NUCLEAR PHYSICS APPLICATIONS WITH EMPHASIS ON:

Instrumentation

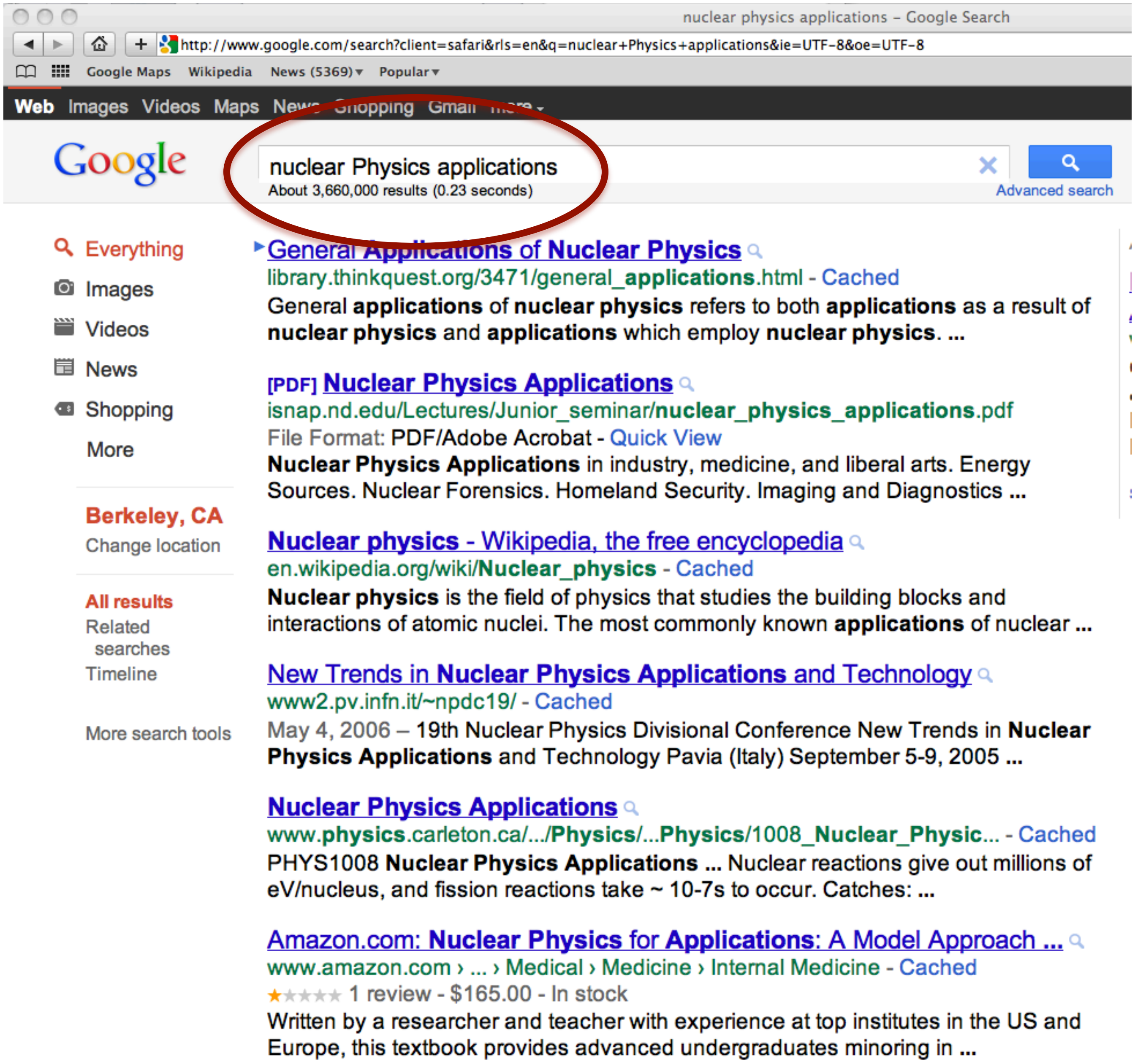
Early Prospecting Gear

Accelerators

First Cyclotron, Berkeley Rad Lab

Lee S. Schroeder*

Presented to the Applications of Nuclear Science & Technology (ANS&T) Meeting
Rockville, Maryland, August 22-23, 2011



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General Applications of Nuclear Physics
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General **applications** of **nuclear physics** refers to both **applications** as a result of **nuclear physics** and **applications** which employ **nuclear physics**. ...

[PDF] **Nuclear Physics Applications**
isnap.nd.edu/Lectures/Junior_seminar/**nuclear_physics_applications**.pdf
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Nuclear Physics Applications in industry, medicine, and liberal arts. Energy Sources. Nuclear Forensics. Homeland Security. Imaging and Diagnostics ...

Nuclear physics - Wikipedia, the free encyclopedia
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Nuclear physics is the field of physics that studies the building blocks and interactions of atomic nuclei. The most commonly known **applications** of nuclear ...

New Trends in **Nuclear Physics Applications** and Technology
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May 4, 2006 – 19th Nuclear Physics Divisional Conference New Trends in **Nuclear Physics Applications** and Technology Pavia (Italy) September 5-9, 2005 ...

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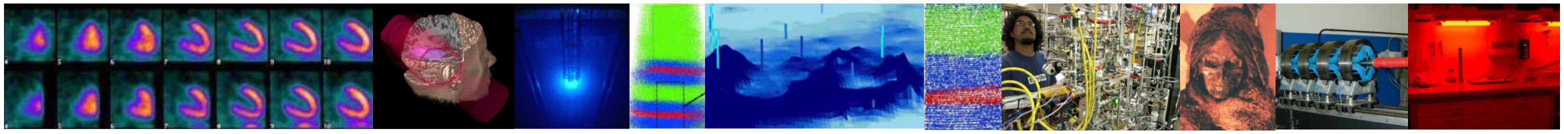
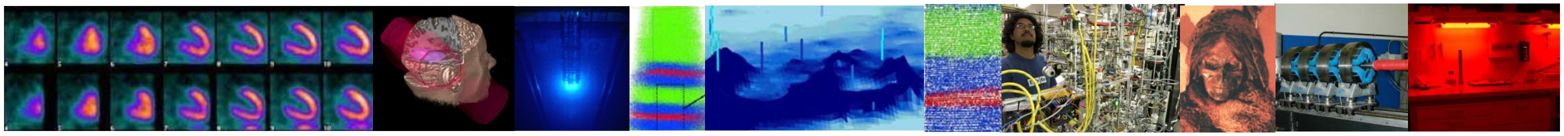


Nuclear Physics Applications

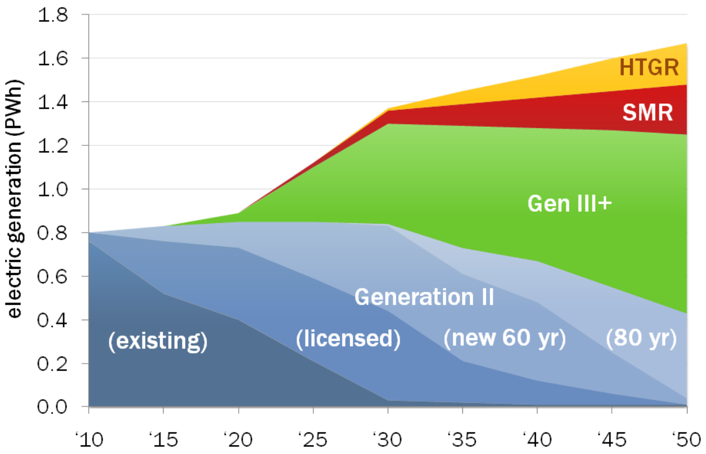
in industry, medicine, and liberal arts

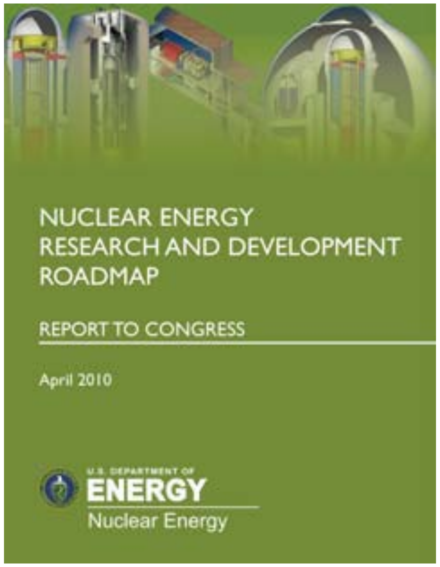
- Energy Sources
- Nuclear Forensics
- Homeland Security
- Imaging and Diagnostics
- Radiation Treatment
- Material Science
- Art and Archaeology



Nuclear Energy R&D Roadmap
The Present: 2010 and Beyond Four Nuclear Energy Objectives
(The Road Map)

- Develop technologies and other solutions that can improve the reliability, sustain the safety, and extend the life of current reactors.
- Develop improvements in the affordability of new reactors to enable nuclear energy to help meet the Administration's energy security and climate change goals.
- Develop sustainable fuel cycles.
- Understanding and minimizing the risks of nuclear proliferation and terrorism.




NUCLEAR ENERGY
RESEARCH AND DEVELOPMENT
ROADMAP

REPORT TO CONGRESS

April 2010

U.S. DEPARTMENT OF
ENERGY
Nuclear Energy

R&D Objective: Sustainable Fuel Cycles

Objectives

- In the near term, define and analyze fuel cycle technologies to develop options that increase the sustainability of nuclear energy
- In the medium term, select the preferred fuel cycle option(s) for further development
- **By 2050**, complete demonstration of the selected fuel cycle options at engineering scale and be ready to turn over to industry for commercialization

Necessary R&D

- Reduce transuranic production
- Implement science-based development program for fuel recycling
- Obtain mechanistic understanding of waste form behavior
- Perform fundamental analysis of fuel fabrication processes, and fuel/clad performance
- Evaluate very high burnup systems that require minimal or no chemical separations
- Develop transmutation systems needed to supplement partial recycling in thermal reactors
- Enable real time nuclear material accountancy and control
- Analyze storage and disposal system performance in a variety of environments

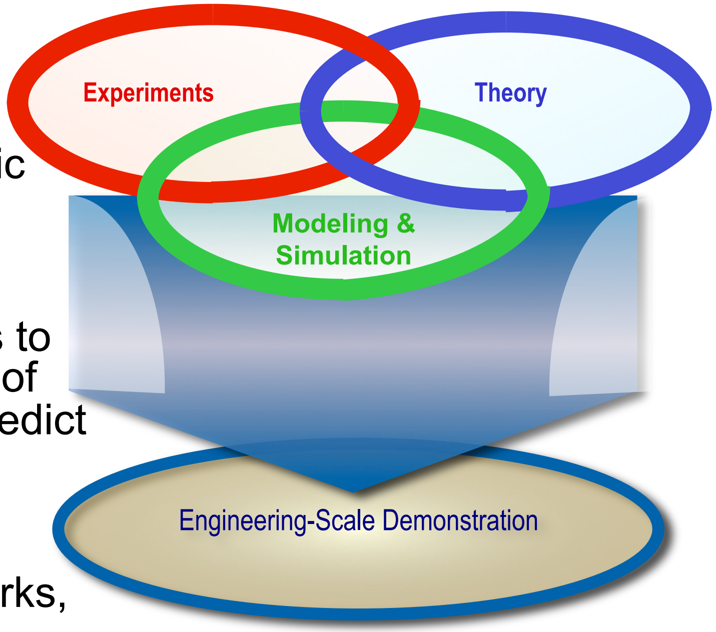
Science Based Approach to Nuclear Energy Development
The Road Map

- ***Experiments*** – Physical tests done to develop understanding of single effects or integrated system behaviors.

- ***Theory*** – Creation of models (i.e. theories) of physical behaviors based on understanding of fundamental scientific principals and/or experimental observations.

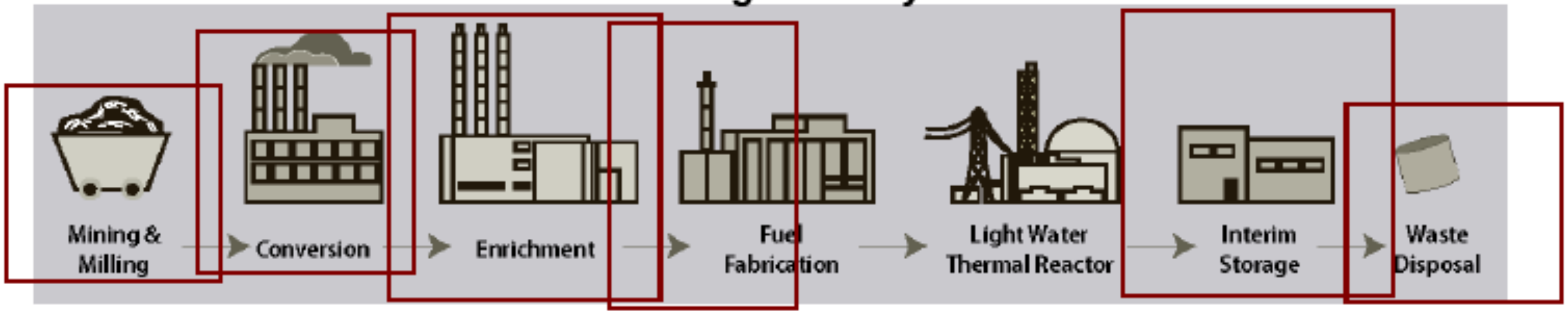
- ***Modeling and Simulation*** – Use of computational models to develop scientific understanding of the physical behaviors of systems. Also used to apply scientific understanding to predict the behavior of complex physical systems.

- ***Demonstrations*** – New technologies, regulatory frameworks, and business models integrated into first-of-kind system demonstrations that provide top-level validation of integrated system technical and financial performance.

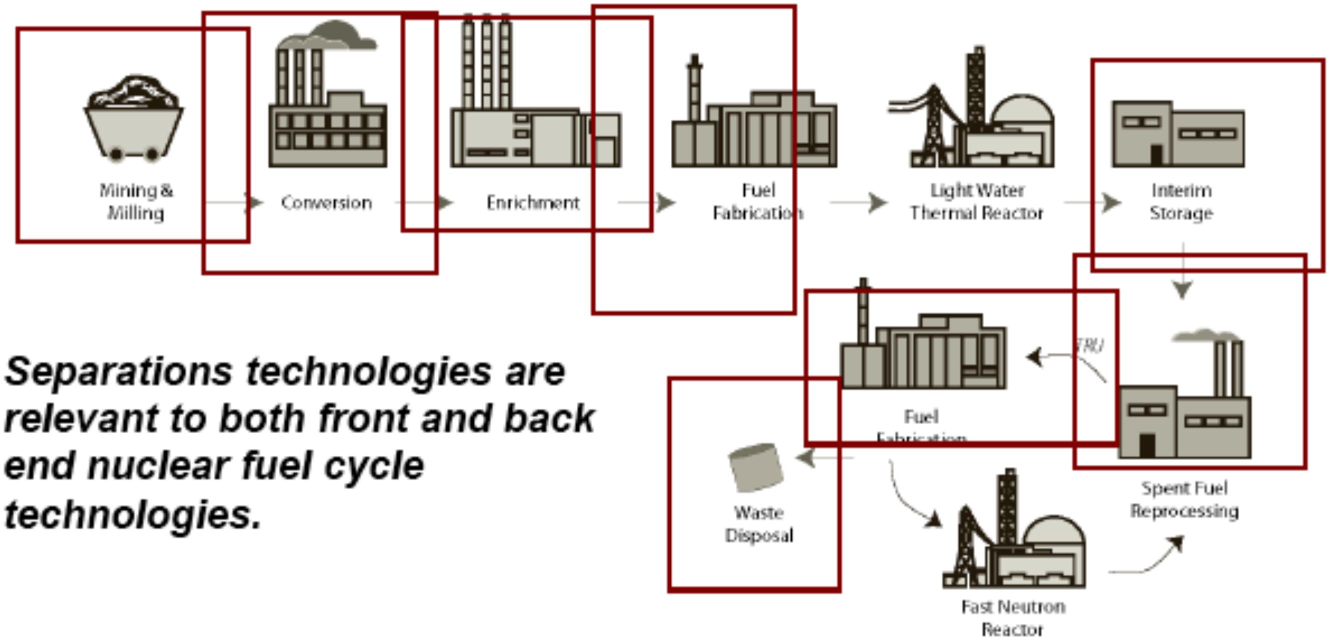


Separations Technologies are Encountered Throughout the Fuel Cycle

Once Through Fuel Cycle



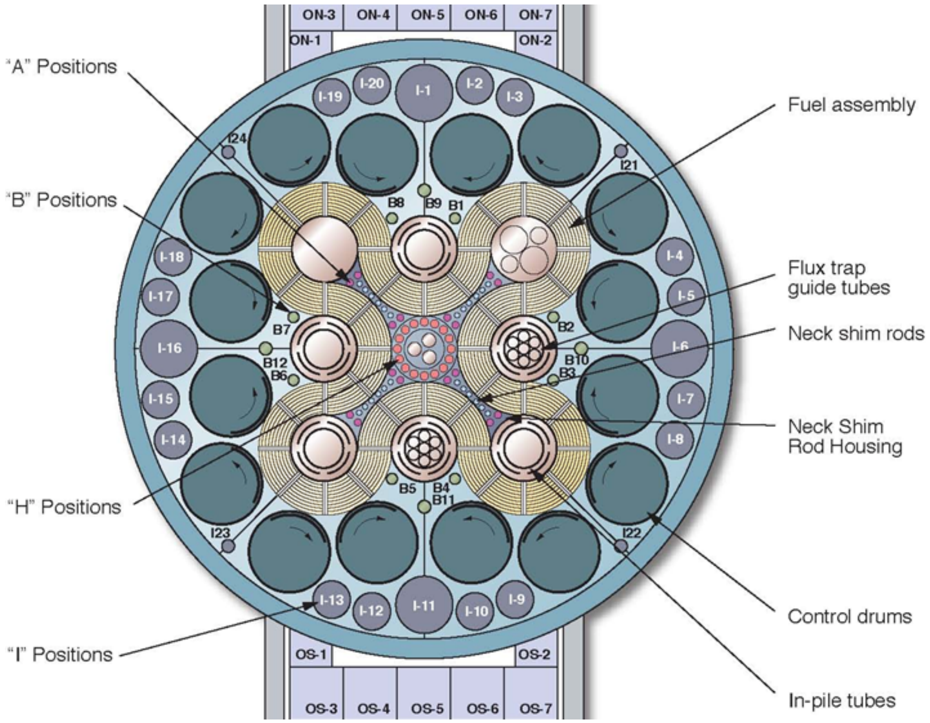
Closed Fuel Cycle



☐ ***Separations technologies are relevant to both front and back end nuclear fuel cycle technologies.***

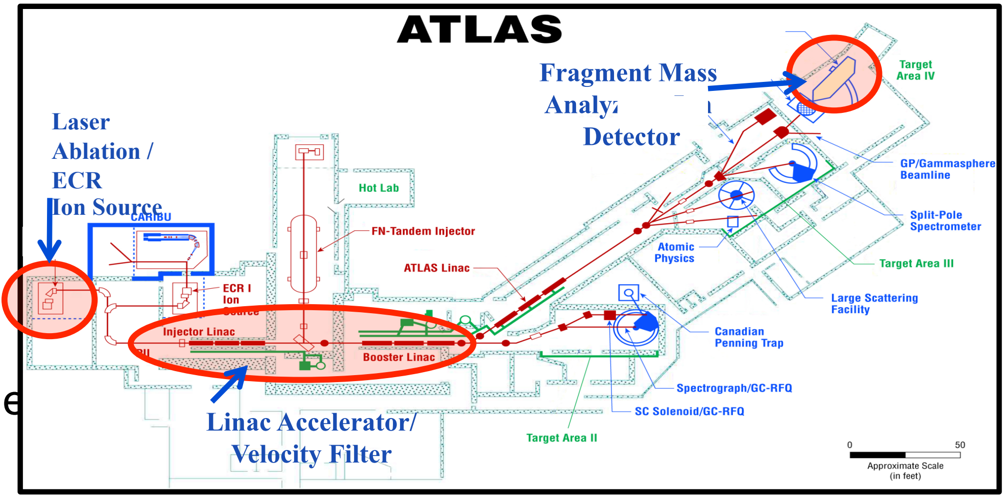
Advanced Test Reactor (ATR) at INL

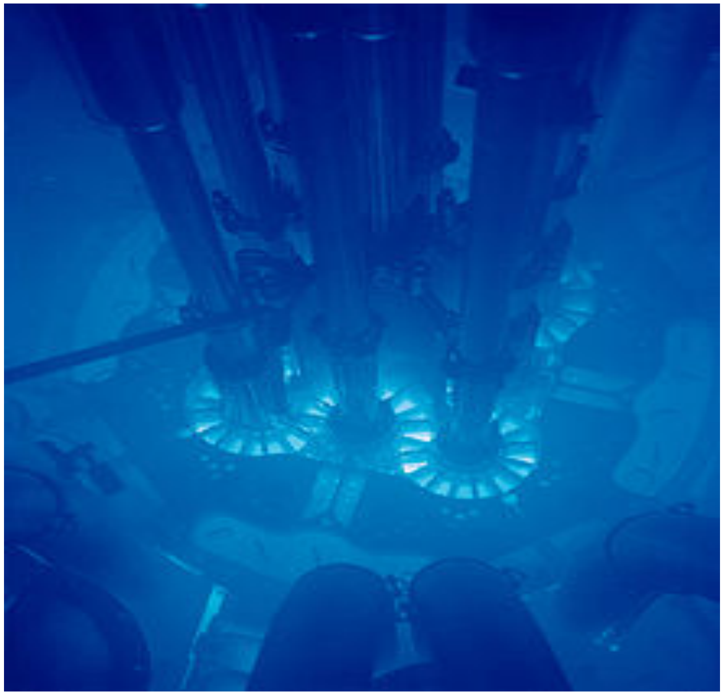
- Material Testing (irradiations) Reactor since 1967
- Now National Scientific User Facility since April 2007
- Test Materials, Nuclear Fuels, and Instruments that Operate in Reactors



