in Europe: PHASY

- 5 years project supported by EU:
  - 2000- 2005
- Aim:
  - thorough study and the full exploitation of the "Diffraction Enhanced Imaging” technique
  - 4 DEI systems developed and installed at the synchrotrons
  - Feasibility and medical applications studies
  - design study of a final synchrotron - and a x-ray tube based system
- Facilities:
  - Elettra (Trieste, Italy)
  - ESRF (Grenoble, France)
  - DESY (Hamburg, Germany)
  - SRS (Daresbury, UK)





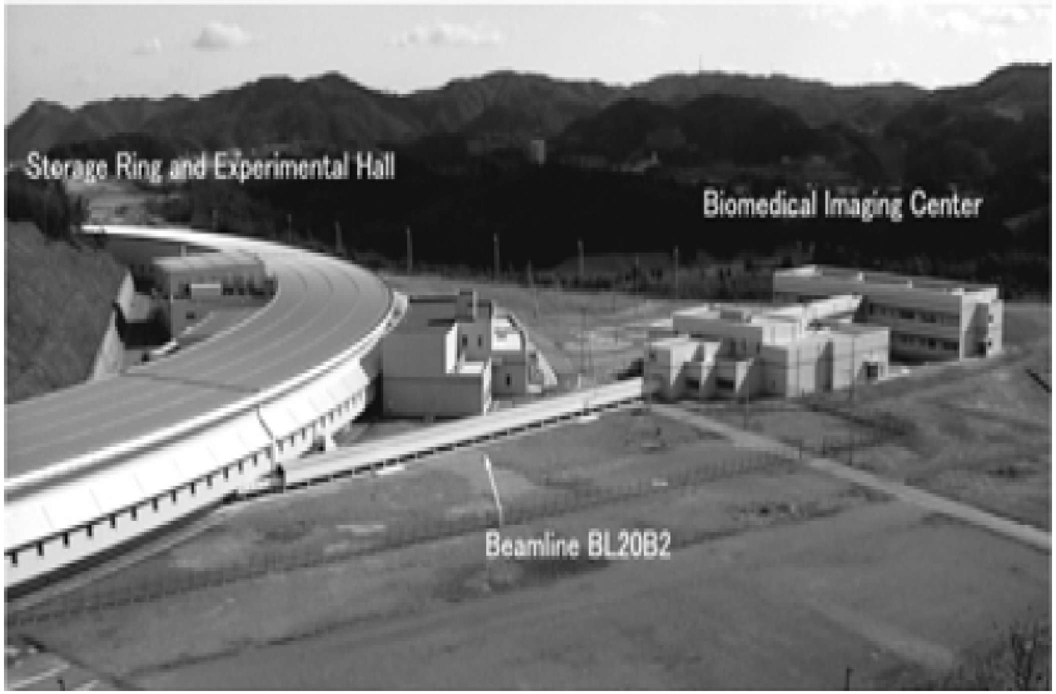




Other Biomedical applications

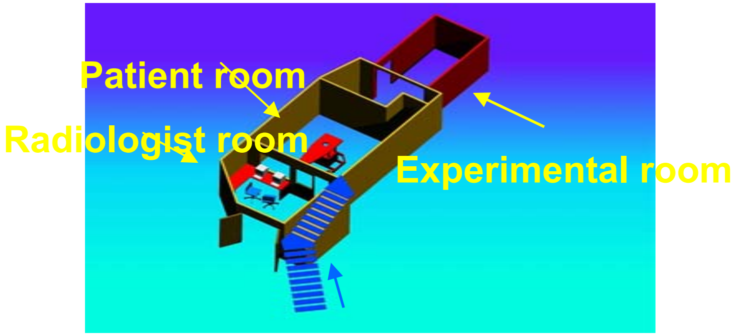
- Cancer Therapy and Radiobiology Research: Microbeam Radiation Therapy (MRT), Photon Activation Therapy
- Cancer Biology
- Tissue specific tomography
- Musculoskeletal Imaging -> Tunability
- Dual-energy K-edge subtraction Imaging -> Contrast agent, functional imaging, perfusion
- Development of new imaging modalities, functional contrast agent development, Neurosciences, protein and cellular localization.

