BNL Capabilities to Support Advanced Material Studies

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Brookhaven National Laboratory

U.S. DEPARTMENT OF ENERGY

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Outline of Presentation

- Overview of the Isotope Program
- Present capabilities at BNL in irradiation and post-irradiation characterizing accelerator and nuclear materials on materials in utilizing its unique experimental facilities
- Discuss some of the previous work
- Outline a path forward in both irradiation damage capabilities, an exciting array of micro-characterization techniques at the NSLS-II synchrotron beamlines
- Present future capabilities at the Material in Radiations Environment MRE for Post Irradiation examination of radioactive materials

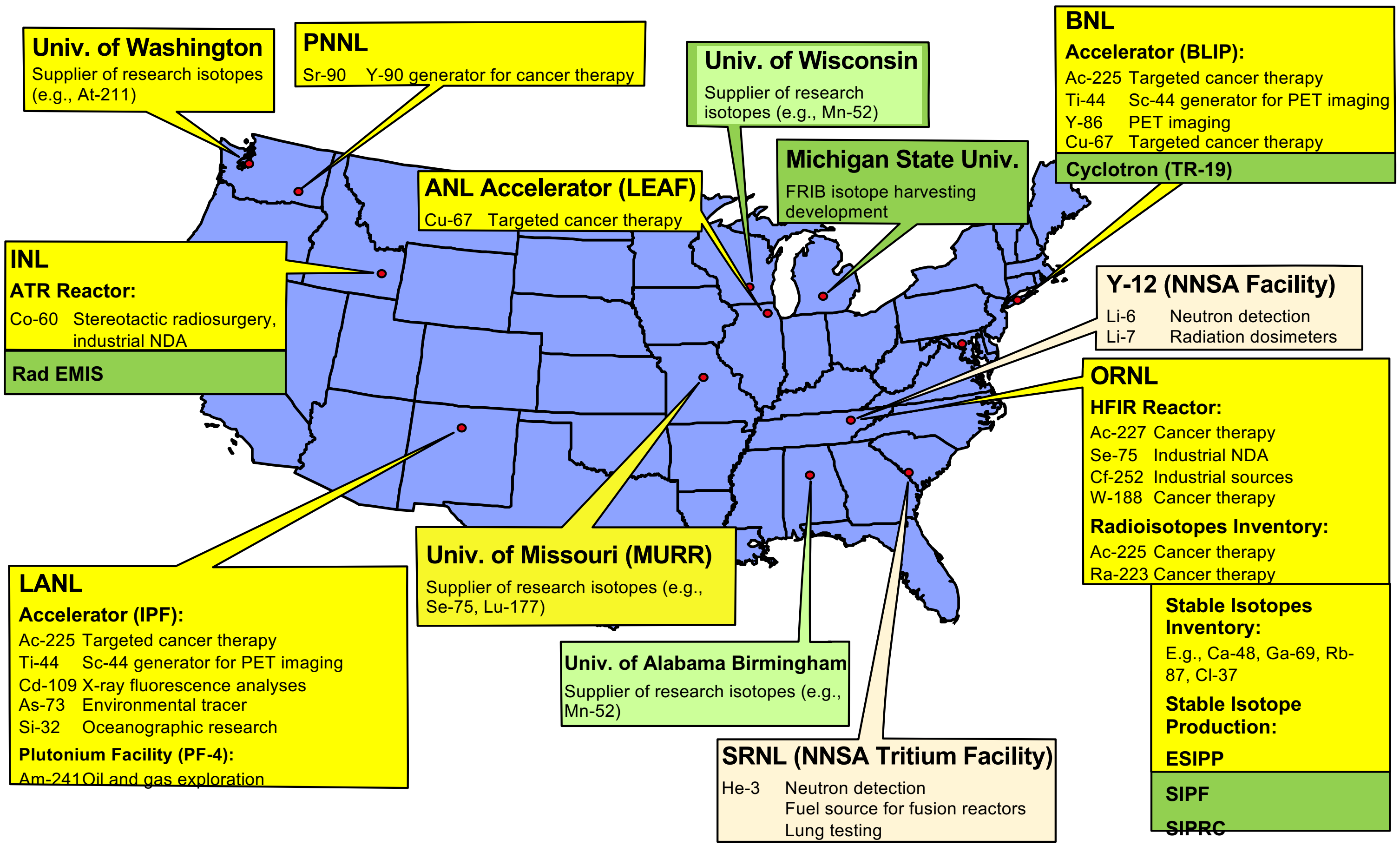
Isotope Program Missions

- Produce and/or distribute radioactive isotopes that are in short supply, including valuable by-products, surplus materials and related isotope services, mitigate reliance on foreign supply
- Maintain the infrastructure required to produce and supply isotope products and related services
- Conduct R&D on new and improved isotope production and processing techniques which can make available new isotopes for research and applications

Attributes:

- Core R&D where there are programmatically stewarded activities
- Competitive R&D
- SBIR/STTR, Early Career Award Program
- Nuclear and Radiochemistry Summer School, Workforce Development

DOE Isotope Program Production Sites



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Office of Isotope R&D and Production SC-24.3

Jehanne Gillo, Director

Valerie Mocca, Admin Assistant (CONT)
Luisa Romero, Financial Management Specialist
Andrea Condrad, Financial Management Analyst
Subcontract Support, Bill Newton (CONTR), Leonard Mausner (CONTR)

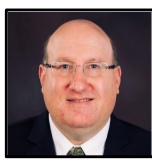
Isotope Program Operations
Vacant

Technical Advisor, IPA

Radioisotope Production R&D
Ethan Balkin

Stable Isotopes
April Gillens

Isotope Accelerator Facilities
Arne Freyberger



Isotope Reactor Facilities
Jon Neuhoff

Alternative Isotope Production
David Bivans

Isotope Projects
Khianne Jackson

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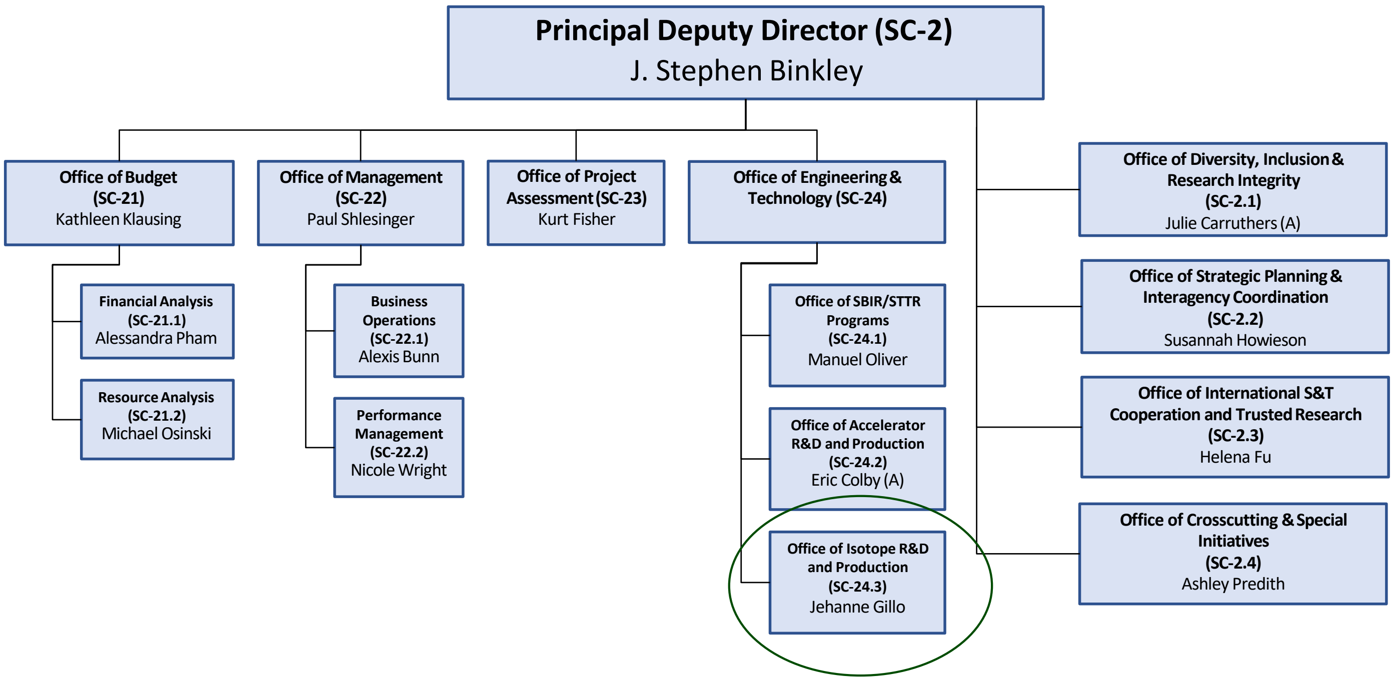
Office of Principal Deputy Director (SC-2)