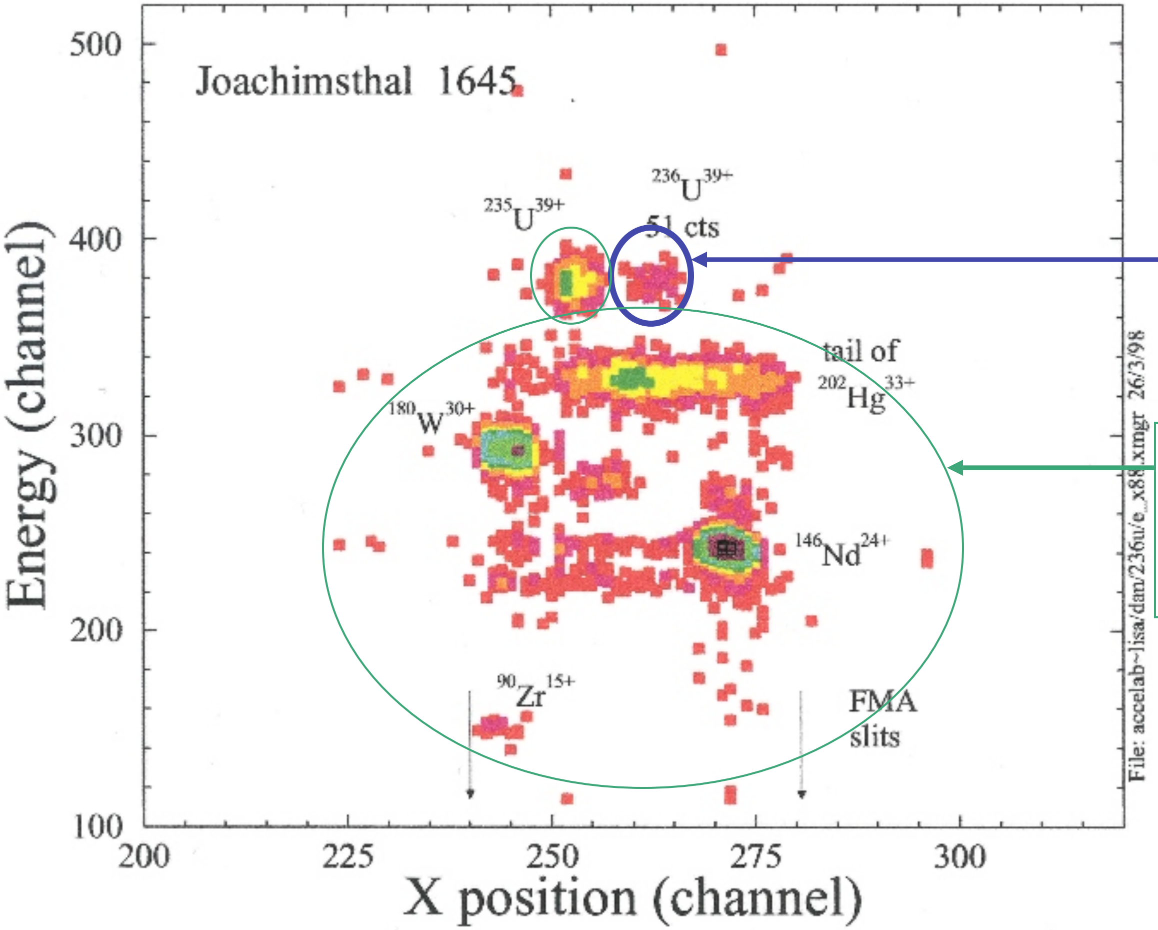
MANTRA: Measurement of Actinide Neutron Transmutation Rate by AMS

- Integral information on actinide neutron cross sections
- Joint INL/ANL project
  - Irradiate sample in ATR at INL
  - Evaluate yields in ATLAS/FMA at ANL
  - Expect sensitivities in $10^{-10} \rightarrow 10^{-12}$ range





Example of a FMA Focal Plane Spectrum for ^{236}U AMS



^{236}U cts (ion of interest)

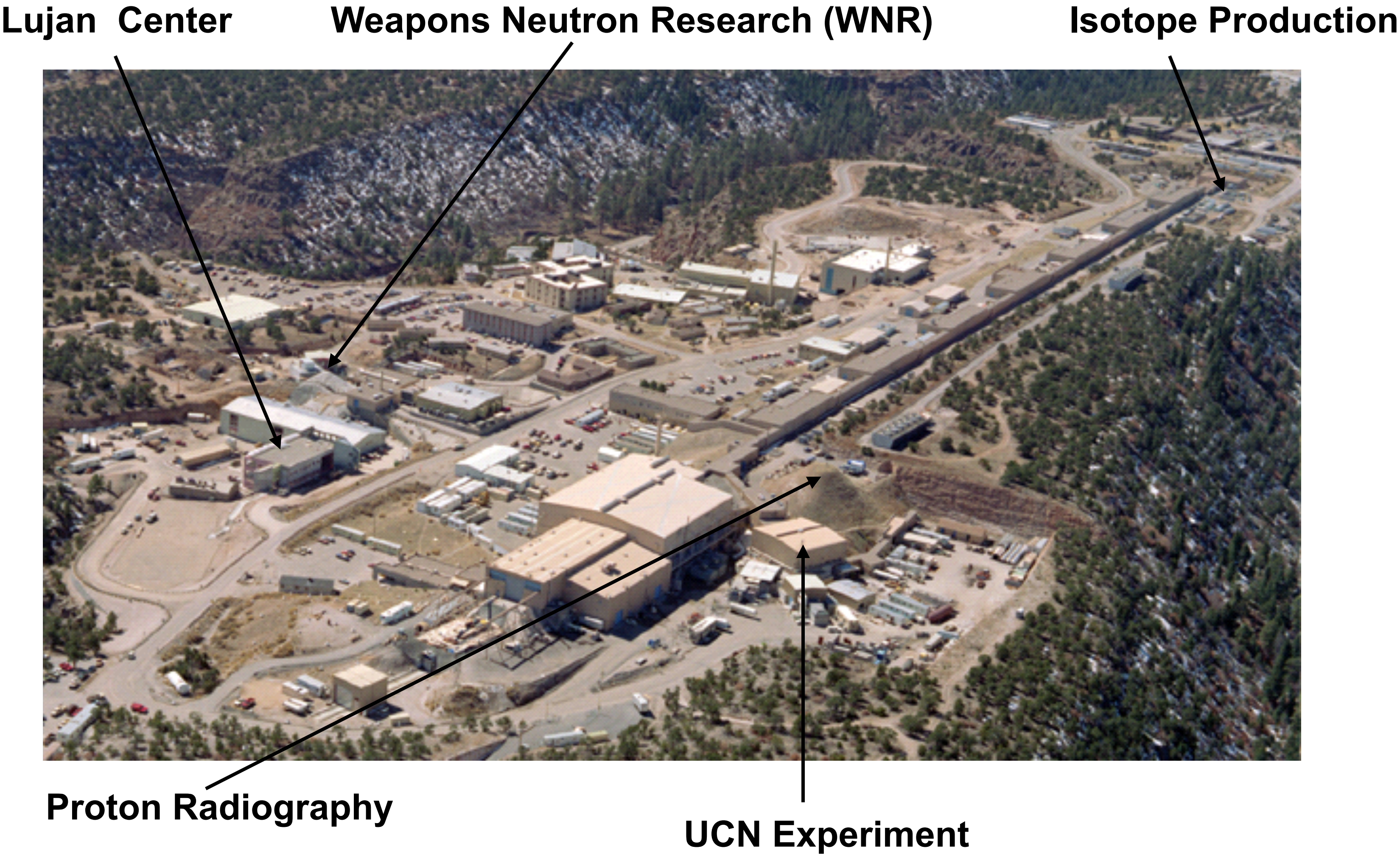
m/q = 236/39

Ions with m/q = 236/39 ± δ
(structural material + cross-talk
from previous runs + ^{235}U)

Isotope spectrum at the FMA focal plane detector for a sample from the Joachimsthal mine – Measurement time ~ 10 min – ^{236}U/U ~ 1x10^{-10}

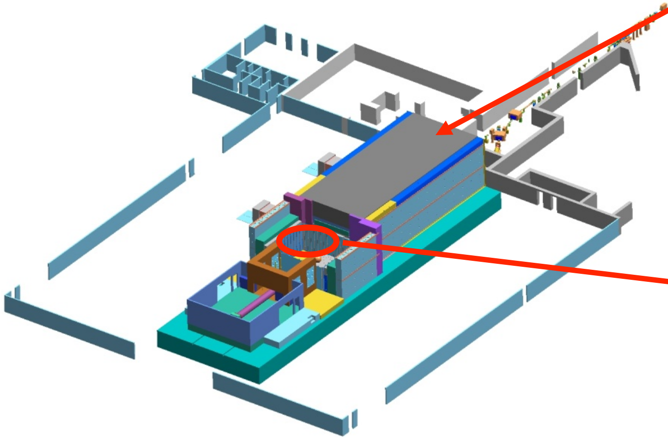
(M. Paul, NIMB, B172, (2000) 688-692)

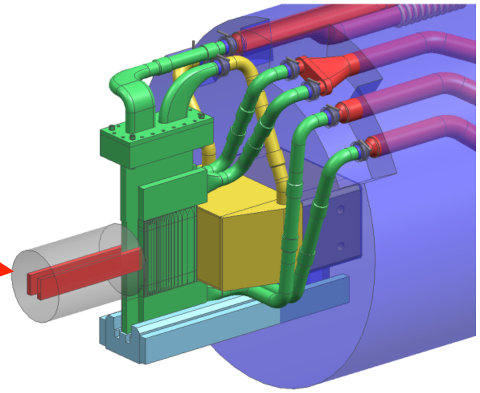
The Los Alamos Neutron Science Center (LANSCE)



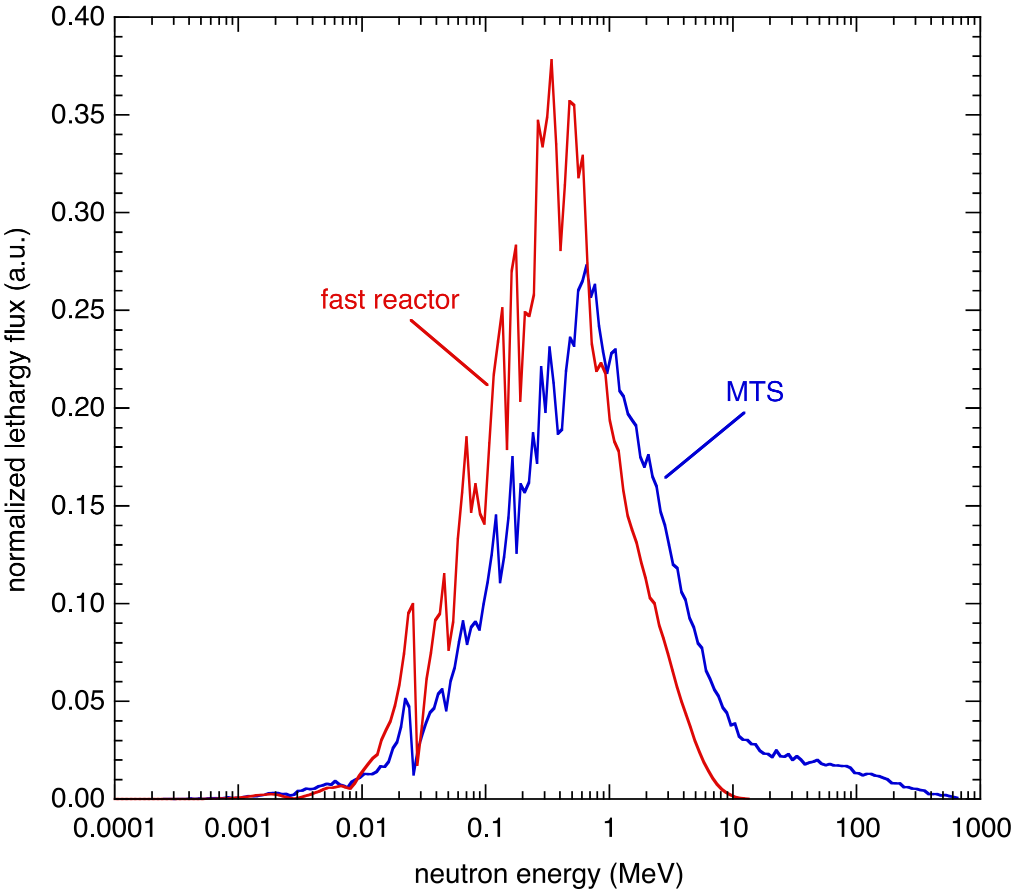
Materials Test Station (MTS): Irradiate Transmutation Fuels and Materials in a Fast Neutron Spectrum

- The MTS will be driven by the 1-MW LANSCE proton beam, producing 10^{17} neutrons per second.
- System is deeply sub-critical, so there are no criticality concerns.





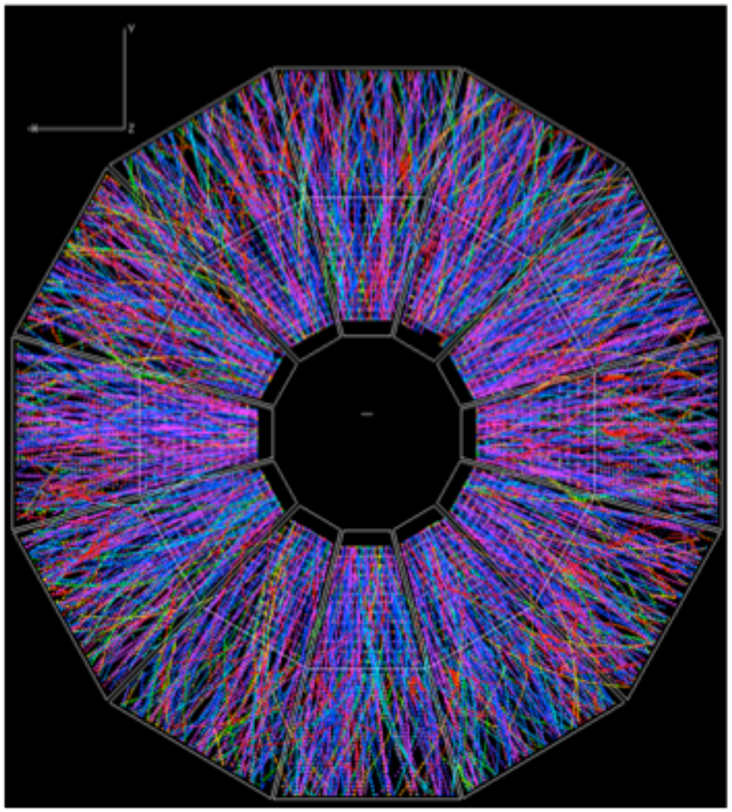
MTS flux level will be one-third to half of the world's most intense research fast reactors



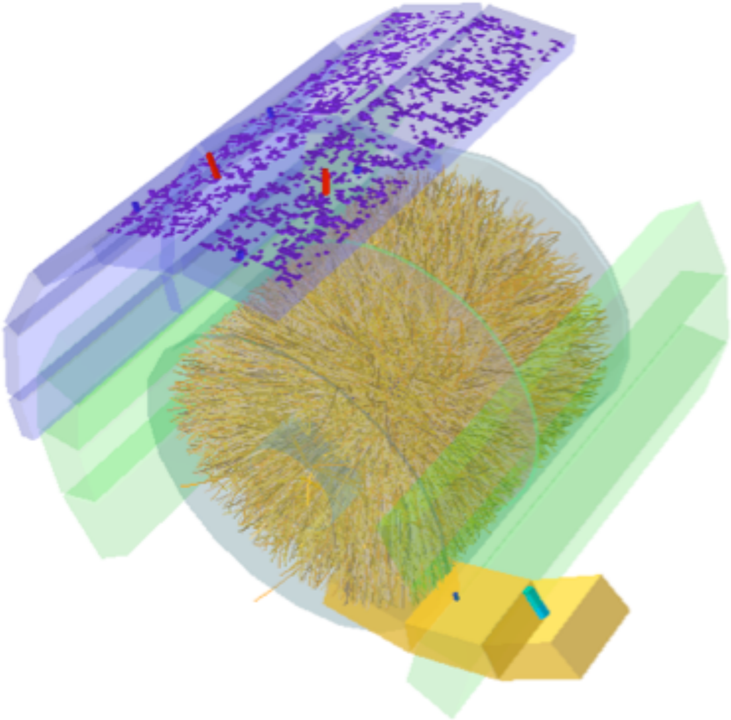
Facility	Peak Fast Flux (10^{15} n/cm^2/s)	Peak Annual Fast Fluence* (10^{22} n/cm^2/y)
MTS (USA)	1.3	2.1
BOR-60 (Russia)	2.8	4.6
JOYO (Japan)	4.0	6.9

- *Accounts for facility availability.

TPC's in Nuclear Physics Today



STAR at RHIC
Au + Au
(0.1 + 0.1) TeV/n



ALICE at LHC
Pb + Pb
(1.38 + 1.38) TeV/n

NIFFTE

Neutron Induced Fission Fragment Tracking Experiment

7 Universities

- Abilene Christian University
- Cal Poly San Luis Obispo
- Colorado School of Mines
- Georgia Institute of Technology
- Idaho State University
- Ohio University
- Oregon State University

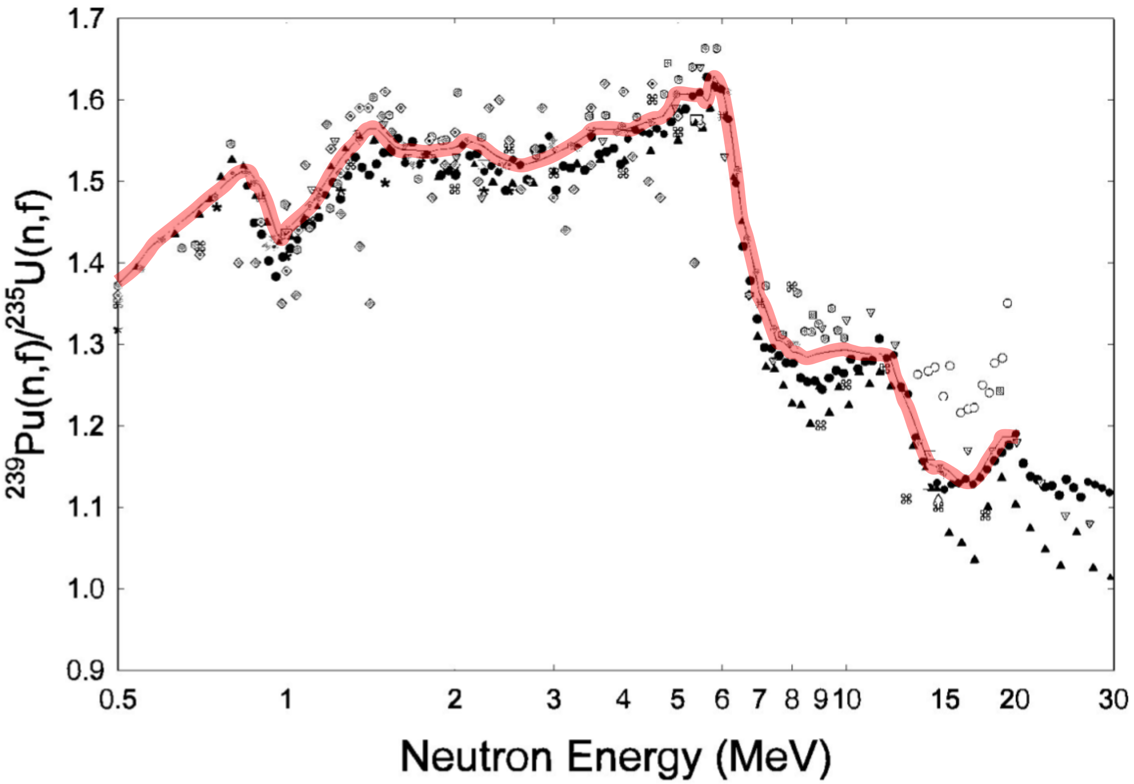
4 National Labs

- Idaho National Laboratory
- Lawrence Livermore National Laboratory
- Los Alamos National Laboratory
- Pacific Northwest Laboratory

The Goal of NIFFTE

- Initiate a fission cross section measurement program to provide data of unprecedented precision.
- By applying TPC technology to these studies we anticipate making sub-1% uncertainty measurements.

