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LLNL-PRES-731439

Medical Applications of Compact Laser-Compton Light Source

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APS physics™

NSF

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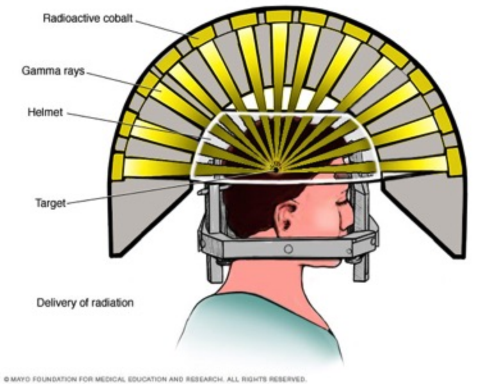
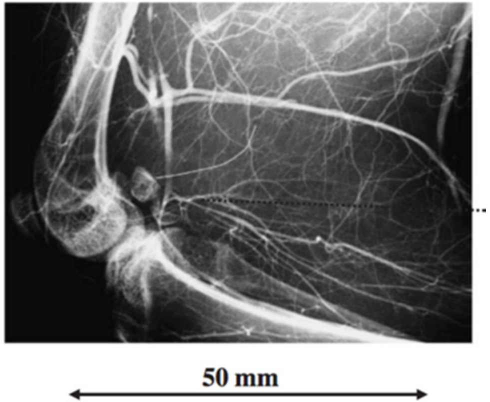
Medical X-ray and γ-ray Sources

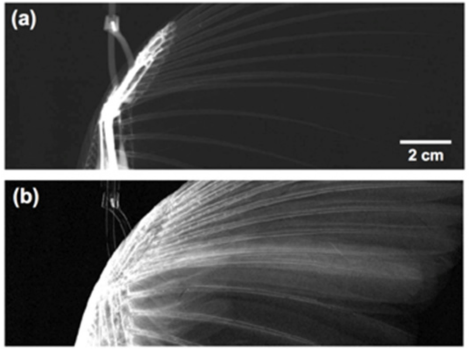
- radioisotopes
  - monochromatic, MeV
  - intensity ~ source size
  - hazardous, radioactive waste
- bremsstrahlung sources
  - wide range of energies (keV-MeV)
  - broad spectrum
- synchrotron radiation
  - mostly <100 keV
  - high flux, monochromatic, tunable -> less dose, more contrast, K-edge subtraction imaging
  - small source size -> sharper image, phase contrast imaging
  - facility too large for clinical use