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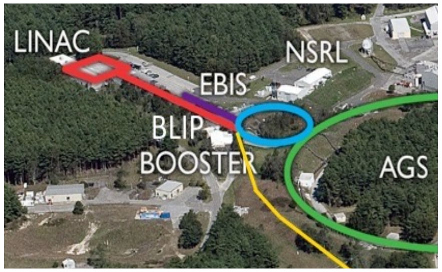
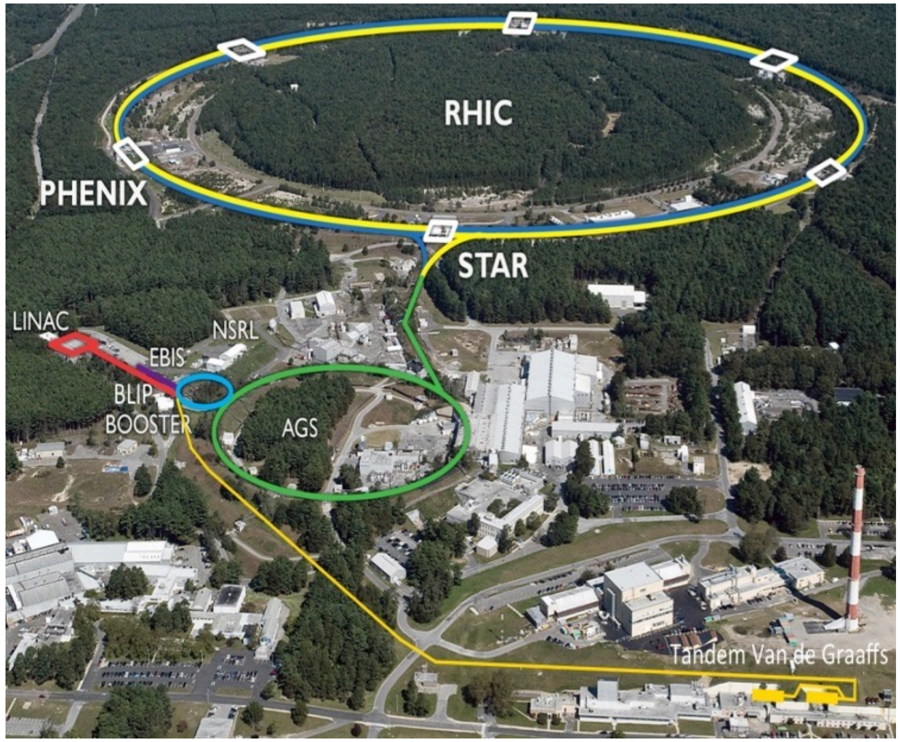
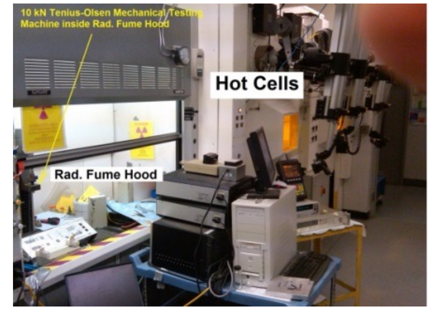
Material Evaluations

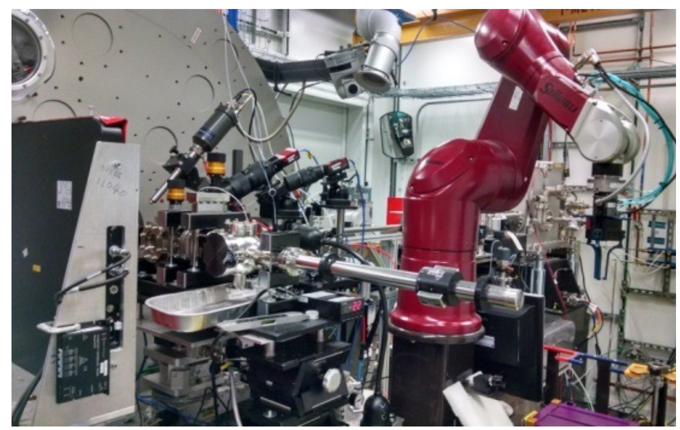
- Need for materials for high power targetry and accelerator components
- Targetry for physics experiments and as IP needs are increasing need for targets that can survive multi-MW irradiations with particle beams.
- As has been demonstrated components that have been used for other applications are not always suitable and evaluations are necessary.
- Necessary to evaluate the long-term accumulated radiations damage as well as the short bursts that result in thermo-mechanical shock.

Irradiation and Post-Irradiation









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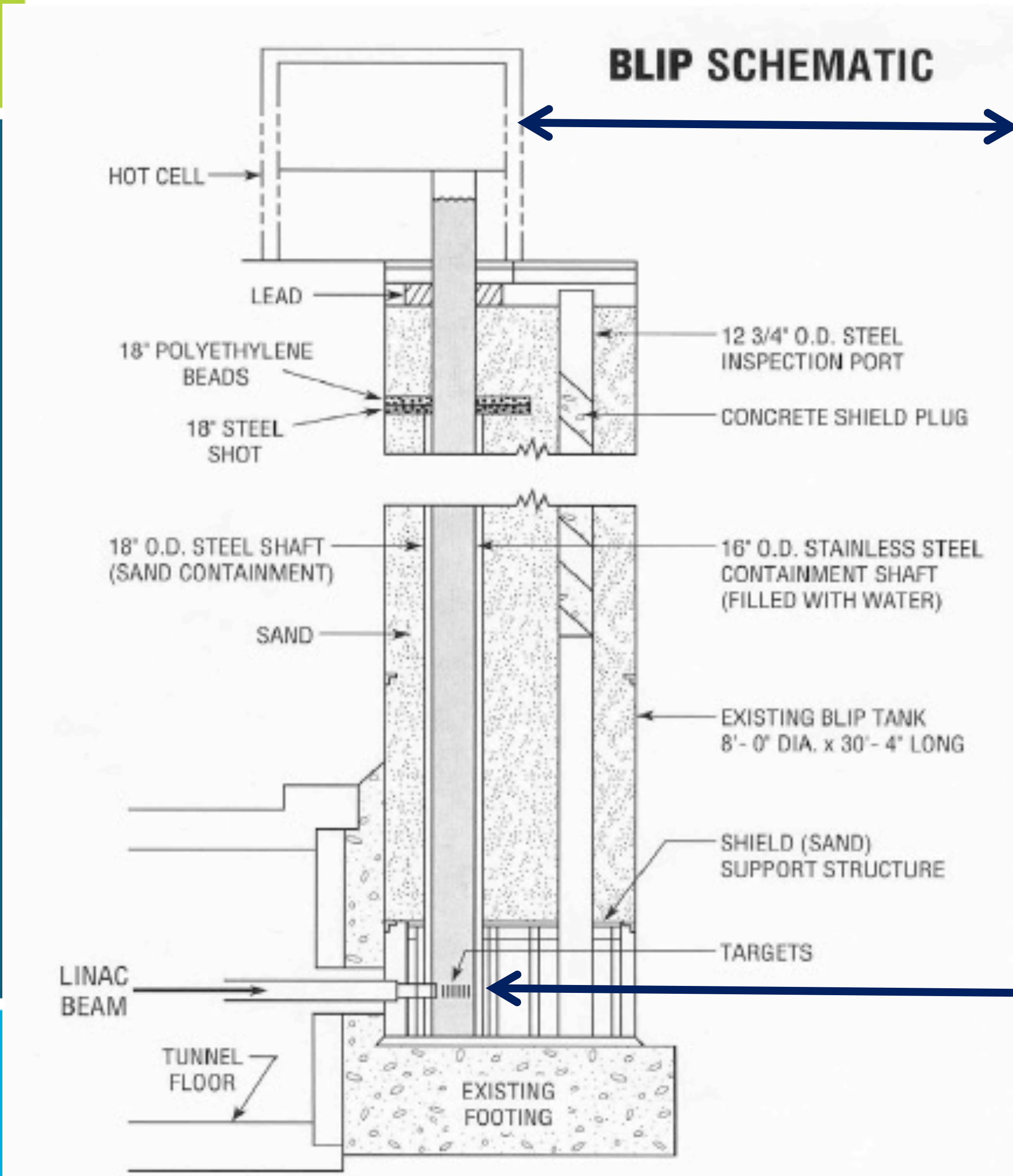
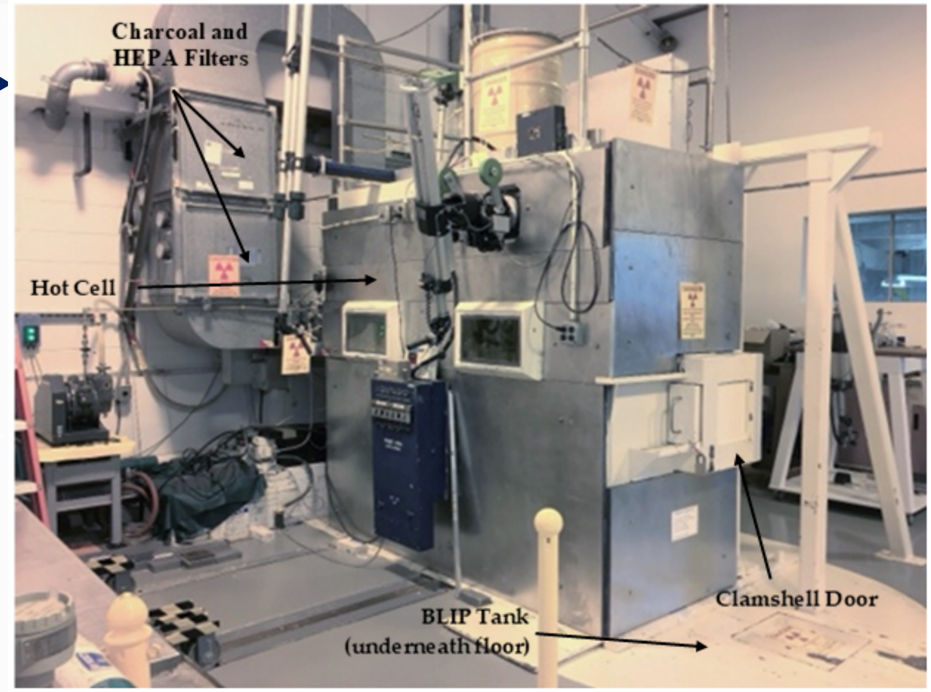
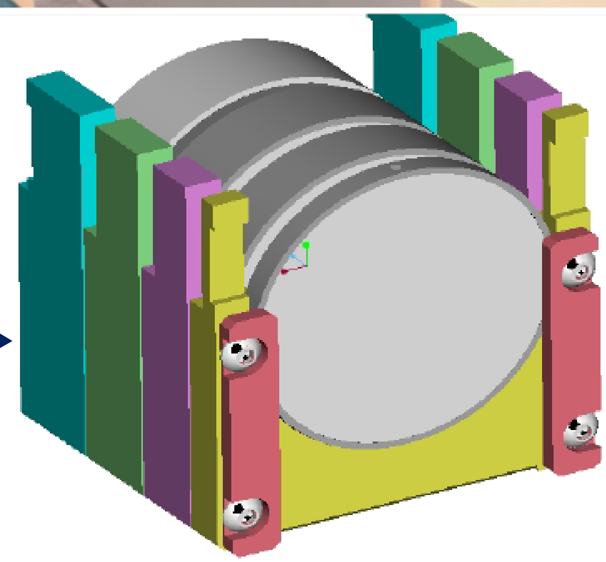
Brookhaven Linear Isotope Producer