Current ^{239}Pu(n,f) measurements

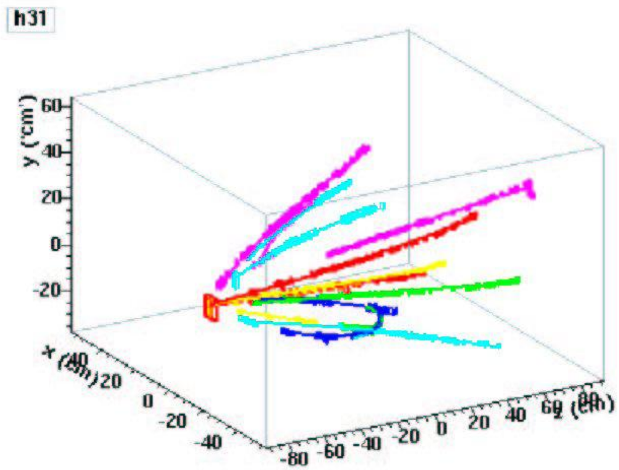


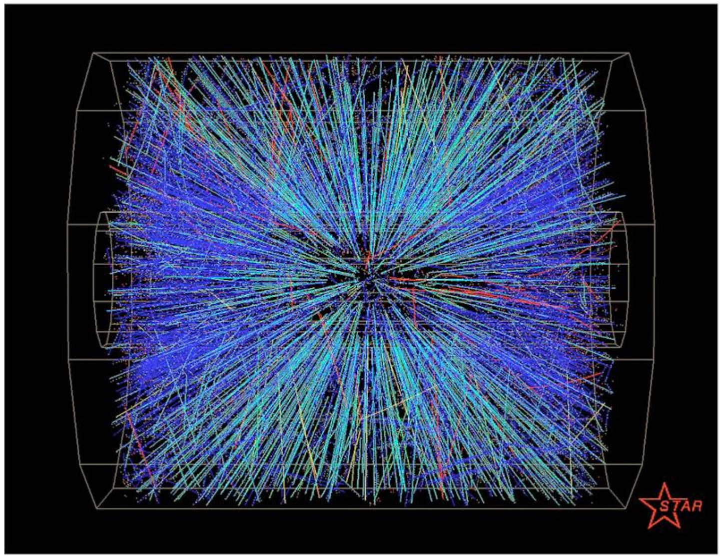
Spread in measurements leads to ~5% uncertainties in ENDF evaluations

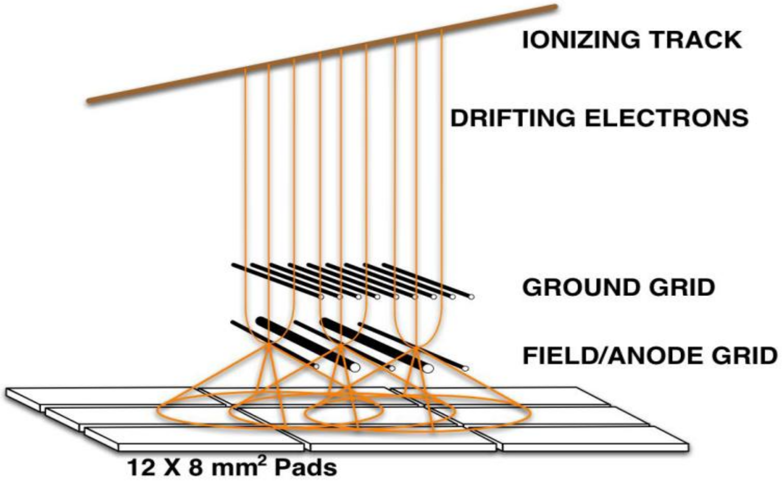
▬ ±1% Uncertainties about ENDF evaluation

History of TPCs

- TPCs have been in use for about 30 years in high energy physics
  - Provide 3-D “pictures” of charged particle trajectories
- Miniaturization is the key to fission measurement implementation
  - Small volume and area constraints with high bandwidth requirements
  - Recent advances in computing and electronics enable this technique

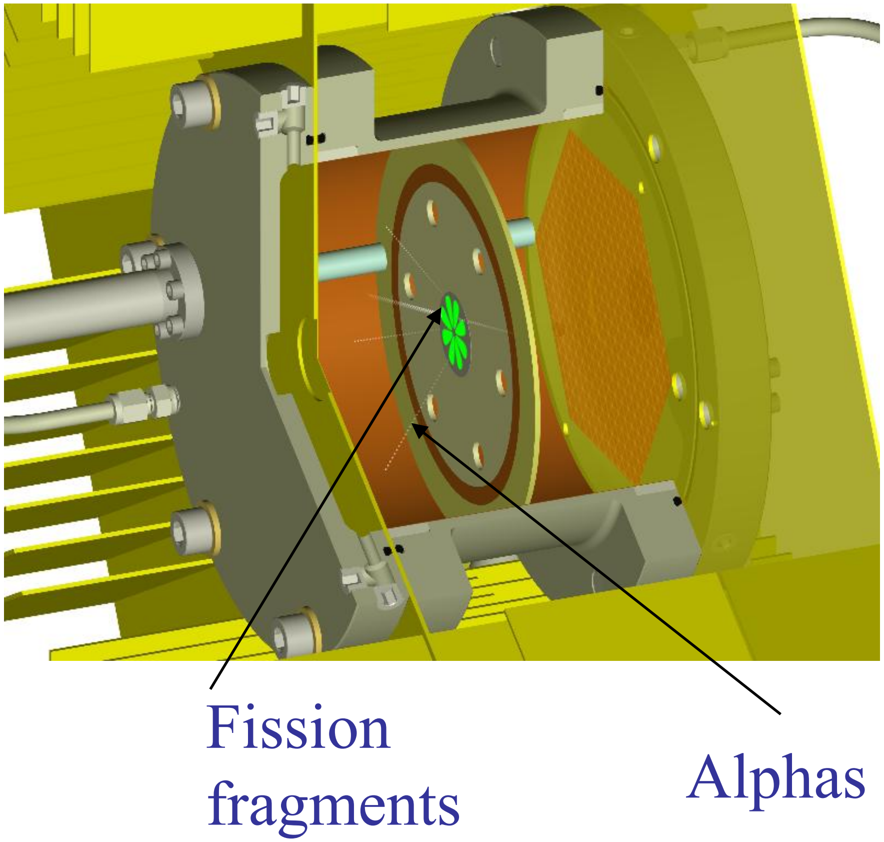




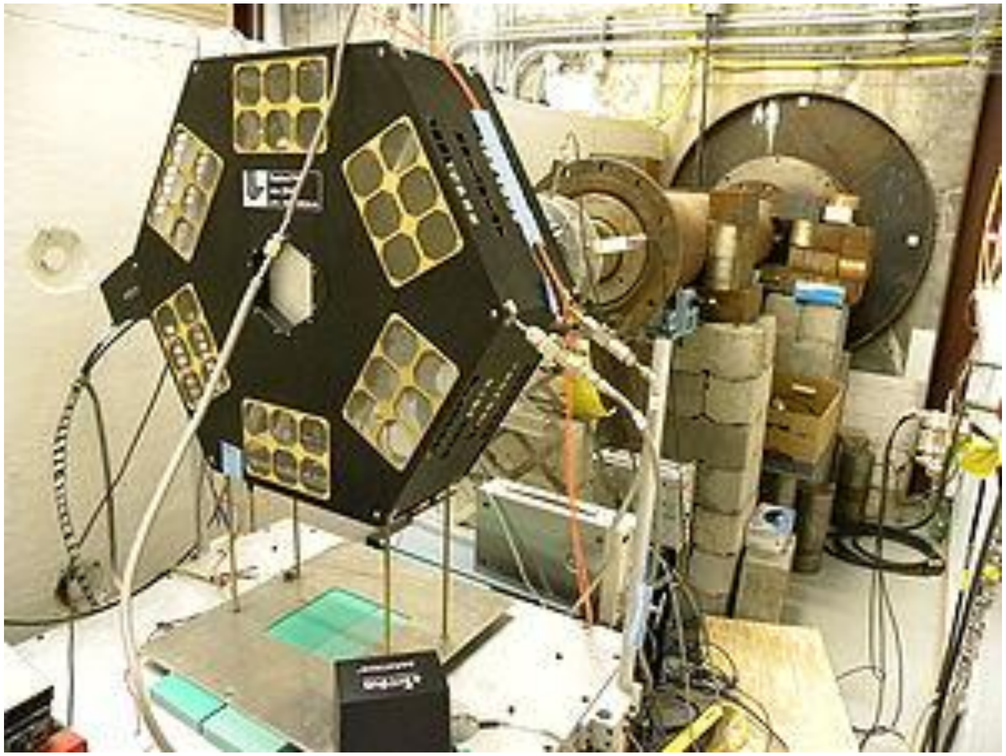


NIFFTE TPC

- TPC will provide 3D "pictures" of the charged particle trajectories
  - Alpha backgrounds removed
  - Beam non-uniformities
  - Multi-actinide targets
  - H_2 drift gas will also minimize scattering
- TPC will use thin backing foils ($<50\mu g/cm^2$)
  - Minimize beam interaction backgrounds
  - Minimize multiple scattering of fragments
  - Alpha particle sample radiograph
- TPC will provide data on both fission fragments simultaneously
  - Random backgrounds removed (vertex requirement)
  - Fission vertex with <100 μm resolution (fission radiograph)

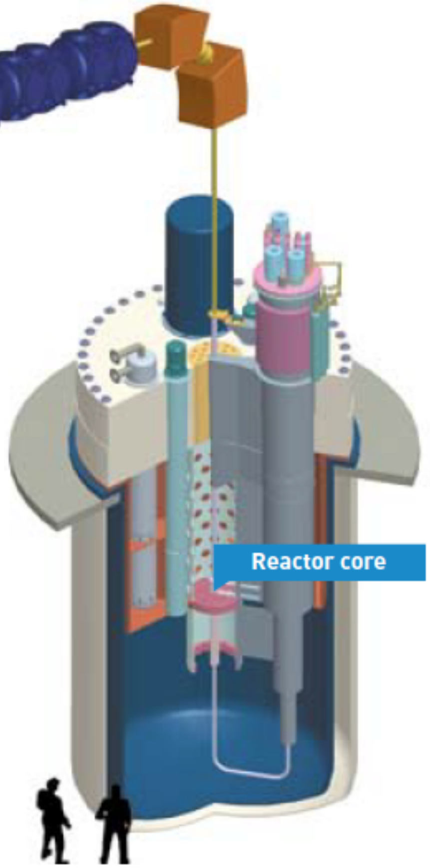


TPC at LANL

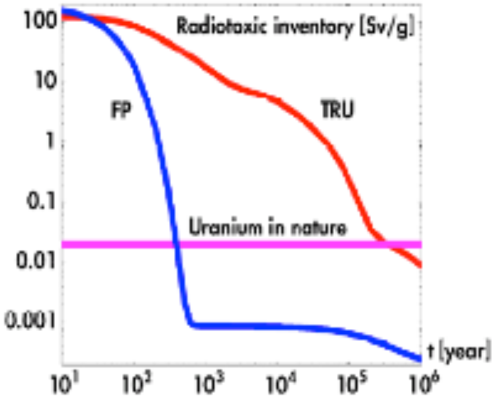


- The TPC installed at 90L at LANSCE
- 6 cards installed for first neutron beam test.
- Aug – Dec 2010

Accelerator Driven Systems
ADS



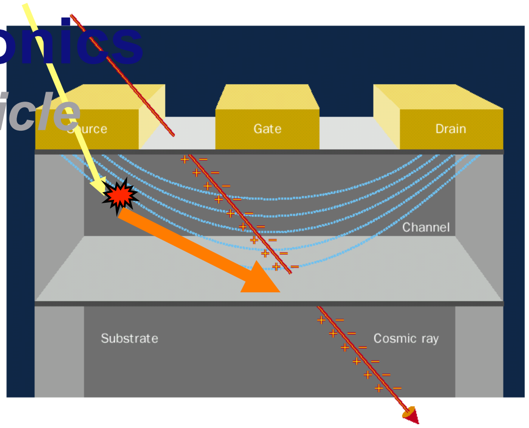
ADS for nuclear waste management



- Beam optics & irradiation system development
- Incineration strategies

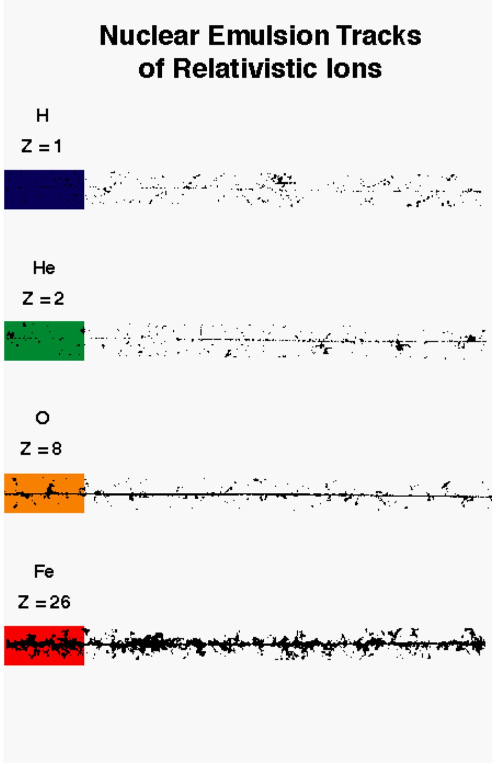
Single Event Effects in Electronics

initiated by a single charged particle



- **Direct ionization**
  - Charge deposit leads to upsets, transients, control failures, destructive failures
  - Energy <u>transfer</u> (LET) matters, not total energy
  - Dominant mechanism for Z>1 particles
- **Indirect ionization**
  - Primary particle scatters (fragments) lattice ion that then deposit charge
  - Interaction probability is energy-dependent
  - Upset probability depends on fragment LET
  - Dominant mechanism for proton SEE

Protons and heavier ions interact by BOTH mechanisms

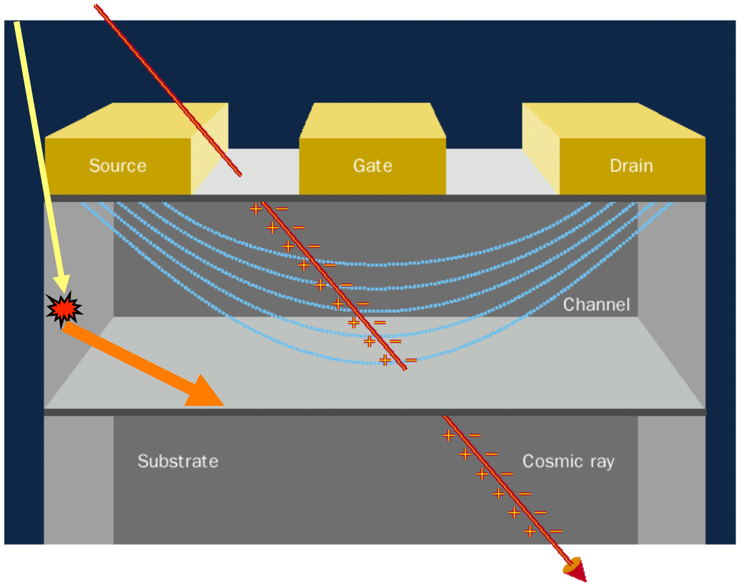

Nuclear Emulsion Tracks of Relativistic Ions

Radiation Effects on Electronics

Single Event Effects (SEE)

caused by a single charged particle

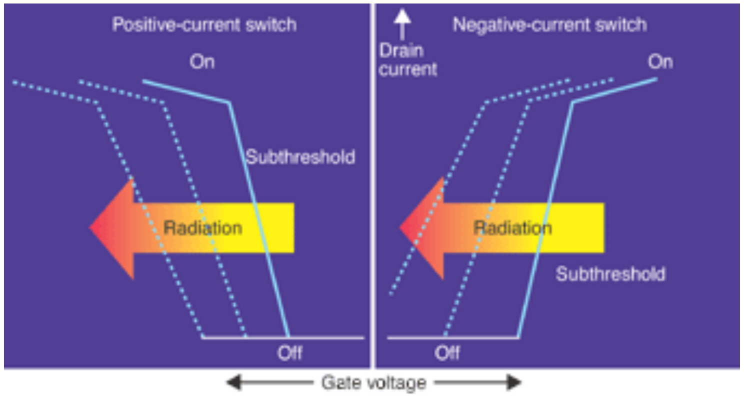
- **“bitflips”, glitches, control failures**
- **Can include destructive burnout**
- **Energy <u>transfer</u> (LET), not total particle energy for direct ionization**
- **Proton SEEs are a secondary process**
  - Energy <u>does</u> matter for nuclear interactions



Cumulative Exposure Effects

material structure changes over time

- Total ionizing dose (TID)
  - *Transistors prefer ON or OFF*
- Displacement damage
  - *Increased leakage currents*



US Heavy Ion SEE Facilities

Facility	Energy (MeV/n)	Ions	LET (MeV-cm^2/mg)	Ion Range (um)	Comments
LBNL	32	He-Ar	0.06-4.5	5560-690	1 m^3 vacuum, 16MeV/n in air 3.5” beam diameter 1x10^6 ions/cm^2/s, ~2000 hrs/yr
	16	N-Kr	1.2-25	506-163	
	10	B-Xe	0.9-58	287-99	
	4.5	B-Bi	1.6-100	79-54	
TAMU	40	Ne-Kr	1-14	1655-622	Air or vacuum, 1” beam diameter ~2000 hrs/yr Good range, slow ion changes
	25	Ne-Xe	1.7-38	799-286	
	15	Ne-Au	2.5-80	316-155	
BNL	1-8	Li-Au	0.3-85	200-20	Many ions beyond Bragg peak SEU time limited, competes with AGS, RHIC, and NSRL
MSU	140 123	Kr Xe	6.6 14.7	4500 3000	SEU run once / 2-3 months Expensive, ~$2500/hr

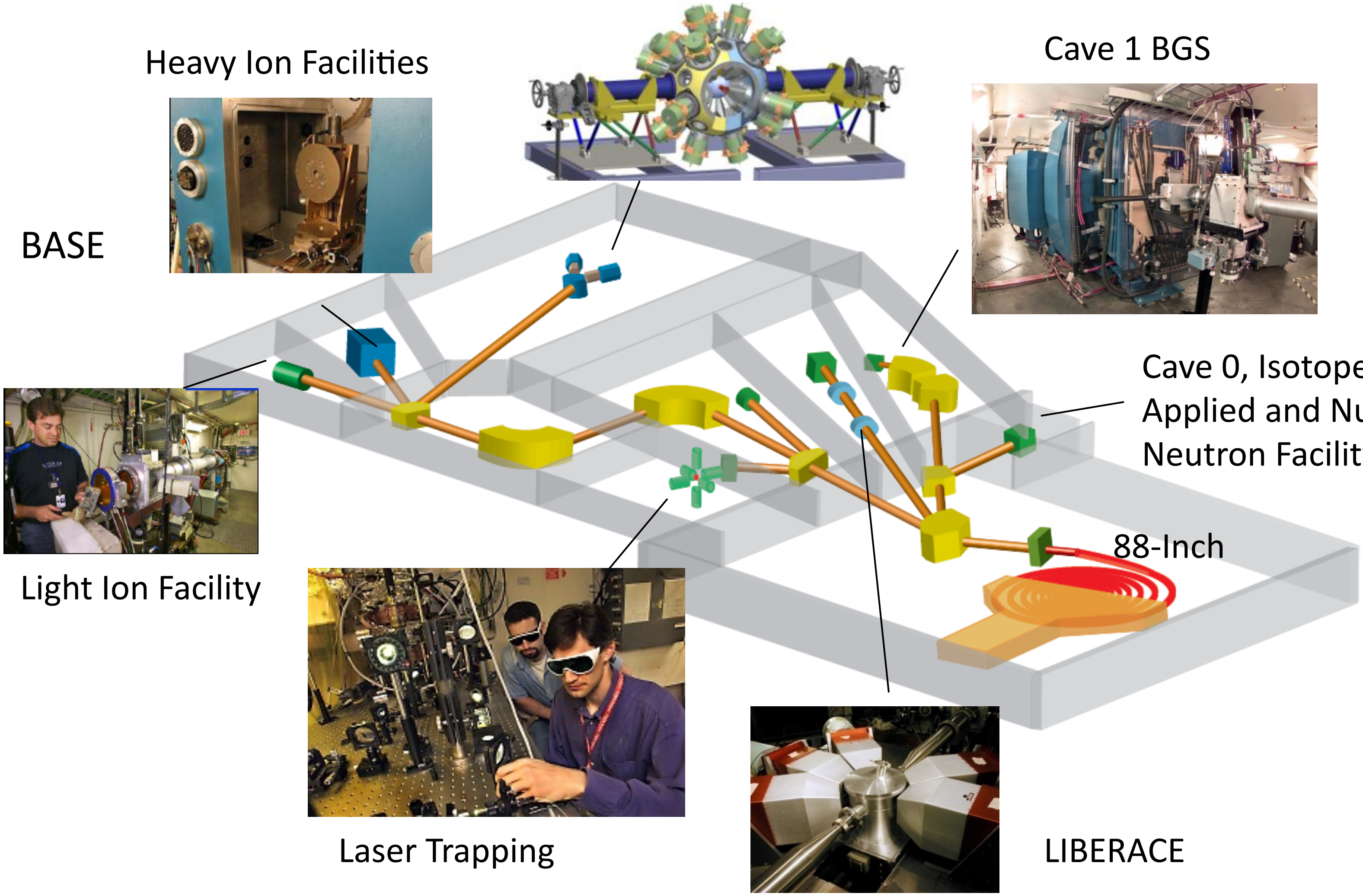
LBNL

- Fast ion changes – “cocktail” beams
- Protons available at same location
- 10-32 MeV neutron beams soon

TAMU

- Greater penetration range
- Higher LET coverage for given energy
- New science beams in 2011, SEU impact?