Mayo Foundation for Medical Education and Research



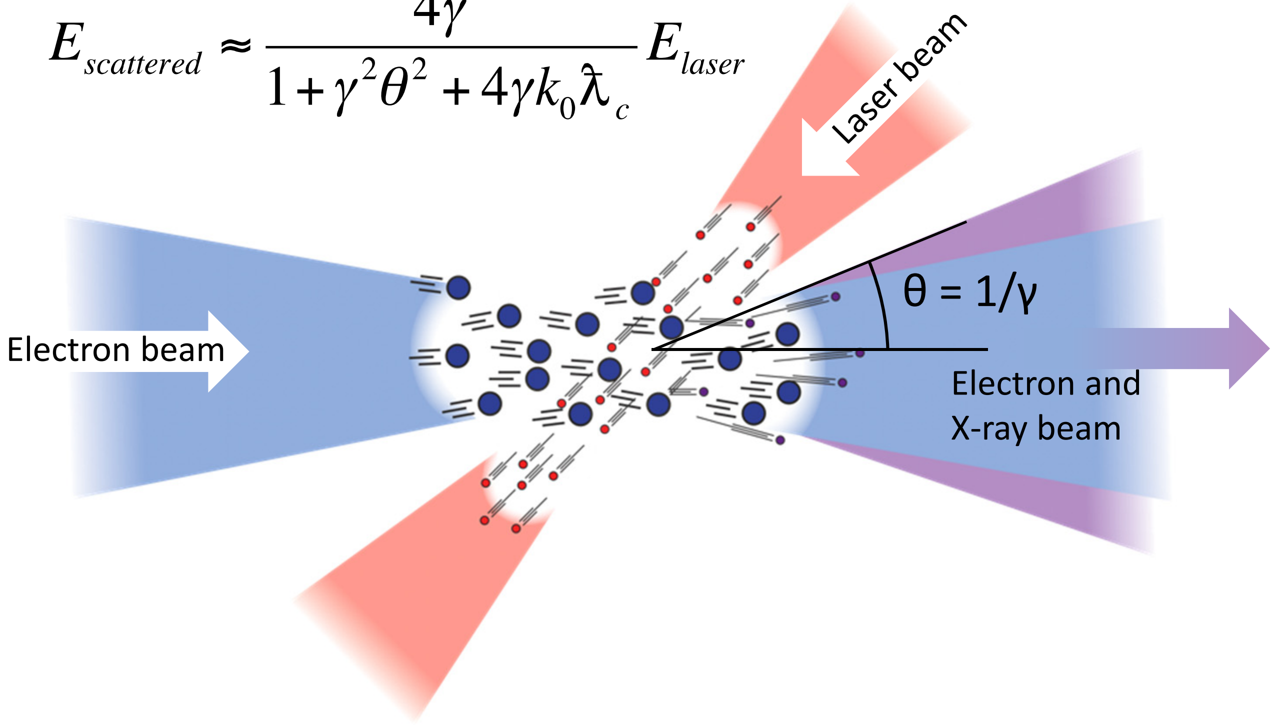
Sato et. al, Jpn. J. Appl. Phys. **44** 8204 (2005)



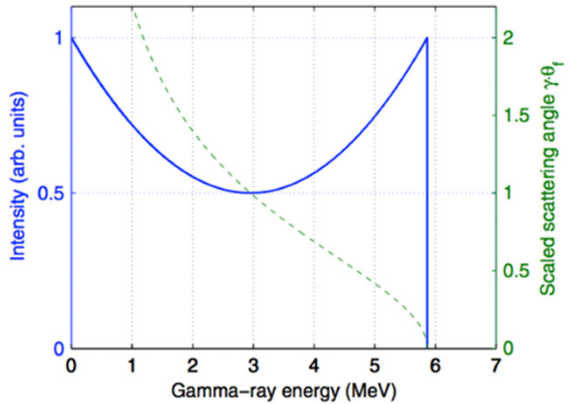
Pfeiffer et al., J. Appl. Phys. **105**, 102006 (2009)

Laser-Compton photon generation

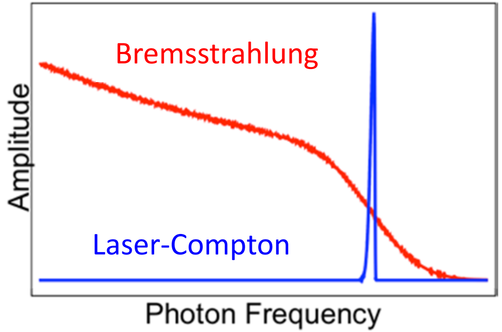
$$E_{scattered} \approx \frac{4\gamma^2}{1+\gamma^2\theta^2+4\gamma k_0 \lambda\!\!\!^{-}_c} E_{laser}$$



