X-ray CT and Applications at the Lawrence Livermore National Laboratory (LLNL)

2017 X-ray 2D and CT Symposium, Baltimore, MD

March 28-31, 2017

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Lawrence Livermore National Laboratory

Nondestructive Characterization Institute

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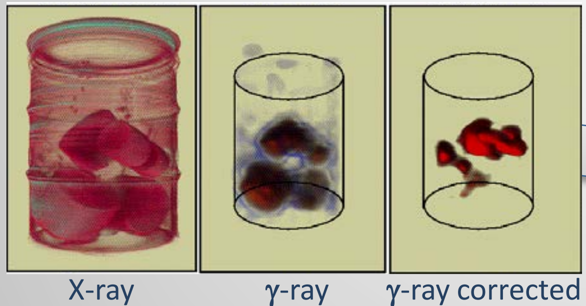
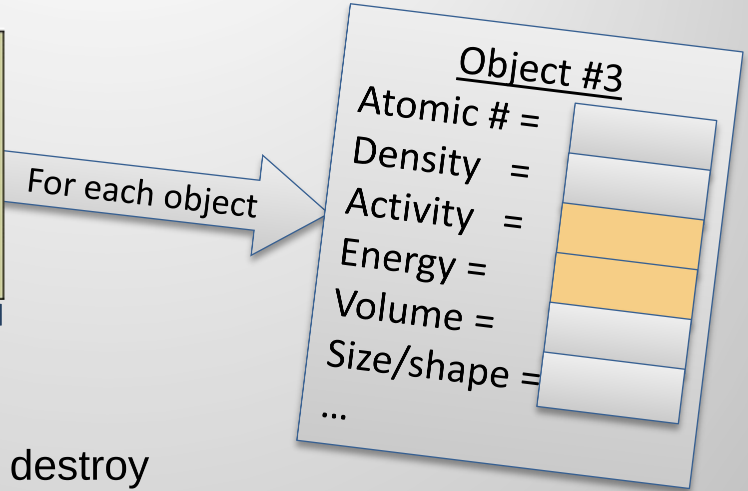
Outline

- Overview of Nondestructive Characterization at LLNL
- X-ray Radiography, CT, Diffraction and Applications
  - eV-to-MeV X-ray energies; nm-to-cm spatial resolution
  - H-to-Pu Z-range; mg/cm^3-to-20 g/cm^3 in density (ρ)
  - Hair-strand to Cargo-container object sizes
- Software & Supporting Technologies
  - Algorithms for CT acquisition, processing, reconstruction, analysis
  - Simulation & Modeling
- Other Modalities (Ultrasound, Radar, Particles, etc.)
- Future directions

Nondestructive Characterization (NDC) is complex and multidisciplinary

Radioactive waste drum assay*



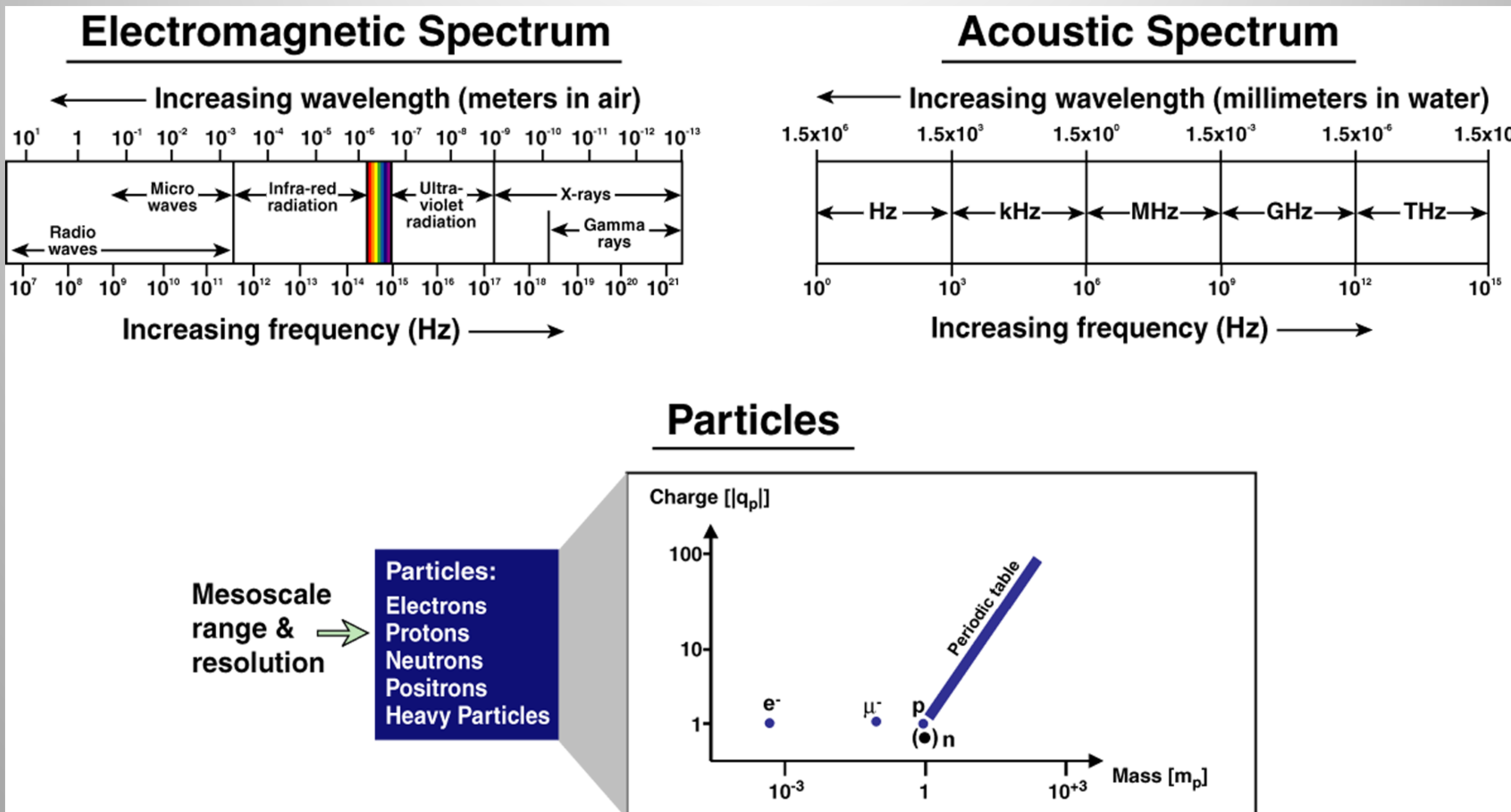


- "Nondestructive"
  - Cannot, or prefer not to, open or destroy
- "Characterization"
  - Not just images (e.g., spatial extent) … need a full understanding of physical/chemical makeup to find subtle differences (e.g., threats vs. non-threats)
- NDC involves the use of sophisticated sources, detectors, data acquisition, simulation/modeling, algorithms, and computing

* R&D100 Award winning method developed by LLNL in 2000

NDC at LLNL has been an important discipline at LLNL since its inception in 1952.

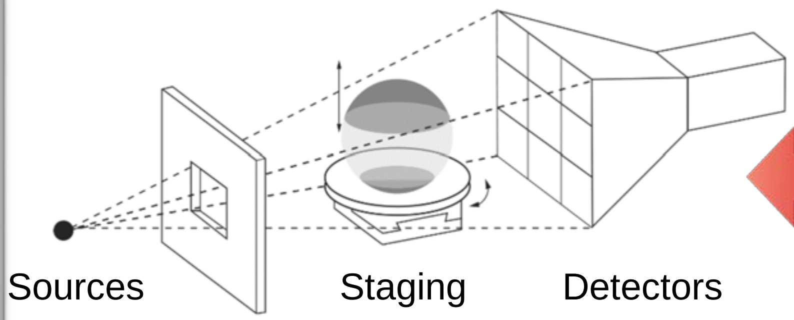
Waves (EM & Acoustic) and Particles help to “see” inside at multiple length-scales



NDC uses all practical physical inspection methods; X- and gamma-rays are most common.

Multiple technologies and disciplines are employed in NDC

Measurement Systems

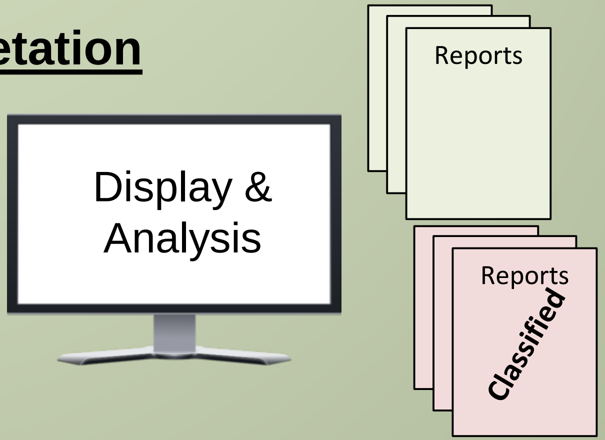


Data Management & Processing

- Experimental Planning
- Instrument Control
- Data Acquisition
- Preprocessing
- Image Reconstruction
- Analysis Post-processing

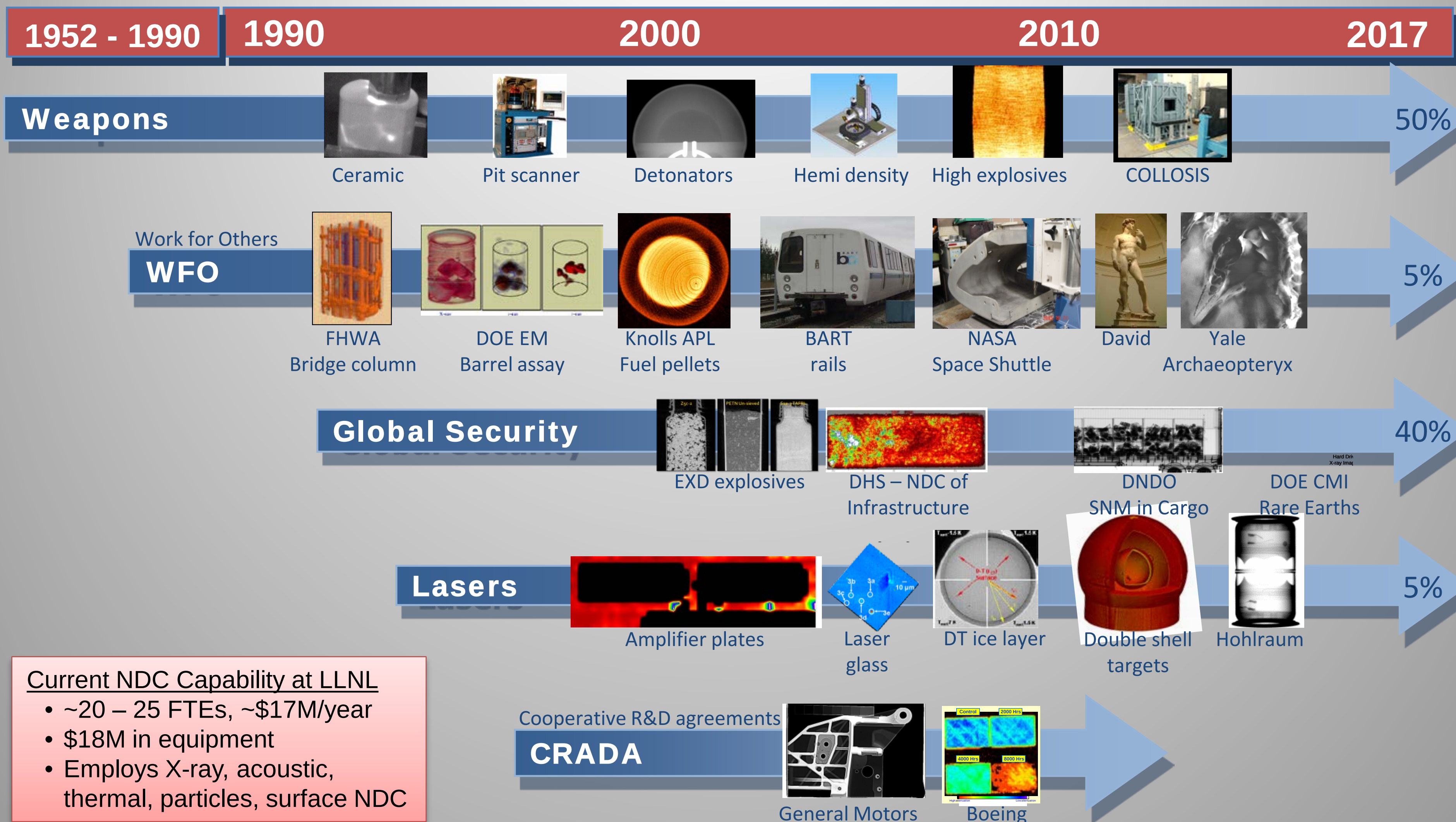
Modeling & Simulation

Interpretation



We solve customers' problems using all aspects of NDC.

Born to support nuclear deterrence, our NDC capability helps a broad spectrum of customers



<u>Current NDC Capability at LLNL</u>

- ~20 – 25 FTEs, ~$17M/year
- $18M in equipment
- Employs X-ray, acoustic, thermal, particles, surface NDC

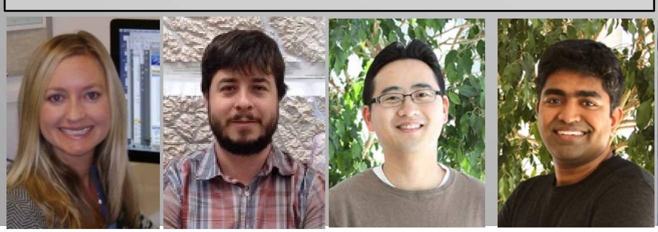
In 2015, LLNL officially formed the NCI

Nondestructive Characterization Institute

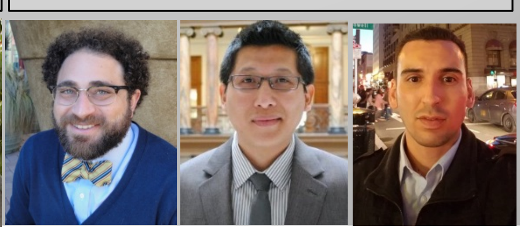
- Recognized for an international level of R&D excellence in NDC
- Institutional to LLNL with outreach to academia, government labs, industry
- Promotes NDC advances and competency
  - R&D collaborations with academia, labs, industry
  - Support programs at LLNL, the US and internationally
  - Host and attend conferences, workshops, visits, tours
  - Develop a pipeline to attract and retain world-class talent

Visiting Professor

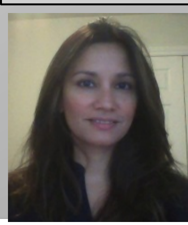
Former Post-Docs (now FTEs)



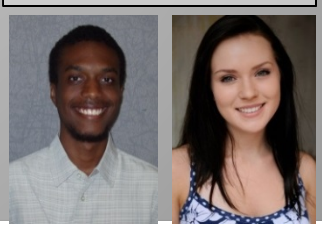
Post-Docs



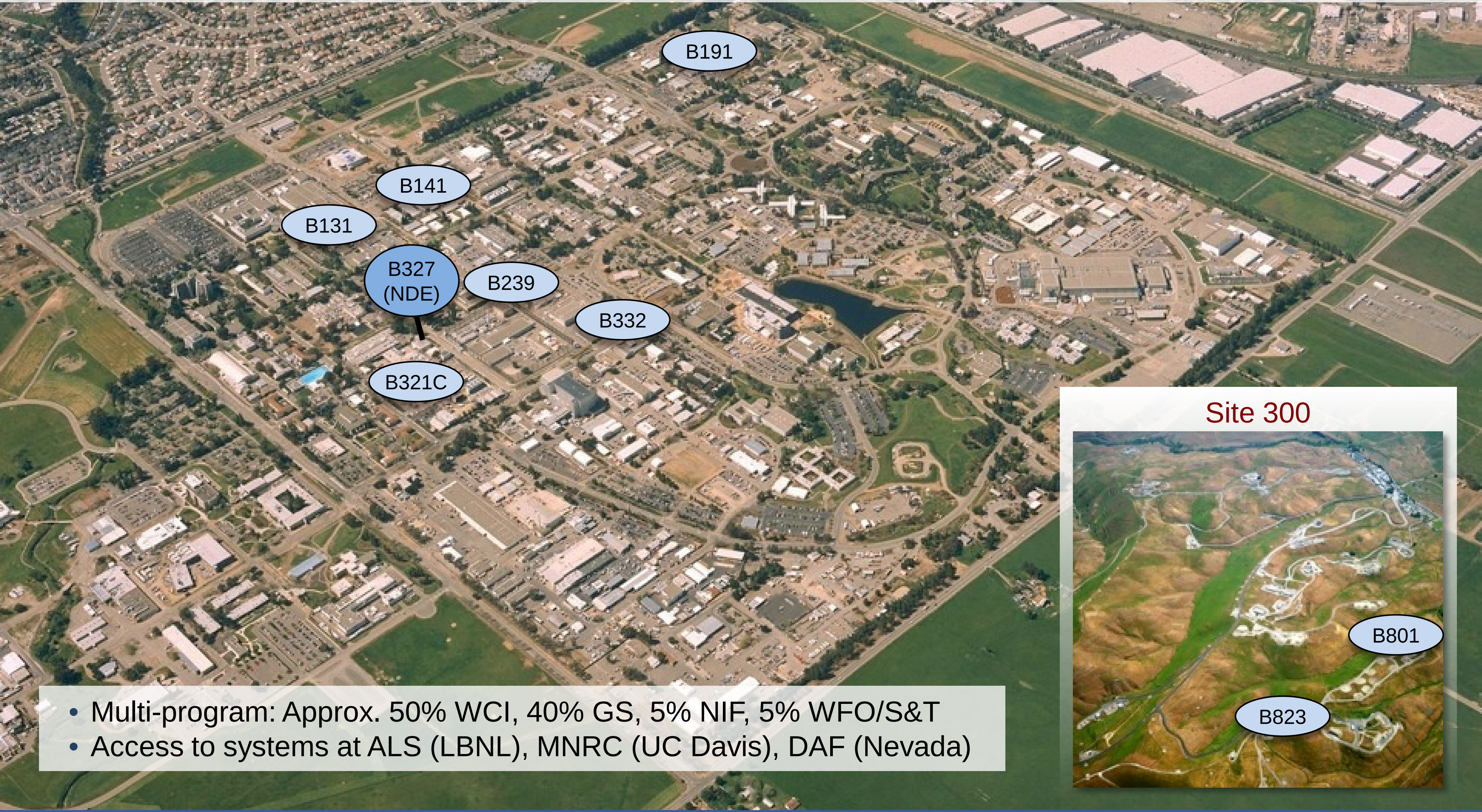
Ph.D. candidate



Summer interns



LLNL's NDC capabilities are distributed



- Multi-program: Approx. 50% WCI, 40% GS, 5% NIF, 5% WFO/S&T
- Access to systems at ALS (LBNL), MNRC (UC Davis), DAF (Nevada)