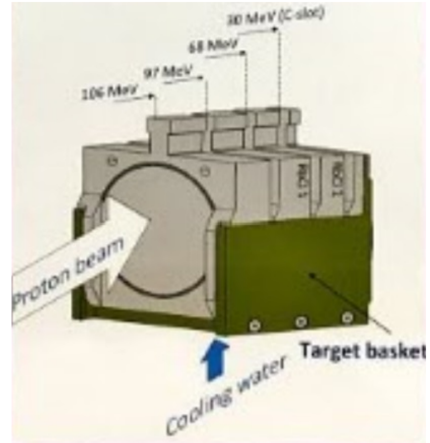




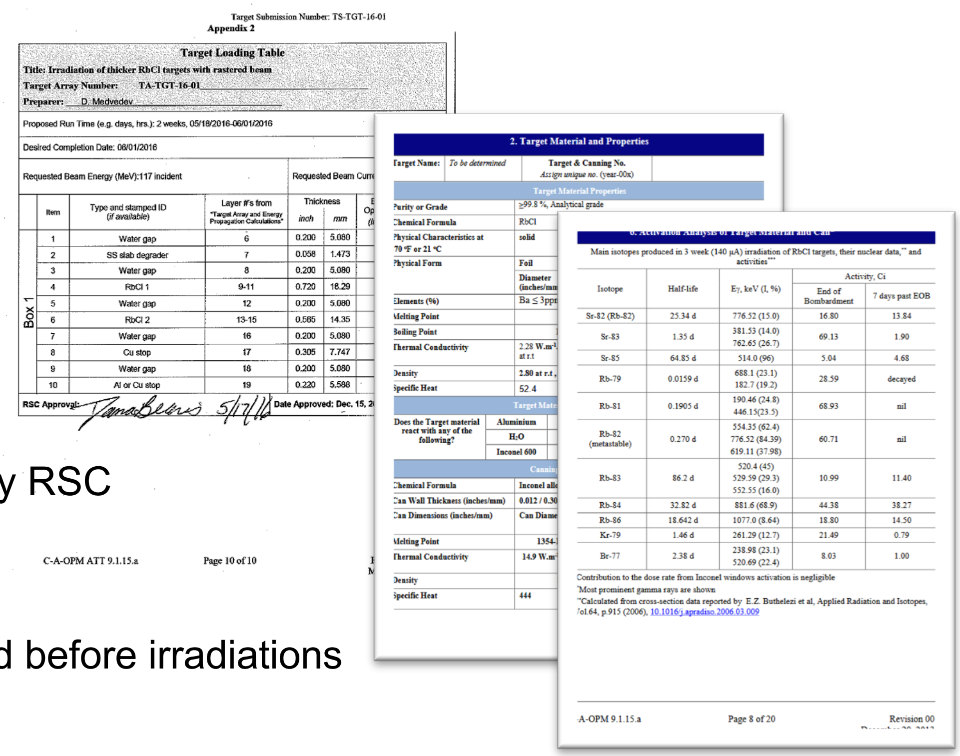


BLIP Targets

Target



- Targets are irradiated by the proton beam
  - Production targets for Sr
  - R & D targets
  - LINAC beam intensity: 50-165 uA
  - Beam raster lowers power density on target to minimize risk of target failure enabling higher current and higher production yields
  - BLIP equipment allows as many as two target boxes per irradiation
- Targets undergo review process by Radiation Safety Sub-Committee including:
  - Radionuclides and activity expected after irradiation
  - Heating profile and heat transfer calculations
- Documentation maintained in “canning record” kept by RSC
- Metal foils used for R & D also reviewed against similar criteria as production targets
- Target arrays are configuration managed and checked before irradiations against target loading table



Target Submission Number: TS-TGT-16-01

Appendix 2

Target Loading Table

Title: Irradiation of thicker RbCl targets with rastered beam

Target Array Number: TA-TGT-16-01

Preparer: D. Medvedev

Proposed Run Time (e.g. days, hrs.): 2 weeks, 05/18/2016-06/01/2016

Desired Completion Date: 06/01/2016

Requested Beam Energy (MeV):117 incident | Requested Beam Curr

	Item	Type and stamped ID (if available)	Layer #'s from "Target Array and Energy Propagation Calculations"	Thickness inch	Thickness mm
Box 1	1	Water gap	6	0.200	5.080
	2	SS slab degrader	7	0.058	1.473
	3	Water gap	8	0.200	5.080
	4	RbCl 1	9-11	0.720	18.29
	5	Water gap	12	0.200	5.080
	6	RbCl 2	13-15	0.565	14.35
	7	Water gap	16	0.200	5.080
	8	Cu stop	17	0.305	7.747
	9	Water gap	18	0.200	5.080
	10	Al or Cu stop	19	0.220	5.588

RSC Approval: 5/17/16 | Date Approved: Dec. 15, 2

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2. Target Material and Properties

Target Name:	To be determined
Target & Canning No. Assign unique no. (year-00x)	
Target Material Properties	
Purity or Grade	≥99.8 %, Analytical grade
Chemical Formula	RbCl
Physical Characteristics at 70 °F or 21 °C	solid
Physical Form	Foil; Diameter (inches/mm
Elements (%)	Ba ≤ 3ppm
Melting Point	
Boiling Point	
Thermal Conductivity	2.28 W.m-1 at r.t
Density	2.80 at r.t ,
Specific Heat	52.4
Does the Target material react with any of the following?	Aluminium; H_2O; Inconel 600
Chemical Formula	Inconel all
Can Wall Thickness (inches/mm)	0.012 / 0.30
Can Dimensions (inches/mm)	Can Diame
Melting Point	1354-
Thermal Conductivity	14.9 W.m
Density	
Specific Heat	444

6. Activation Analysis of Target Material and Can

Main isotopes produced in 3 week (140 µA) irradiation of RbCl targets, their nuclear data,** and activities***