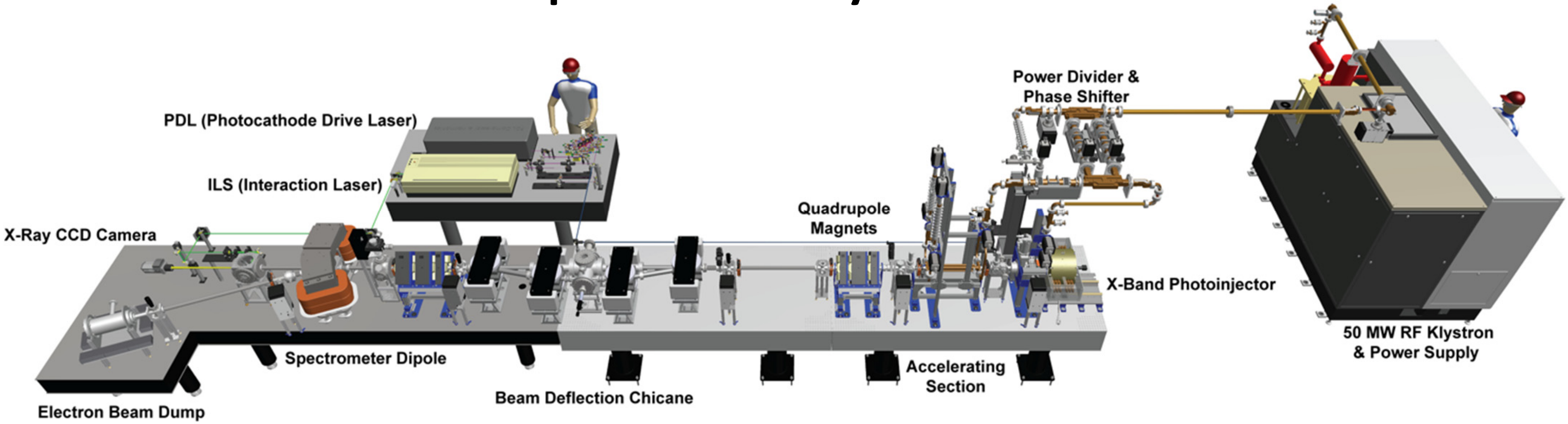
Spectrum and angle correlation



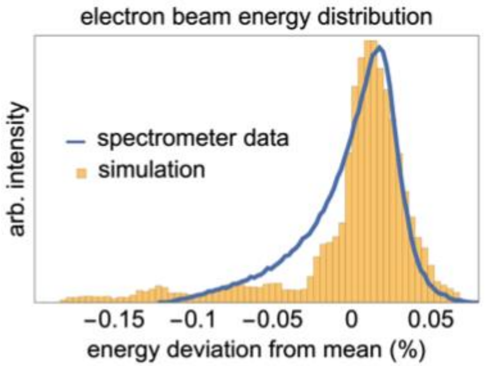
Sun et. al, PRSTAB **14**, 044701 (2011)