We have delivered systems worldwide: TRMG (FL), TSL (NJ), Pantex (TX), ALS, Israel, U. Bologna

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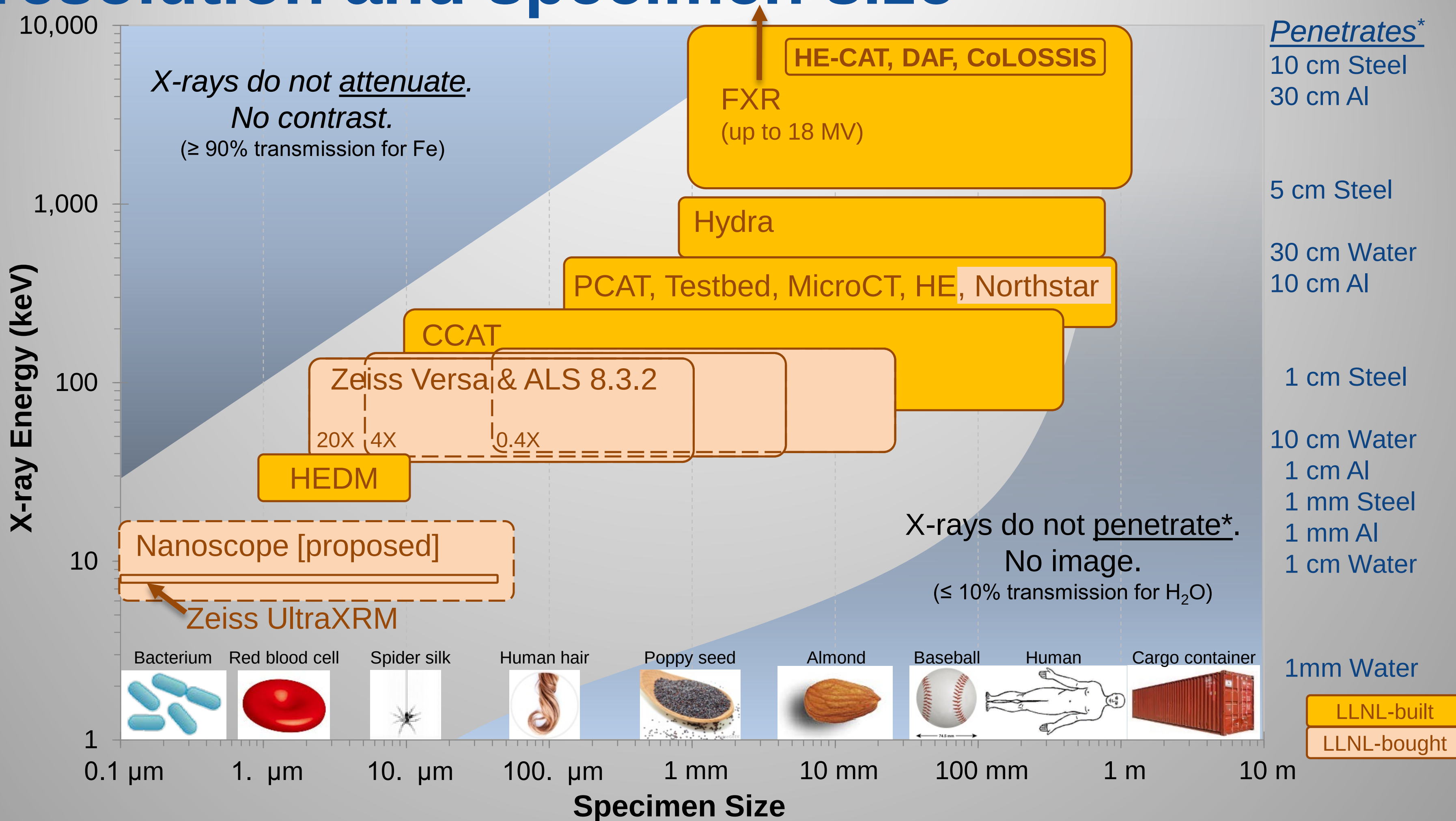
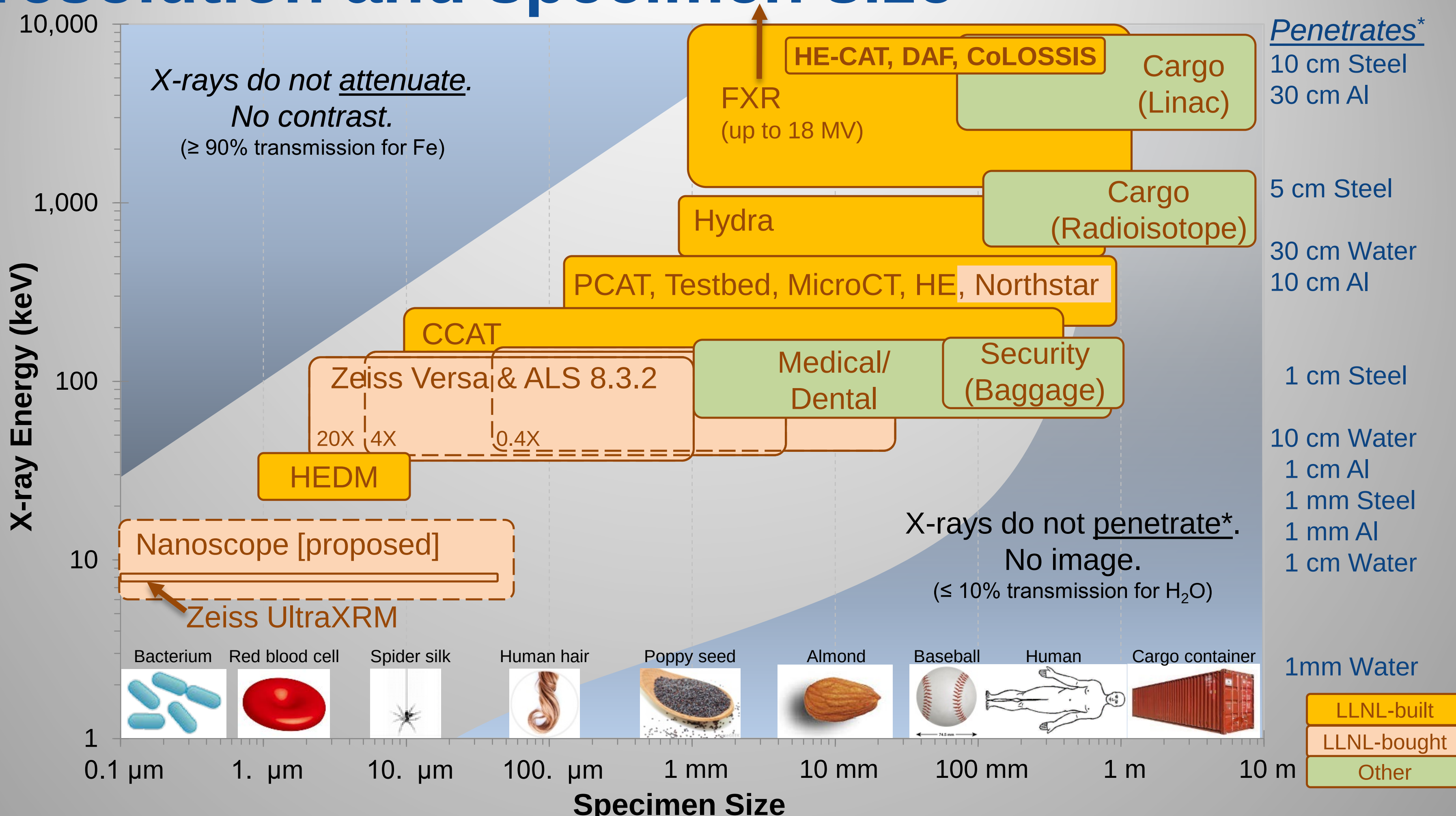
LLNL X-ray Imaging and CT systems span resolution and specimen size



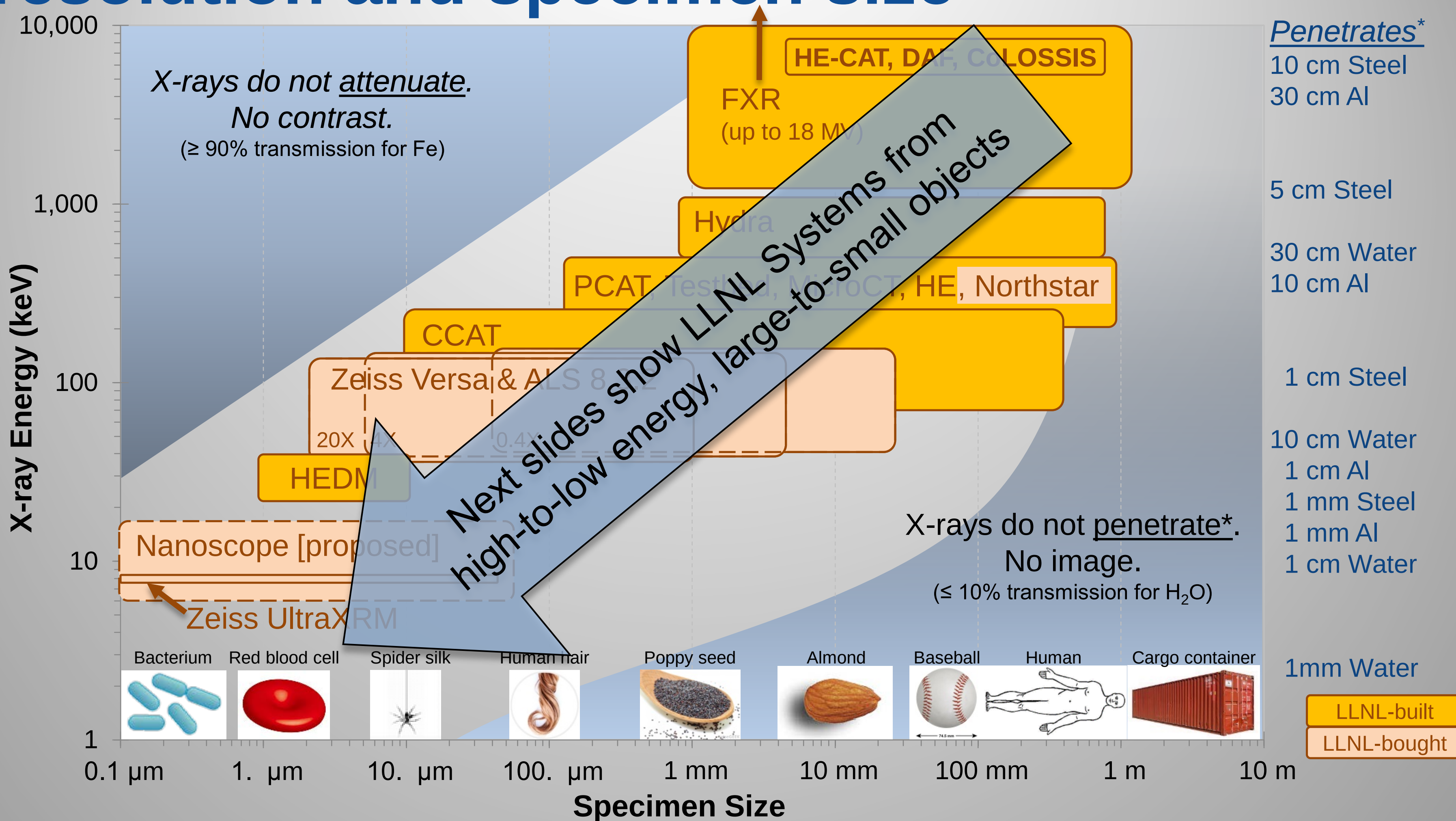
* Penetration is defined as μL~2-3 for attenuation coefficient μ and material path length L.

LLNL X-ray Imaging and CT systems span resolution and specimen size



LLNL systems are designed for accurate characterization of objects, not for speed/production.

LLNL X-ray Imaging and CT systems span resolution and specimen size



* Penetration is defined as μL~2-3 for attenuation coefficient μ and material path length L.

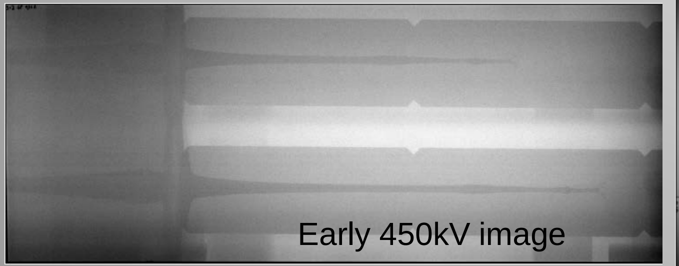
Flash X-ray (FXR) radiographs dense hydrodynamic events

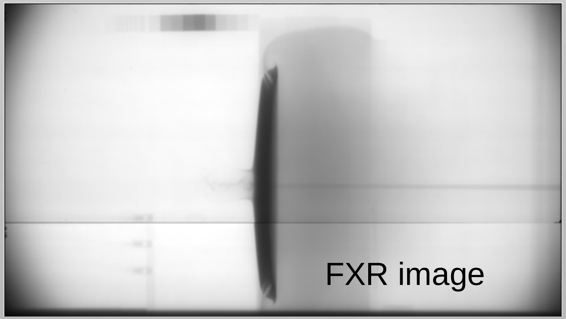
Description
- High-speed Radiography of explosions in the Contained Firing Facility (CFF); no CT capability
- One 18-MV linac source, and up to 12 co-timed 450-kV flashes
- CFF rated to 60 kg of high-explosives (HE)

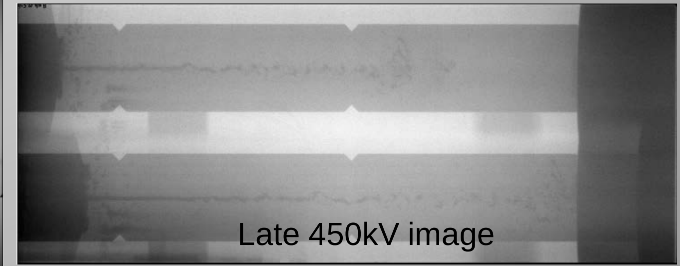
System
- FXR Source – 18-MV linear induction accelerator with tantalum target; 60-ns pulse, 1.6-mm spot size
- Co-timed Sources – 450-kV tubes; 20-ns pulses; ~1-mm spot
- Imagers – Film or image plates (collimated to sources)
- FOV – ~1-m at 10 m with ~500 μm spatial resolution

Location

LLNL Site-300 (East-bay hills) Bunker 801 since the 1980's


Early 450kV image


FXR image


Late 450kV image

Early, middle and late views of an explosively-formed jet, taken through over an inch of attenuating blast protection.