Isotope	Half-life	Eγ, keV (I, %)	Activity, Ci: End of Bombardment	Activity, Ci: 7 days past EOB
Sr-82 (Rb-82)	25.34 d	776.52 (15.0)	16.80	13.84
Sr-83	1.35 d	381.53 (14.0) 762.65 (26.7)	69.13	1.90
Sr-85	64.85 d	514.0 (96)	5.04	4.68
Rb-79	0.0159 d	688.1 (23.1) 182.7 (19.2)	28.59	decayed
Rb-81	0.1905 d	190.46 (24.8) 446.15(23.5)	68.93	nil
Rb-82 (metastable)	0.270 d	554.35 (62.4) 776.52 (84.39) 619.11 (37.98)	60.71	nil
Rb-83	86.2 d	520.4 (45) 529.59 (29.3) 552.55 (16.0)	10.99	11.40
Rb-84	32.82 d	881.6 (68.9)	44.38	38.27
Rb-86	18.642 d	1077.0 (8.64)	18.80	14.50
Kr-79	1.46 d	261.29 (12.7)	21.49	0.79
Br-77	2.38 d	238.98 (23.1) 520.69 (22.4)	8.03	1.00

Contribution to the dose rate from Inconel windows activation is negligible

*Most prominent gamma rays are shown

**Calculated from cross-section data reported by E.Z. Buthelezi et al, Applied Radiation and Isotopes, Vol.64, p.915 (2006), 10.1016/j.apradiso.2006.03.009

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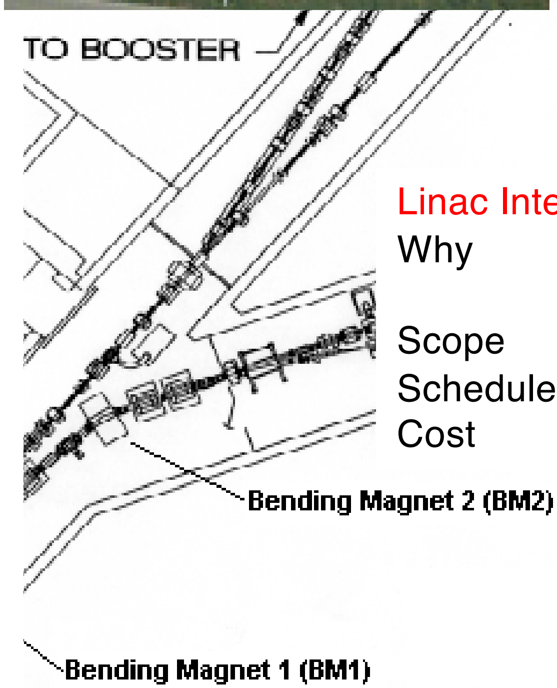
200 MeV H- beams LINAC/BLIP

- First beam: fall 1972
- 85-100% of all Linac pulses go to BLIP
- Target irradiation with 66 – 200 MeV, 165 μA
- Radioisotope production for diagnostic (e.g. ^{82}Sr, ^{68}Ge) and therapeutic (^{225}Ac) use

Contact: D. Raparia



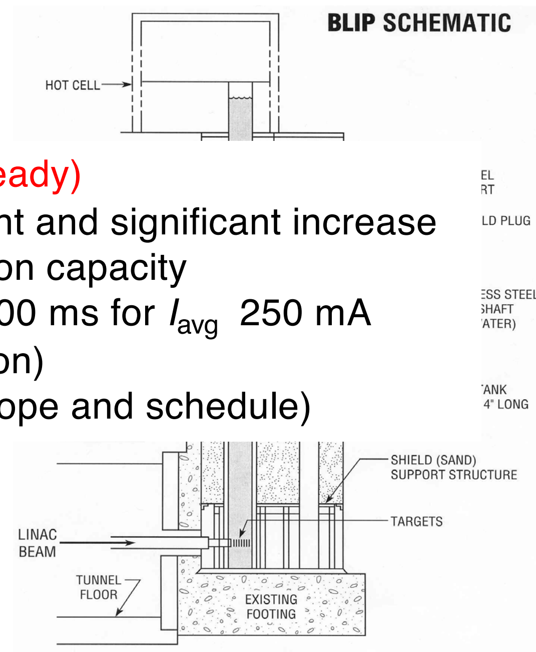
Linac Intensity Upgrade Phase II (shovel-ready)

Why : 2x increase in beam current and significant increase in isotope production capacity

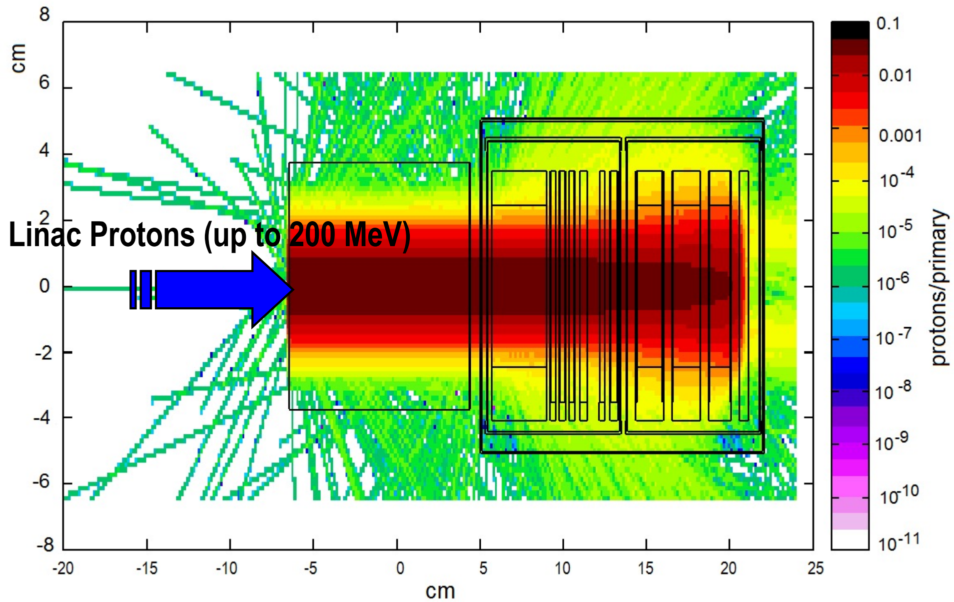
Scope : Linac pulse length doubling to 900 ms for I_{avg} 250 mA

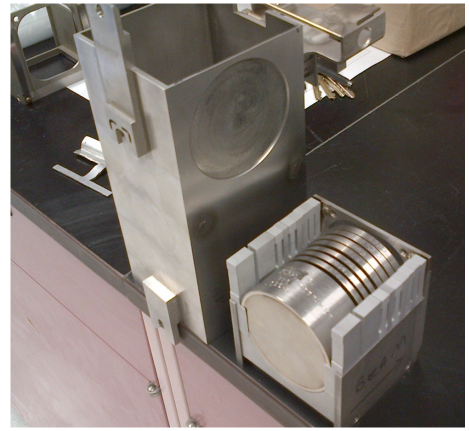
Schedule: ~3-4 years (with cost minimization)

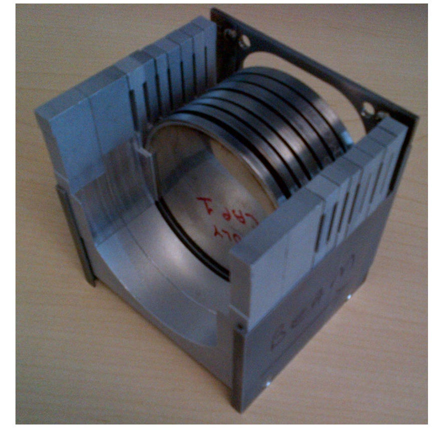
Cost : ~$17.4M (depending on scope and schedule)



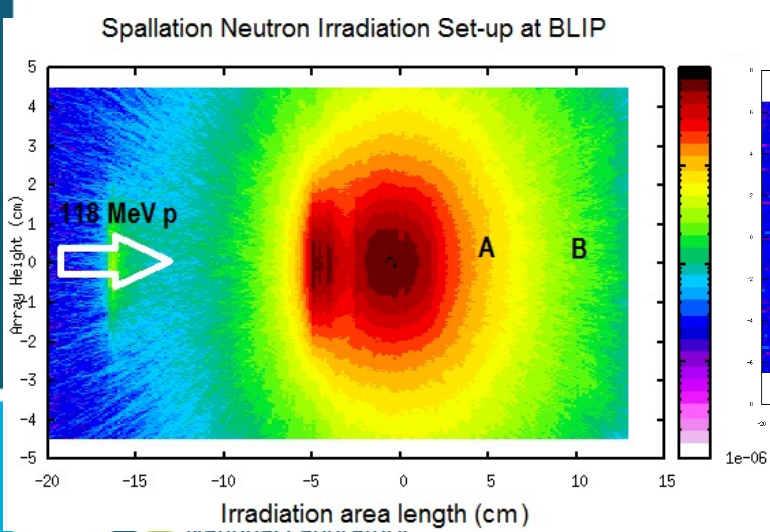
BNL Irradiation Facilities and Capabilities