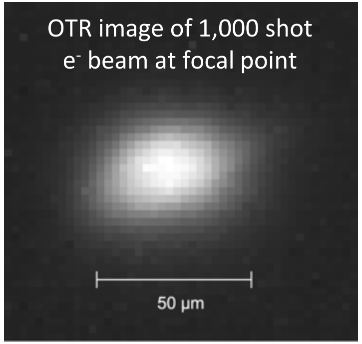


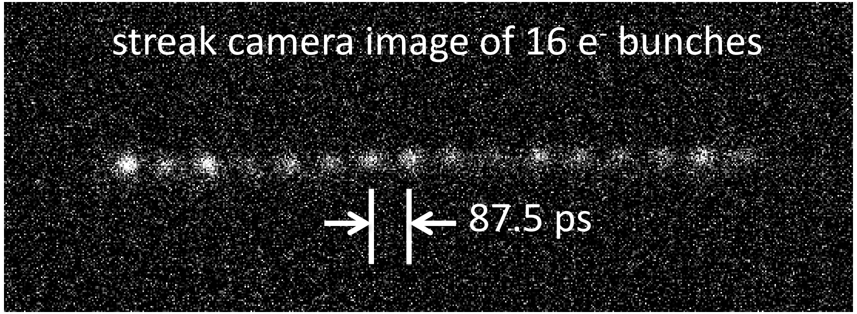
Laser-Compton X-ray Source at LLNL



LLNL X-band Electron Linear Accelerator







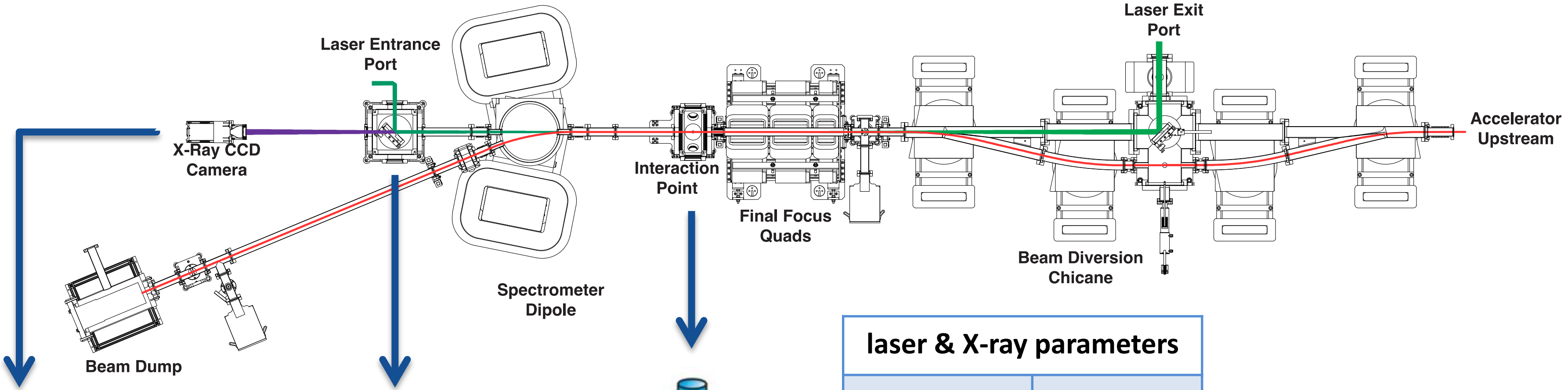
- LLNL/SLAC photoinjector[1]
  - 185 MV/m, ~7 MeV
- 1 T53 accelerating section
  - 45 MV/m, ~30 MeV
- 50 MW klystron, modulator
- up to 16 bunches per pulse (MOPIK111)
- energy upgrade: pulse compressor & 2nd section
  - >85 MeV electrons
  - >270 keV X-rays

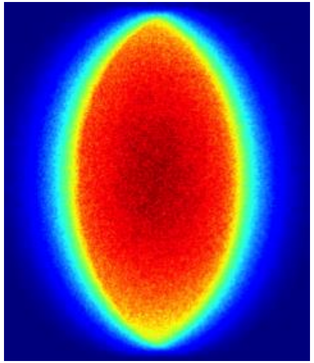
[1] R. A. Marsh et al., PRSTAB **15**, p. 102001

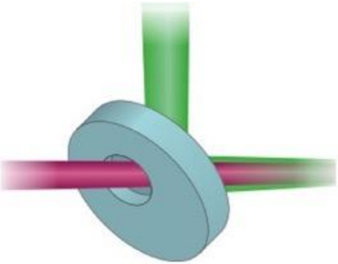
measured e^- beam parameters	
energy	30 MeV
charge	10-200 pC
bunch length	2 ps*
spot size	14x11 μm
pos. jitter	5x2 μm
energy spread	0.03%
energy jitter	0.06%
emittance	0.3 mm-mrad
RF frequency	11.424 GHz
rep. rate	10 Hz