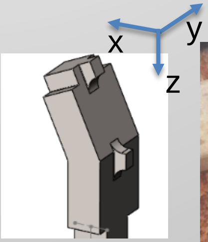
HE-CAT is a high-energy CT system for large, dense objects

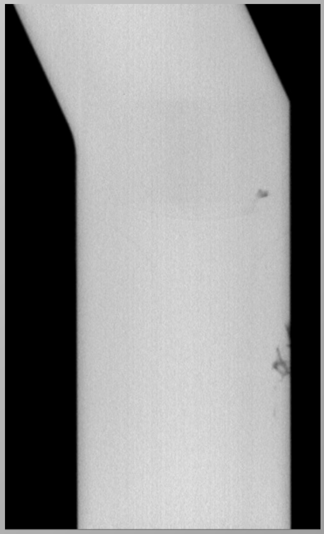
Description
- Flexible high-energy Radiography or CT for many applications, esp. nuclear weapons components
- Able to scan classified parts

System
- Source – Linac 6/9 MV (selectable), ~1-mm spot
- Imager – PE amorphous-Si panel; 200-μm pixel size
- FOV – 40-cm at 6.6-m Src-Det distance

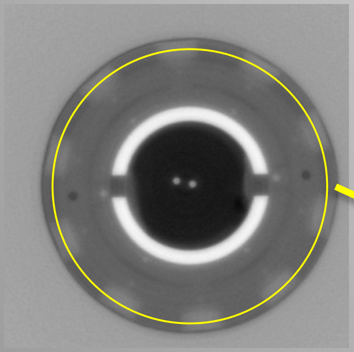
Location

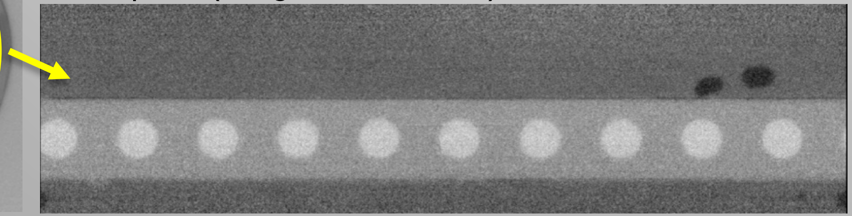
LLNL site, in a buried hi-bay of B239
[an identical system at Site-300 for explosives]





CT of conventional munition aft radial plate (imaged at Site-300)





XY-slice

Annulus Z-slice of boosters

Titanium bow frame

X-Z CT slice

Device Assembly Facility (DAF) has CT capability for nuclear/non-nuclear parts

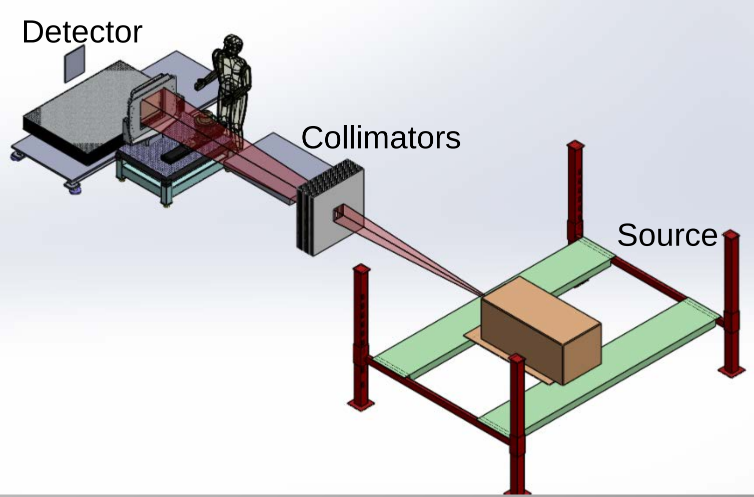
Description
- LLNL-designed imager for product design and evaluation
- LLNL performs radiography & CT imaging/reconstruction
- LANL performs radiography up to 30 lb (14 kg) of HE

System
- Source – Linac 9 MV, ~2-mm spot (soon 15 MV, <1-mm)
- Imager – Film or PE* amorphous-Si panel; 100-μm pixel size
- FOV – 40-cm at 6-m source-detector distance (sdd)

Location

DAF, Nevada Nat'l Security Site

Radiograph of cylindrical test object



* Perkin Elmer

Confined Large Optical Scintillator Screen and Imaging System (CoLOSSIS)

Description
- LLNL-built large-format CT for nuclear weapon components

System
- Source – Linac 6/9 MV, ~1.5-mm spot
- Imager – Scintillator coupled to pyramid-shaped central mirror to four gimbal mirrors to four high-resolution CCD cameras
- FOV – ~23-cm; 30 μm pixels; v.2 will have 30-cm FOV with LLNL GLO scintillators; 6-m source-detector distance (sdd)

Location

Pantex Plant, Amarillo, TX


Example of four stitched radiographs

6 m

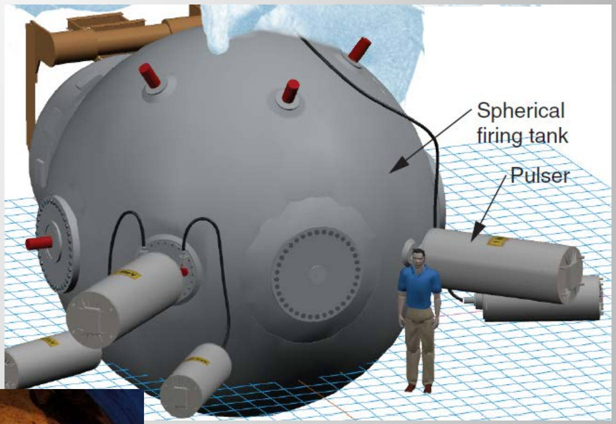
Hydra Flash X-ray system can image high-speed explosions

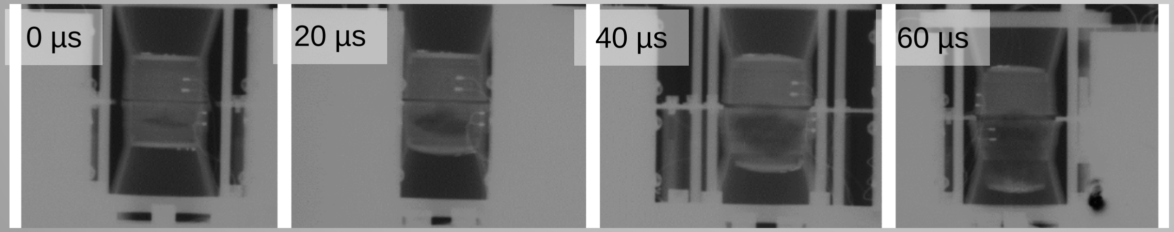
Description
- Multi-channel X-ray imaging of dynamic events with up to four independently-timed 10-ns x-ray flashes
- Can image up to 10-kg of high-explosives (HE) detonating in a 4.9-m-diam tank from different angles

System
- Source – Two 1-MV and two 450-kV pulsers
- Imager – Film (16-in square); <1-mm spatial res
- FOV – ~30-cm at 6-m source-detector distance

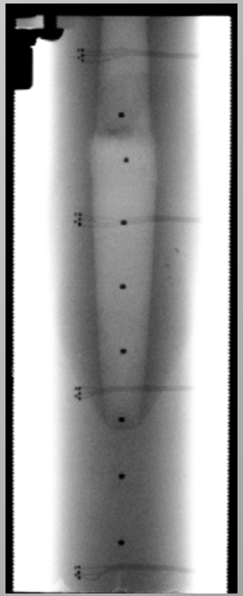
Location

LLNL High-Explosives Application Facility (HEAF)





Time sequence of thermal explosion



Deflagration to detonation transition

PCAT is one of the first CCD-based CT systems

Description

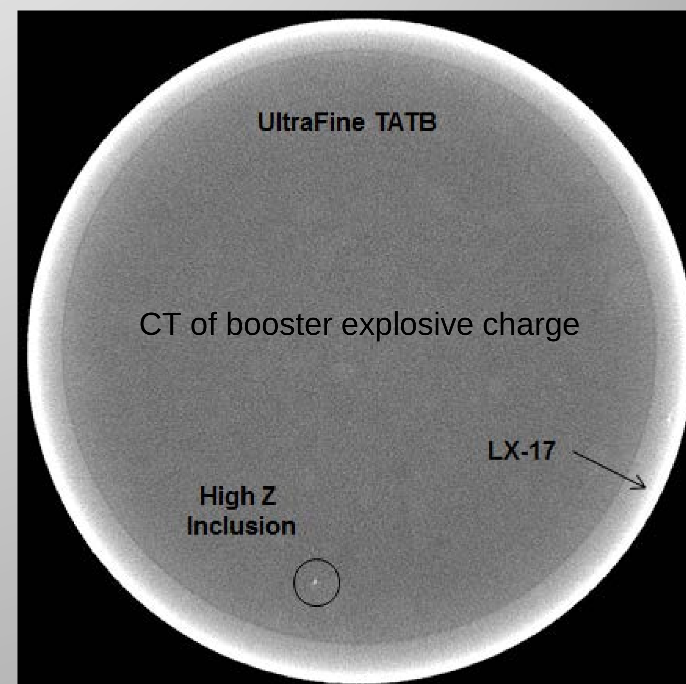
- Flexible lab-based Radiography or CT
- Many applications, esp. nuclear weapons components
- Rated to 125 g of HE; Able to scan classified parts

System

- Source – 450-kV tube (Yxlon); 0.4- or 1-mm spot size
- Imager – Scintillator to Cooled-CCD via a turning mirror; 50 to 200-μm pixel size
- FOV – <50-cm; up to 5-m source-detector distance

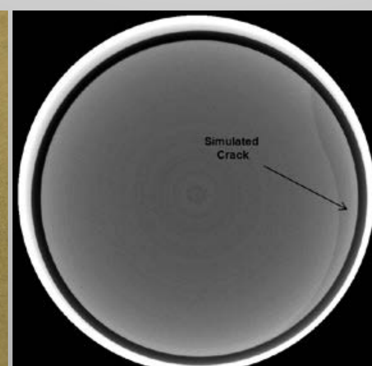
Location

LLNL site, basement of B327



CT of booster explosive charge

Teflon and Rulon mock explosive with manufactured crack



"Micro"CT Test-bed is a reconfigurable and flexible flat-panel system

Description

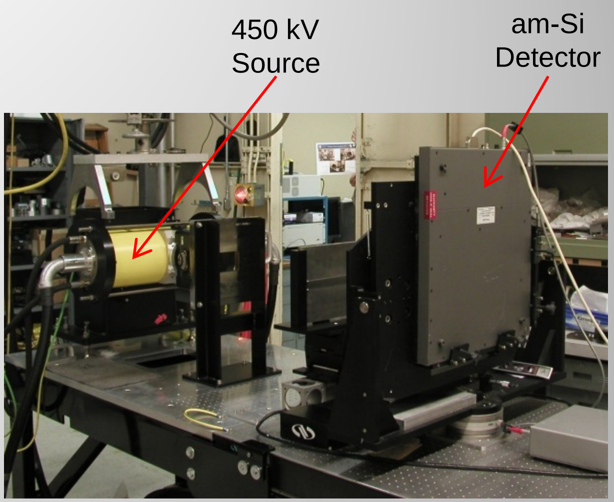
- Flexible up-to-450-kV Radiography or CT for many applications, esp. nuclear weapons components
- Used to test hardware and software configurations
- Rated to 125 g of HE; Able to scan classified parts

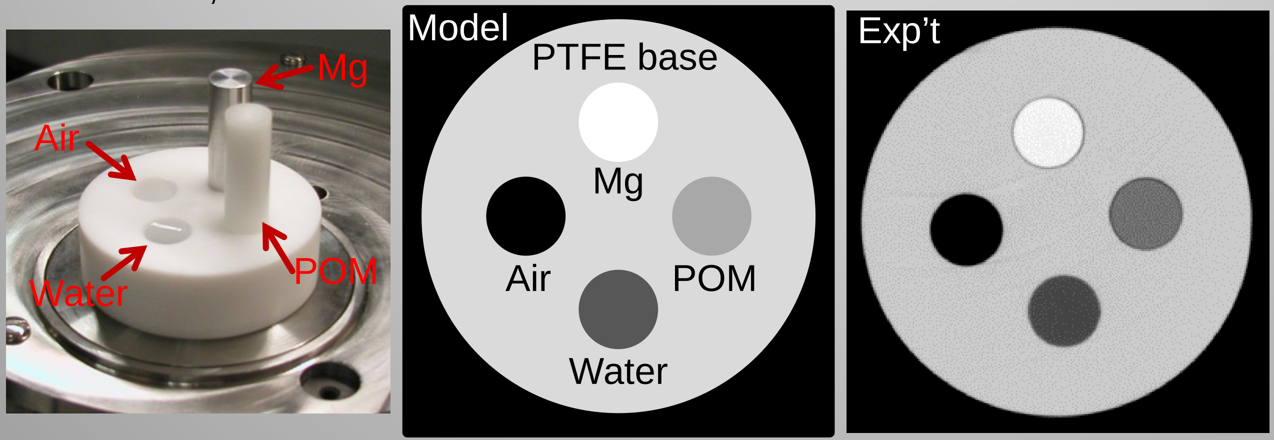
System

- Source – 450-kV tube (Yxlon); 0.4 or 1-mm spot size
- Imager – PE amorphous-Si (am-Si) panel; 200-μm pixel size
- FOV – 40x40 cm^2; <3-m source-detector distance

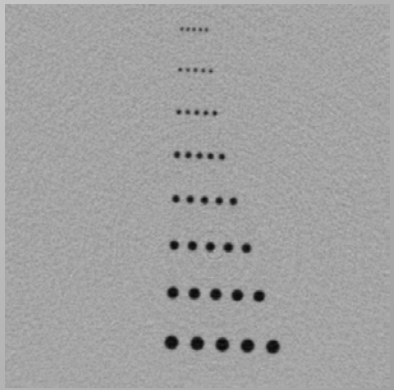
Location

LLNL site, basement of B327





Calibrated test object



Medical Phantom

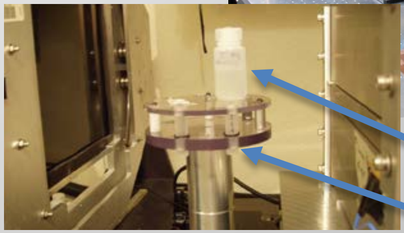
"Micro"CT HEAF systems characterize homemade explosives (HMEs) for DHS

Description

- Accurate and QA-controlled production CT for explosives characterization (small quantities) over many years
- Four similar systems at LLNL, TSL*, TRMG †, and Israel
- Each different HME is cross-measured, used for Cert

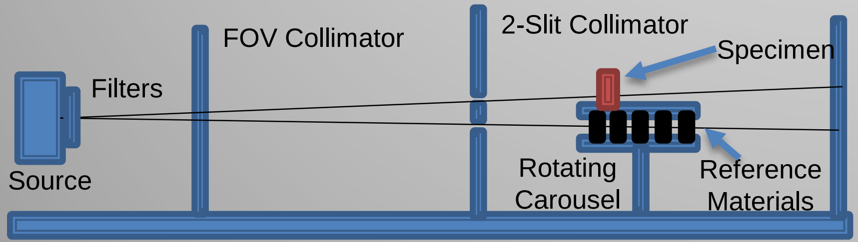
System

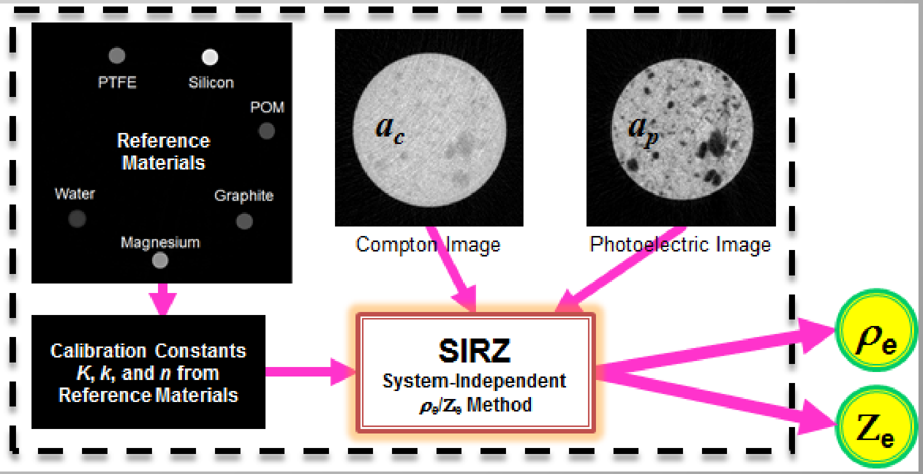
- Source – 450-kV tube (Yxlon); 0.5- to 2-mm spot size
- Imager – PE amorphous-Si panel; 200-µm pixel size
- FOV – 40-cm at ~1-m source-detector distance
- 11x mag without geometric unsharpness



Location

Production systems in LLNL (HEAF building), New Jersey, Florida and Israel





* Transportation Security Laboratory, New Jersey
† Tyndall Reactive Materials Group, Tyndall AFB, Florida

A Leidos CT80-DR checked-bag scanner is installed in HEAF for TSA

Description
- Production Expl. Det. System (EDS), same as in airports, used to characterize home-made explosives (HMEs)
- Dual-energy CT capability; LLNL access to raw data
- Remote HME mixing and handling allows for safe testing
- Room rated to 1 kg of HE

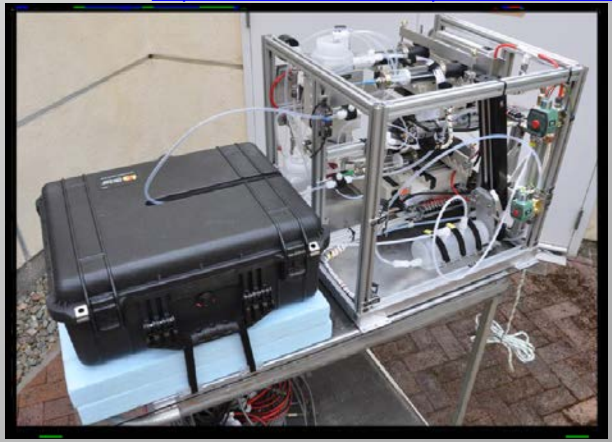
System
- Source – 160-kV tube;
- Imager – Dual-row; ~1 mm in plane pixel size
- FOV – ~160-cm bore

Location

LLNL High-Explosives Application Facility (HEAF)