88-Inch Cyclotron Complex - Experimental Facilities



Cave 4C GRETINA/GRETA

Heavy Ion Facilities

Cave 1 BGS

BASE

Cave 0, Isotope production
Applied and Nuclear Science
Neutron Facility

88-Inch

Light Ion Facility

Laser Trapping

LIBERACE

Texas A&M University Cyclotron Institute Radiation Effects Testing

- Began in 1995 with 10 MeV/u ions, limited list of beams
- Added high energy series (15, 25, 40 & 55 MeV/u) over 1997-2005
- Offered "in-air" testing in 2000 - usage hours increased from ~500/yr to ~2,500/yr
- Usage by 1/3 Government/University and 2/3 Commercial agencies
- Increase in international agencies in the past few years, mainly France.

Testing Agencies

Actel Corporation
Aeroflex Corporation
Aerospace Corporation
Air Force
AMTEC Corporation
ASTRUM - France
ATK Mission Research
BAE Systems
Ball Aerospace
Boeing Corporation
Boeing Research & Technology
Boeing Satellite Systems
Broadcom Communications
CAMBR / University of Idaho
CEA - France
Cisco Systems
Data Device Corporation
Full Circle Research
General Dynamics
Georgia Tech University
Harris Semiconductor
HIREX - France
Honeywell
Hughes Space Communications
IBM Corporation
ICS Radiation
Innovative Concepts, Incorporated
Intel Corporation
International Rectifier
Intersil Corporation
ITT Aerospace
ITT Communications
JD Instruments
Johns Hopkins
Lockheed Martin
Los Alamos National Laboratory
Makel Engineering
Maxwell Engineering
McDonnell-Douglas
MD Robotics
MDA Corporation
Michigan State University-NSCL
Micro RDC
MicroSemi Corporation
Mitsubishi Heavy Industries
Motorola Corporation
NASA Goddard Space Flight Center
NASA Jet Propulsion Laboratory
NASA Johnson Space Center
NASA-Goddard Space Flight Center
National Semiconductor
Naval Research Laboratory
Naval Surface Warfare Center
Northrop Grumman
Novous Technologies
OptiComp Corporation
Peregrine Semiconductor
Prairie View A&M Center For Applied Radiation Research
Radiation Assured Devices
Raytheon Corporation
SAIC
Sandia National Laboratory
Save Incorporated
SEAKR Engineering
Silicon Space Technologies
Silicon Turnkey Solutions
SOREQ - Israel
Southwest Research Institute
Stapor Research
Star Vision
Sun Tronics
Texas Instruments
Thales Alenia-France
TRAD-France
United Space Alliance
University of Colorado
University of Idaho
University of Texas - El Paso
Vanderbilt University
VPT Incorporated
White Sands Army Research Laboratory
Xilinx Corporation

The Brookhaven Tandem Van de Graaff Facility

Ions for science and technology

Purpose:

To support nuclear physics research at the Relativistic Heavy Ion Collider (RHIC), radiobiology at the NASA Space Radiation Laboratory, and provide reimbursed services to a large community of industrial and technological users

Sponsor:

- U.S. Department of Energy Office of Nuclear Physics
- NASA

Funding:

The use as a RHIC injector is funded by DOE's Office of Nuclear Physics as part of the RHIC complex.

The services for industrial and space applications are provided on a full cost-recovery basis.

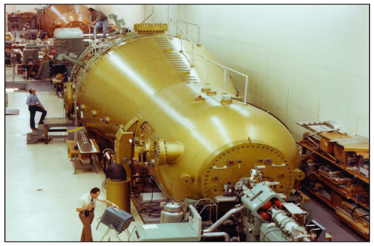
Features:

- Many different ion species
- Wide range of energies
- Wide range of intensities
- High beam quality
- Accurately known beam characteristics
- Reliable operation
- User friendly environment

Users:

- 55 U.S. companies, 9 universities, 8 agencies and laboratories, and NASA
- 8 European companies, the French AEC, and the European Space Agency
- 4 Japanese corporations and the Japanese Space Agency

Testing the radiation hardness of microchips at BNL's Tandem Van de Graaff facility



BNL's Tandem Van de Graaff accelerators

Two large electrostatic Tandem Van de Graaff accelerators are part of the Relativistic Heavy Ion Collider and NASA Space Radiation Laboratory complex, injecting beams of ions into other accelerators for studies of the fundamental components of matter and their interactions and the effects of simulated space radiation. They also provide a large variety of ion beams to a community of high tech industrial and space applications users on a cost-recovery basis. Thus valuable services are provided while maintaining good operational continuity and adequate staffing levels.

The ion species available range from protons to gold, and the energies and intensities can be accurately controlled and continuously varied over many orders of magnitude. This unusual versatility results in applications that would otherwise be impossible or inconvenient.

Two main user applications of beams produced in the Tandems are the testing of critical space related hardware and the fabrication of ultra small-pore filter materials.

Simulated space radiation

Computers in space, and other instrument components, are susceptible to radiation damage and transient errors due to the impact of energetic ions — which do not reach us on Earth, where we are protected by the Earth's atmosphere and magnetic field. The susceptibility of microchips to radiation has increased over the years as the size of the features shrinks to achieve increased computer power at reduced cost, weight, and power consumption.

The ions provided at the Brookhaven Tandem Facility enable users to test the radiation hardness of microchips and other materials under a wide variety of well-controlled conditions, which is essential for a detailed understanding and mitigation of the failures. For example, NASA used these beams to test some components of the Mars Rovers, one of which continues exploring that planet's surface today after landing seven years ago.

Making very fine filters

There is only one method for fabricating filter materials with very uniform pores down to 50 nanometers, or billionths of a meter, in diameter. Thin plastic films are irradiated with energetic heavy ions, and pores are developed later through preferential etching along the radiation-damaged tracks left behind by the ions.

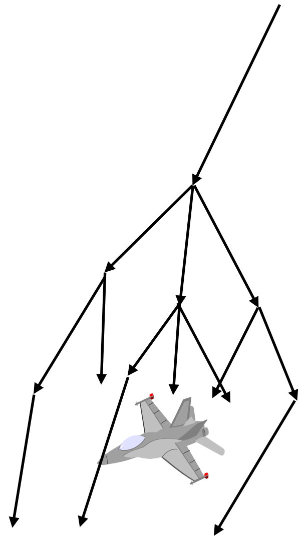
The irradiation part of this procedure is carried out at the Brookhaven Tandem Facility in a unique irradiation chamber owned by the General Electric Corporation. There are very few similar facilities worldwide.

Alternative (but much less appealing) sources of ions used for this purpose are fission products produced inside a nuclear reactor. By using a particle accelerator such as the Tandem, material activation problems are avoided, parallel pores can be generated, and there is control over the ion species and energy, leading to better quality and wider range of products.

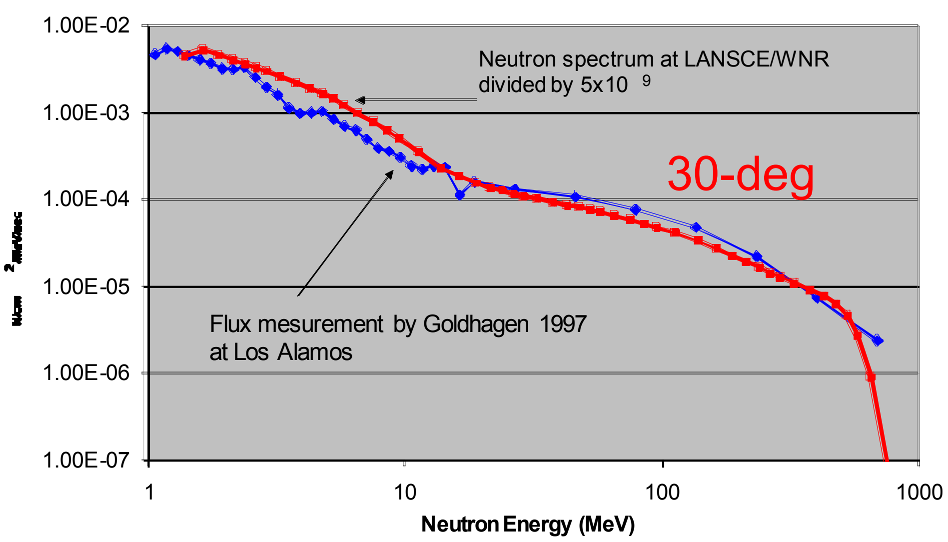
These fine-pore filters are used by the semiconductor industry to obtain particle-free water for rinsing silicon wafers; in medical and biological studies to separate microbes, viruses, and cells; and in other applications including filtration in the wine and beer industries.

(03-11)

Neutron Single Event Effects (SEE) are faults in electronic devices caused by neutrons from cosmic rays



- Neutrons are produced by cosmic rays in the upper atmosphere
- Neutrons have long mean-free paths so they penetrate to low altitudes
- Neutrons interact with Si and other elements in the device to produce charged particles
- Charged particles deposit charge in the sensitive volume which can cause the state of a node to change
- The neutron spectrum at WNR is similar to the neutron spectrum produced by cosmic rays in the atmosphere
- Industry can test their semiconductor parts by placing them in the WNR beam and measuring the failure rate with an acceleration factor of ~10^7
- 1 hour of testing at WNR is equivalent to several hundred years of use



Neutron Flux at Los Alamos and LANSCE/WNR

Results of LANSCE/WNR measurements determine problem with ASCI Q-Machine

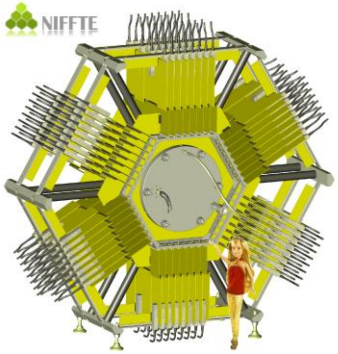
- The ASCI Q-Machine has 2048 nodes with a total of 8192 processors.
- During commissioning, it was observed that the Q-machine had a larger than expected failure rate. Approximately 20 fails / week (~3 fails / day).
- The question was whether this could be the result of neutron single-event upset.
- The system response was measured by putting one module of the Q-Machine in the LANSCE/WNR beam.
- Results of measurement accounted for approximately 80% of the failures. (IEEE Trans. Dev. Mat. Reliab. 5 2005)
- The failures were traced to a cache memory that was not error corrected.
- This result may have significant impact on future large computer systems

ASCI Q-Machine at Los Alamos National Laboratory

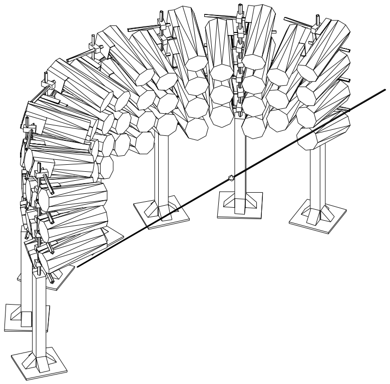
One module of the Q-Machine being tested at WNR

Nuclear science instruments at LANSCE

TPC, ionization chambers



FIGARO (n,xn+γ)

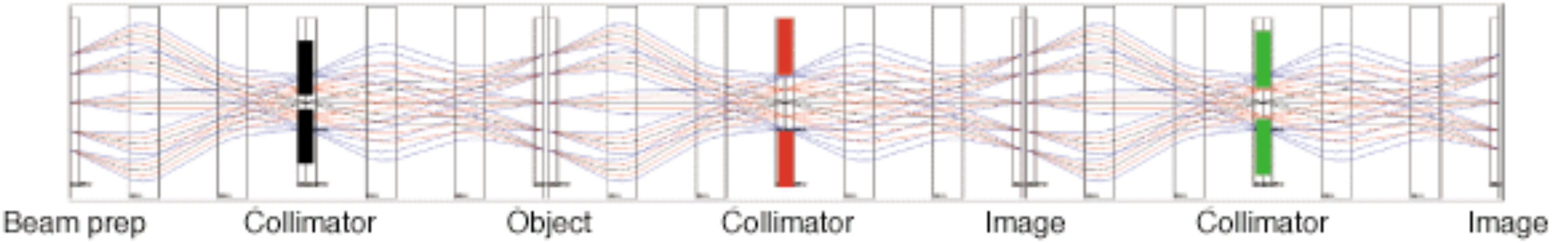


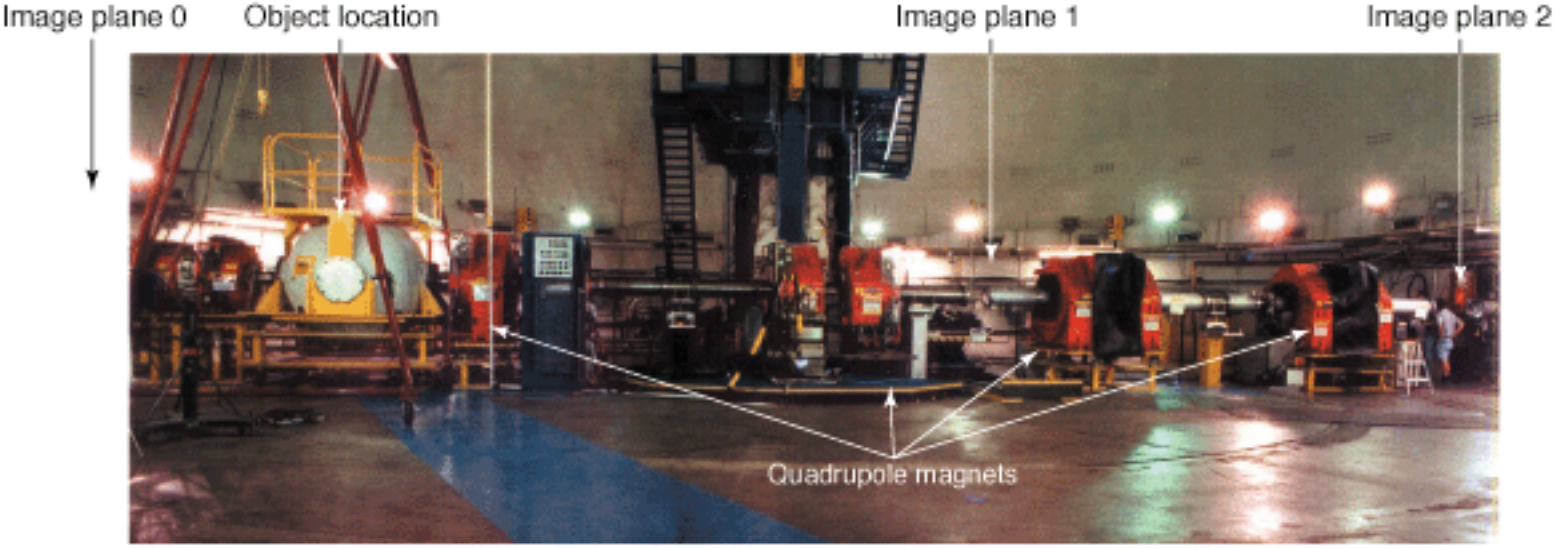
DANCE (capture)

N,Z (n, charged particle)

GEANIE (n,xγ)

Proton Radiography (PRAD)





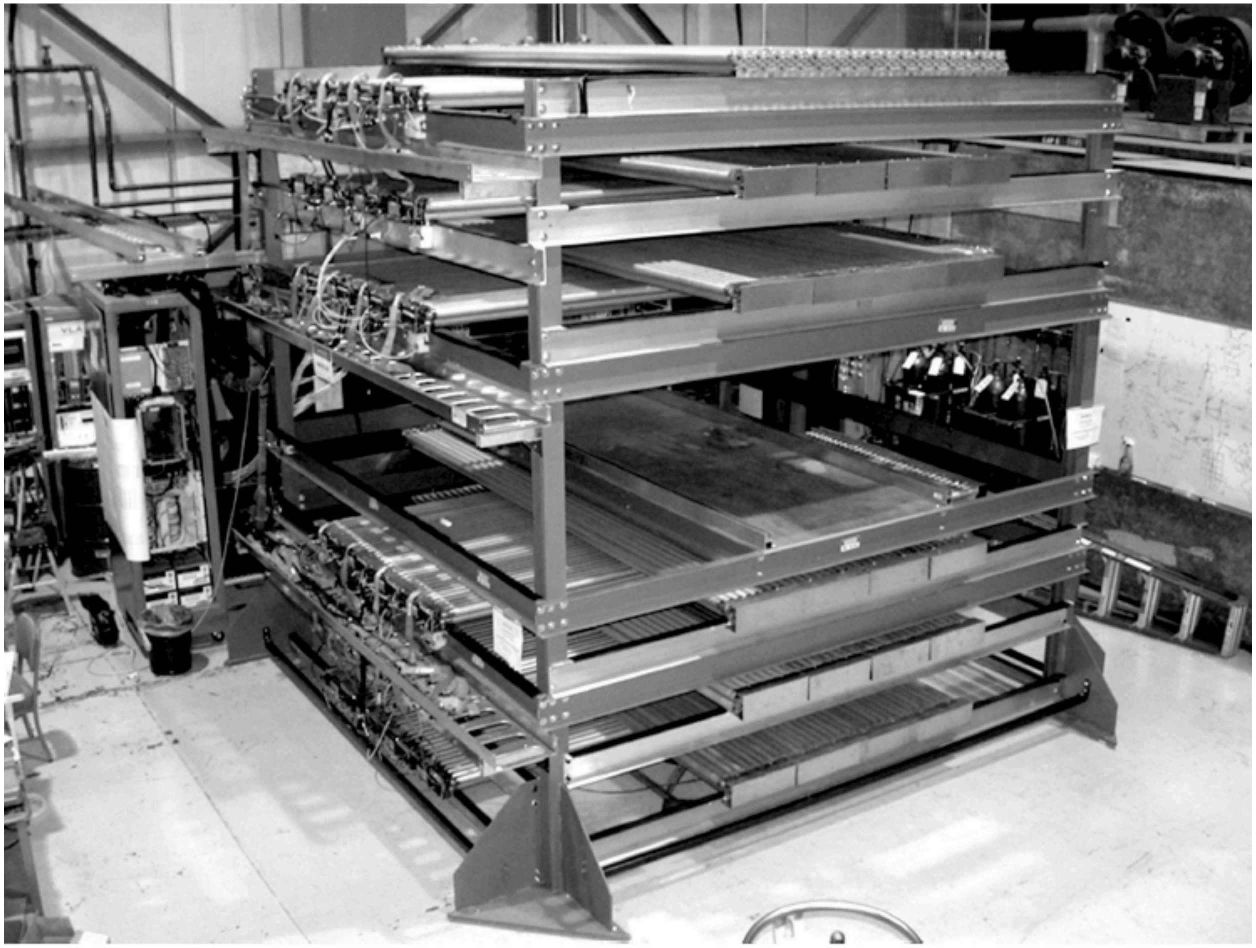
Explosive proton radiography experiments are conducted at the Los Alamos Neutron Science Center facility. In these experiments, a proton beam traveling inside a tube penetrates a target placed in a spherical vessel (left) to contain the explosion. Quadrupole magnets (orange) focus the scattered protons onto imaging detectors. This particular setup uses three imaging stations, including one installed in front of the target to examine the profile of the incoming proton beam. Collimators are located inside the beam tube.

Proton Radiography (PRAD)

Some experiments have investigated the hydrodynamic properties of shocked metal. (a) A 4-centimeter-diameter tin disk sits on a block of high explosive that is sandwiched between two layers of aluminum. (b) Some 10 microseconds following the blast, a radiograph reveals how the top aluminum plate is bent by the blast and how the tin falls apart from the explosive shock wave. The radiographs also reveal how gas and small chunks of matter intermix. (c) A computer simulation of the proton radiography experiment in (a) and (b).

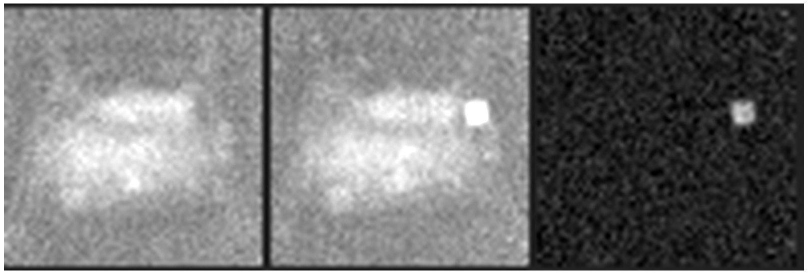
Cosmic Ray Muon Tomography

The experimental apparatus



Pb + Automobile Engine

Photograph of the engine in the LMT



Mean scattering angle for a slice through the scene 50 cm above the base plate. The left panel shows the engine, the middle panel the engine plus the 10x10x 10 cm3 lead sample, and the right panel the difference.