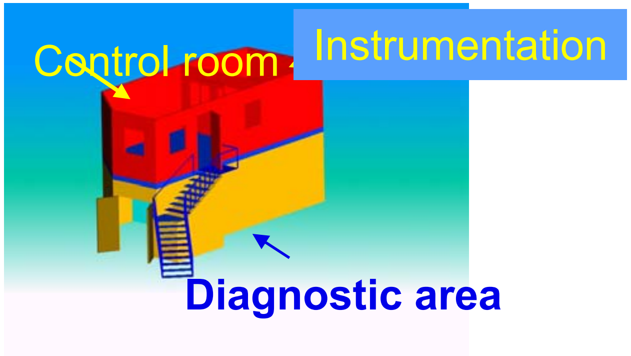
Other facilities



Spring-8

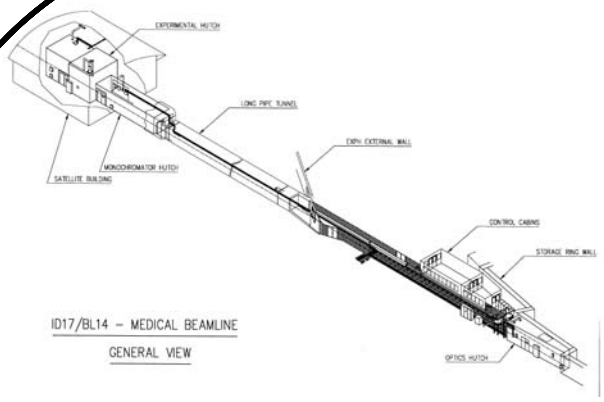
SYRMEP, Elettra





ESRF BIOMEDICAL BEAMLINE

ID17



ESRF

ID17

Summary

- DEI of human breast and knee specimens, as well as in vivo animals, show:
- DEI refraction highlights boundaries between different tissue types (e.g. breast tissue and tumor), provides information on lesion border detail and associated features that are not detected by conventional imaging -> early diagnosis of breast cancer.
- lungs were substantially highlighted in the "apparent absorption" image -> relevant for diagnosis of early stages of emphysema and edema.
- DEI differentiates between normal and damaged cartilage within knee joint. -> Potential for assessment of cartilage damage *in vivo*.

2002-3 X15A DEI Publications

- 1. C. Muehleman,L.D. Chapman, K. E. Kuettner, J Rieff, J A. Mollenhauer, K. Massuda, and Z. Zhong, “Radiography of Rabbit Articular Cartilage with Diffraction Enhanced Imaging”, *Anatomical Record* **272A** (2003) 392-397.
- 2. J. Li, Z. Zhong, R. Litdke, K. E. Kuettner, C. Peterfy, E. Aleyeva, and C. Muehleman, “Radiography of Soft Tissue of the Foot and Ankle with Diffraction Enhanced Imaging”, *J. Anatomy* **202** (2003) 463-470.
- 3. M. Z. Kiss, D. E. Sayers and Zhong Zhong, “Measurement of image contrast using diffraction enhanced imaging”, *Phys. Med. Bio.* **48** (2003) 325-340.
- 4. M. Hasnah, O. Oltulu, Z. Zhong, and D. Chapman, “Single Exposure Simultaneous Diffraction Enhanced Imaging”, *Nucl. Instrum. Meth. Phys. Res A* **492** (2002) 236-240.
- 5. Z. Zhong, D. Chapman, D. Connor, A. Dilmanian, N. Gmür, M. Hasnah, R. E. Johnston, M. Kiss, J. Li, C. Muehleman, O. Oltulu, C. Parham, E. Pisano, L. Rigon, D. Sayers, W. Thomlinson, M. Yaffe, and H. Zhong, “Diffraction Enhanced Imaging of Soft Tissues”, *Syn. Rad. News* **15 (6)** (2002) 27-34.
- 6. M.O. Hasnah, Z. Zhong, O. Oltulu, E. Pisano, R.E. Johnston, D. Sayers, W. Thomlinson and D. Chapman, “Diffraction Enhanced Imaging Contrast Mechanisms in Breast Cancer Specimens”, *Medical Physics* **29** (2002) 2216-2221.
- 7. C. Muehleman, M. Whiteside, Z. Zhong, J. Mollenhauer, M. Aurich, K.E. Kuettner and L.D. Chapman, “Diffraction enhanced imaging for articular cartilage”, *Biophys. J*. **82** (2002) 2292.
- 8. M. Z. Kiss, D. E. Sayers and Z. Zhong, “Comparison of X-ray detectors for a diffraction enhanced imaging system”, *Nucl. Instrum. Meth. Phys. Res.,* **A491** (2002) 280-290.
- 9. M. Hasnah, O. Oltulu, Z. Zhong and D. Chapman, “Application of Absorption and Refraction Matching Techniques for Diffraction Enhanced Imaging”, *Rev. Sci. Instrum.* **73** (2002) 1657-1659.
- 10. J. Mollenhauer, M. Aurich, Z. Zhong, C. Muehleman, A. A. Cole, M. Hasnah, O. Oltulu, K. E. Kuettner, A. Margulis and L. D. Chapman, "Diffraction Enhanced X-ray Imaging of Articular Cartilage", *J. Osteoarthritis and Cartilage,* **10** (2002) 168-171.