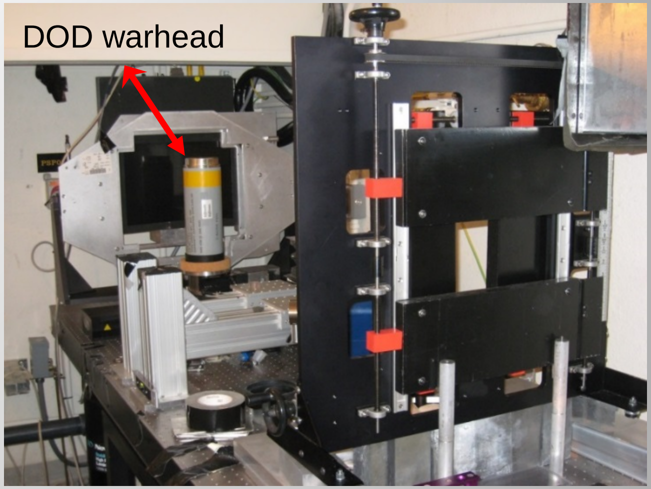
This EDS is the same as in airports and serviced by Leidos through TSA contract
https://www.leidos.com/products/security/reveal-ct-80dr

LEXI robot can deliver explosive material from LabRam to shot stand



Remote HME Delivery and Purification

HEAF-CAT is for production imaging of weapons and explosives



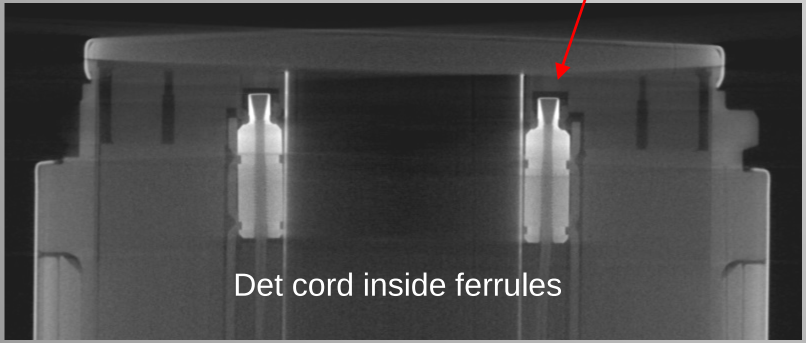
Description
- Modified MicroCT for weapons, munitions and explosives in HEAF
- Rated to 10 kg of HE; Able to scan classified parts

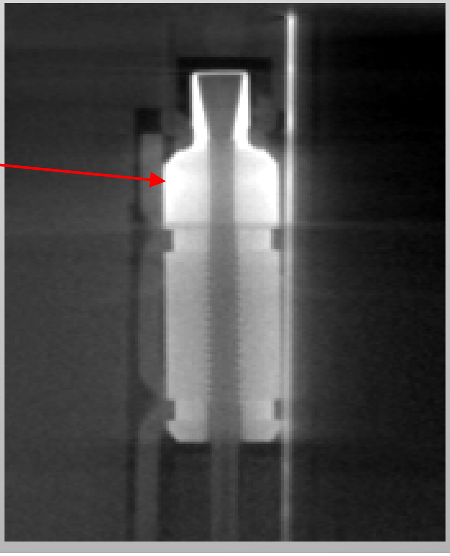
System
- Source – 450-kV tube (Yxlon); 0.5- to 2-mm spot size
- Imager – PE amorphous-Si panel; 200-μm pixel size
- FOV – 40-cm at ~1-m Src-Det distance

Location

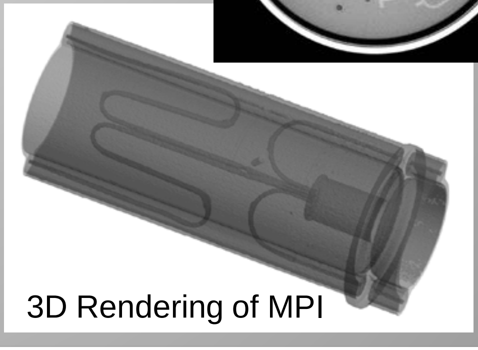
LLNL High-Explosives Application Facility (HEAF)

Ferrule





CT slice of Multi-Point Initiator (MPI) Radial Plate



Northstar

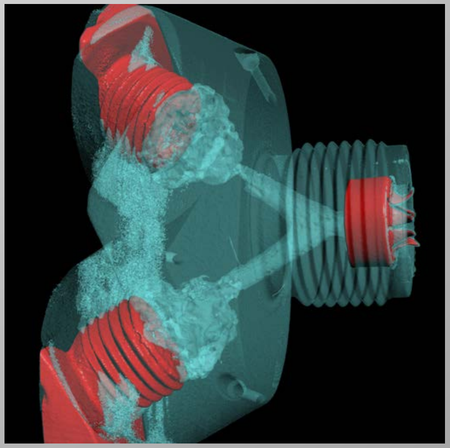
Recently-purchased North Star Imaging system images explosives

Description
- NSI X25 is a flexible commercial system for many Radiography or CT applications (e.g., explosives)
- Reduces the workload on other HEAF systems
- Room rated to 10 kg of HE;

System
- Source – 160 kV tube; ~0.5-μm spot
- Imager – Flat-panel or linear detector array
- FOV – ~180-cm at <1-m source-detector distance

Location

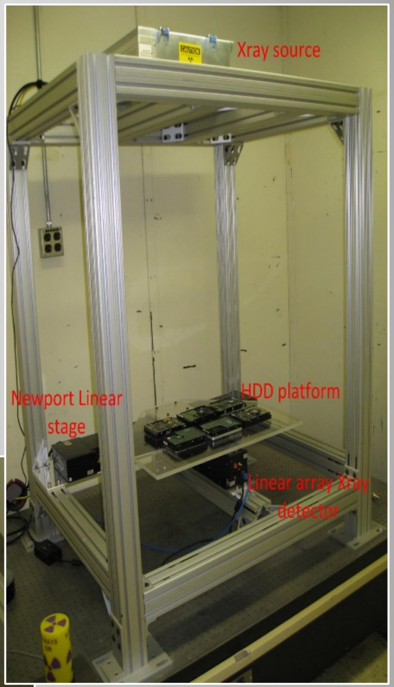
LLNL High-Explosives Application Facility (HEAF)

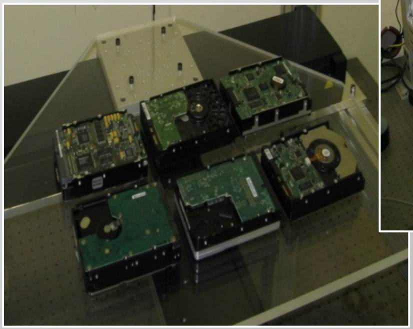


Courtesy NSI

CMI Testbed

An example of rapid response – X-ray Imaging for Rare-earth Recovery





Description

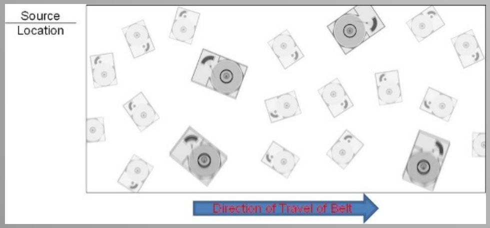
- We quickly modified an existing x-ray chamber for DOE’s Critical Materials Institute (CMI) to scan hard-disk drives (HDDs)
- Feasibility study for conveyer-belt scanner to find rare-earths
- Achieved throughput of 248 HDD/hour for an Oak Ridge extraction system

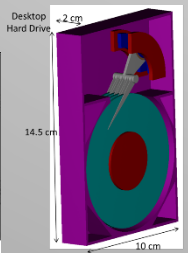
System

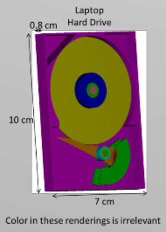
- Source – 80-160-kV tube source (200 W)
- Imager – Linear 3072-element array; 0.1-mm pixel size; frame rate of 1500 Hz
- FOV – 30-cm fan-beam; ~250-μm spatial resolution
- Linear stage moved at 5 mm/sec

Location

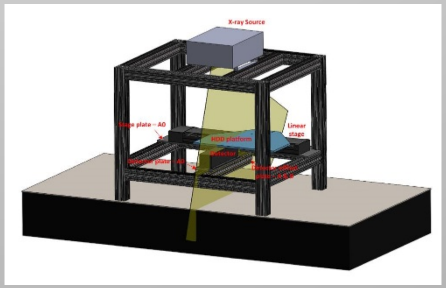
LLNL site, basement of B327

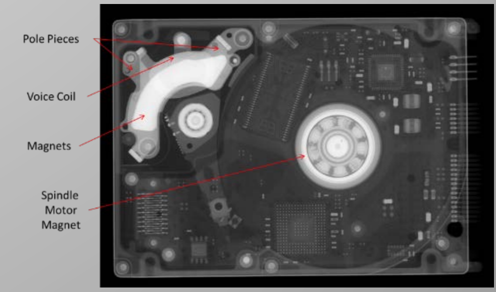






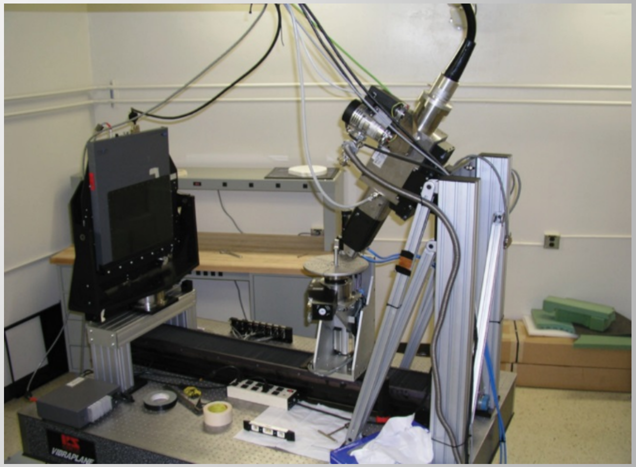
Modeling





Hard-disk drives contain rare-earth magnets for re-use and recycling.

CCAT* provides high magnification using a micro-focus source

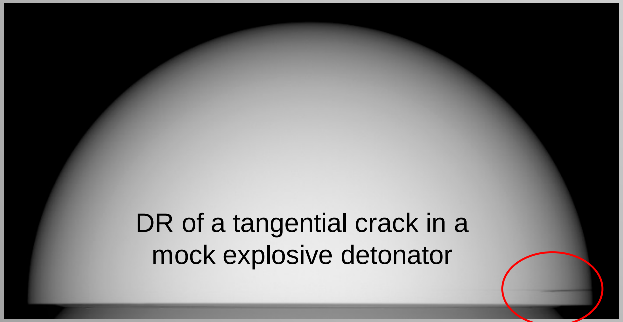


Description
- Flexible FeinFocus Radiography or CT with up to 20x mag
- Many applications, esp. nuclear weapons components
- Rated to 20 g of HE; Able to scan classified parts

System
- Source – 125- to 225-kV FeinFocus tube; 10-µm spot
- Imager – PE** amorphous-Si panel; 100-µm pixel size
- FOV – 2- to 40-cm; 20- to 400-µm spatial resolution
- ~1-m source-detector distance; 1.25x to 20x mag

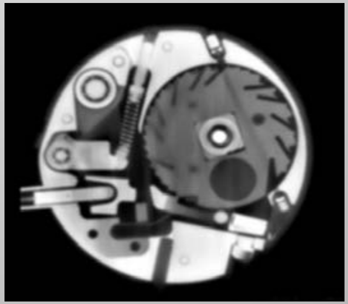
Location

LLNL site, sub-basement of B327

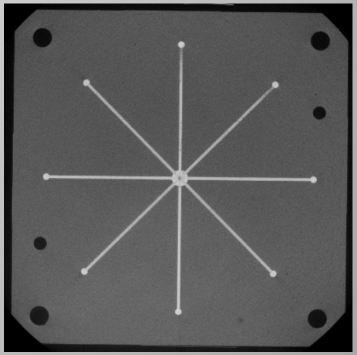


DR of a tangential crack in a mock explosive detonator

CT slice # 686



CT slice of a Mechanical Safe and Arm Device (MSAD)



“Starburst” HE lines in a rigid high density foam

* Clint’s Computed Axial Tomography
** Perkin Elmer

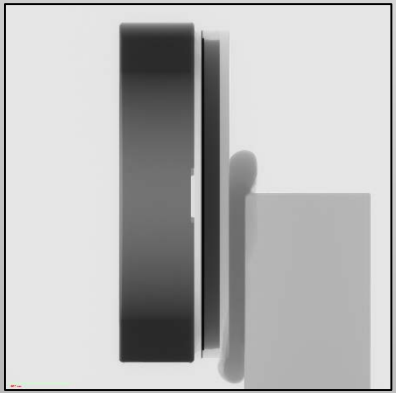
ZEISS Xradia 510 Versa provides micro-scale imaging in the lab

Description
- Micro-scale ZEISS Xradia 510 Versa for intermediate sizes
- Flexible Radiography or CT for many applications
- Room rated to 10 mg of HE; Able to scan classified parts

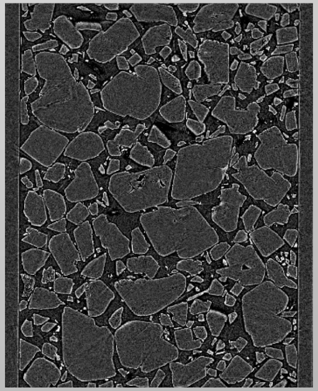
System
- Source – Nordson Dage microfocus (30 – 160 kV); 3-μm spot
- Imager – CCD optically-coupled scintillator with 0.4 to 20x magnification; 20- to .5-μm pixels
- FOV – 1- to 50-mm at ~1-m source-detector distance
- 0.9- to 20-μm spatial resolution

Location

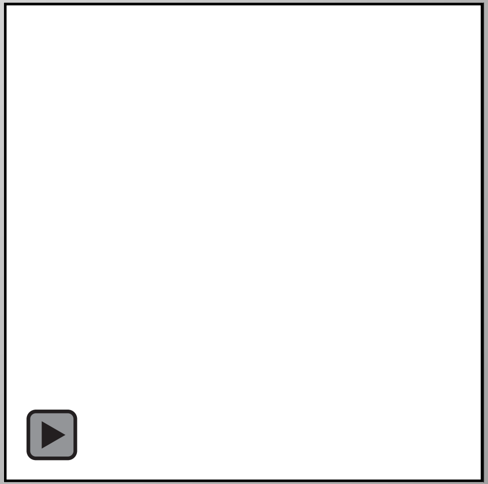
LLNL site, B321C



NIF* target drive assembly radiograph



CT of HE crystals



CT 3D-rendered Ti64 AM truss [MOVIE]

* National Ignition Facility, LLNL

LLNL has installed an x-ray imaging system at the Advanced Light Source (ALS)

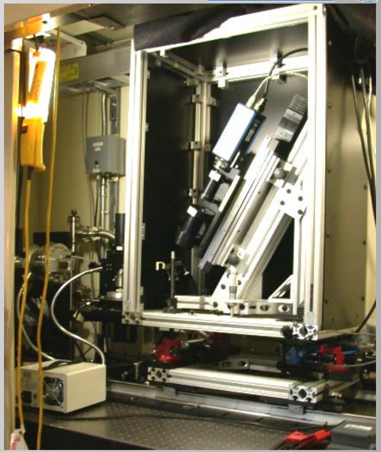
Description
- Built under an LLNL/ALS collaboration
- Now operated by ALS as open access beamline

System
- Source – ALS Synchrotron; 8.3.2; 8 – 46 keV
- Imager – Choice $CdWO_4$, LuAG, GGG, Yag:Ce scintillator to PCO.4000 CCD; 0.32- to 7.2-µm pixels; ~1.5 cm to 1.5 m sample-to-detector distance
- FOV – 1.8 - to 40 mm;

Location

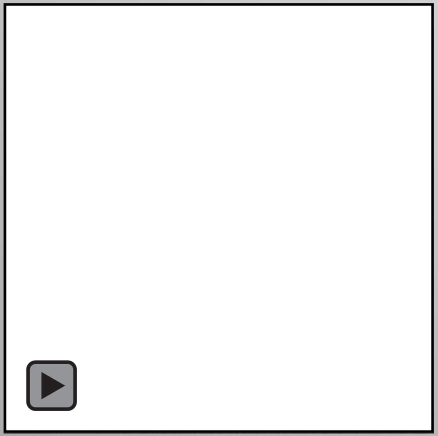
Advanced Light Source (ALS), LBNL, Berkeley, CA

Beamline 8.3.2 hutch

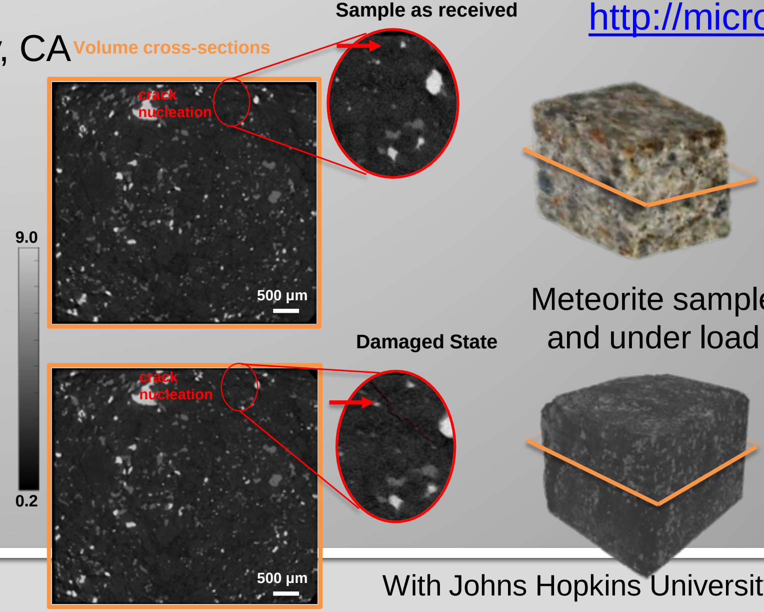


Micro-tomography camera

http://microct.lbl.gov



AM strut 0.5-mm o.d. [MOVIE]