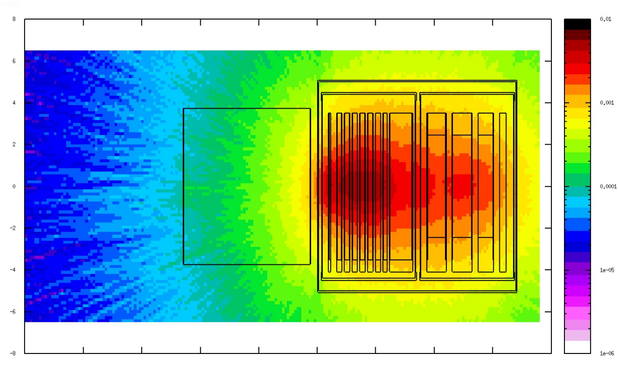


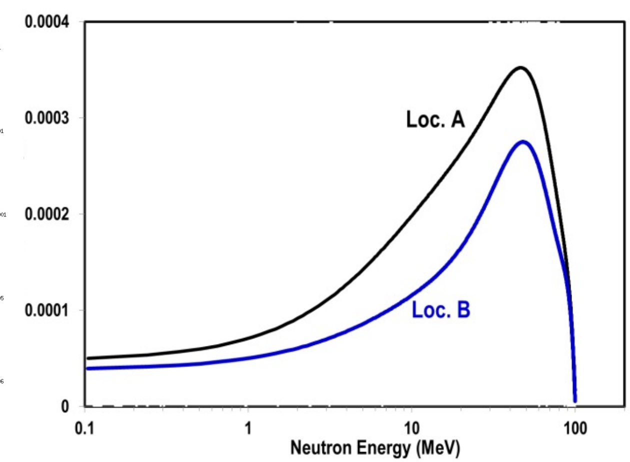




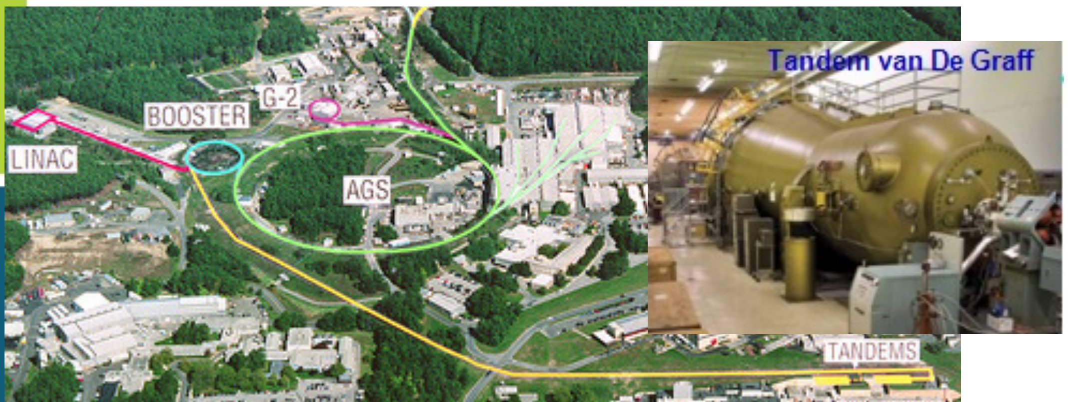
Fast Neutron Spectra and Nuclear Materials at BNL/BLIP



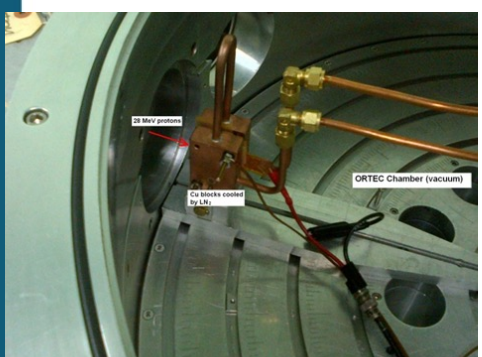


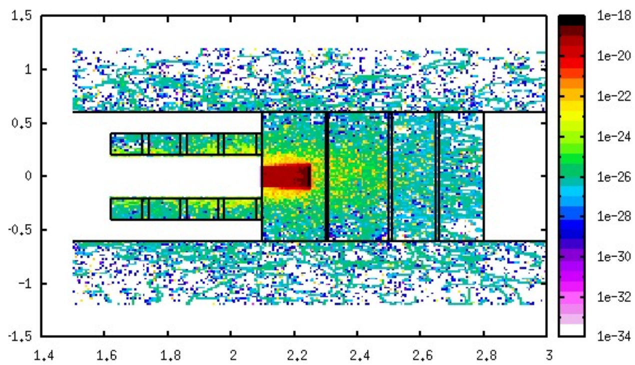


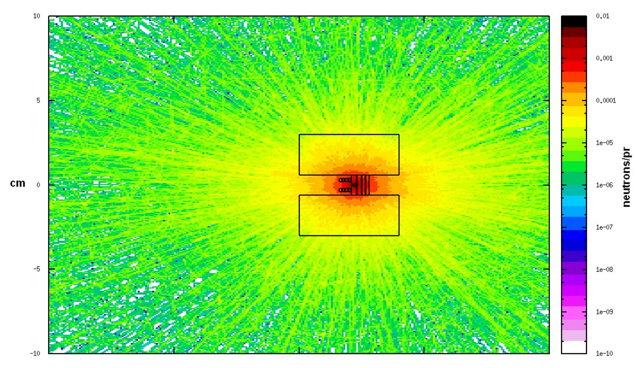
Ion irradiation at BNL Tandem



28 MeV irrad. at sub-zero temp.







		Mass	Max Energy		Surface LET	Range	Surface LET	Range
Z	Symbol	AMU	MeV	MeV/AMU	MeV/mg/cm^2	Microns	MeV/mg/cm^2	Microns
1	^{1}H	1.0079	28.75	28.52	0.0153	4550	0.0118	2610
3	^{7}Li	7.0160	57.2	8.15	0.369	390	0.273	240
5	^{11}B	11.0093	85.5	7.77	1.08	206.13	0.754	132.55
6	^{12}C	12.0000	99.6	8.30	1.46	180.43	1.03	115.82
8	^{16}O	15.9994	128	8.00	2.61	137.78	1.83	88.9
9	^{19}F	18.9954	142	7.48	3.51	118.88	2.45	77.12
12	^{24}Mg	23.9927	161	6.71	6.01	84.16	4.17	55.13
14	^{28}Si	28.0855	187	6.66	7.81	77.16	5.42	50.66
17	^{35}Cl	34.9688	212	6.06	11.5	64.41	7.93	42.71
20	^{40}Ca	39.9753	221	5.53	15.8	51.89	10.9	34.7
22	^{48}Ti	47.9479	232	4.84	19.6	47.8	13.4	32.36
24	^{52}Cr	51.9405	245	4.72	22.3	45.86	15.3	31.06
26	^{56}Fe	55.9349	259	4.63	25.1	44.24	17.2	30.09
28	^{58}Ni	57.9353	270	4.66	27.9	44.56	19.1	30.47
29	^{63}Cu	62.9296	277	4.40	30.1	42.06	20.6	28.79
32	^{72}Ge	71.9221	273	3.80	35.9	37.94	24.4	26.25
35	^{81}Br	80.9163	287	3.55	41.3	37.50	28.0	26.11
41	^{93}Nb	92.9060	300	3.23	47.5	36.32	32.1	25.4
47	^{107}Ag	106.9051	313	2.93	59.2	32.48	39.9	22.89
53	^{127}I	126.9045	322	2.54	66.9	32.54	45.0	23.17
79	^{197}Au	196.9665	337	1.71	84.6	29.21	56.2	21.18