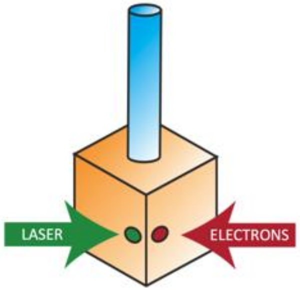
*PARMELA simulation value

Laser-Electron Interaction





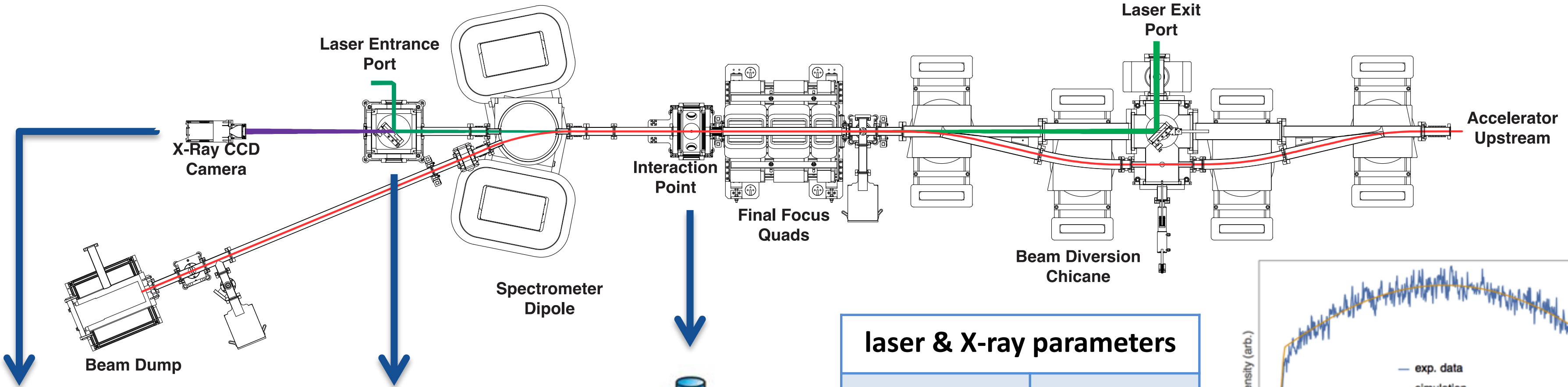


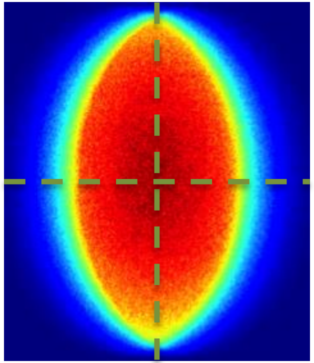


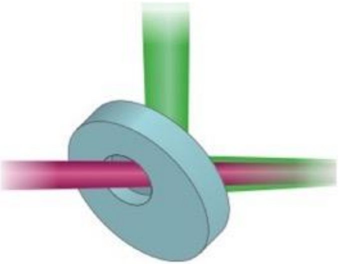
laser & X-ray parameters	
laser energy	750 mJ
wavelength	532 nm
pulse length	6.5 ns
beam waist	50 μm
X-ray energy	30 keV
X-ray flux	$3x10^5$/shot

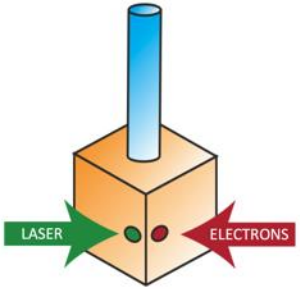
IPAC’16 TUPOW052 (X-ray characterization)
NAPAC’16 WEPOB35 (source size measurement)
IPAC’17 MOPAB146 (K-edge filter diagnostic)

Laser-Electron Interaction









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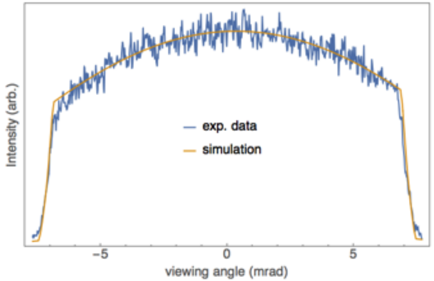