Meteorite sample and under load

With Johns Hopkins University

ZEISS Xradia UltraXRM provides nano-scale imaging in the lab

Description

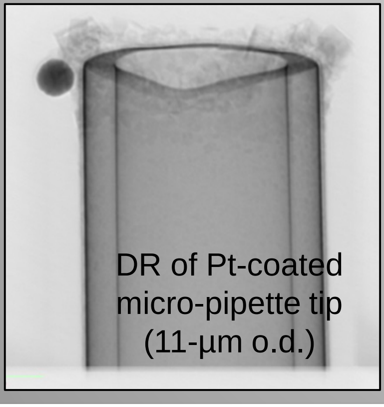
- Xradia UltraXRM-L200 nanoscale radiography system
- Flexible Radiography, CT and phase-contrast imaging
- Rated to 10 mg of HE; Able to scan classified parts

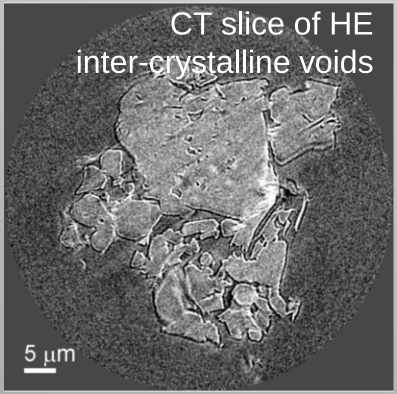
System

- Source – Rigaku MicroMax^{TM}-007 HF; 8.04 kV (quasi-monoenergetic); near-parallel beam
- Imager – Princeton Instruments Pixis CCD camera; 200x and 800x mag; 50- to 200-nm spatial res
- FOV – 16- to 65-μm

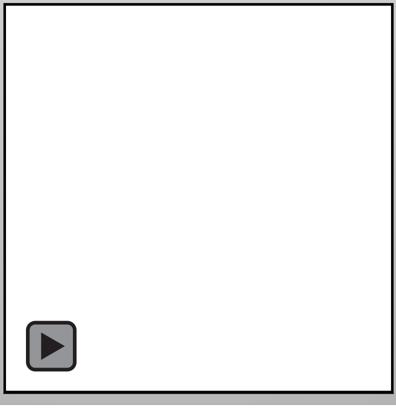
Location

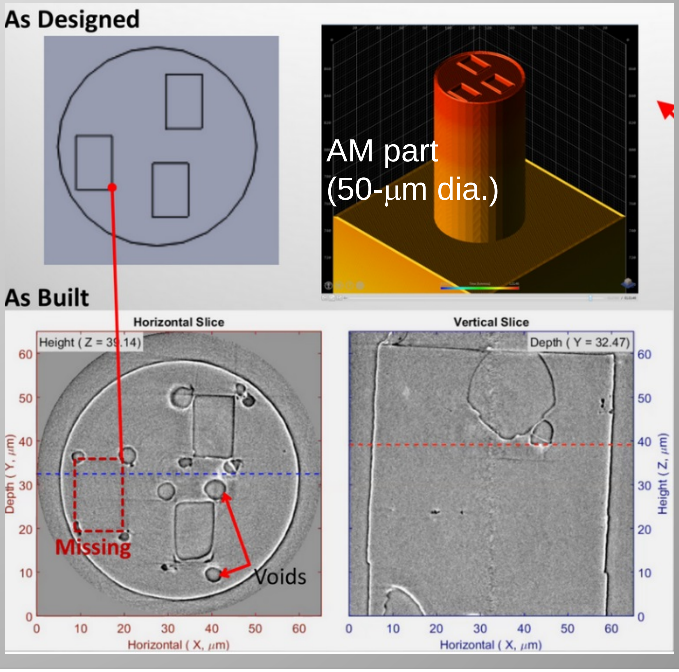
LLNL site, in a buried hi-bay of B327


DR of Pt-coated micro-pipette tip (11-µm o.d.)


CT slice of HE inter-crystalline voids

[MOVIE] 3D rendered polystyrene beads (720-nm dia.)





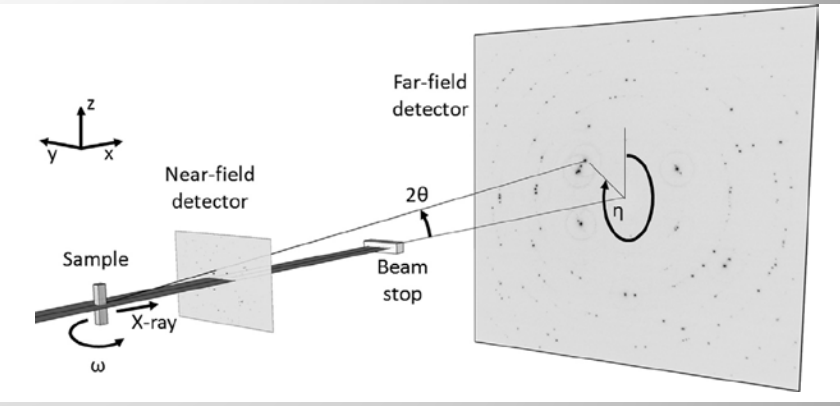
High-Energy Diffraction Microscopy (HEDM) for crystal surface studies

Description
- Transportable X-ray diffraction system for polycrystalline materials
- Two modes
  - Near-field for spatial res (5-15 mm SDD*) yields lattice orientation, grain boundaries, defect structure
  - Far-field for angular res (0.2-2 m sdd*) yields orientation, strain/stress, centroids

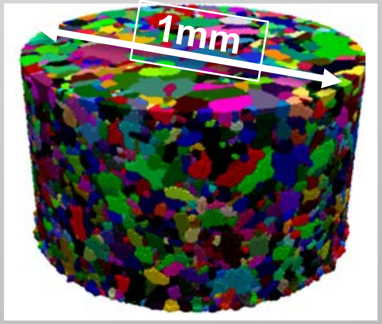
System
- Source – Synchrotron (52-91 kV); varying beam sizes of 1.5-mm by either 0.002- or 1.0-mm
- Imager – PE amorphous-Si panel; 200-μm pixel size; continuous integration over a rotation interval (typ. 0.25°)
- FOV – ~1-mm

Location

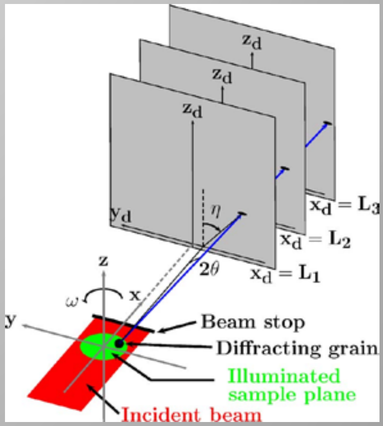
ALS Berkeley or APS Argonne
[lab source under development]



Near- and Far-field – Simultaneous measurement showing typical image data for a polycrystalline sample



Reconstructed 1-mm^3 nickel sample with several thousand grains, where color indicates lattice orientation



Near-field – Schematic w/ three detector locations

* Source-to-detector distance

Nanoscope proposed to be installed for chip assurance

Description

- Purchased by DARPA-TRUST program at LLNL
- Needs light-source in 8- to 12-keV range
- May be able to scan classified parts

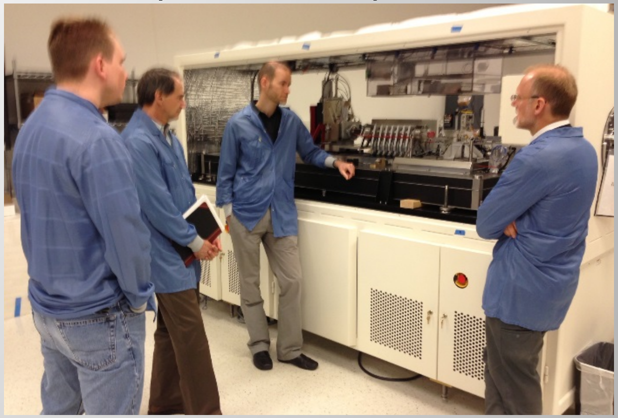
System

- Source – ALS or Lyncean compact light source;
  8- to 35-keV (chip assurance at 9 keV)
- Imager – Retiga 2k x 2k CCD camera; 7.4 μm pixels
- FOV – 40 μm; 20-nm pixels

Location

LLNL site; In storage until source is identified

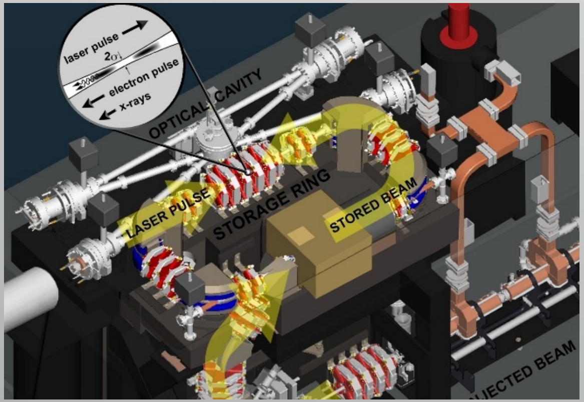
Nanoscope before shipment to LLNL



Advanced Light Source (ALS), Berkeley, CA

Chip imaging

120-nm metal features imaged at SLAC
(courtesy Michael Bajura)



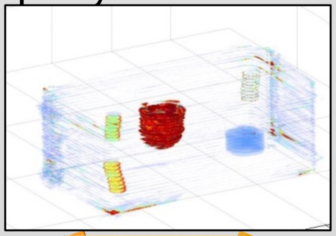
Lyncean Compact Light Source (CLS)
(courtesy Michael Feser)

Work-for-others on Aviation Security supports DHS S&T* Explosives Division

EDS† Technical Support (EDS-TS)

HME Intel, Formulate & Prep., X-ray signatures

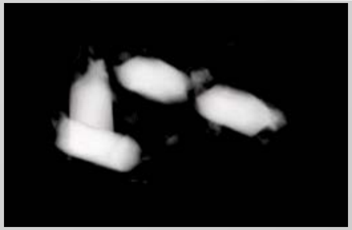
Algorithm R&D and 3rd-party collaboration‡



Explosives detection algs, ADSA workshops

Advanced X-ray Material Detection (BAA 13-05)

ScanTech Sentinal III



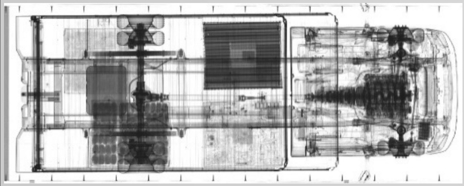
Carry-on scanner FAR reduced by 4.7x

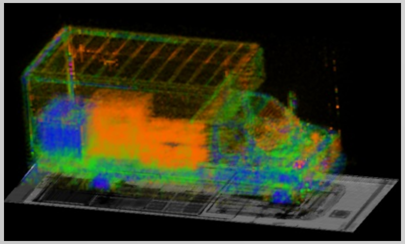
* Department of Homeland Security, Science and Technology Directorate
† Explosive Detection Systems for checked baggage
‡ DHS S&T University Programs funds a series of Advanced Development for Security Applications (ADSA) Workshops for third-party involvement in explosives detection (university, industry, government labs).

For DHS/DNDO*, LLNL leads Technical Support for Vehicle and Cargo Security Characterization

Nuc/Rad Imaging Platform (NRIP) †	Passive & X-ray Imaging Screening (PAXIS) †	Vehicle-borne IED (VBIED) Detection	Wearable Intelligent Nucl. Det. (WIND)

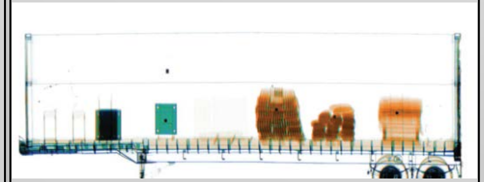
Nuc/Rad Imaging Platform (NRIP) †





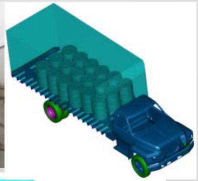
Multi-mode detection

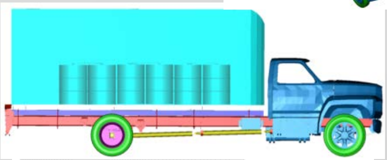
Passive & X-ray Imaging Screening (PAXIS) †

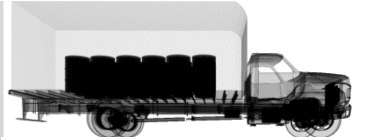


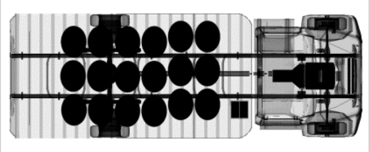
Mobile X-ray scanner for cargo containers

Vehicle-borne IED (VBIED) Detection



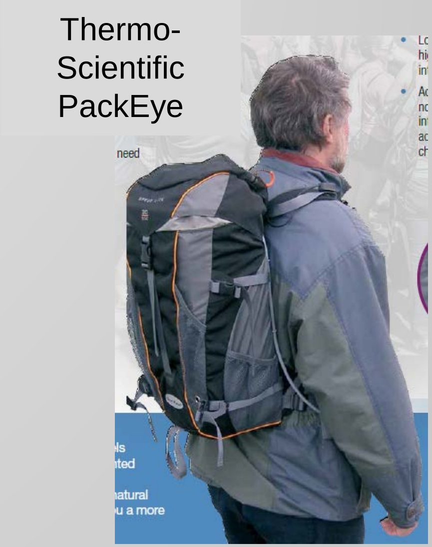






Test & analysis for First Responders

Wearable Intelligent Nucl. Det. (WIND)

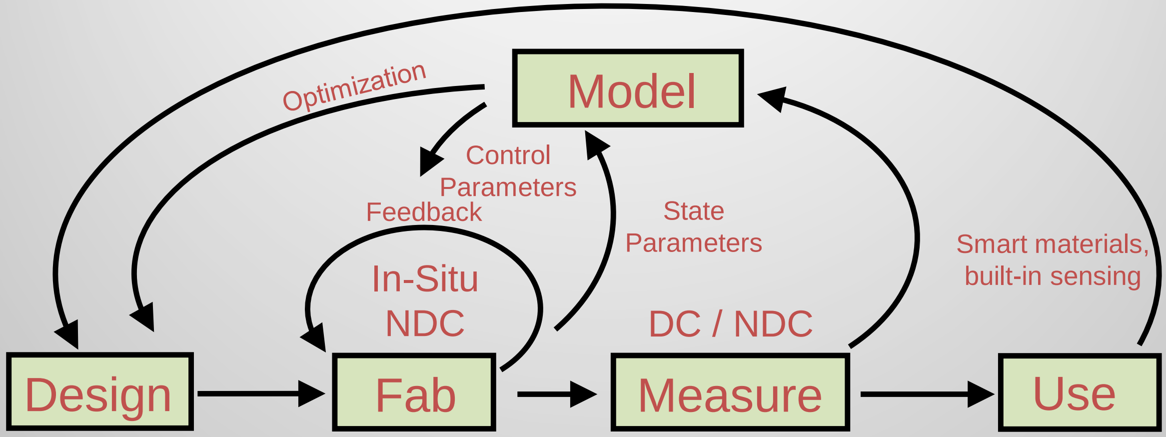


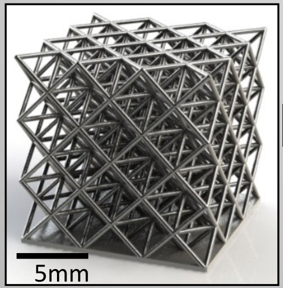
Backpack-able Nuclear Detection

* Department of Homeland Security / Domestic Nuclear Detection Office

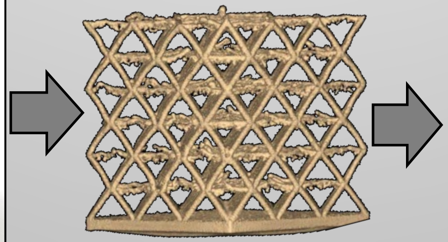
† Martz, H.E., Glenn, S.M., Smith, J.A., Divin, C.J., and Azevedo, S.G., “Poly- versus Mono-energetic Dual-spectrum Non-intrusive Inspection of Cargo Containers,” (accepted for publication 2017), *IEEE Transactions on Nuclear Science*.