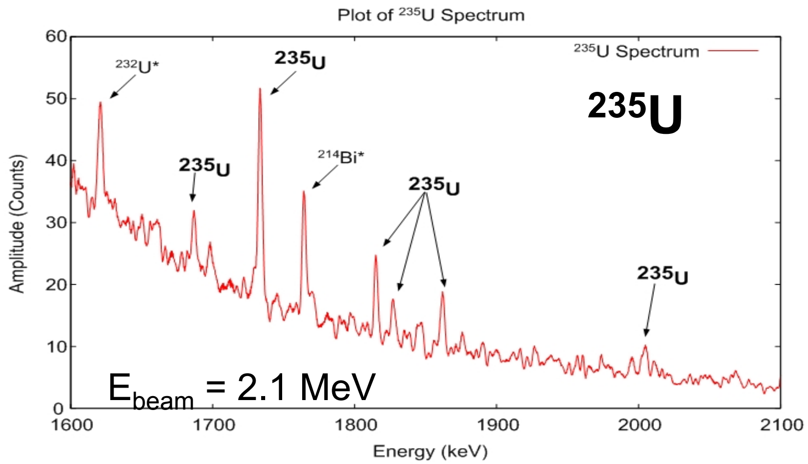
NRF for Nuclear Materials Management

- **Properties of NRF inspection**
  - Identification of stable isotopes without sample preparation and destruction
  - Identification of isotopic content inside sealed containers
  - Identification of stable and radioactive isotopes behind shielding
  - Rapid isotopic identification

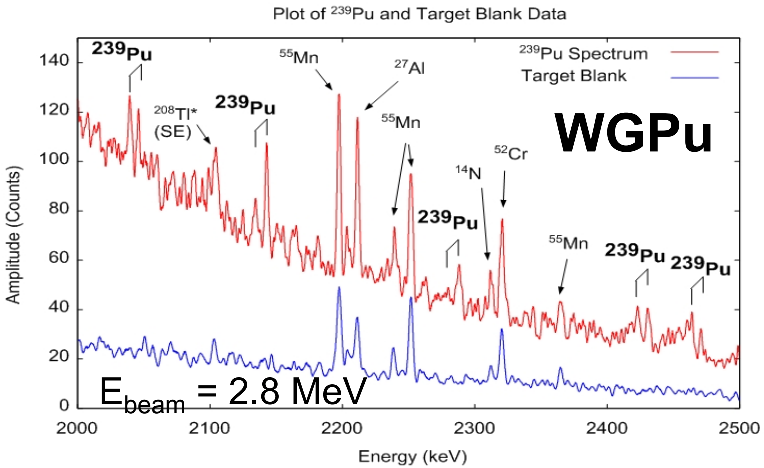
- **Potential Applications**
  - SNM: ^{235}U, ^{239}Pu and the power cycle actinides
  - MOX fuel pellets: ~ 3% HEU, country specific elements
  - Storage containers: 3013, 9975, 48Y, 30B
  - Fuel Reprocessing Waste products: technique and country specific
  - Reprocessed and Ore Refined SNM: technique and country specific
  - Nuclear Fuel cladding: Alloys specific to country and industry
    - Zircaloy alloy: Sn (USA), Nb (Russia), Others: Al, Ni, Cr, Fe, Ti and N.
  - Geographical fingerprints: O, C, Pb isotopes

- **"*Nuclear Forensic Analysis*", Kenton J. Moody, Ian D. Hutcheon, and Patrick M. Grant, Taylor & Francis, CRC Press, 2005**

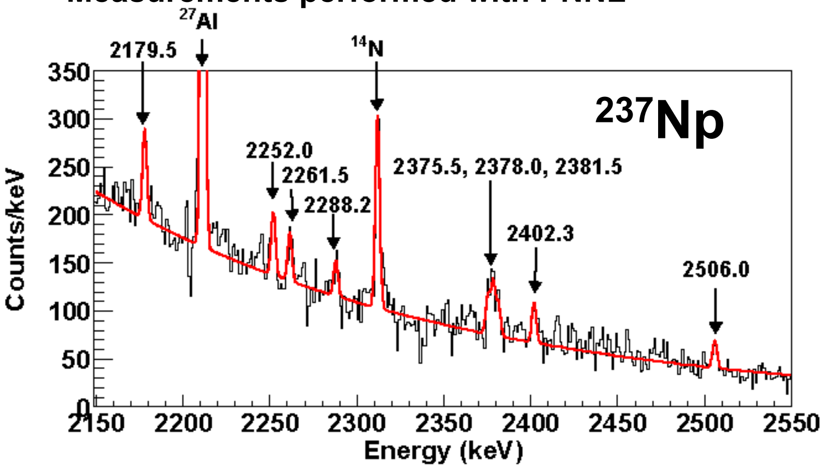
Actinide NRF Signatures



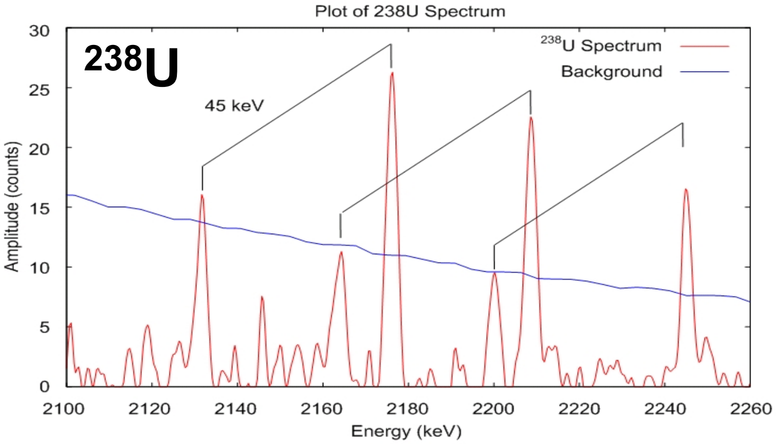
Measurements performed with PNNL



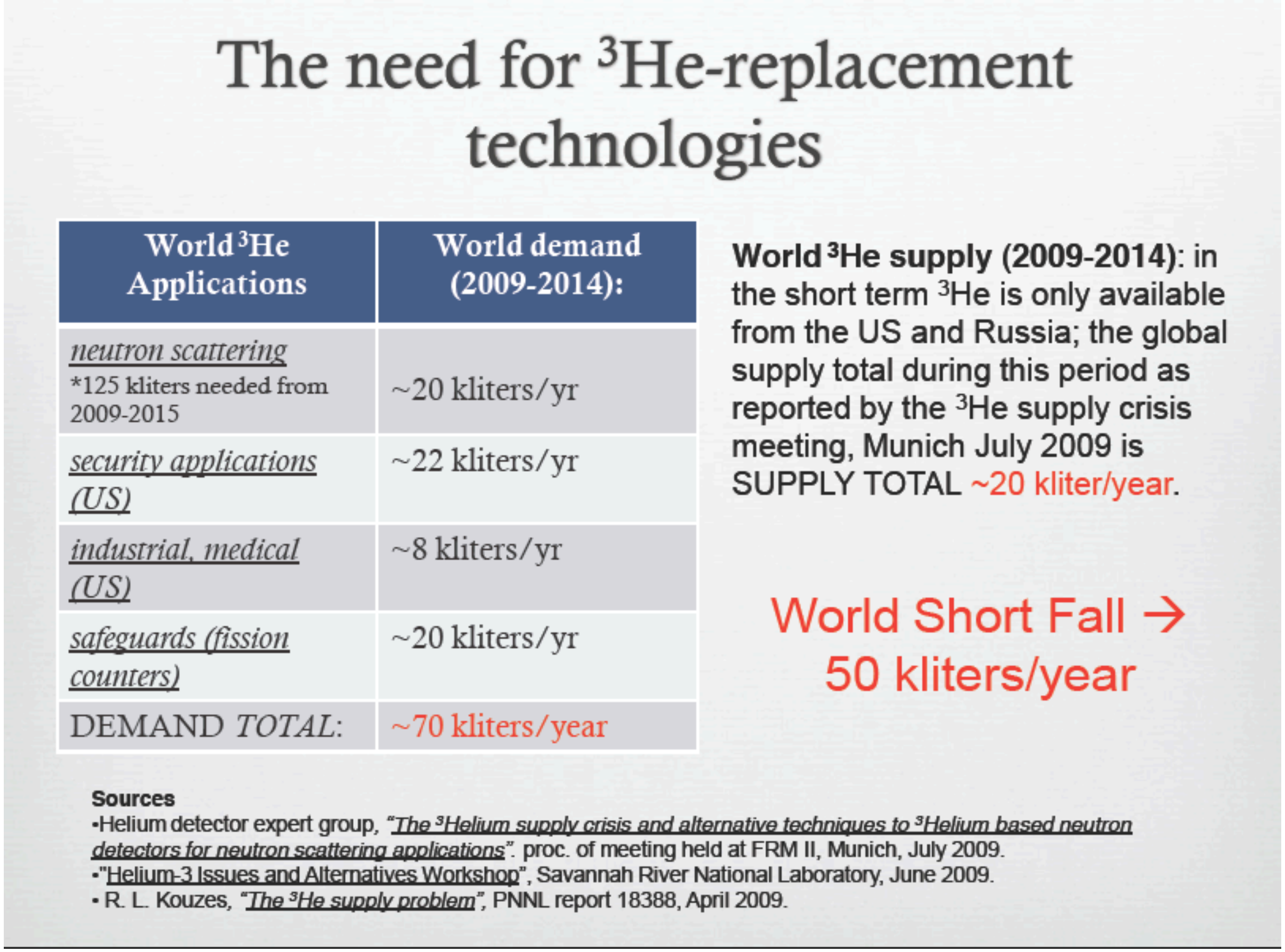
Measurements performed with LLNL



Measurements performed with UC-Berkeley



- Unambiguous signature for SNM isotopes and other Actinides
- NRF states in SNM < 3 MeV



The need for ^{3}He-replacement technologies

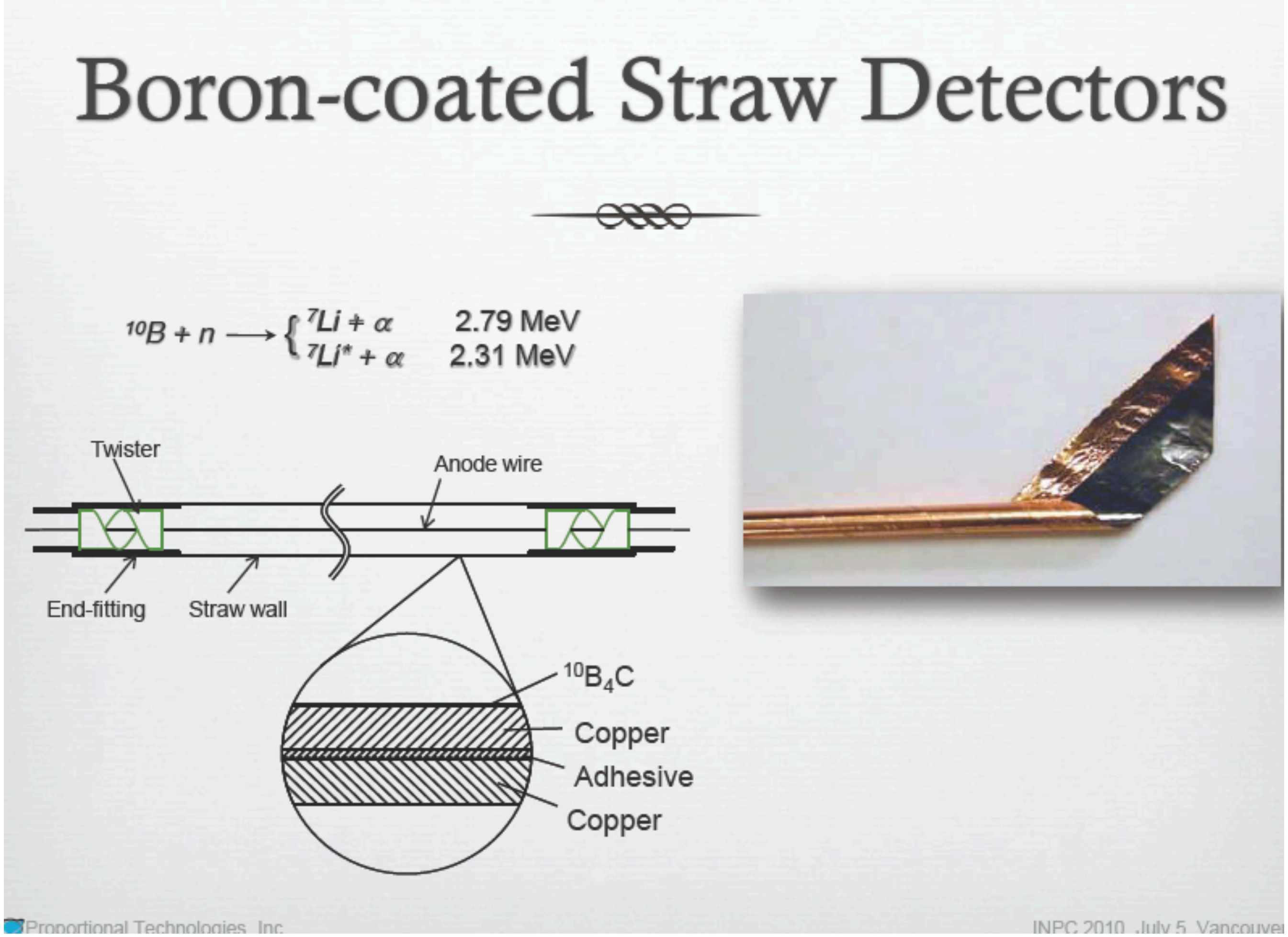
World ^{3}He Applications	World demand (2009-2014):
neutron scattering *125 kliters needed from 2009-2015	~20 kliters/yr
security applications (US)	~22 kliters/yr
industrial, medical (US)	~8 kliters/yr
safeguards (fission counters)	~20 kliters/yr
DEMAND *TOTAL*:	~70 kliters/year

World ^{3}He supply (2009-2014): in the short term ^{3}He is only available from the US and Russia; the global supply total during this period as reported by the ^{3}He supply crisis meeting, Munich July 2009 is SUPPLY TOTAL ~20 kliter/year.

World Short Fall → 50 kliters/year

Sources

- Helium detector expert group, *"The ^{3}Helium supply crisis and alternative techniques to ^{3}Helium based neutron detectors for neutron scattering applications"*. proc. of meeting held at FRM II, Munich, July 2009.
- "Helium-3 Issues and Alternatives Workshop", Savannah River National Laboratory, June 2009.
- R. L. Kouzes, *"The ^{3}He supply problem"*, PNNL report 18388, April 2009.

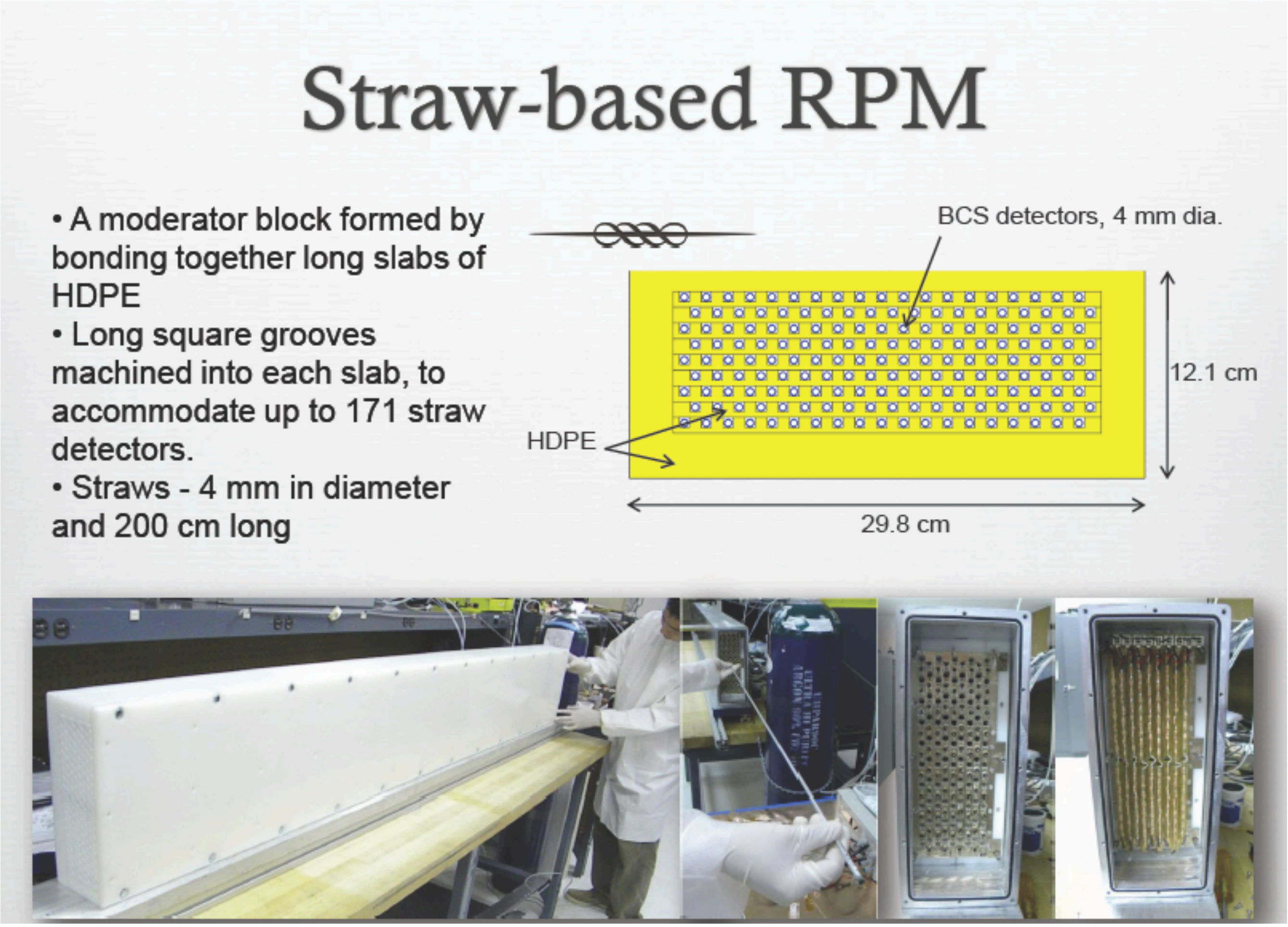


Boron-coated Straw Detectors

$$^{10}B + n \longrightarrow \begin{cases} ^{7}Li + \alpha & 2.79\ \text{MeV} \\ ^{7}Li^{*} + \alpha & 2.31\ \text{MeV} \end{cases}$$

Proportional Technologies, Inc

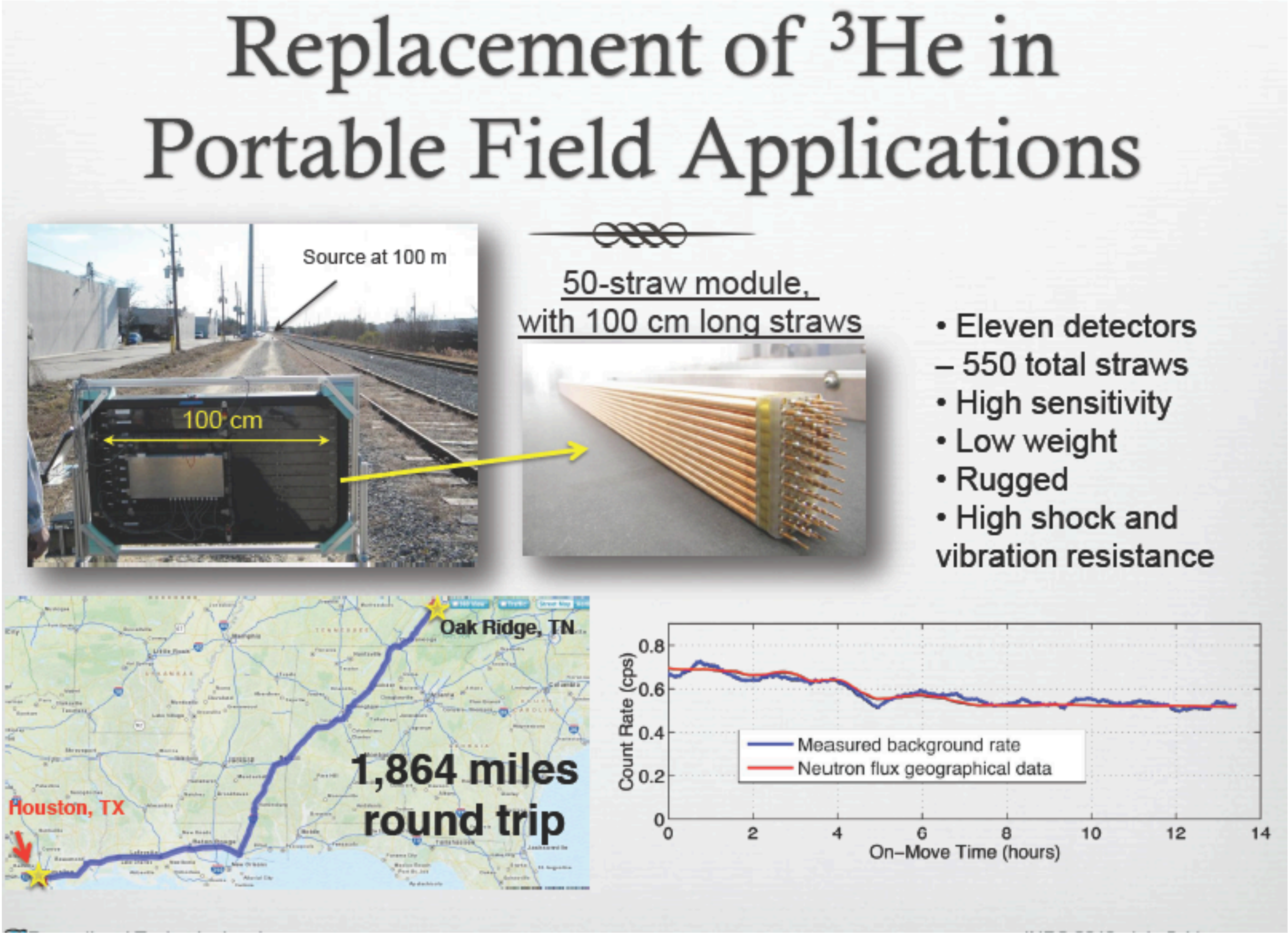
INPC 2010, July 5, Vancouve



Straw-based RPM

- A moderator block formed by bonding together long slabs of HDPE
- Long square grooves machined into each slab, to accommodate up to 171 straw detectors.
- Straws - 4 mm in diameter and 200 cm long

LBNL and Tech Source Inc.