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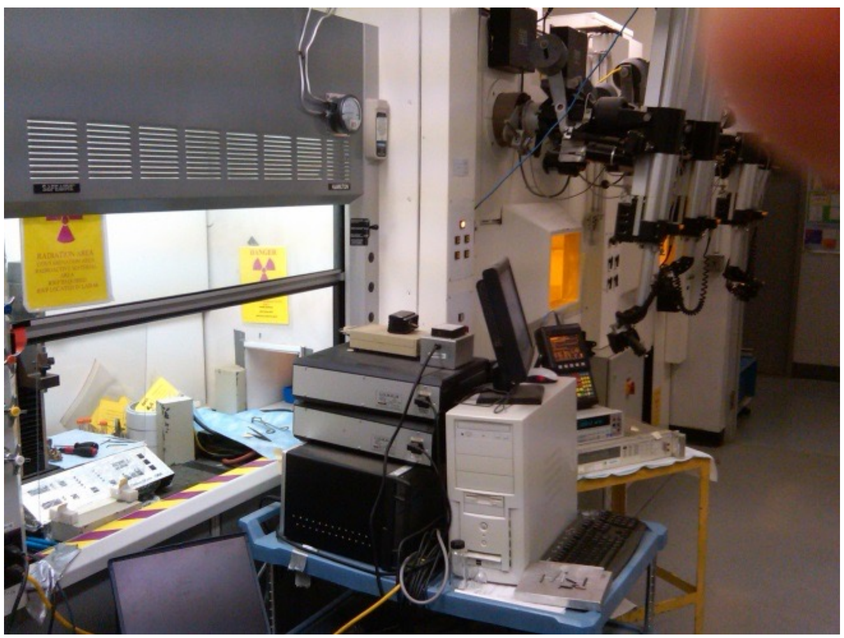
BNL Post-Irradiation Facilities
Isotope Extraction and Processing

Experimental Facility occupies 2 hot cells
and a HEPA-filtered fume hood

PLUS
Photon spectra and isotopic analysis
Activity measurements
Weight loss or gain



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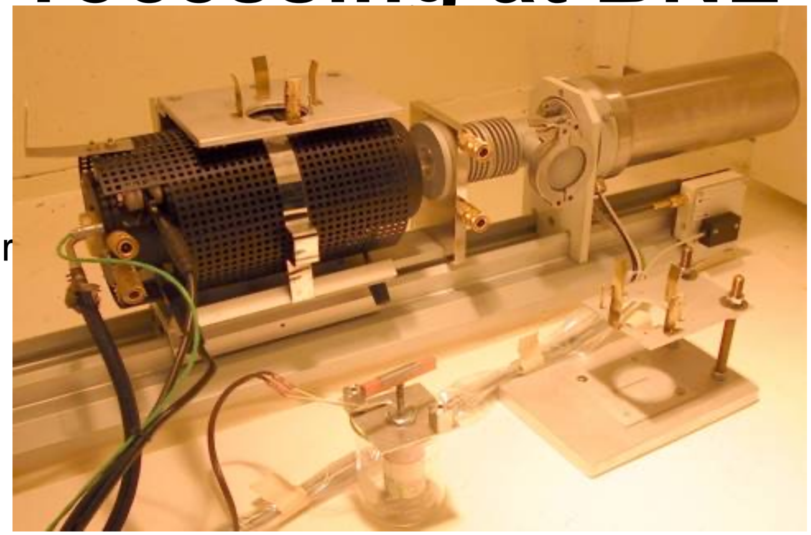
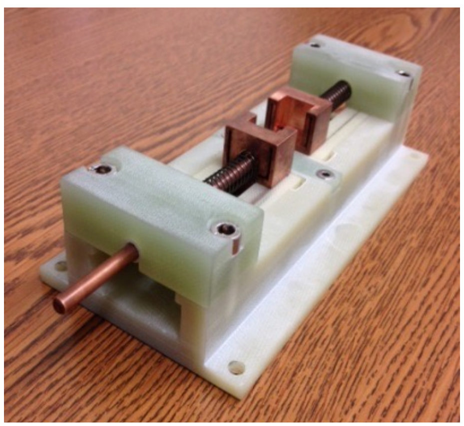
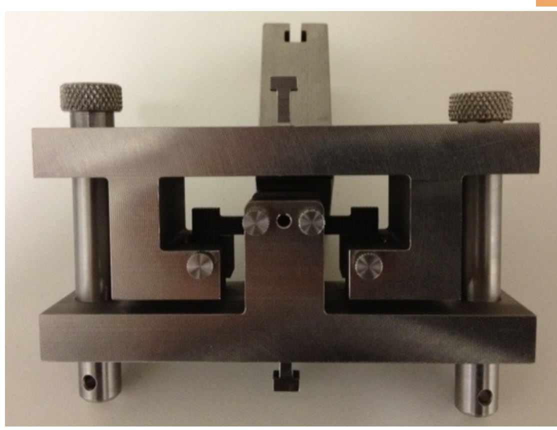
BNL Post-Irradiation Facilities
Isotope Extraction and Processing at BNL



Macroscopic PIE analyses performed are:

Stress-strain (tension, 3-point and 4-point bending)
Thermal Expansion and annealing (sensitive dilatometer
Linseis)
Thermal Conductivity (electrical resistivity)
Magnetic Whole probe
Ultrasonic measurements





Post-Irradiation Characterization at BNL Synchrotrons

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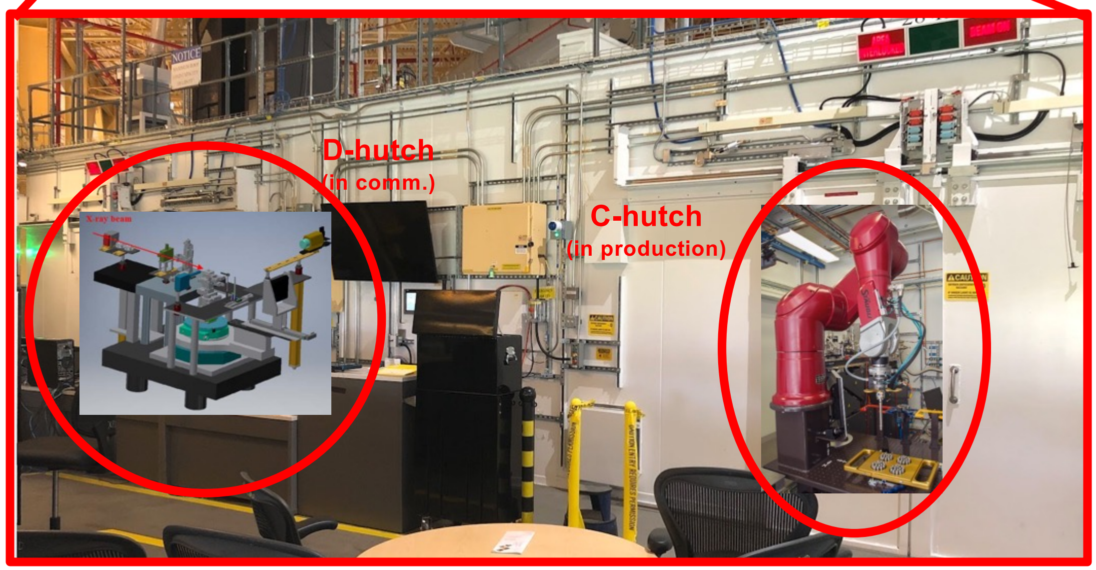
PIE: X-ray diffraction of irradiated materials

High-resolution X-ray diffraction beamline (XPD) at NSLS-II



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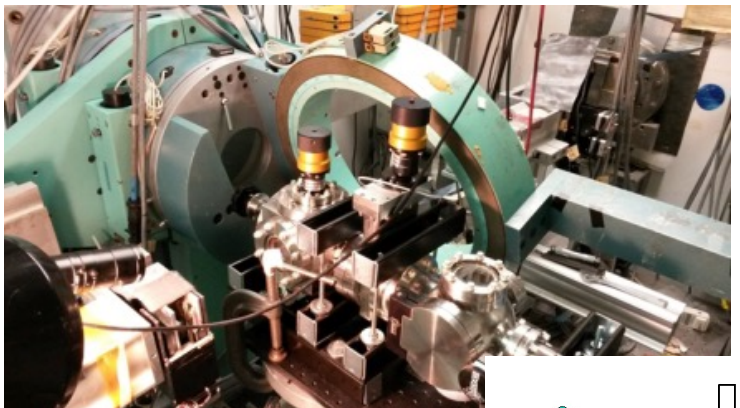
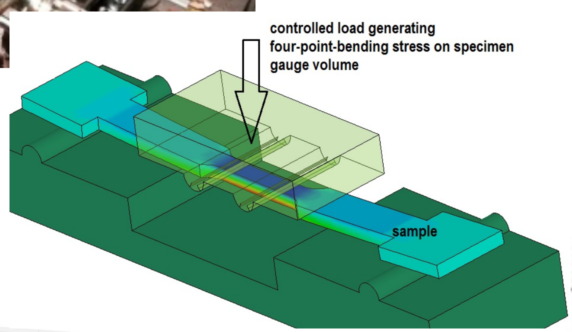
NSLS (end of life)