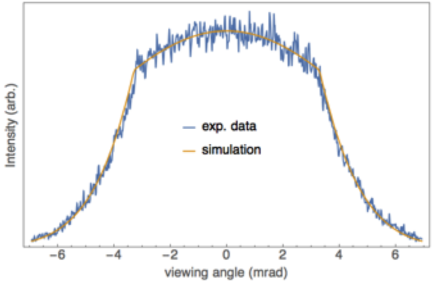

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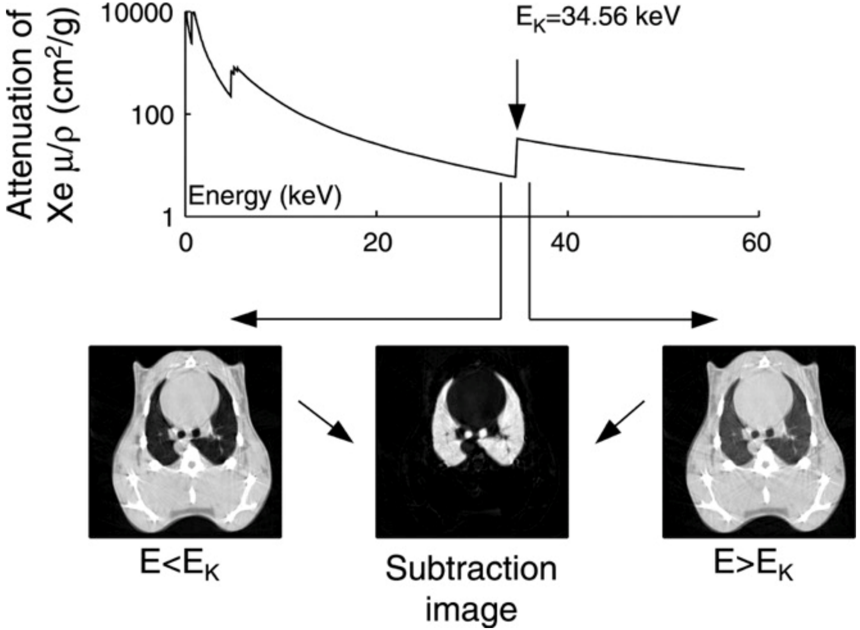
K-edge subtraction imaging

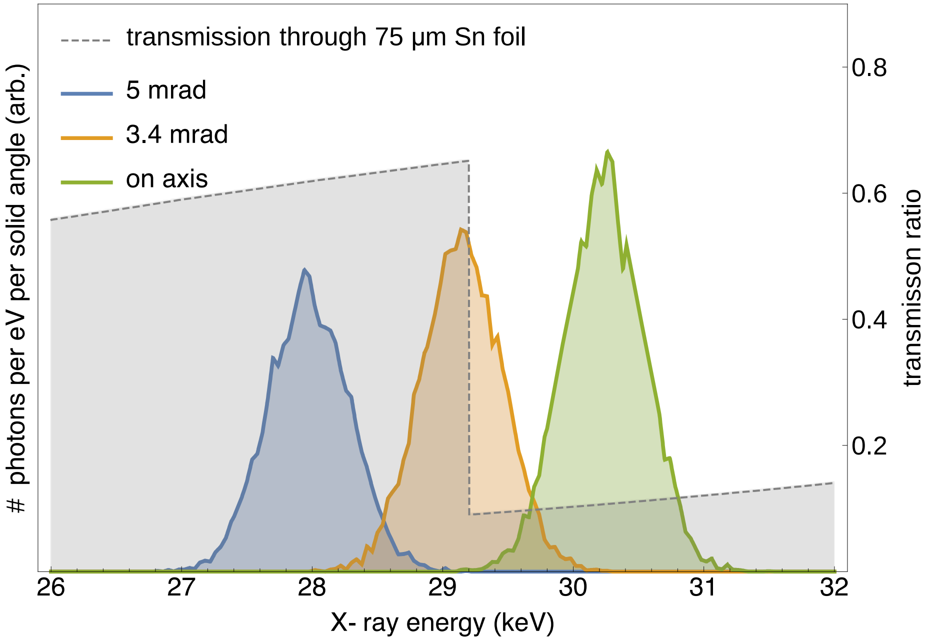
- two images above and below contrast agent K-edge
  - I (33.2 keV), Gd (50.7), Au (80.7)
- requires narrowband dual-color X-ray beam
  - change in e^- energy, viewing angle