Replacement of ^{3}He in Portable Field Applications

50-straw module, with 100 cm long straws

- Eleven detectors
  – 550 total straws
- High sensitivity
- Low weight
- Rugged
- High shock and vibration resistance

LBNL and Tech Source Inc.

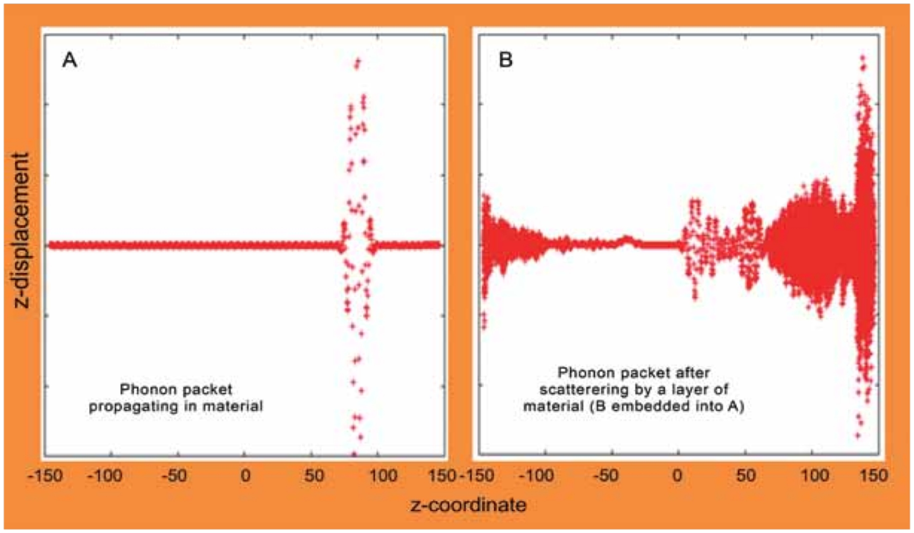
Center for Materials Science of Nuclear Fuels (CMSNF)

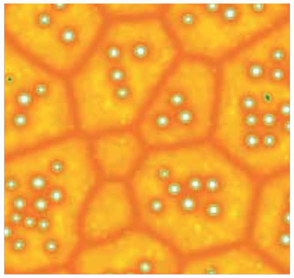
Director
Todd Allen

Lead Institution
Idaho National Laboratory

Partner Institutions
Argonne National Laboratory
Colorado School of Mines
University of Florida
Florida State University
Oak Ridge National Laboratory
University of Wisconsin

Research Topics
nuclear, extreme environment, defects, matter by design, high performance computing, inorganic materials, actinides





ABOVE: Model prediction of void nucleation under irradiation. **TOP:** A packet of phonons in silicon (material A) propagate and interact with a thin slab of silica (material B) embedded along its trajectory, resulting in a complex scattering of the heat transferring phonons (right). The outcome of similar scattering events at voids and dislocations will provide input to the simulations of thermal transport in uranium oxide.

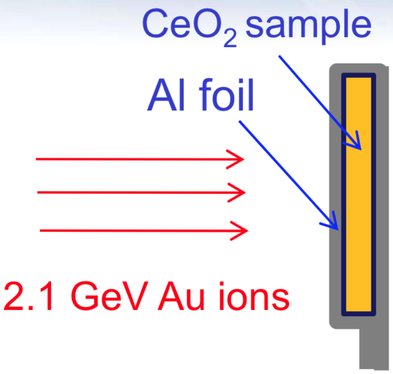
Mission

To achieve a first-principles based understanding of the effect of irradiation-induced defects and microstructures on thermal transport in oxide nuclear fuels.

Achievements

Scientists at CMSNF are developing capabilities to link models that describe nanometer-sized phenomena to models that describe important physical properties in nuclear fuel. The specific nanometer-sized phenomena these models predict are the formation of defects in irradiated nuclear fuel. Key physical properties include the physical dimensions of a sample and the ability to transfer heat. Researchers at CMNSF have successfully developed a model that describes how nanometer-sized pockets empty of atoms, known as voids, are formed under irradiation and how those voids block heat flow, also known as phonon transport. Contrary to the previously held beliefs, CMSNF scientists discovered that the time evolution of the formation of voids during irradiation differs from the time evolution of the increase in material volume, known as swelling. From a heat transfer point of view, voids act to block the carriers of heat (phonons) in the material. CMSNF scientists are now investigating in greater detail how the voided spaces limit heat flow. These results may ultimately help improve the performance of fuel in nuclear reactors under normal and accident scenarios.

Swift Heavy Ion Irradiation

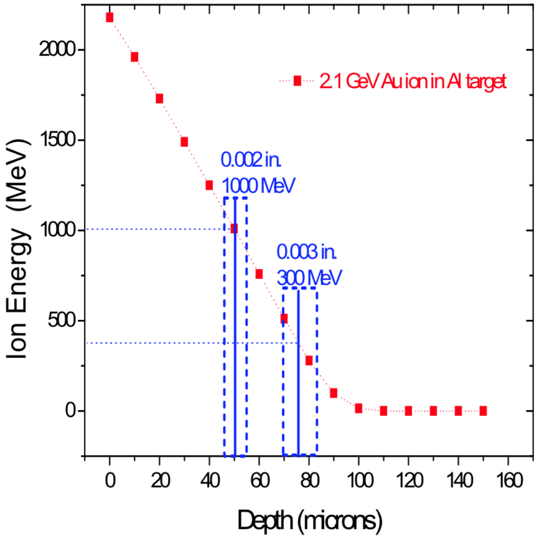


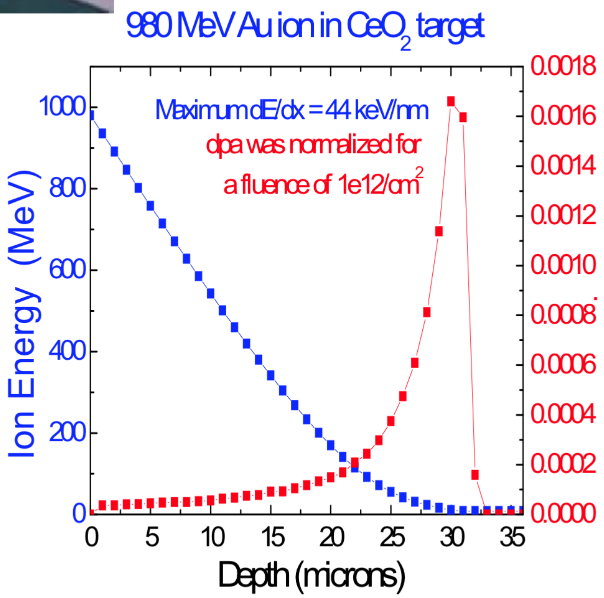
CeO_2 sample

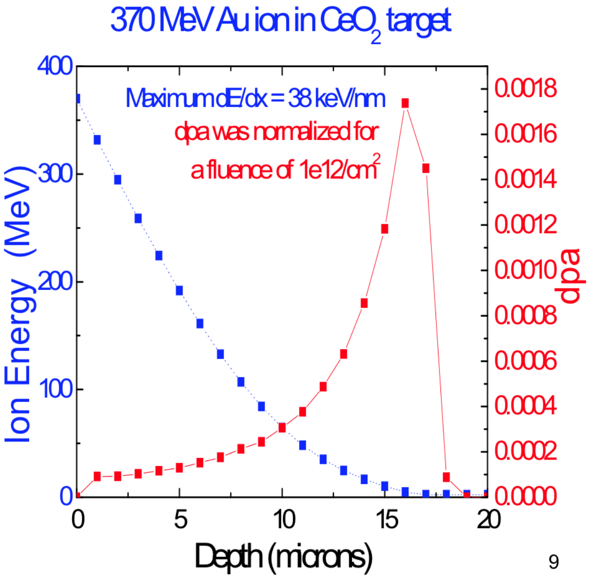
Al foil

2.1 GeV Au ions

- Polycrystalline CeO_2
    - 3mm discs, 1mm thick
- Au ions
- Two energies:
    - 1GeV ± 120MeV
    - 300MeV ± 200MeV
- Fluences (ions/cm^2):
    - $5\times10^{10} \sim 5\times10^{12}$
- Room Temperature

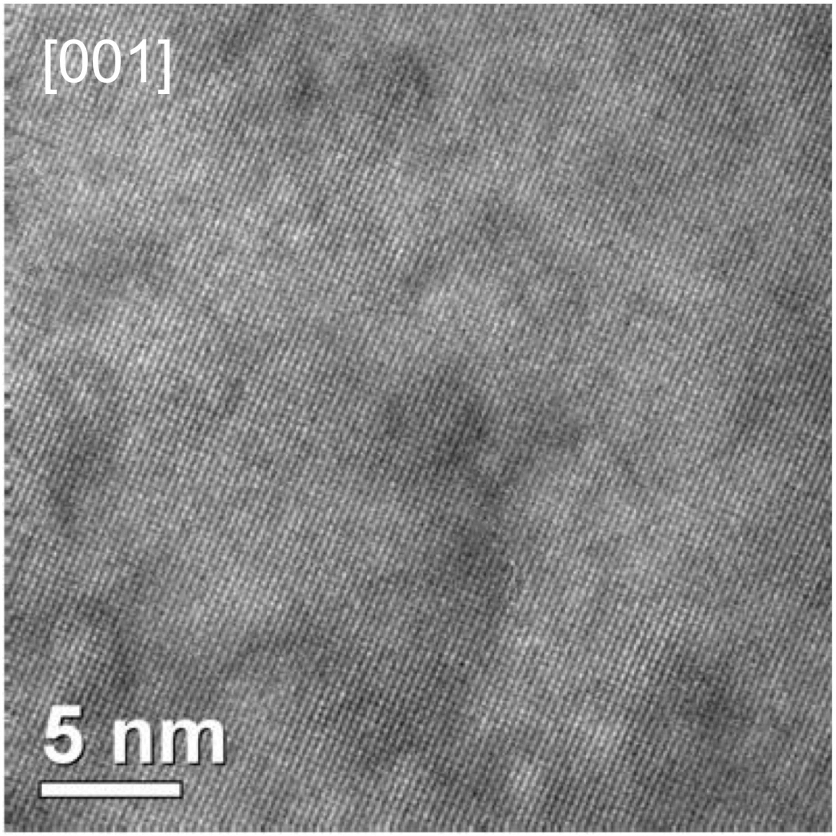






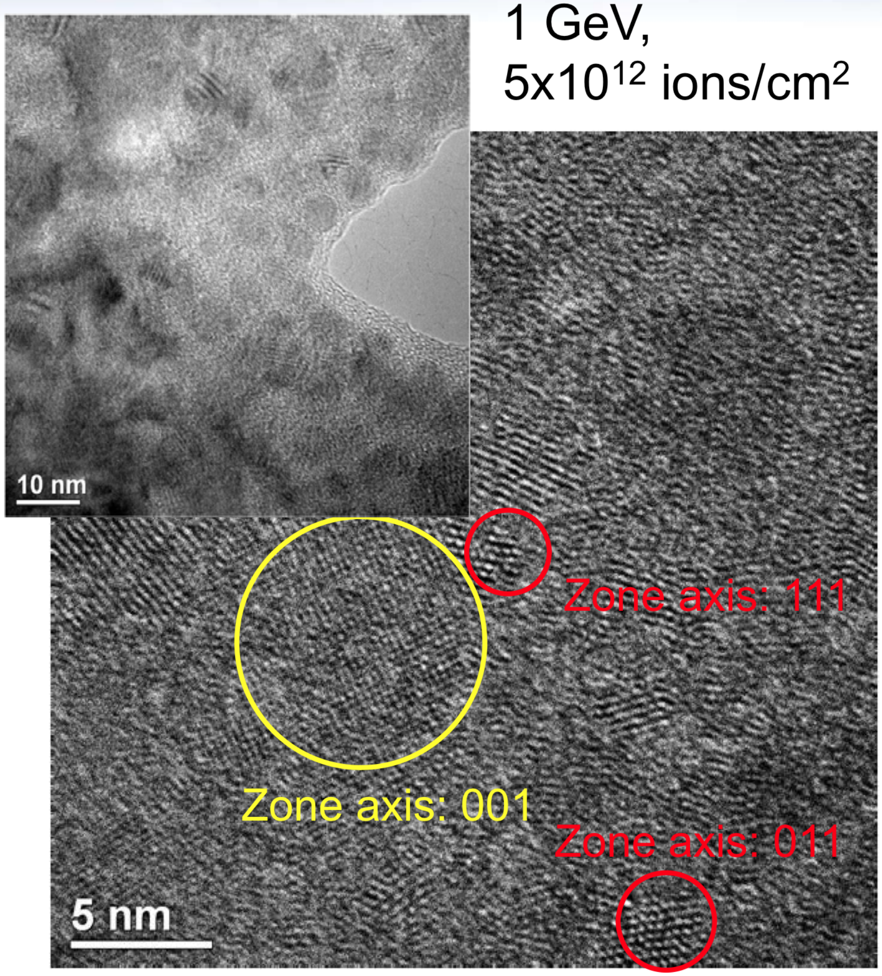
Substructure:

300 MeV,
5x10^{10} ions/cm^{2}



- No apparent damage from ion tracks
- Low defect content

1 GeV,
5x10^{12} ions/cm^{2}



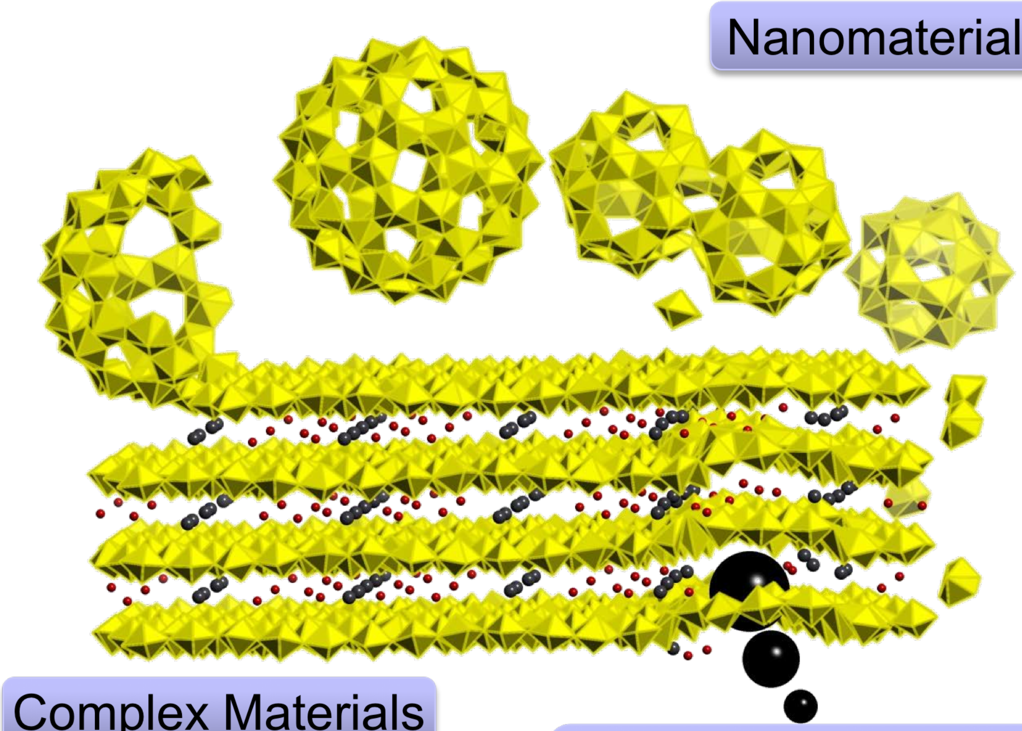
- Ion track damage apparent
- Extensive number of recrystallized regions

Materials Science of Actinides

Energy Frontier Research Center

Office of Science
U.S. Department of Energy

Nanoscale behavior
Thermochemistry
Synthesis
Computational Models
Applications



Nanomaterials

Complex Materials

Extreme Environments

MICHIGAN

THE UNIVERSITY OF CALIFORNIA DAVIS

MINNESOTA

THE GEORGE WASHINGTON UNIVERSITY WASHINGTON DC

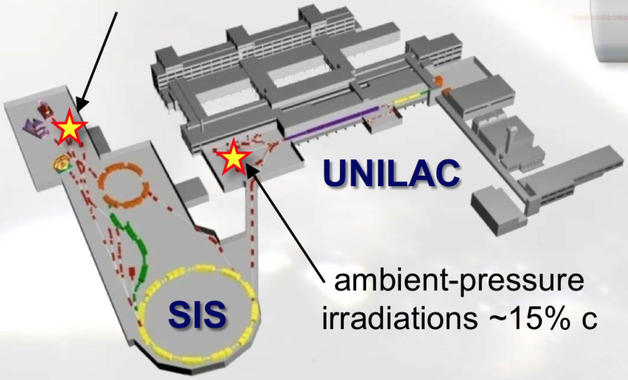
RENSSELAER POLYTECHNIC INSTITUTE 1824

OAK RIDGE National Laboratory

Sandia National Laboratories

SRNL
SAVANNAH RIVER NATIONAL LABORATORY

Experimental Approach



high-pressure
irradiations ~50% c

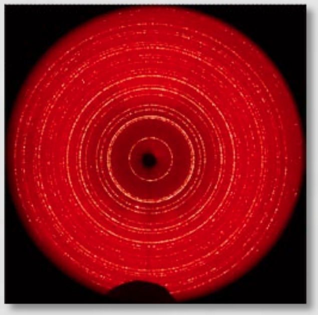
ambient-pressure
irradiations ~15% c

GSI Helmholtz Center for Heavy Ion Research Darmstadt, Germany

heavy ions:	^{197}Au, ^{208}Pb, ^{238}U
kinetic energy:	2 – 50 GeV
energy loss:	10 – 55 keV/nm
ion dose:	10^{13} ions/ cm^2

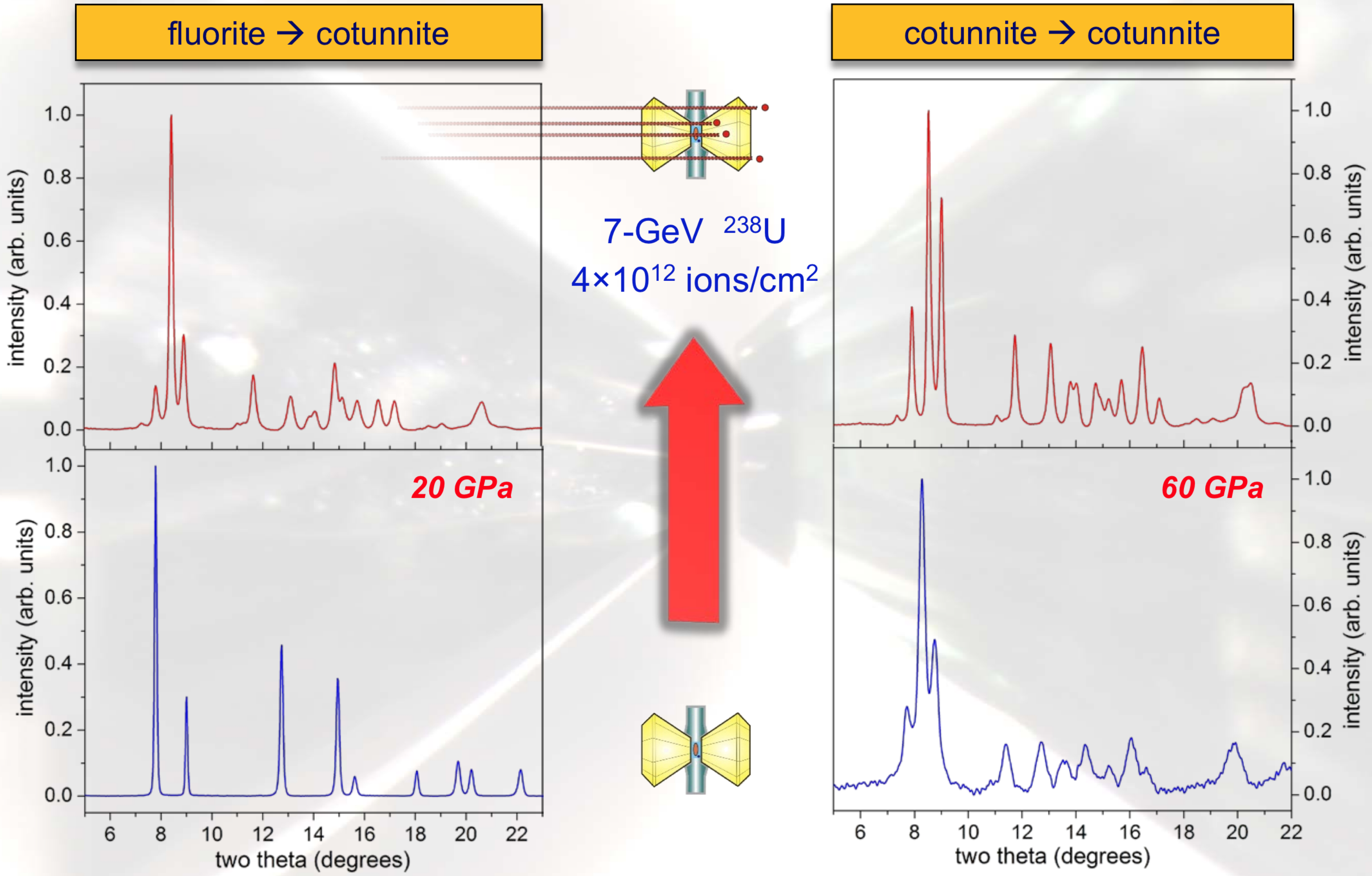
transmission electron
microscopy (TEM)