For DOD and DOE, Quantitative NDC for Additive Manufacturing (AM) design feedback

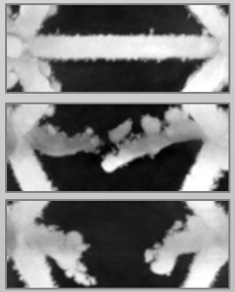




3D CAD rendering of an octet truss (3x3x3 unit cells)



Iso-surface from 3D X-ray CT (30-µm resolution)



X-ray CT slices of solid, broken, and missing struts

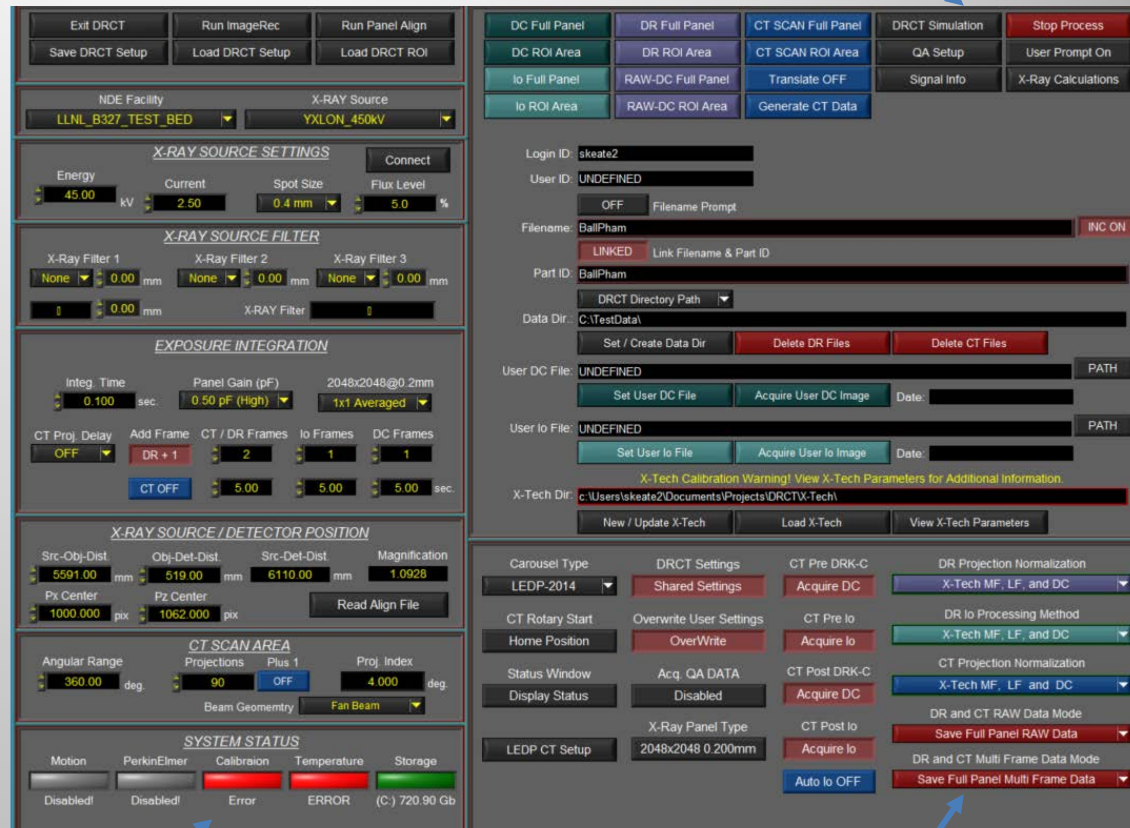
Outline

- Overview of Nondestructive Characterization at LLNL
- X-ray Radiography, CT, Diffraction and Applications
  - eV-to-MeV X-ray energies; nm-to-cm spatial resolution
  - H-to-Pu Z-range; mg/cm^3-to-20g/cm^3 in density (ρ)
  - Hair-strand to Cargo-container object sizes
- Software & Supporting Technologies
  - Algorithms for CT acquisition, processing, reconstruction, analysis
  - Simulation & Modeling
- Other Modalities (Ultrasound, Radar, Particles, etc.)
- Future directions

LLNL's DRCT code provides flexible data acquisition for x-ray radiography and CT

- Emphasizes scan repeatability, efficiency and image quality
- Flexible scan geometries, equipment and methods
- Wide range of equipment (sources, detectors, and motion control)
- Embedded QA features (e.g., logging source temperature, spectrum, intensity fluctuations...)

Setup Parameters (DR or CT, etc.)

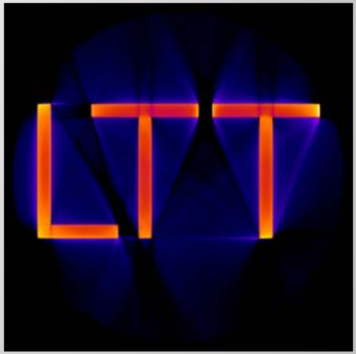


System Status

Scan data processing

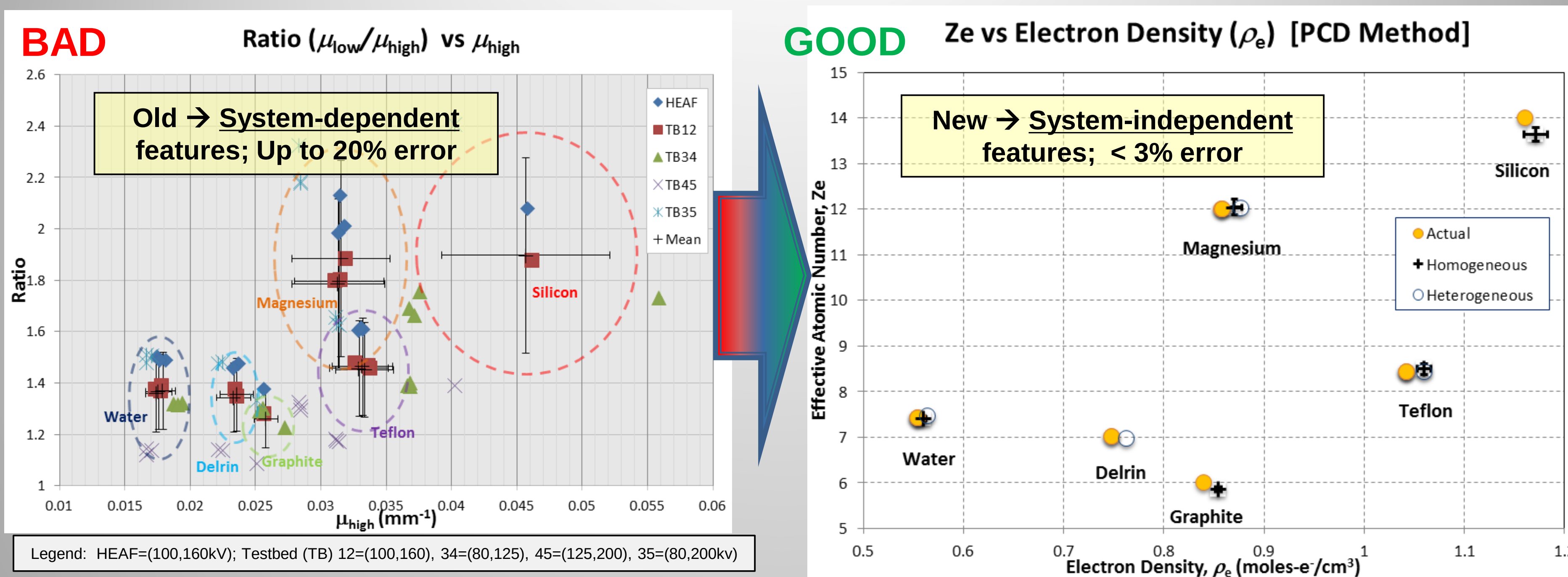
Livermore Tomography Tools (LTT) contain powerful CT processing codes

- State-of-the-art Algorithms for CT
  - **20X speedup** over previous software (large cost savings or expanded throughput)
  - **2.5X improvement** in contrast- and signal-to-noise ratios (statistical CT algorithms)
  - Includes many state-of-the-art and novel algorithms (e.g., SIRZ)
  - Supports parallel-, fan-, & cone-beam geometries, and modern fixed-gantry
  - Produces quantitatively-accurate results (with units) in a timely manner
  - Contains extensive modeling capabilities



- State-of-the-art Code Features
  - Cross-platform (Windows, Mac, Linux) written entirely in C/C++
  - Multi-threaded (OpenMP) and utilizes GPU processing (OpenCL)
  - Standard file format that converts to/from DICOM, DICOS, DICONDE and others
  - Data sets that are too large to fit into memory are processed in smaller chunks
  - Connects smoothly with LLNL's DR/CT acquisition software
  - Processes CT data from raw detector counts to reconstructed images and beyond

System-independent (ρ_e, Z_e) method (SIRZ*) makes dual-energy CT more quantitative

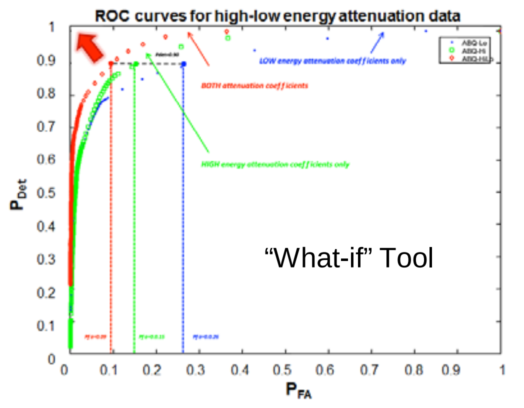


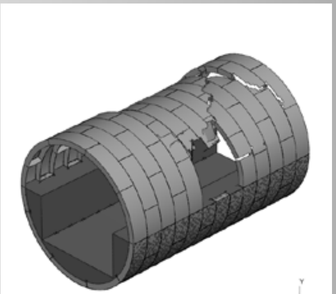
- SIRZ gives system-independent results **without beam-hardening correction (BHC)**
  - Tested with 7 specimens on 4 different CT scanners, 3 different detectors and 5 spectra
- Recommending that DHS and vendors adopt SIRZ for HME characterization and scanner certification; the UK Home Office adopted SIRZ

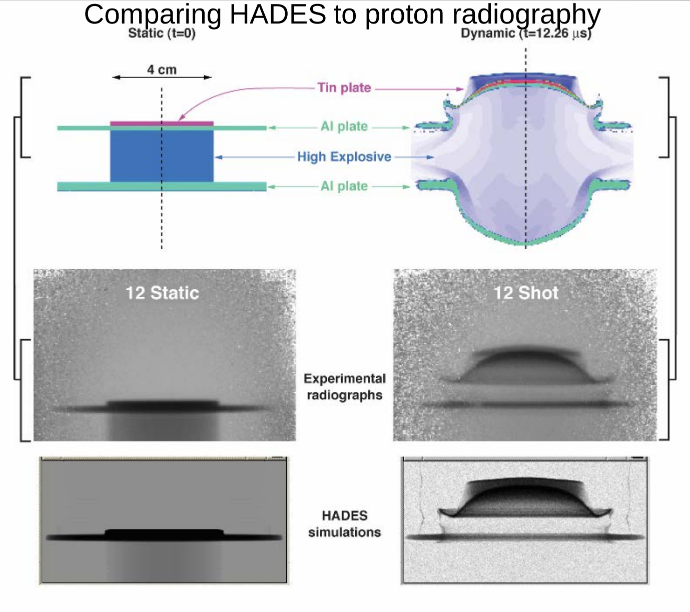
* Azevedo, et.al., System-independent characterization of materials using dual-energy computed tomography. IEEE Trans. Nuc. Sci., 63(1), pp.341-350, 2017. Martz, et.al., CT dual-energy decomposition into x-ray signatures ρe and Ze. In SPIE Defense+ Security (pp. 98470D-98470D), May 2016.

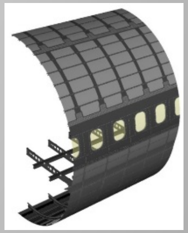
Modeling and Simulation are important to NDC

- Straight-ray (limited physics; fast)
  - LTT
    - Energy-dependent Cross Section Tables from 1 keV to 10 MeV of elements 1 to 100
    - X-ray Tube Spectral Distributions
    - Detector response model
    - CT Data Simulation with analytic ray-tracing
  - HADES
  - ZeCalc *
- Monte Carlo (full physics; slow)
  - MCNP (LANL)
  - Geant (CERN)
- Others
  - "What-if" tool
  - ParaDyn, ALE3D – High-fidelity massively-parallel multi-physics simulation codes
  - Generate simulated radiographs from finite element results







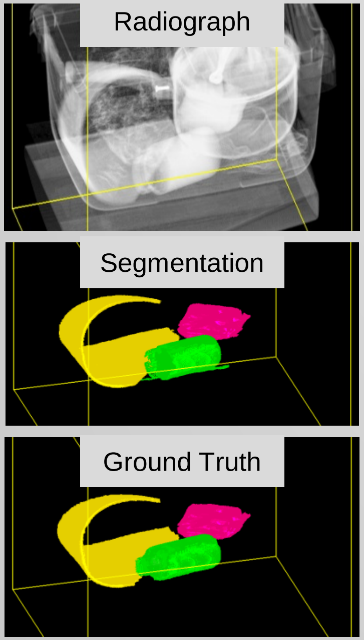


ALE3D Simulations

* Bond, K.C., Smith J. A., Treuer J. N., Azevedo S., Kallman J. S., and Martz, Jr. H. E., ZeCalc Algorithm Details, Version 6, LLNL Tech. Rep., LLNL-TR-609327, Jan. 2013, To request a copy of ZeCalc software, contact Mary Holden-Sanchez at holdensanchez2@llnl.gov..

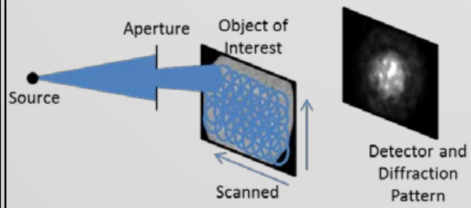
Internal funds* enable forward-looking R&D efforts that apply directly to national needs

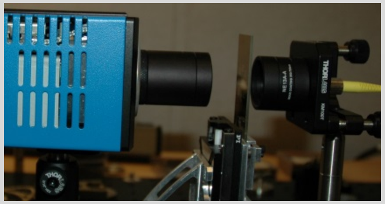
Image Segmentation

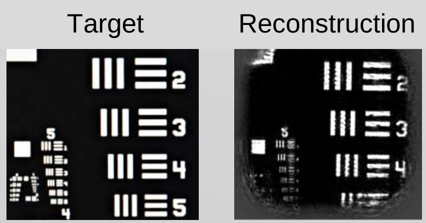


Differentiating threats from non-threats

Ptychography
(Lensless Microscopy)

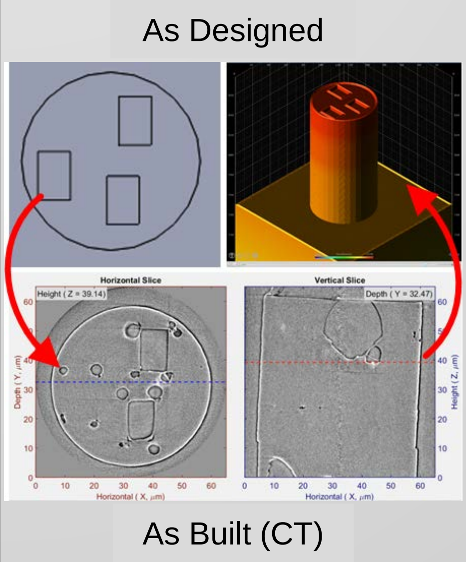






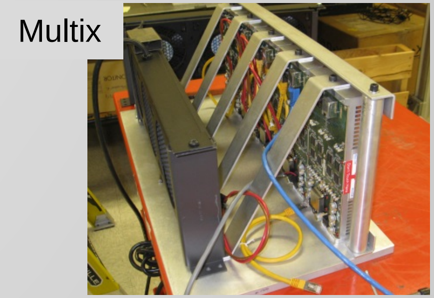
New 3D Conjugate Gradient Recon

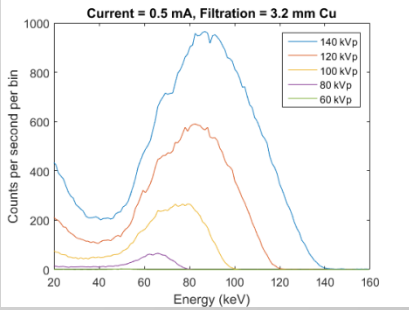
Error Budgeting



Extracting best results from our systems

New Multi-energy Detector Array





Novel detector will help many NDC apps

* Funded by LLNL through internal R&D funding mechanisms.