Bayat et al., J. Appl. Physiol., **100** 1964 (2006)

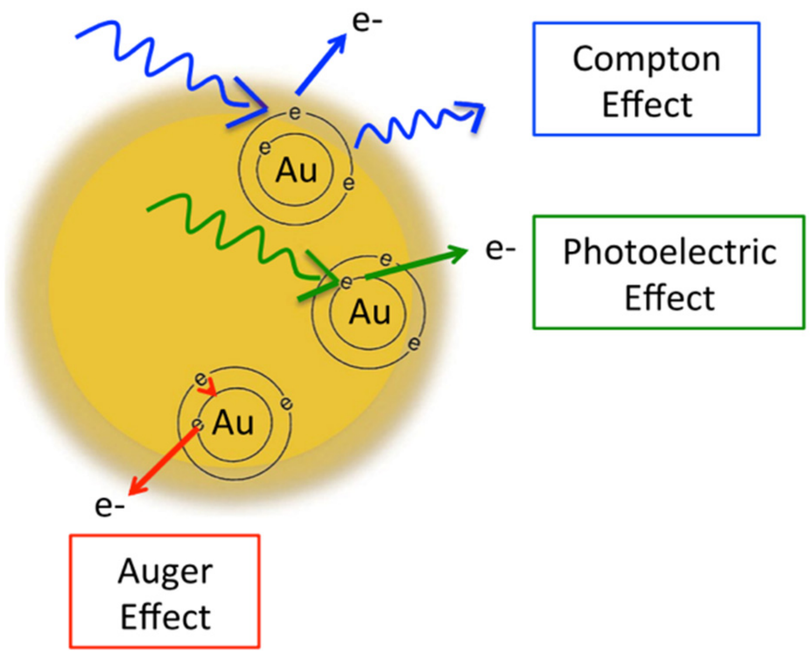
K-edge subtraction imaging

- two images above and below contrast agent K-edge
  - I (33.2 keV), Gd (50.7), Au (80.7)
- requires narrowband dual-color X-ray beam
  - change in e^- energy, viewing angle
- applications in angiography, bronchography
- experiment with capillary tubes
  - Ag (25.5 keV) in current setup



Auger therapy

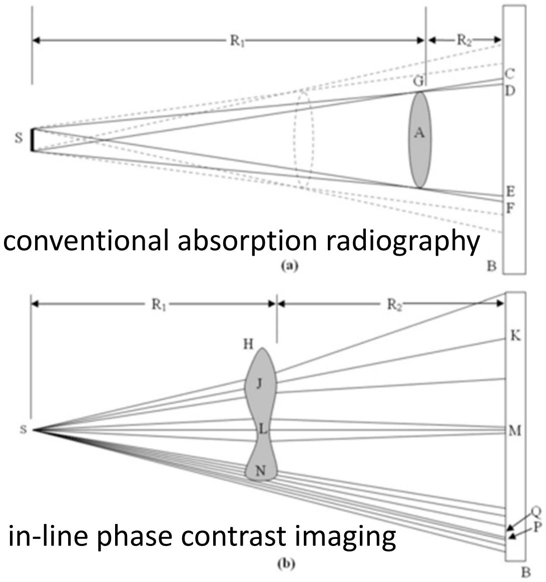
- Auger cascade from external X-rays causes dose enhancement
  - must be close to cancer cells
- nanoparticle cancer targeting
  - nanoparticles naturally accumulate at tumor - enhanced permeability and retention (EPR) effect
  - cancer-seeking molecules can be attached to nanoparticles
  - AuNPs most widely studied
- diagnostics + therapy-> 'theranostics'