***Synchrotron Facilities:
APS, ALS, NSLS, CHESS***



X-ray diffraction (XRD)
Infrared Spectroscopy (IR)

Combined Pressure & Irradiation in CeO_2



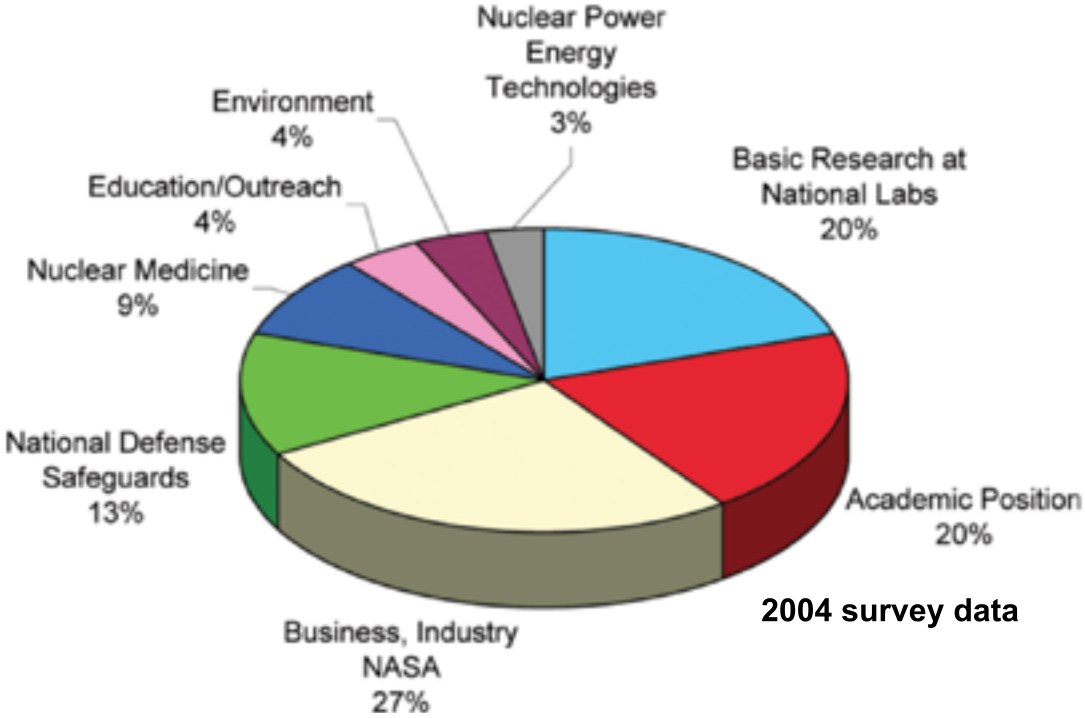
fluorite → cotunnite

cotunnite → cotunnite

7-GeV ^{238}U

4×10^{12} ions/cm^2

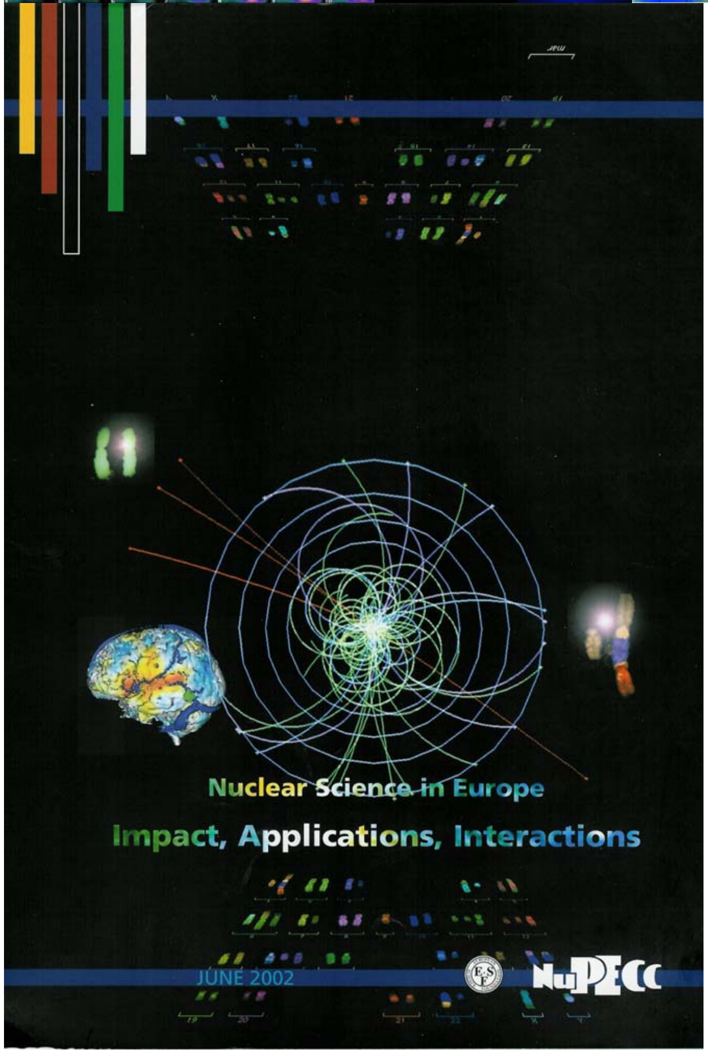
Training the Next Generation of Innovators



2004 survey data

The pie chart above shows that many scientists who receive Ph.D.s in nuclear science go on to apply their knowledge working in professions outside the field after five to 10 years. Nuclear physics research facilities serve as training grounds for the next generation of scientists and engineers.

The Office of Nuclear Physics within the Department of Energy's (DOE) Office of Science has a long and productive partnership with universities and provides education opportunities and support to university professors and students associated with its basic nuclear physics research.
This educational pipeline further fuels our economy through work in fields as diverse as national security, medicine, energy generation, space exploration, and more.



Nuclear Science in Europe

Impact, Applications, Interactions

JUNE 2002

NuPECC

Physics Applications

Energy

- ADS & Transmutation
- Fusion confinement
- Nuclear Waste
- Energy Storage

Life Science

- Medical Diagnostics
- Medical Therapy
- Radiobiology
- Biomedical tracers

Nuclear Defense

- Weapon Analysis
- Functionality
- Long-Term Storage

Nuclear Forensics

- Homeland Security
- Risk Assessments
- Nuclear Trafficking
- Proliferation

Material Analysis

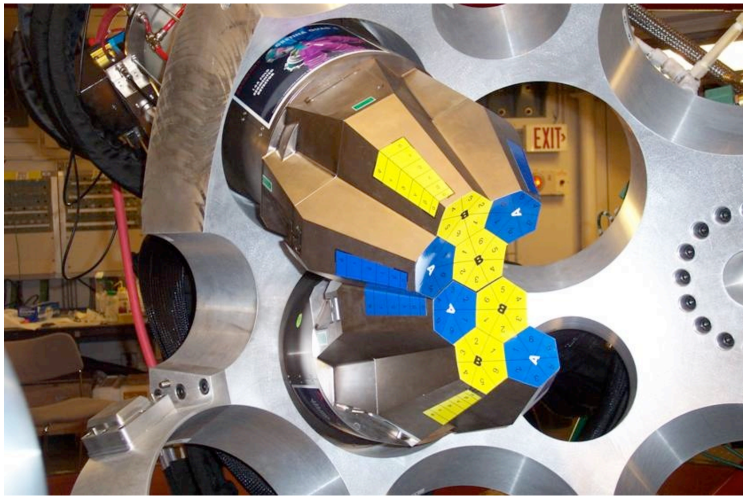
- Nanotechnology
- Ion Implantation
- Material Structure
- Geology & Climate
- Environment
- Art & Archaeology

Computation

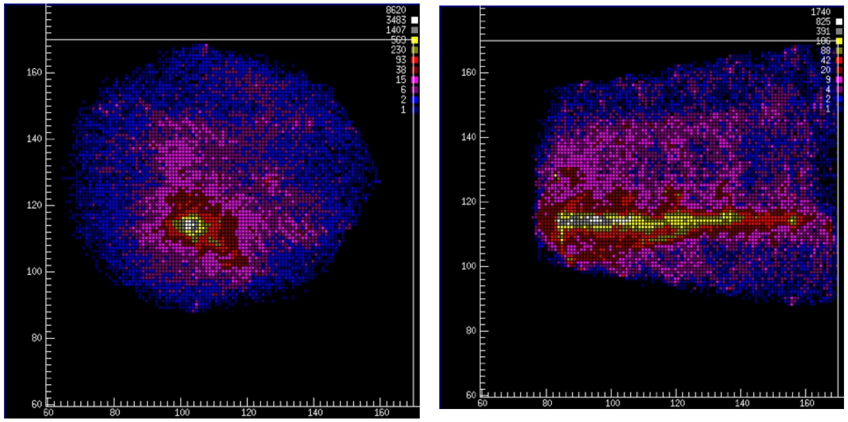
- Monte Carlo Simulation
- Network Simulation
- Software Development
- Quantum computing

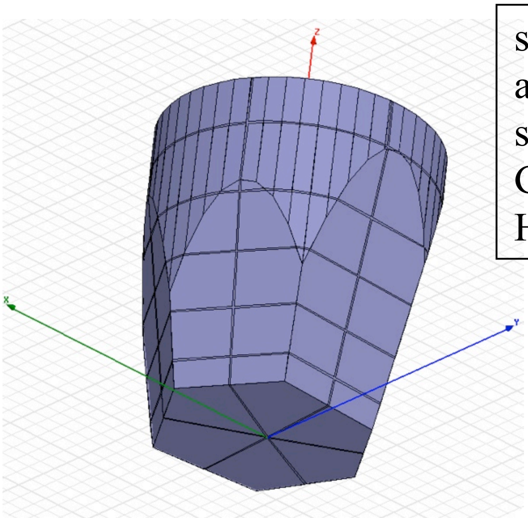
The GRETINA Spectrometer

- first-generation gamma-ray tracking detector
  - eff. > 5.4% @ 1.3MeV
  - P/T > 55% @ 1.3 MeV
- employs highly-segmented HPGe detectors enabling:
  - high energy resolution
  - position determination



^{137}Cs pencil beam

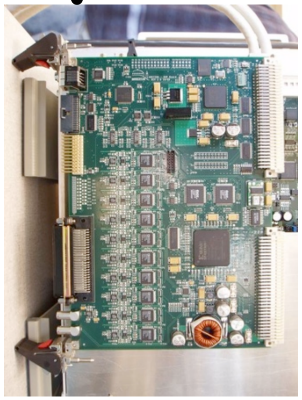




schematic of a 36-way segmented GRETINA HPGE crystal

Tracking Procedure, Applications

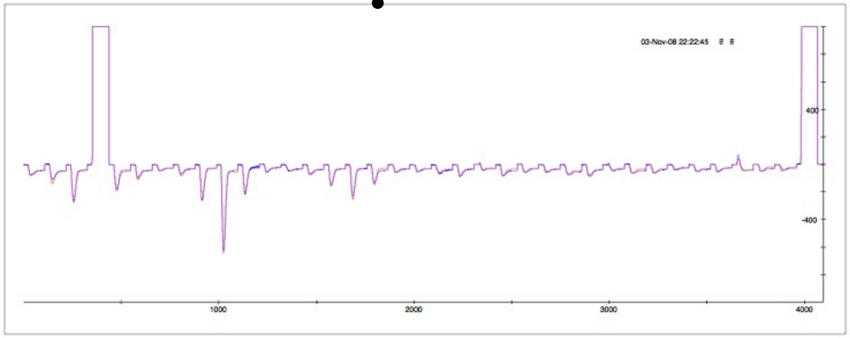
digitize segment signals

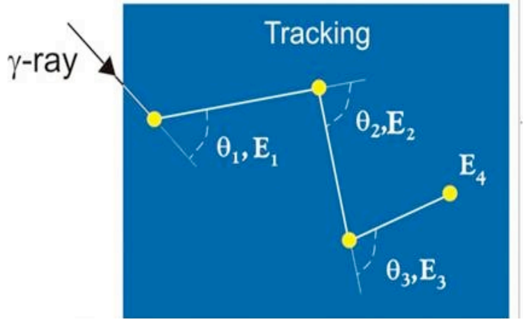


locate interaction points by comparison to detector simulation

group/order interaction points by best fit to Compton scattering formula

- technology applicable to gamma-ray imaging applications:
  - location and identification of sources for verification, homeland security
  - medical imaging





Nuclear Science

*N*uclear Science is the study of the structure, properties, and interactions of the atomic nuclei. Nuclear scientists calculate and measure the masses, shapes, sizes, and decays of nuclei at rest and in collisions. They ask questions, such as: Why do nucleons stay in the nucleus? What combinations of protons and neutrons are possible? What happens when nuclei are compressed or rapidly rotated? What is the origin of the nuclei found on Earth?

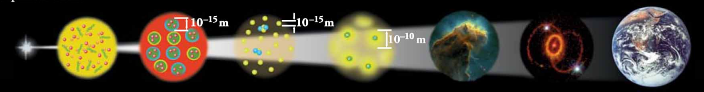
Legend
- *proton*
- *neutron*
- *electron* (e^-)
- *positron* (e^+)
- *neutrino* (ν)
- *antineutrino* ($\bar{\nu}$)
- *quark*
- *gluon field*
- *gluon*
- *photon* (γ)

A *mass number*, Z *atomic number*: $^{14}_{6}\mathrm{C}$

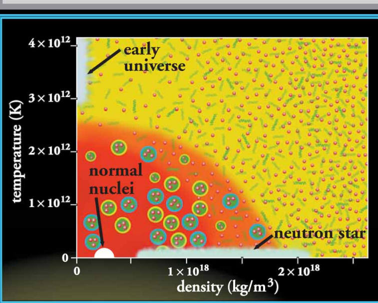
$N_{\text{neutron number}} = A - Z$

Expansion of the Universe

*A*fter the Big Bang, the universe expanded and cooled. At about 10^{-6} second, the universe consisted of a soup of quarks, gluons, electrons, and neutrinos. When the temperature of the Universe, $T_{universe}$, cooled to about 10^{12} K, this soup coalesced into protons, neutrons, and electrons. As time progressed, some of the protons and neutrons formed deuterium, helium, and lithium nuclei. Still later, electrons combined with protons and these low-mass nuclei to form neutral atoms. Due to gravity, clouds of atoms contracted into stars, where hydrogen and helium fused into more massive chemical elements. Exploding stars (supernovae) form the most massive elements and disperse them into space. Our earth was formed from supernova debris.



	Big Bang	quark-gluon plasma	proton & neutron formation	formation of low-mass nuclei	formation of neutral atoms	star formation	dispersion of massive elements	today
$T_{universe}$		$>10^{12}$ K	10^{12} K	10^{9} K	4,000 K	50 K–3 K	<50 K–3 K	3 K
time		10^{-6} s	10^{-4} s	3 min	400,000 yr	3×10^{8} yr	$>3 \times 10^{8}$ yr	14×10^{9} yr

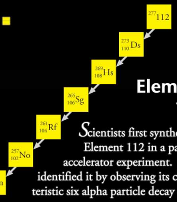


Phases of Nuclear Matter

*N*uclear matter can exist in several phases. When collisions excite nuclei, individual protons and neutrons may evaporate from the nuclear fluid. At sufficiently high temperature or density, a gas of nucleons (red background) forms. At even more extreme conditions, individual nucleons may cease to have meaningful identities, merging into the quark-gluon plasma (yellow background). Current data provide hints that physicists have glimpsed the quark-gluon plasma.

Unstable Nuclei

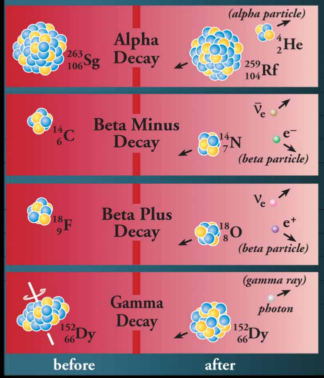
*S*table nuclides form a narrow white band on the Chart of the Nuclides. Scientists produce unstable nuclides far from this band and study their decays, thereby learning about the extremes of nuclear conditions. In its present form, this chart contains about 2500 different nuclides. Nuclear theory predicts that there are at least 4000 more to be discovered with Z ≤ 112.



Element 112

*S*cientists first synthesized Element 112 in a particle accelerator experiment. They identified it by observing its characteristic six alpha particle decay chain.

Radioactivity

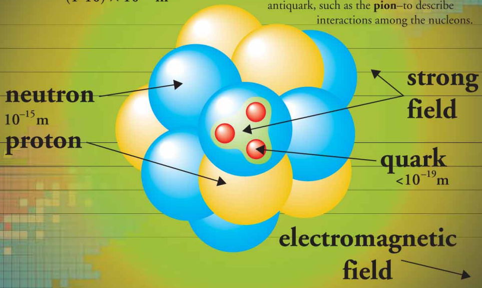


*R*adioactive decay transforms a nucleus by emitting different particles. In **alpha** decay, the nucleus releases a $^{4}_{2}$He nucleus –an alpha particle. In **beta** decay, the nucleus either emits an electron and antineutrino (or a positron and neutrino) or captures an atomic electron and emits a neutrino. A positron is the name for the antiparticle of the electron. Antimatter is composed of antiparticles. Both alpha and beta decays change the original nucleus into a nucleus of a different chemical element. In **gamma** decay, the nucleus lowers its internal energy by emitting a photon–a gamma ray. This decay does not modify the chemical properties of the atom.

The Nucleus

$(1\text{-}10) \times 10^{-15}$ m

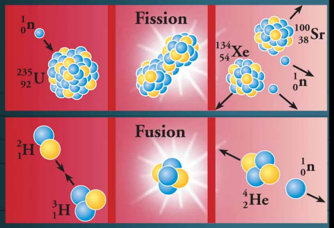
*A*t the center of the atom is a nucleus formed from **nucleons**–protons and neutrons. Each nucleon is made from three **quarks** held together by their strong interactions, which are mediated by gluons. In turn, the nucleus is held together by the **strong** interactions between the gluon and quark constituents of neighboring nucleons. Nuclear physicists often use the exchange of mesons–particles which consist of a quark and an antiquark, such as the **pion**–to describe interactions among the nucleons.



*I*n an atom, **electrons** range around the nucleus at distances typically up to 10,000 times the nuclear diameter. If the electron cloud were shown to scale, this chart would cover a small town.

Nuclear Energy

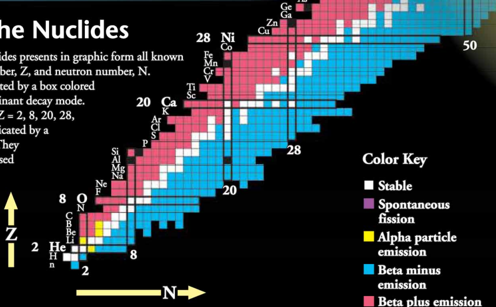
*N*uclear reactions release energy when the total mass of the products is less than the sum of the masses of the initial nuclei. The "lost mass" appears as kinetic energy of the products ($E = mc^2$). In fission, a massive nucleus splits into two major fragments that usually eject one or more neutrons. In fusion, low mass nuclei combine to form a more massive nucleus plus one or more ejected particles—neutrons, protons, photons, or alpha particles.