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  - eV-to-MeV X-ray energies; nm-to-cm spatial resolution
  - H-to-Pu Z-range; mg/cm^3-to-20g/cm^3 in density (ρ)
  - Hair-strand to Cargo-container object sizes
- Software & Supporting Technologies
  - Algorithms for CT acquisition, processing, reconstruction, analysis
  - Simulation & Modeling
- Other Modalities (Ultrasound, Radar, Particles, etc.)
- Future directions

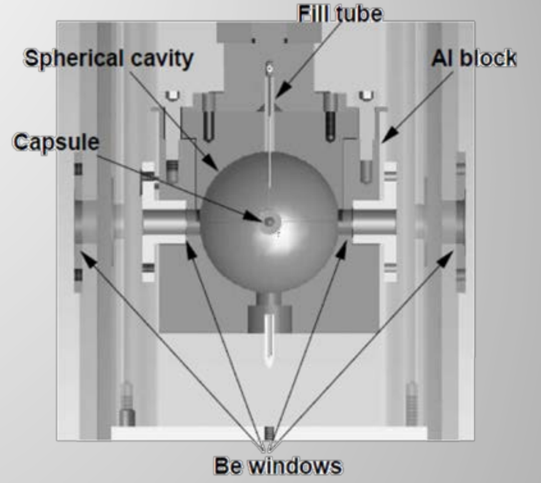
Phase-contrast x-ray image of Deuterium-Tritium ice inside a Be(Cu) shell

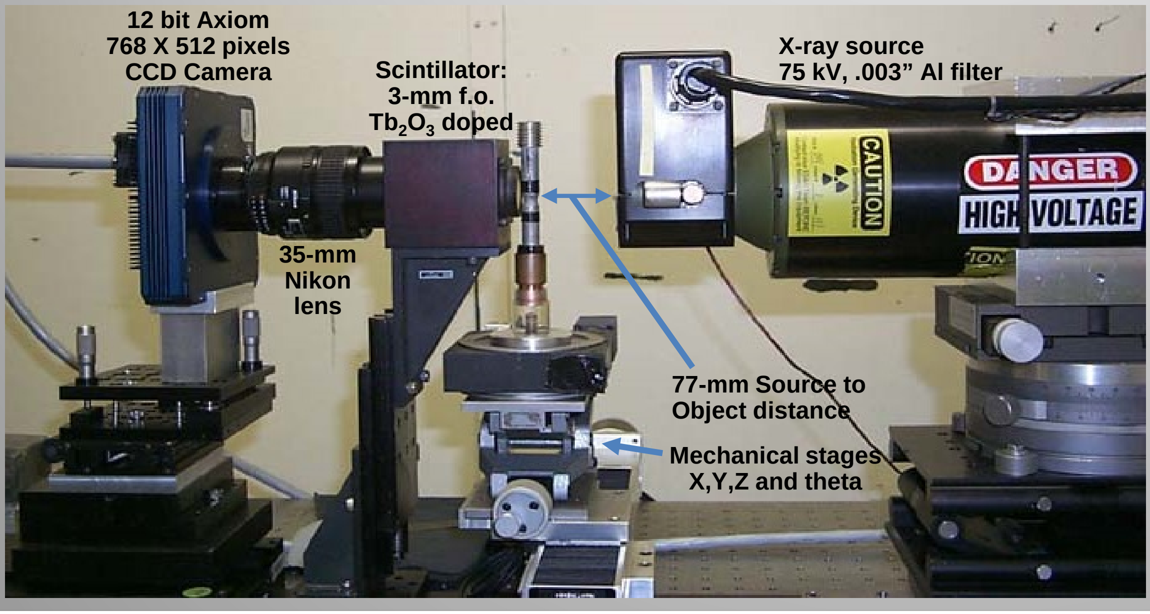
Description

- KCAT a reconfigurable CT system
- Used for deuterium-tritium ice layer imaging

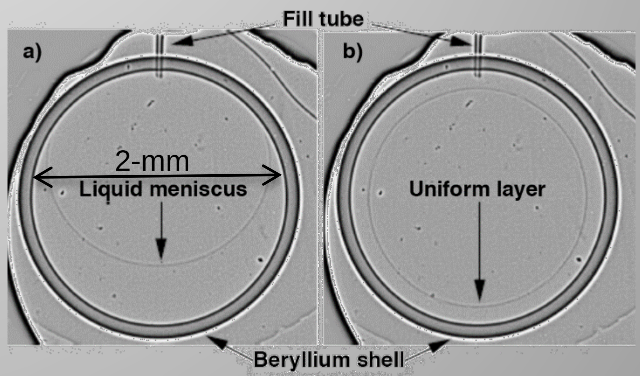
System

- Source – 150 kV, ~15 μm spot
- Imager – Tb_2O_3 scintillator coupled to Nikon lens and 3k x 2k Quantix CCD 9 μm pixels
- FOV – ~7-mm; 2.3 μm pixels; 3.9 magnification; 275-mm source-detector distance





2-mm dia., 105-μm-wall Be shell doped with Cu



Phase-contrast image of (a) liquid deuterium-tritium (D-T) and (b) solid D-T in a beryllium-copper shell

X-ray Tomosynthesis images planar structures

Description
- Multi-Planar Tomosynthesis
- Application for large aspect ratio or planar parts

System
- Source – 60 - 130 kV, 0.015-mm spot
- Imager – PE amorphous-Si panel; 200-µm pixel size
- FOV 2.5 – 40-cm; 15 to 200 μm pixels; 1-m Src-Det distance

Location

LLNL B327

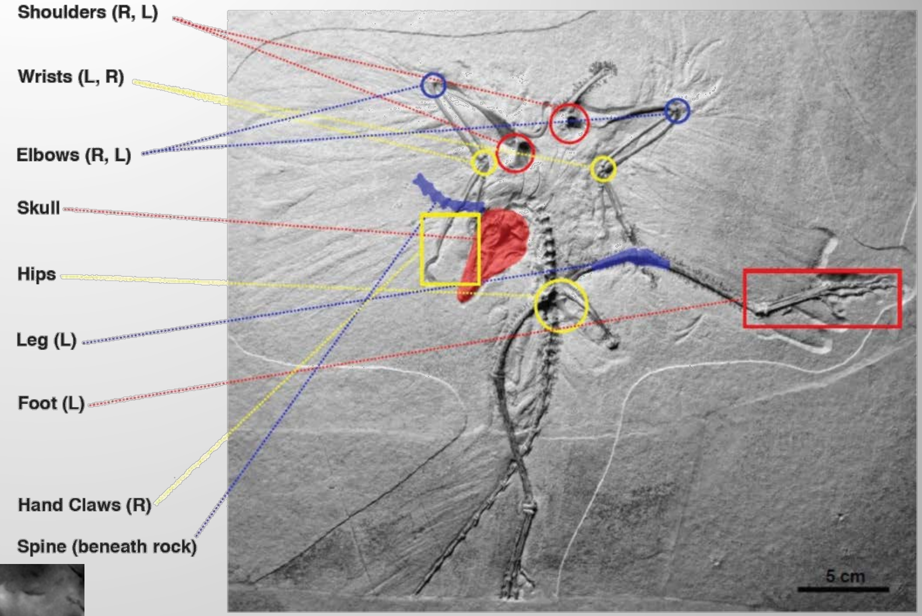
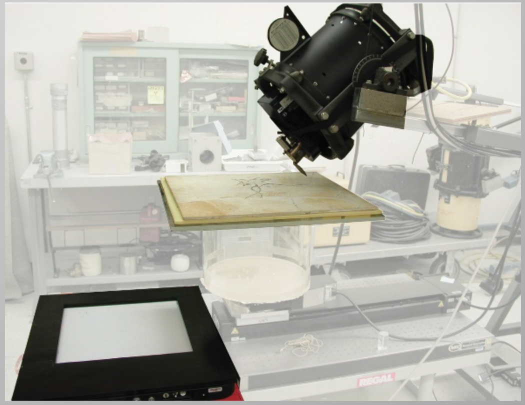


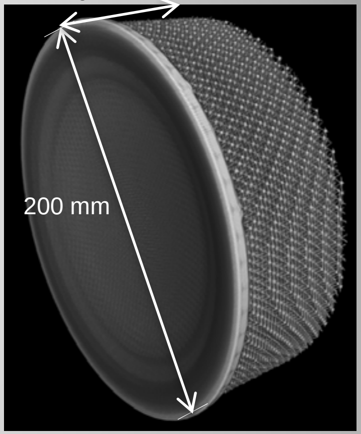
Photo of Archaeopteryx fossil from Thermopolis (collaboration with Yale)

Tomosynthesis stack image of the skull and right hand



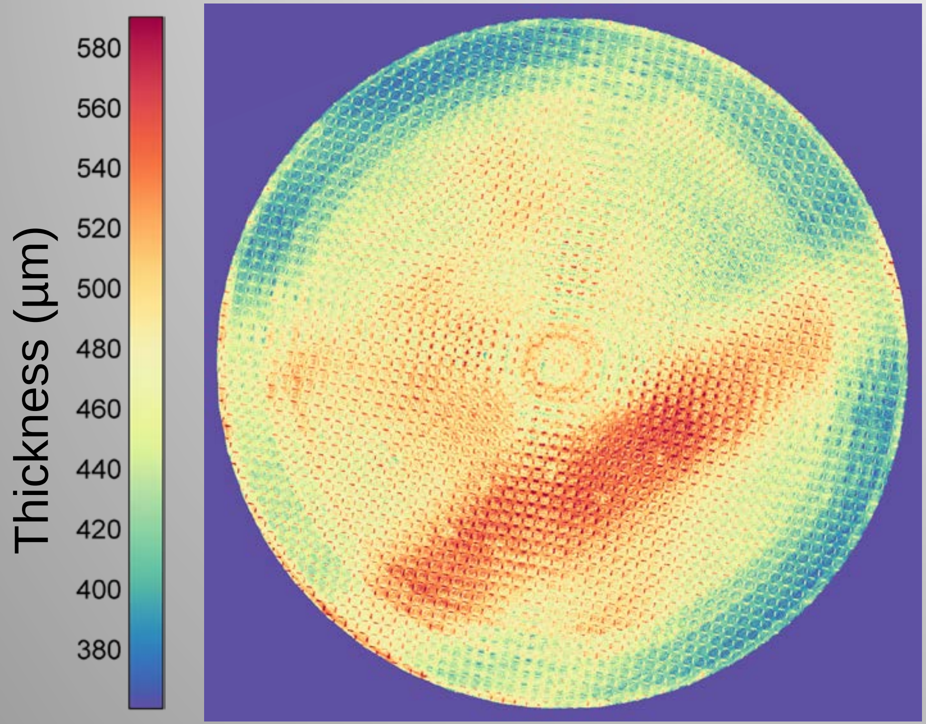
Tomosynthesis set up

UT and X-ray CT of AM parts

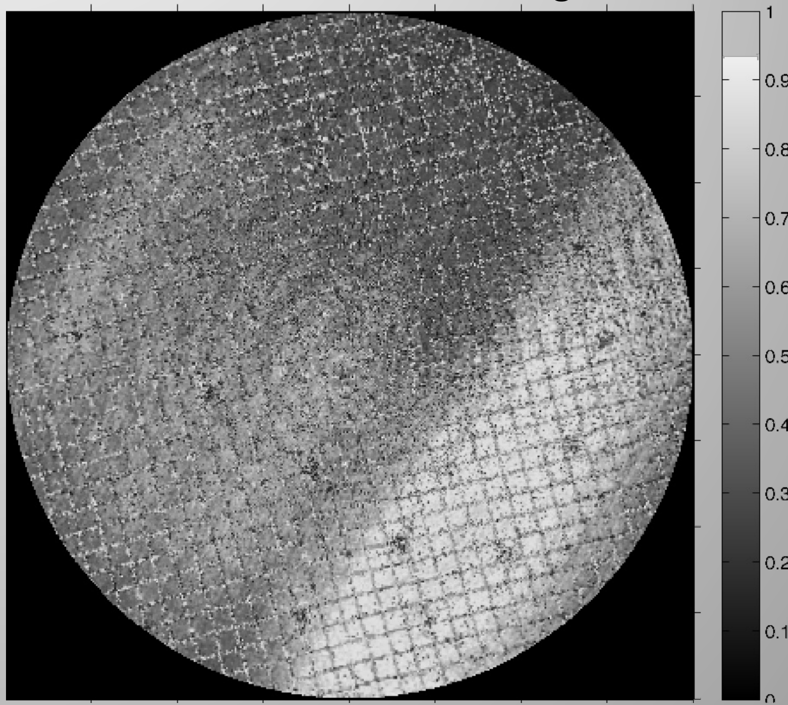


Conformal tessellation of octet titanium trusses (0.35-mm strut dia.)

X-ray CT of Machined Part

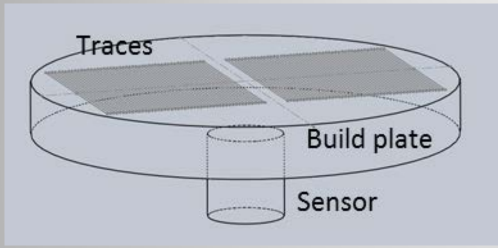


Ultrasound Time of Flight

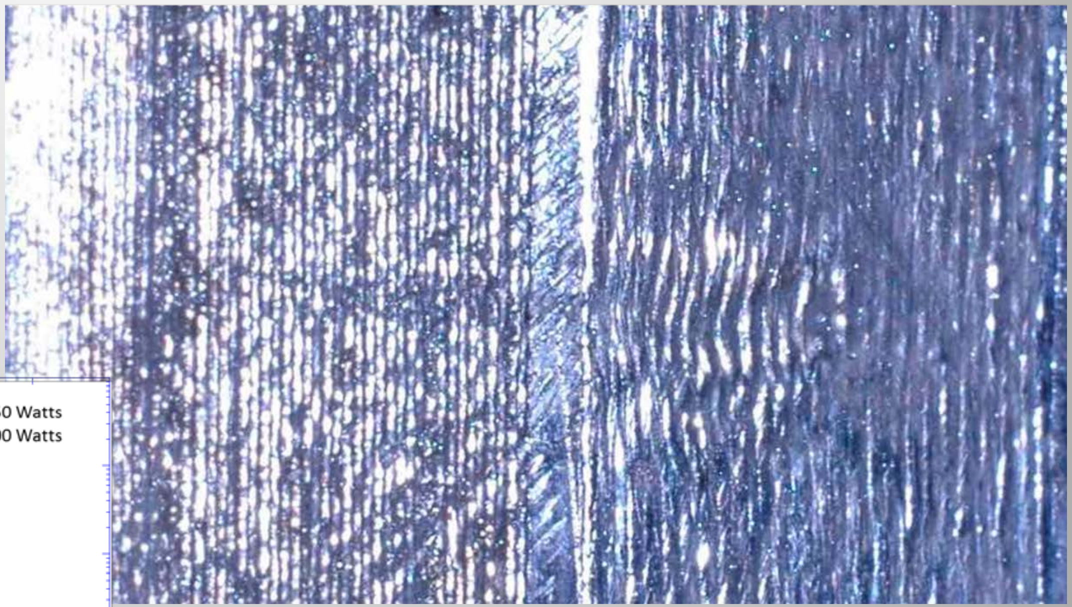


UT and CT show the raised region; UT shows larger changes relative to surrounding face sheet.

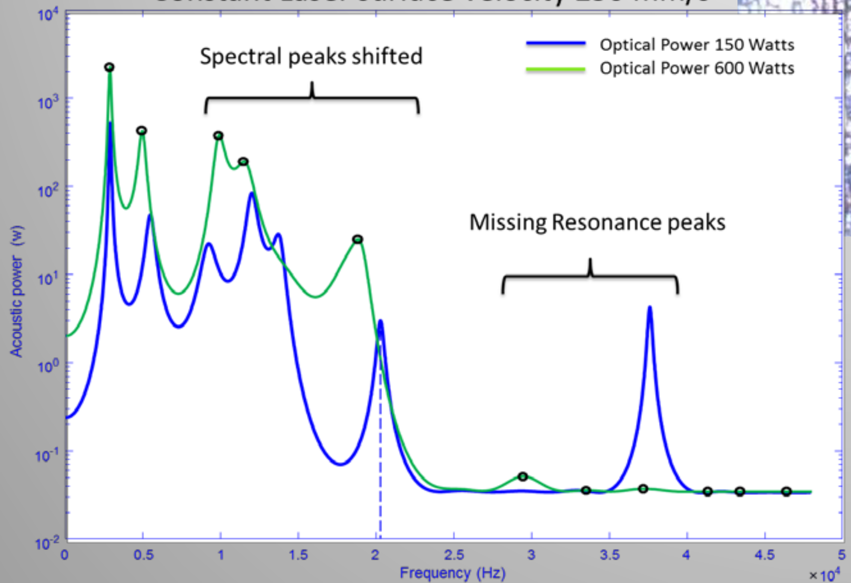
Acoustic Emission for AM provides process feedback and control



SLM traces on Build Plate



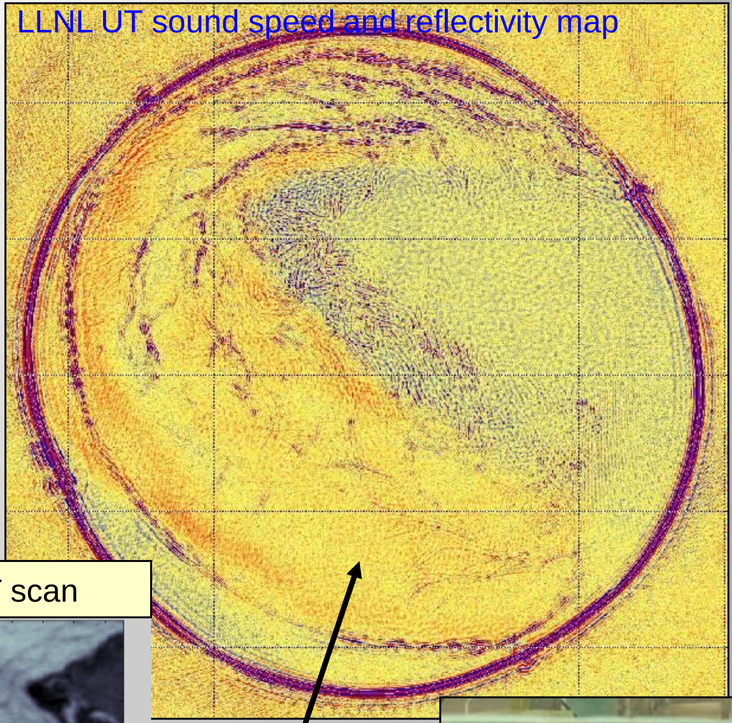
Constant Laser surface velocity 250 mm/s



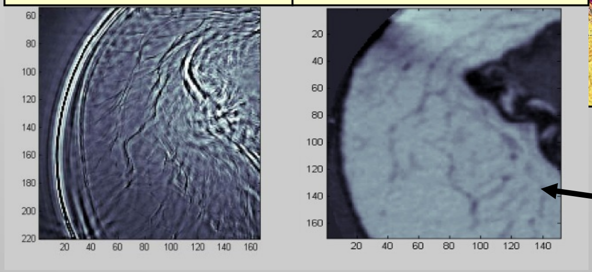
Different optical power settings contain shifted and missing resonance peaks

LLNL expertise was applied to Ultrasound Breast Tomography

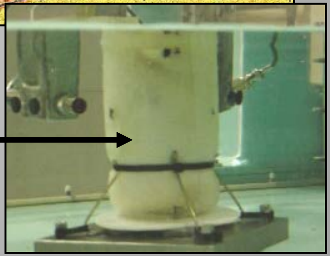
- Full-breast ultrasound tomography (UT) provides
  - New information in the fight against breast cancer
  - Safe, thorough, reflection *and* transmission modes
  - 3D acoustic properties: Sound speed, attenuation
- LLNL contributions
  - Full-wave simulations (using ACSI Blue)
  - Pre-prototype scanner and experiments (Panametrics 5-axis UT immersion scanning system, with adjustable working volume to 90 cm x 45 cm x 130 cm)
  - Reconstruction algs based on x-ray, acoustic, microwave and seismic experience



LLNL UT data | X-ray CT scan



Excised human breast sample



Clinical prototype (artist's rendering)

Funded by: Karmanos Cancer Institute
Collaborators: U. New Mexico, U. Muenster (Germany), Techni-Scan, Inc.