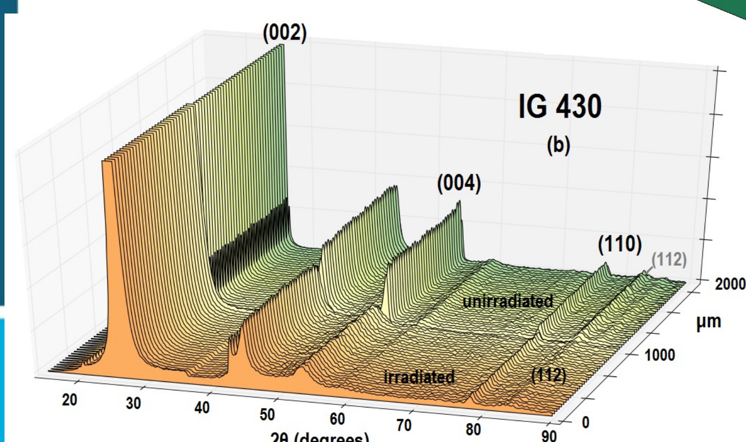
- X17B1 Beamline (200 keV, polychromatic beam, EDXRD)
- X17A (70 keV, monochromatic X-rays, XRD)

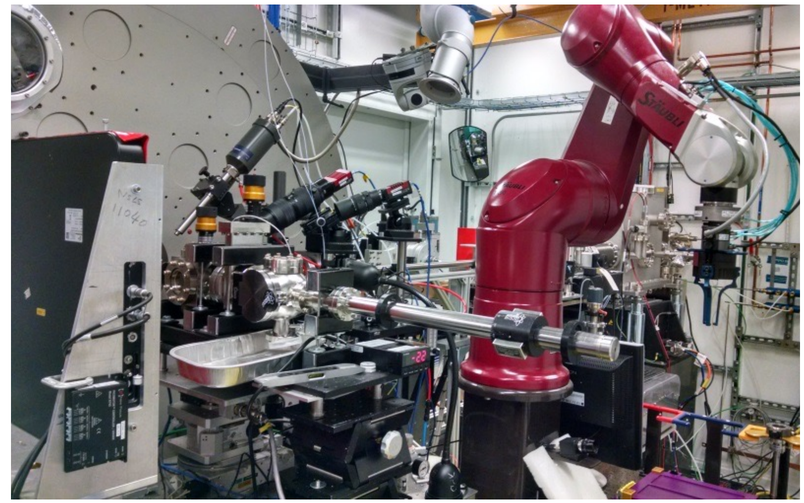
NSLS II (XPD) Beamline

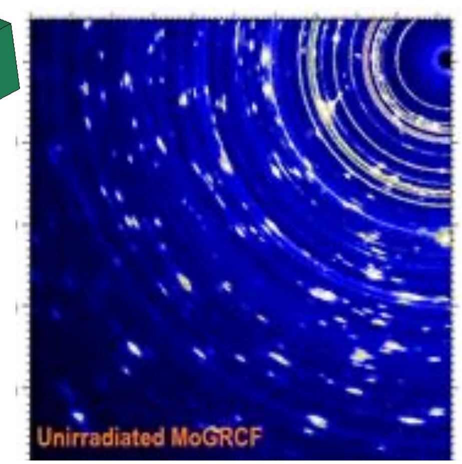
- XRD
- PDF
- X-Ray Tomography*

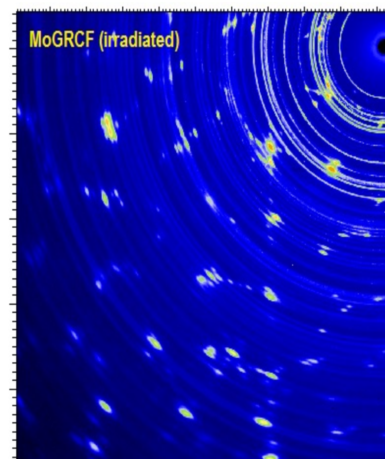






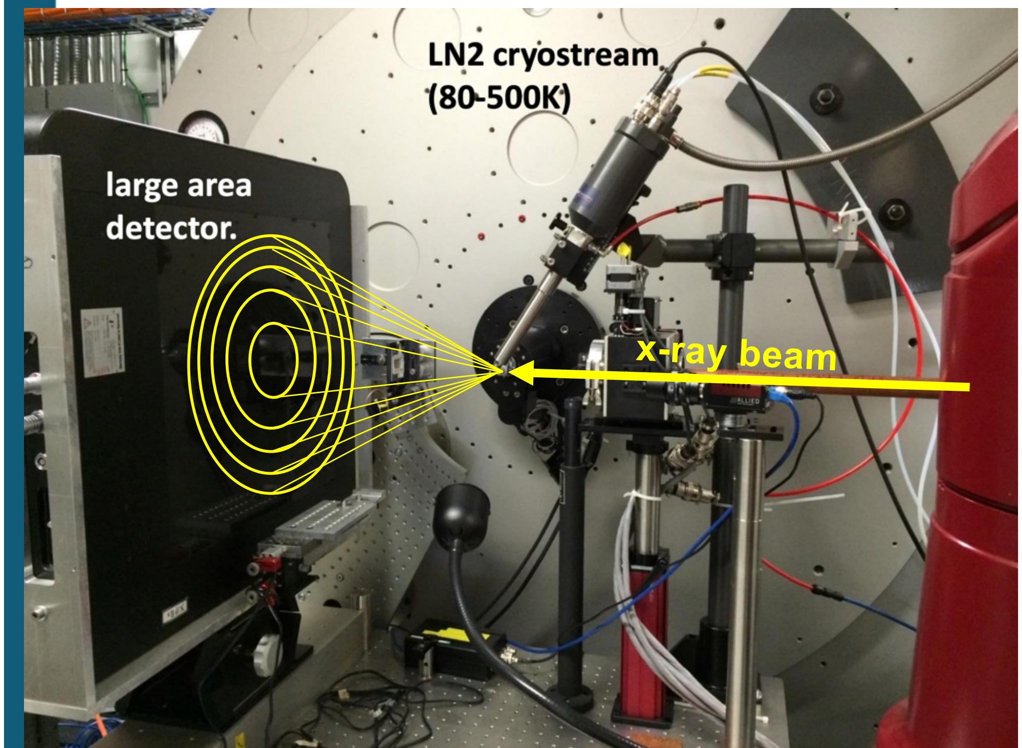




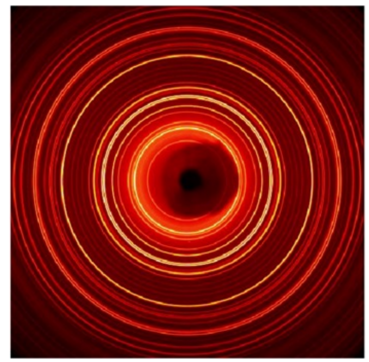


One-slide on X-ray diffraction method

A typical X-ray diffraction setup with area detector

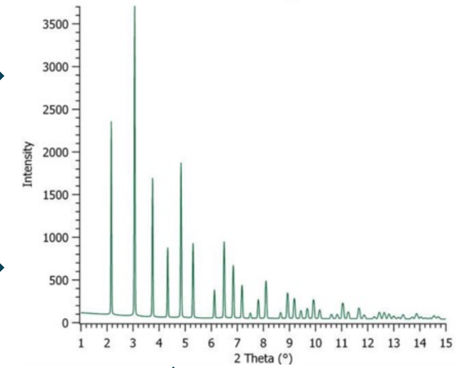


2D image

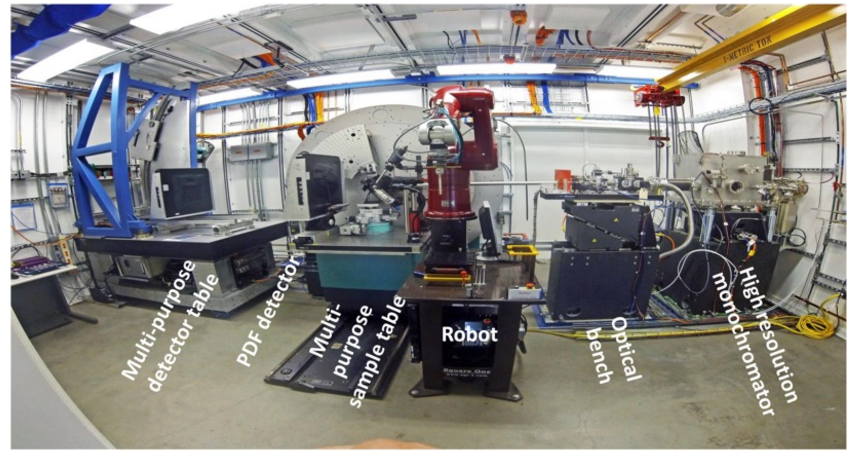


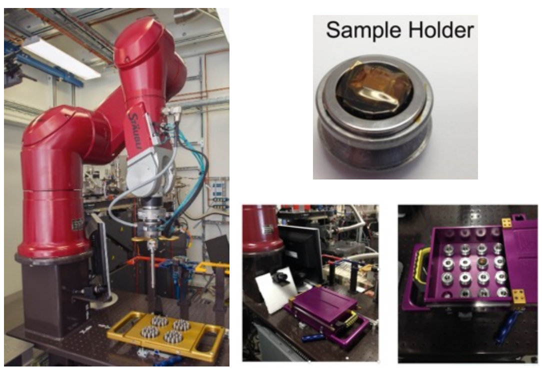
Azimuthal integration

1D pattern

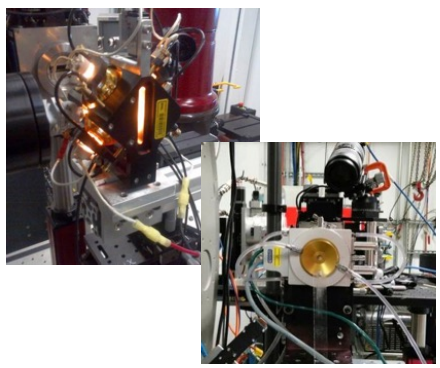


- Phase information
- Lattice parameters
- Phase mass fraction
- Micro strain
- Crystalline size
- Stacking faults