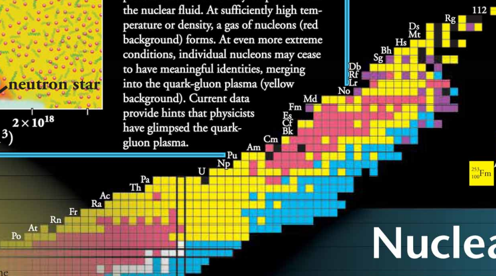


*I*n the early stages of stellar evolution of our sun and other stars, hydrogen fuses to form helium, releasing energy in the form of photons (light) and neutrinos. During the later stages of stellar evolution, more massive nuclei up to and beyond uranium are synthesized by fusion. By measuring the number of neutrinos that come from the Sun, scientists recently have demonstrated that neutrinos must have a mass greater than zero.

Chart of the Nuclides

*T*he Chart of the Nuclides presents in graphic form all known nuclei with atomic number, Z, and neutron number, N. Each nuclide is represented by a box colored according to its predominant decay mode. **Magic numbers** (N or Z = 2, 8, 20, 28, 50, 82 and 126) are indicated by a rectangle on the chart. They correspond to major closed shells and show regions of greater nuclear binding energy.





Color Key
- ■ **Stable**
- ■ **Spontaneous fission**
- ■ **Alpha particle emission**
- ■ **Beta minus emission**
- ■ **Beta plus emission or electron capture**

Applications

Radioactive Dating

*N*aturally occurring radioactive isotopes such as $^{14}_{6}$C are used to date objects that were once living, such as wood. For example, from a study of artifacts found at the site, scientists determined that Stonehenge was built nearly 4,000 years ago.

Space Exploration

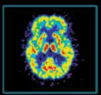
*S*ojourner used alpha particles to identify chemical elements present in Martian rocks. On Earth, nuclear reactions are used in many areas from criminal investigations to art authentication.

Nuclear Reactors

*N*uclear reactors use the fission of $^{235}_{92}$U or $^{239}_{94}$**Pu** nuclei to produce electric power. Reactors and most other nuclear applications generate radioactive waste; disposal of this waste is a subject of current research.

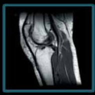
Smoke Detectors

*M*any smoke detectors use a small amount of the alpha emitter $^{241}_{95}$**Am** to ionize the air. Smoke entering the detector reduces the current and sets off the alarm.



Nuclear Medicine

*R*adioactive isotopes, such as $^{99m}_{43}$Tc, $^{60}_{27}$Co and $^{131}_{53}$I, are commonly used in the diagnosis and treatment of disease. Positron emitters such as $^{18}_{9}$F are used in Positron Emission Tomography (PET) to generate images of brain activity.



Magnetic Resonance Imaging

*M*agnetic Resonance Imaging (MRI) makes use of atomic transitions involving the magnetic field of a nucleus to study the local chemical environment. This technique accurately maps the density of hydrogen to produce three-dimensional images of the human body.

Astrophysical pictures courtesy NASA/JPL/Caltech and AURA/STScI.

www.CPEPweb.org

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- Applications account for ~20-25% of the present Wall Chart

RECOMMEND

- Produce a separate Applications Wall Chart
- Have the Nuclear Science Community put it together along with the CPEP Organization

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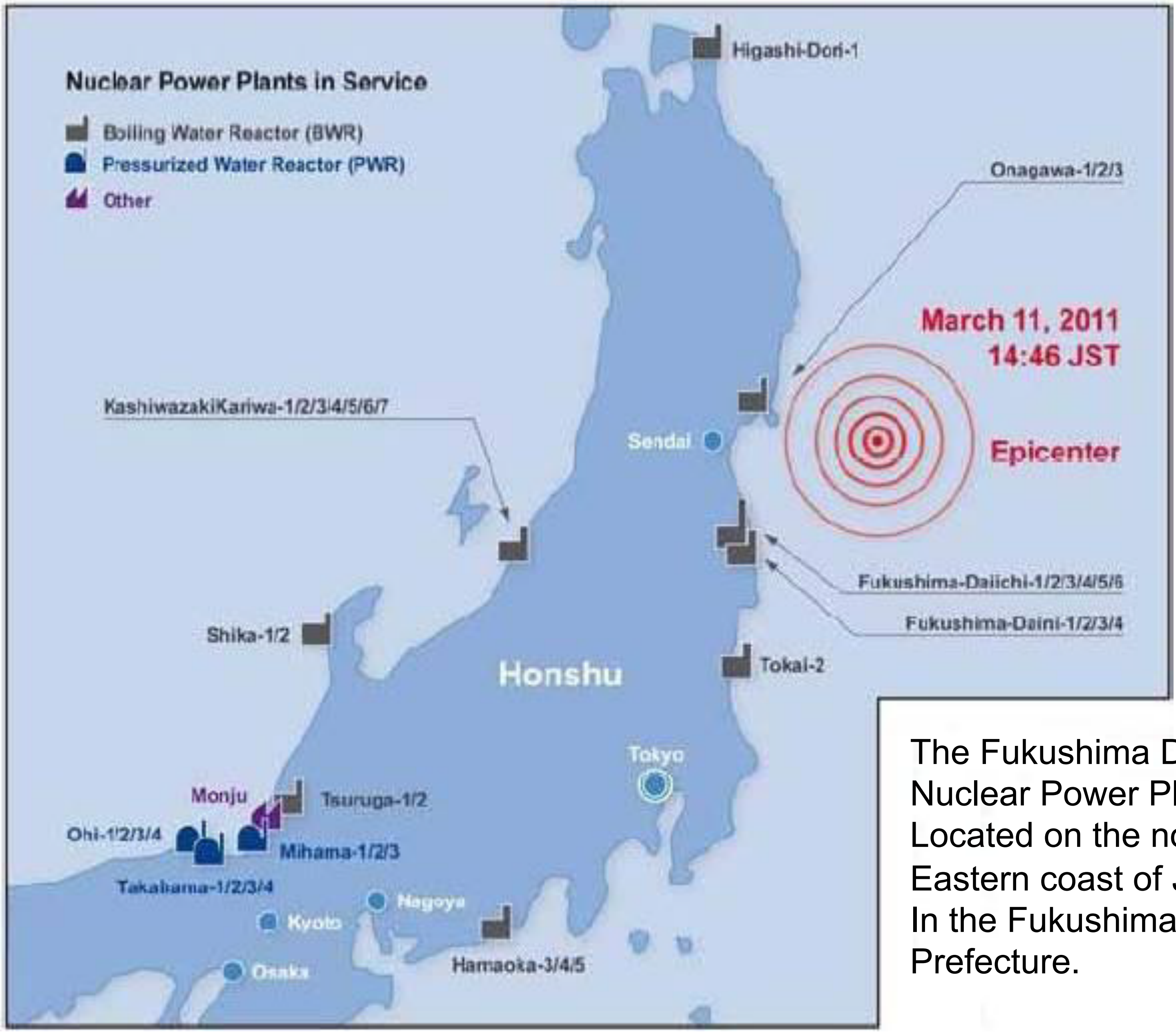
BACKUP SLIDES

Nuclear Forensics

Role, State of the Art, and Program Needs

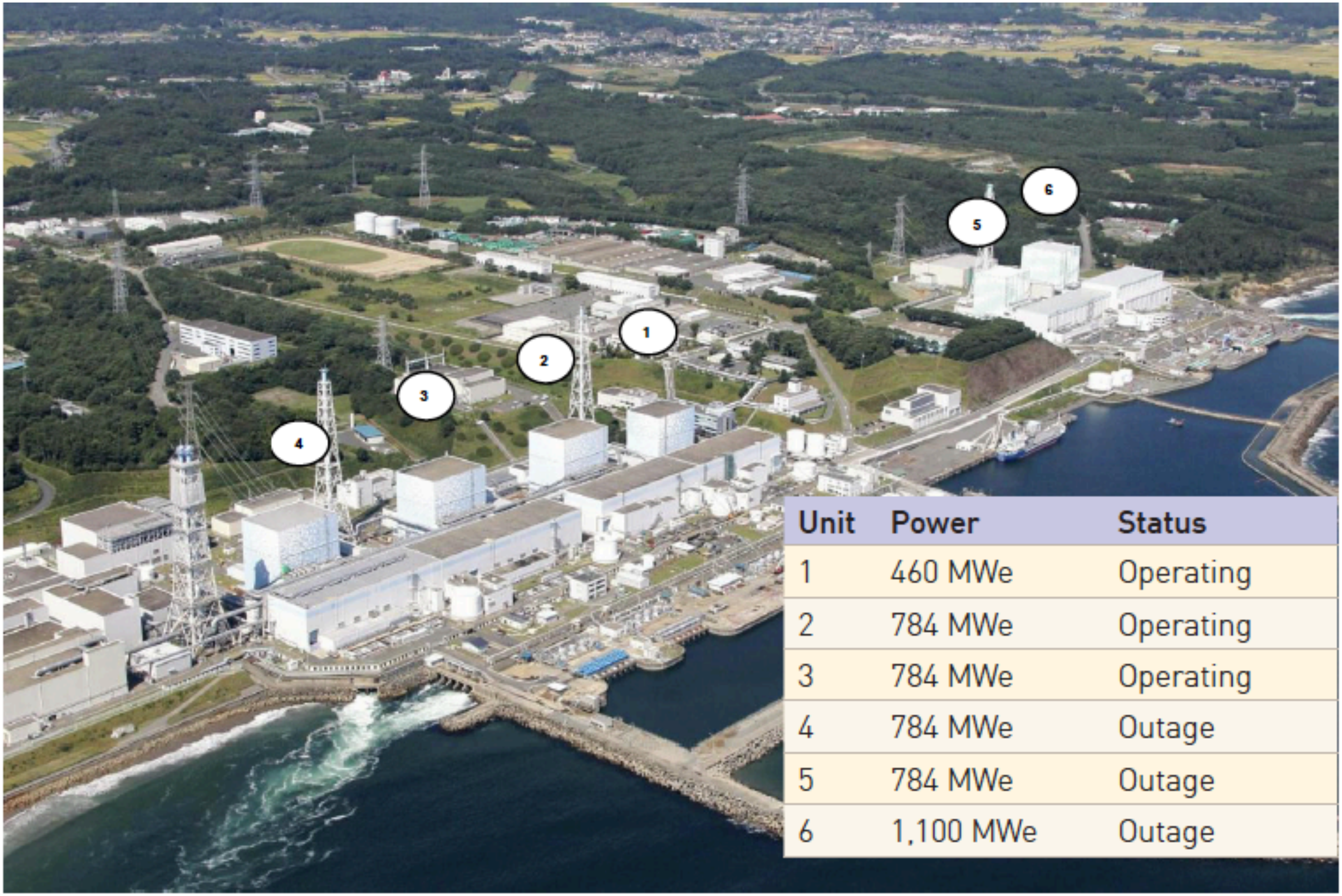
Joint Working Group of the American Physical Society
and the American Association for the Advancement of Science



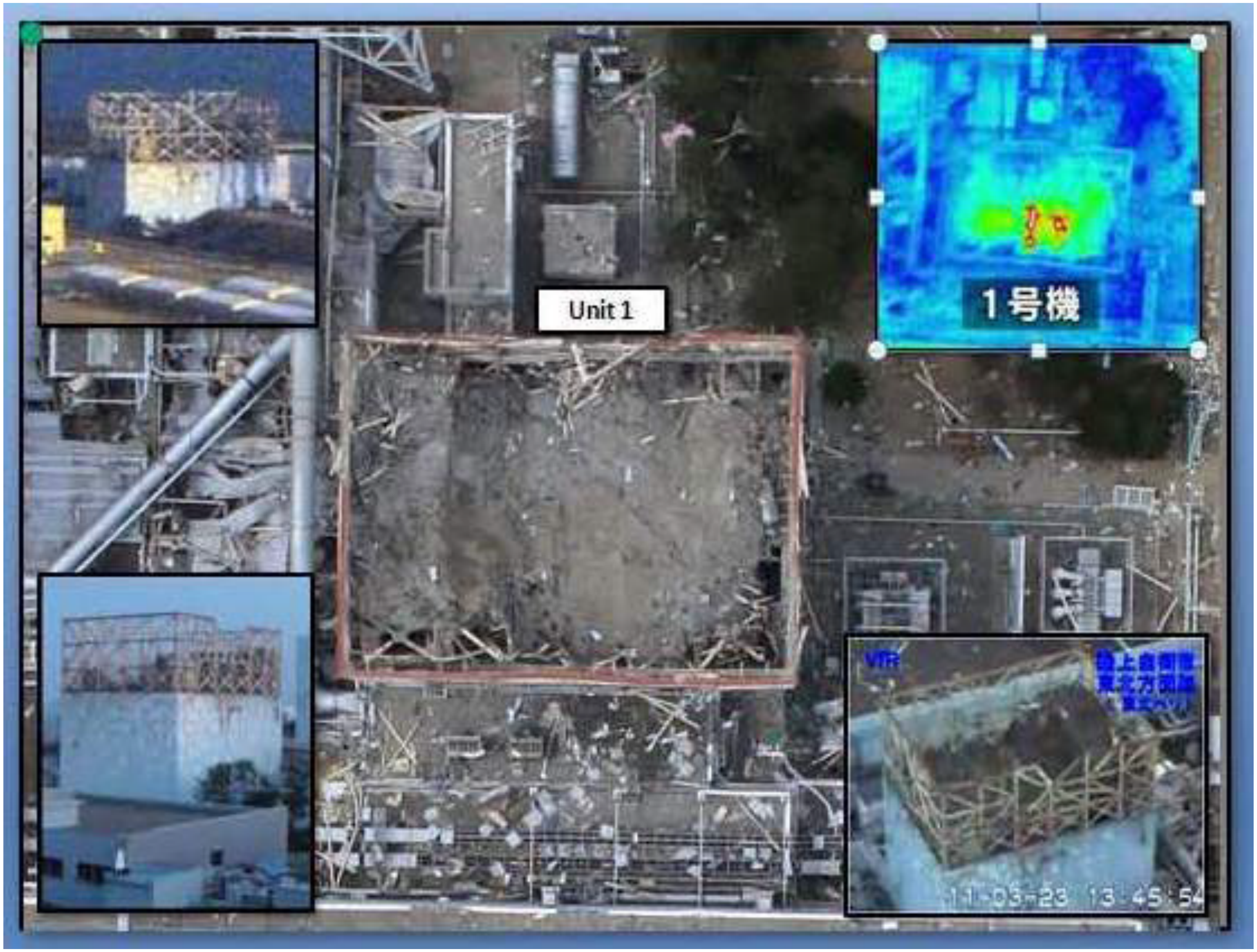
The Fukushima Dai-ichi Nuclear Power Plant is Located on the north-Eastern coast of Japan In the Fukushima Prefecture.

Nuclear Power Plants in Japan

Fukushima Dai-ichi Nuclear Power Plant (status before earthquake)

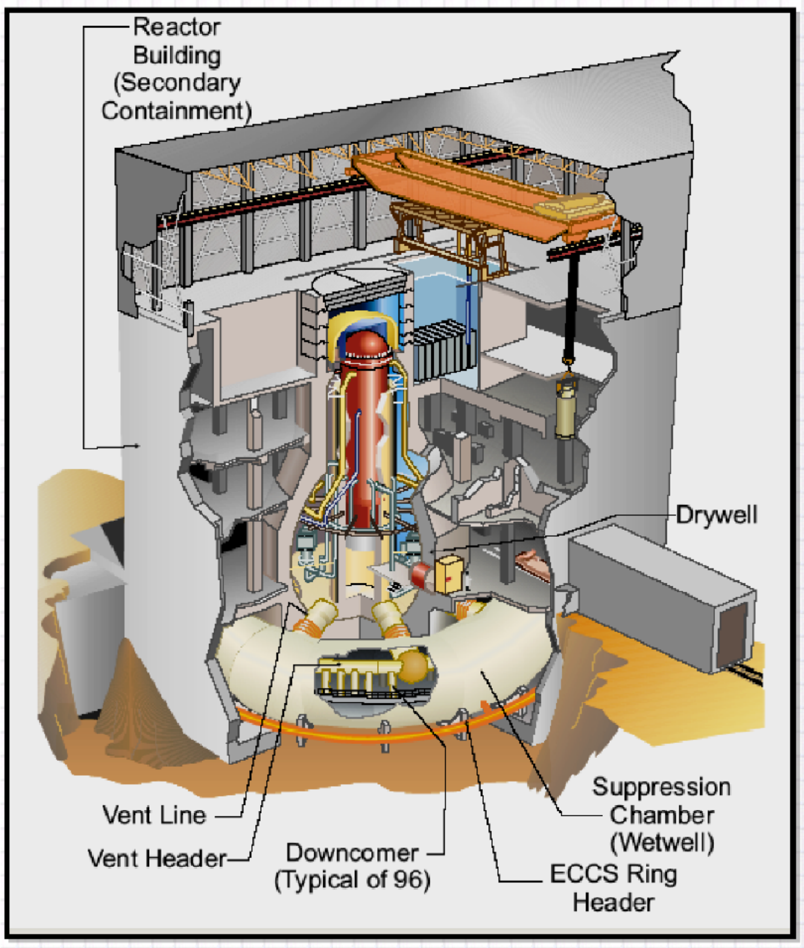


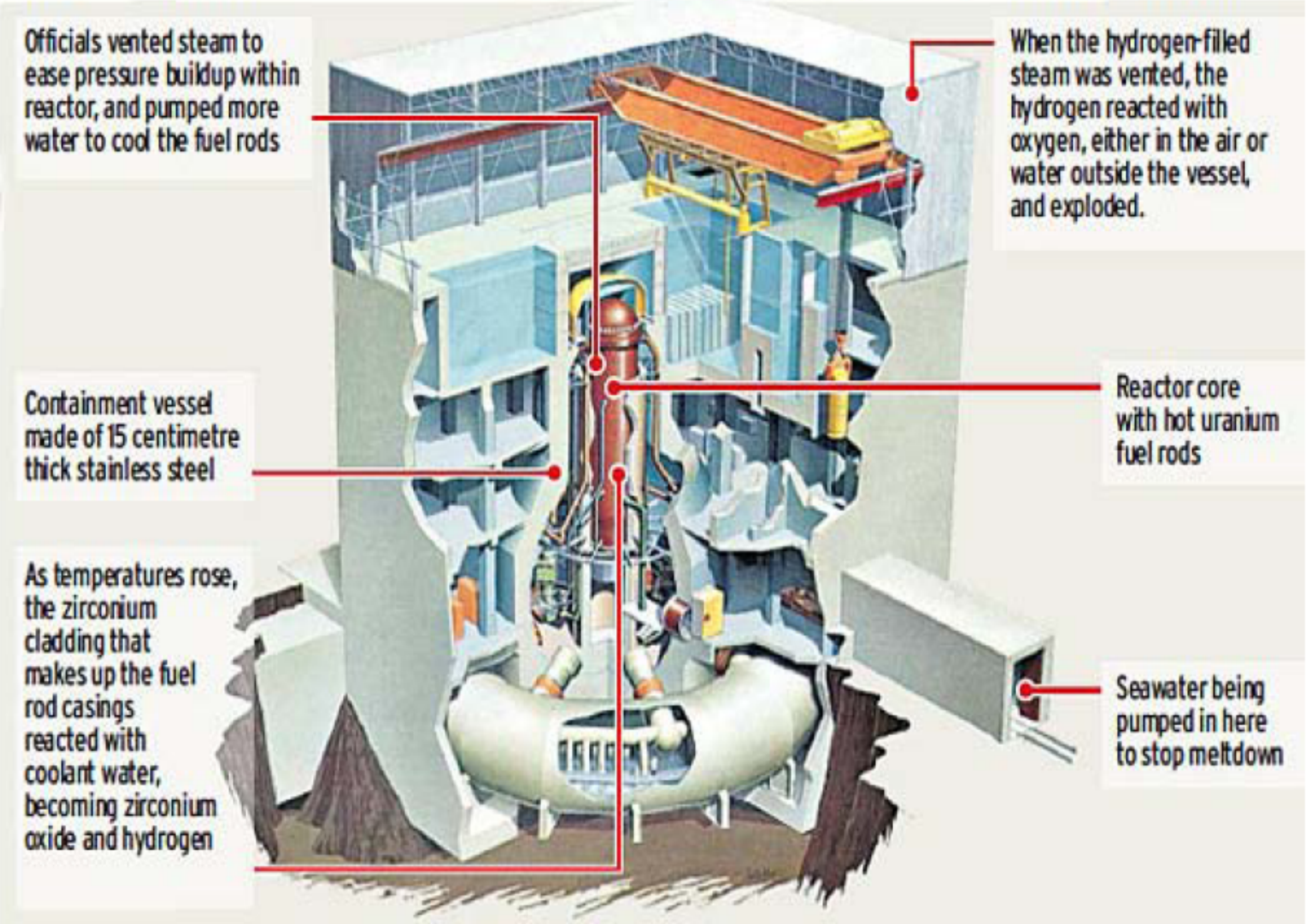
Unit	Power	Status
1	460 MWe	Operating
2	784 MWe	Operating
3	784 MWe	Operating
4	784 MWe	Outage
5	784 MWe	Outage
6	1,100 MWe	Outage



Damage to Unit 1

Boiling Water Reactor





Officials vented steam to ease pressure buildup within reactor, and pumped more water to cool the fuel rods

When the hydrogen-filled steam was vented, the hydrogen reacted with oxygen, either in the air or water outside the vessel, and exploded.

Containment vessel made of 15 centimetre thick stainless steel

Reactor core with hot uranium fuel rods

As temperatures rose, the zirconium cladding that makes up the fuel rod casings reacted with coolant water, becoming zirconium oxide and hydrogen

Seawater being pumped in here to stop meltdown