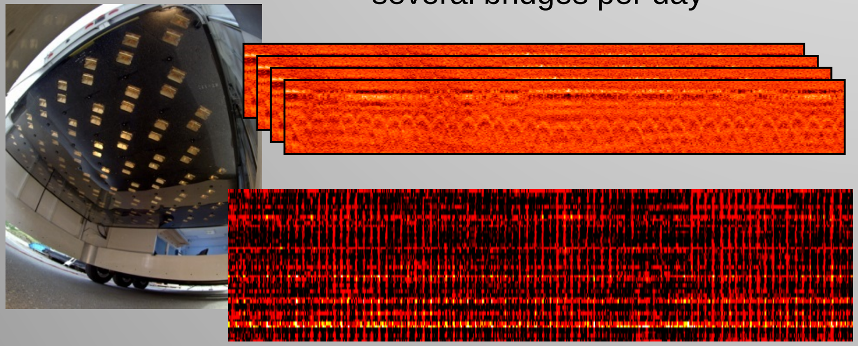
BARBARA ANN KARMANOS CANCER INSTITUTE

Microwave tomography is used for bridge inspection and mine detection

High speed (55 mph)

64 radar array concept proven inspection at highway speed

HERMES Radar 3-D tomographic imaging of several bridges per day

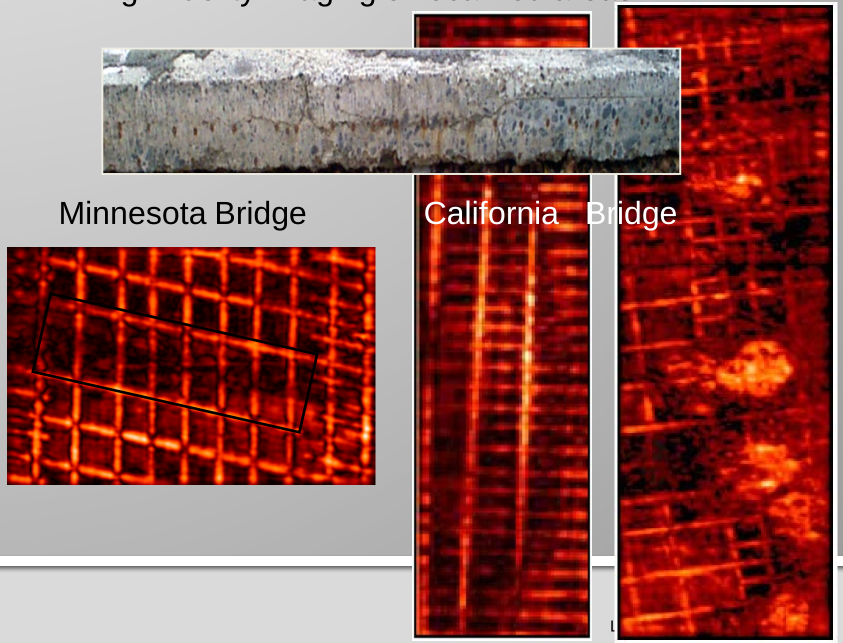


Funded by Federal Highway Administration

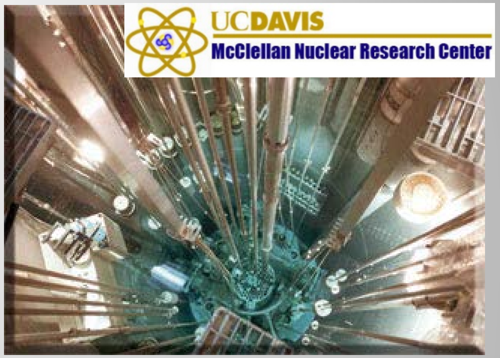
Low speed (55 feet/h)

PERES single-radar scanning system

High fidelity imaging of localized areas



Neutron imaging and CT are available through LLNL & partner labs



MNRC reactor & detector

Description

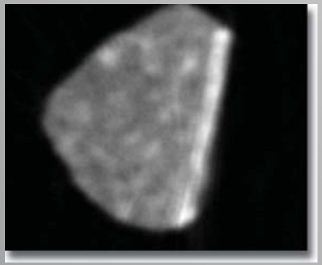
- Different attenuation contrast than x-rays produces more information about objects
- Neutrons are attenuated by light materials, such as H, B, Li, but penetrate many heavy materials such as Ti and Pb.

System

- Source – MNRC reactor; 2MW sustained (400MW pulsed)
- Imager – Film or image plate
- FOV – 40-cm

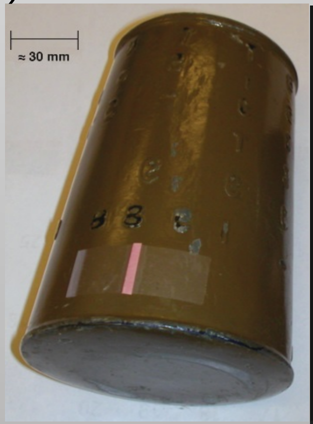
Location

McClellan Nuclear Research Center (MNRC) at McClellan AFB, CA

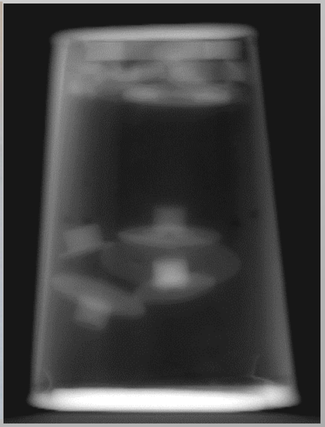


Neutron CT slice of UCD rock sample

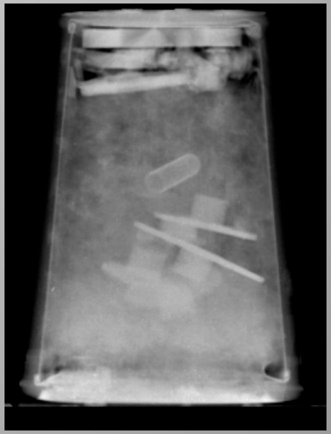
Kinked O-ring in stainless steel valve housing (not seen).



Lead canister



X-ray image



Neutron image

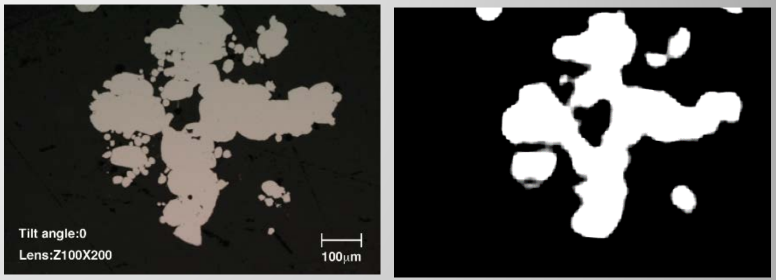
(Some images courtesy MNRC, LLNL)

Outline

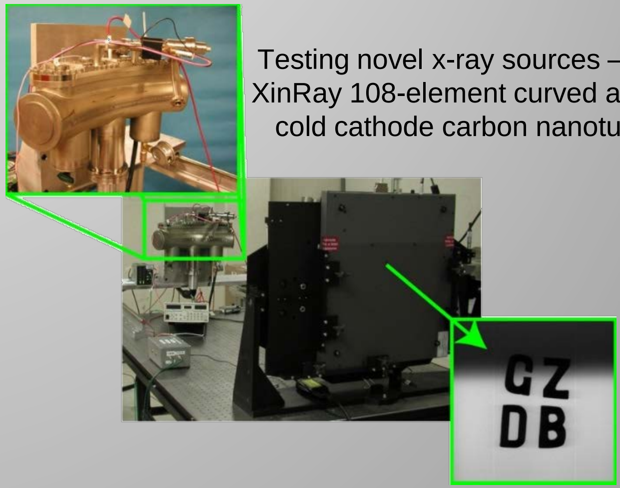
- Overview of Nondestructive Characterization at LLNL
- X-ray Radiography, CT, Diffraction and Applications
  - eV-to-MeV X-ray energies; nm-to-cm spatial resolution
  - H-to-Pu Z-range; mg/cm^3-to-20g/cm^3 in density (ρ)
  - Hair-strand to Cargo-container object sizes
- Software & Supporting Technologies
  - Algorithms for CT acquisition, processing, reconstruction, analysis
  - Simulation & Modeling
- Other Modalities (Ultrasound, Radar, Particles, etc.)
- ➡ Future directions

Future Plans and Challenges

- Quantitative NDC for Additive Manufacturing (AM)
  - Acoustic emission feedback for AM
- NDC for Chip Assurance
  - Nanoscope at synchrotron or with Lyncean
  - X-ray ptychography
  - High-speed nano-CT, limited-view
- Multi-spectral CT coupled with SIRZ
- Additional NCI Goals
  - Faster 3D imaging of dynamic events
  - Fused neutron and x-ray CT algorithms
  - Faster more accurate models
  - Partner with gov't, academia, labs & industry



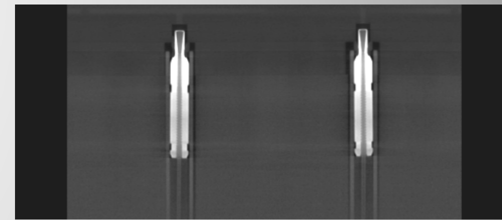
Destructive analysis (left) used to verify to CT data (right)

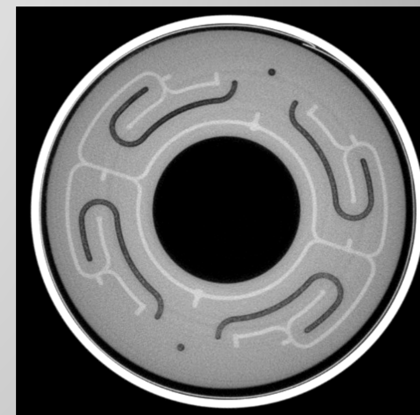


Testing novel x-ray sources – the XinRay 108-element curved array, cold cathode carbon nanotube

With decades of investment, NCI at LLNL is a resource to the nation.

Summary

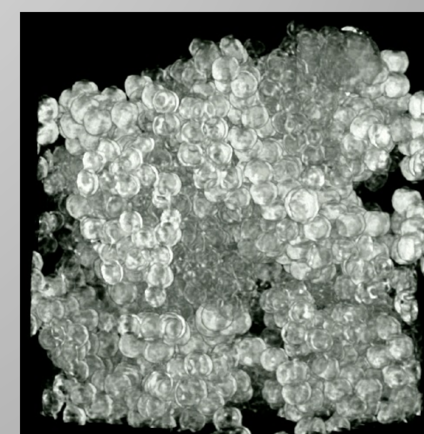




- Nondestructive Characterization (NDC) has been a core competency at LLNL since its inception in 1952
  - Unique facilities and expertise in systems, simulation, algorithms, computations, analysis
  - Started CT in the early 1980's
- Nondestructive Characterization Institute (NCI) is
  - Newly-formed in 2015 from earlier thrusts
  - Growing in expertise and partnerships

Nondestructive Characterization Institute

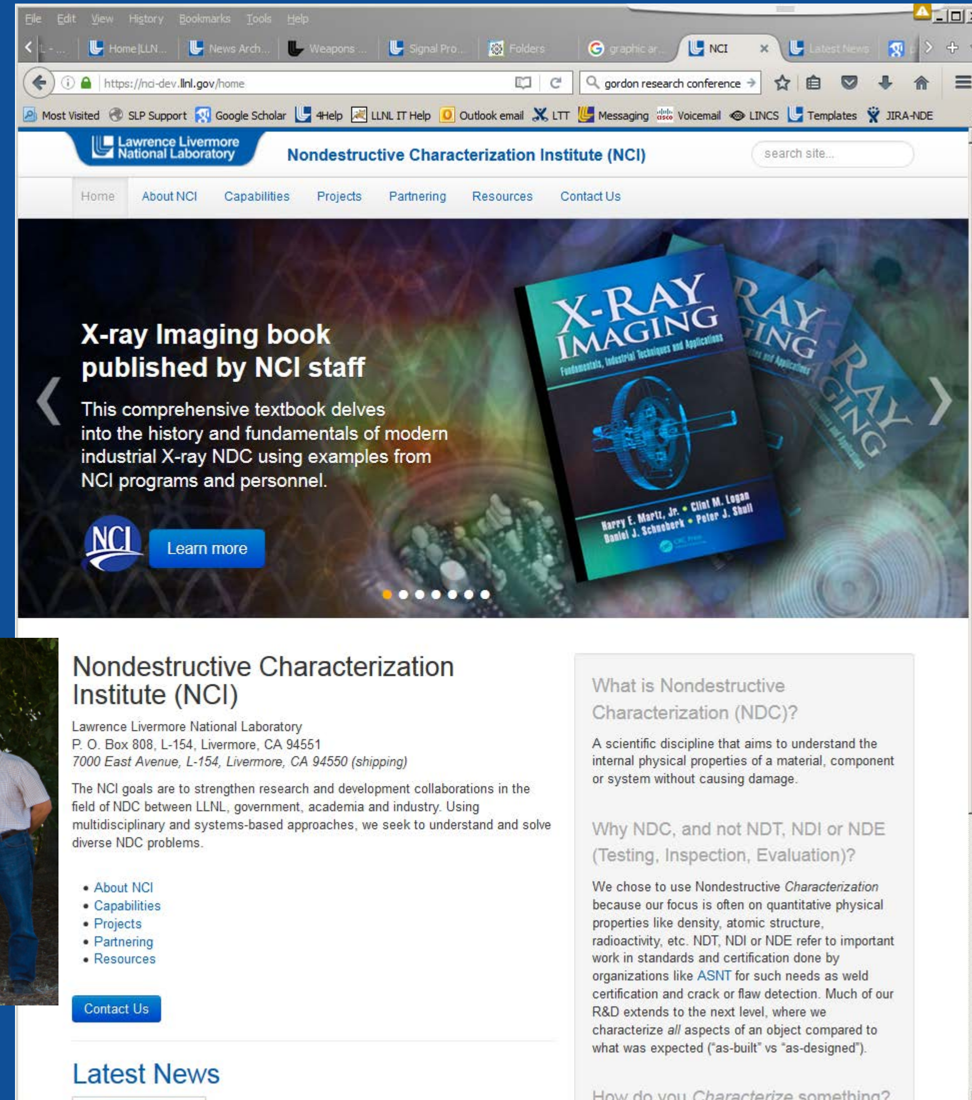
- Computed Tomography is core to our work
  - Many CT systems supported; more coming
  - Internal R&D complements our customers' needs
  - We continue to collaborate and address new problems

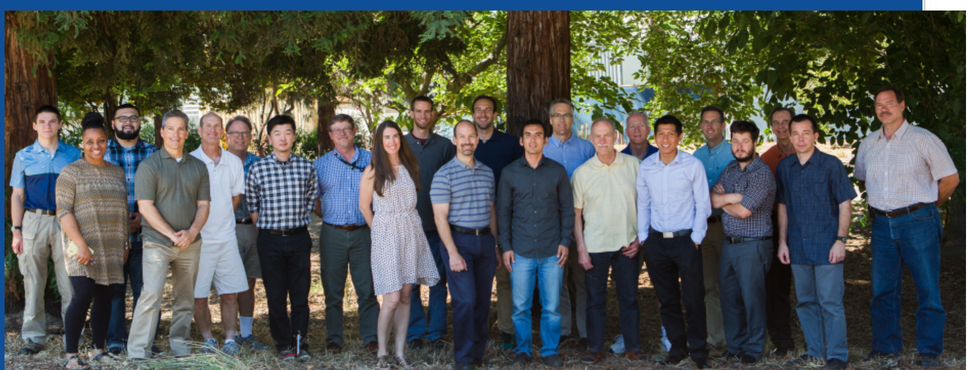


1-μm Copper spheres

We build systems and use them to solve multi-agency problems for the U.S.

https://nci.llnl.gov





Nondestructive Characterization Institute

Lawrence Livermore National Laboratory