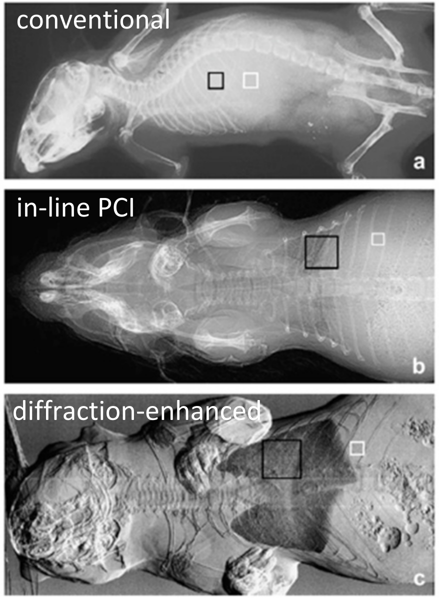
Rosa et al. Cancer Nano, **8**:2 (2017)

Phase contrast imaging

- phase change information to enhance contrast
- in-line PCI
  - simplest geometry
  - requires small source size
- diffraction-enhanced
  - crystal to detect small angle change
  - requires monochromatic beam
- interferometry, diffraction grating
- demonstrated by Lyncean, AIST, etc.



Gureyev et al., J. Appl. Phys. **105** 102005 (2009)



Kitchen et al., Br. J. Radiol., **78** 1018 (2005)

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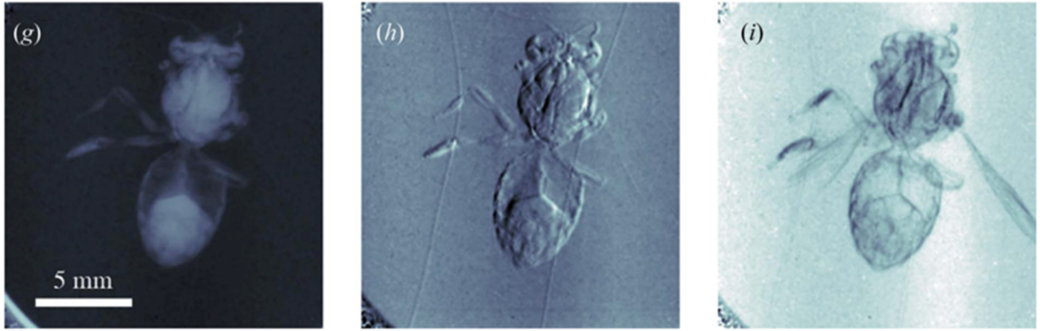
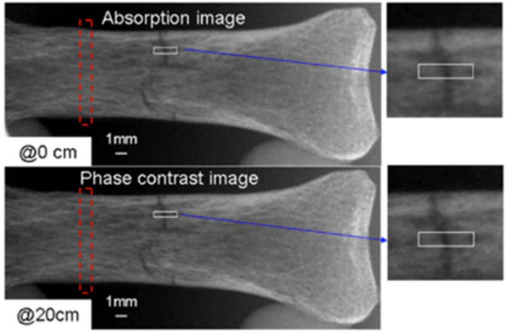
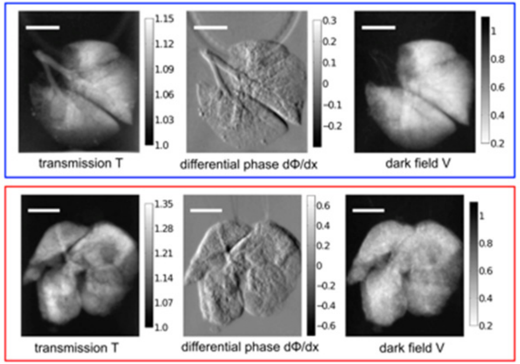


Bech et al., J. Synchrotron Rad. **16**, 43 (2009)



Kuroda et al., NIMA **637**, S183 (2011)



Schleede et al., PNAS **109**, 17885 (2012)

Summary

- Laser-Compton light sources can produce tunable, narrow bandwidth, small source size X-ray beam for medical use in a much smaller footprint than those of synchrotron facilities
- A compact X-band linac has been built at LLNL and is producing 30 keV X-rays, upgradable to >250 keV
- e^- beam and X-ray characterization is nearly complete and matches the modeling very well
- K-edge subtraction imaging and Auger therapy experiments are being planned