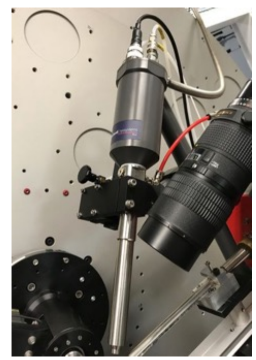




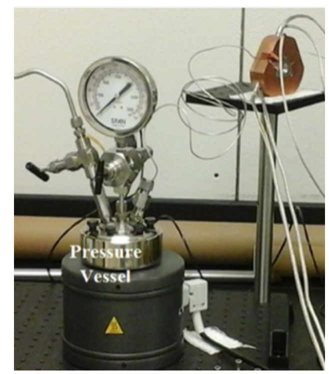
Robot for high-throughput sample changing



Heating up to 1500C



Cryostream (80K-500K)



Corrosion cell

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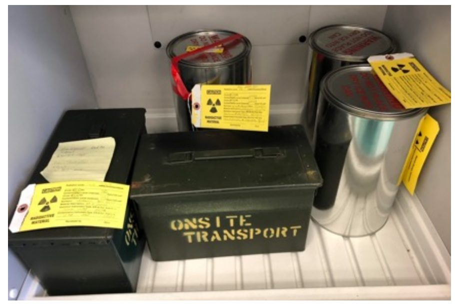
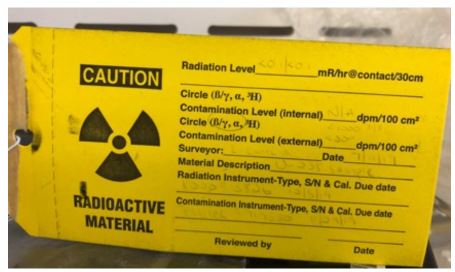
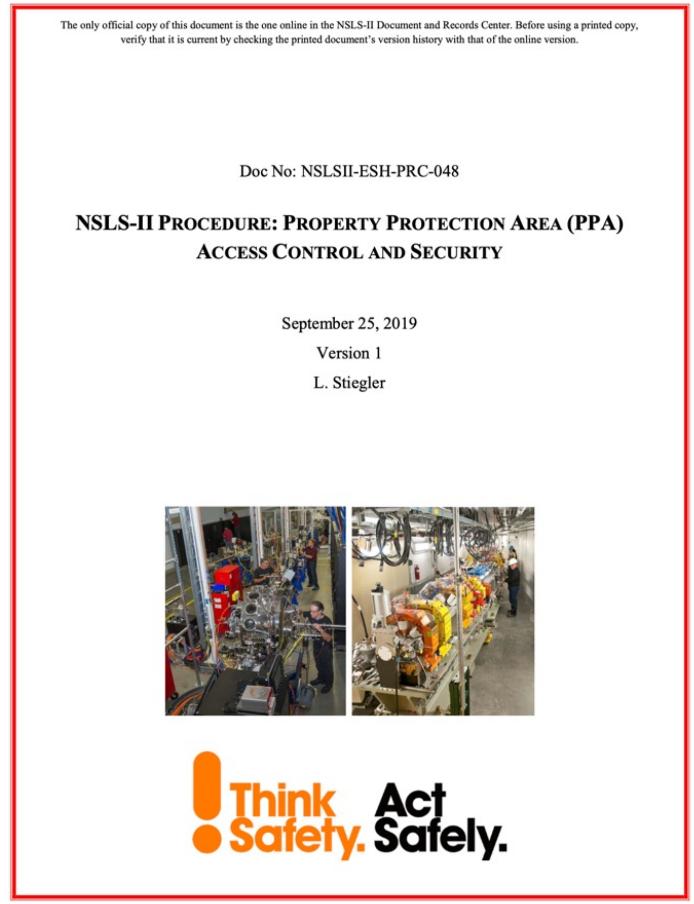
We are experienced with radioactive materials at NSLS-II







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September 25, 2019

Version 1

L. Stiegler

Think Safety. Act Safely.

Brookhaven National Laboratory

Mehmet Topsakal – mtopsakal@bnl.gov

Overview of nuclear material studies at BNL

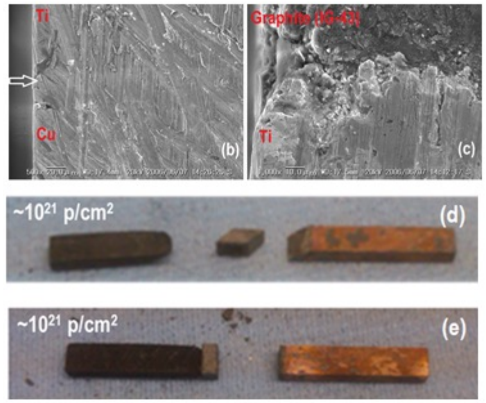
Radiation damage effects – from Graphite to Tungsten

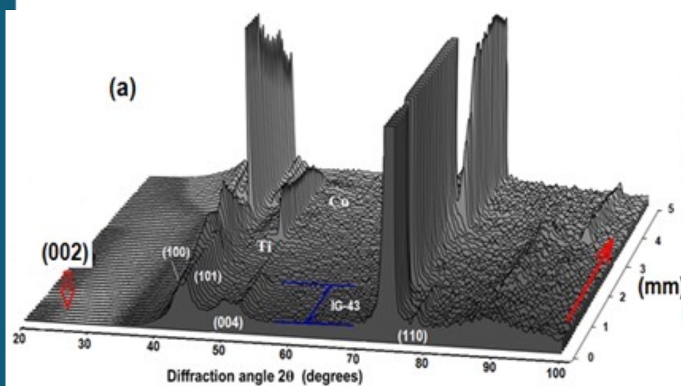
Linking macrostructure to radiation-induced lattice defects

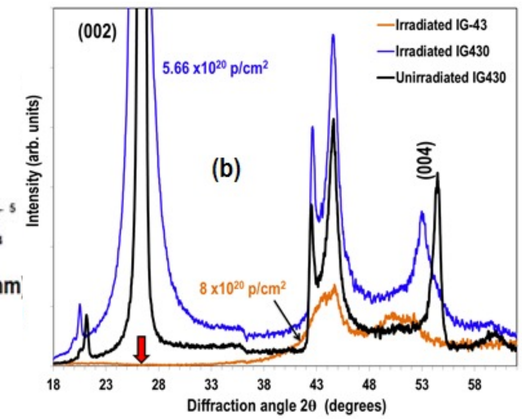
Brookhaven National Laboratory

Research on Graphite: Irradiation ➔ Post-irrad

J-PARC Muon target – BNL Studies



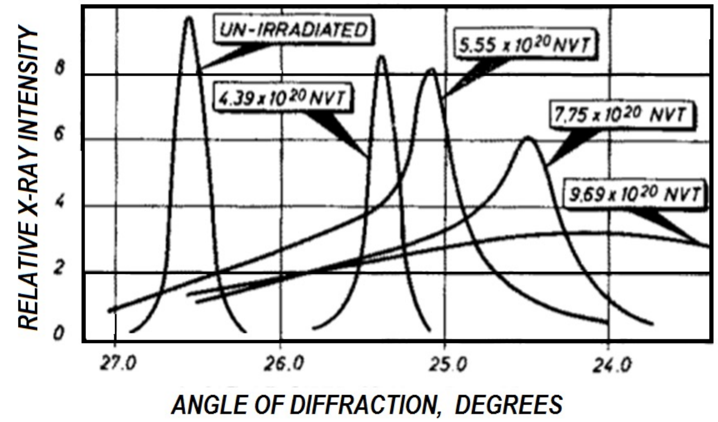


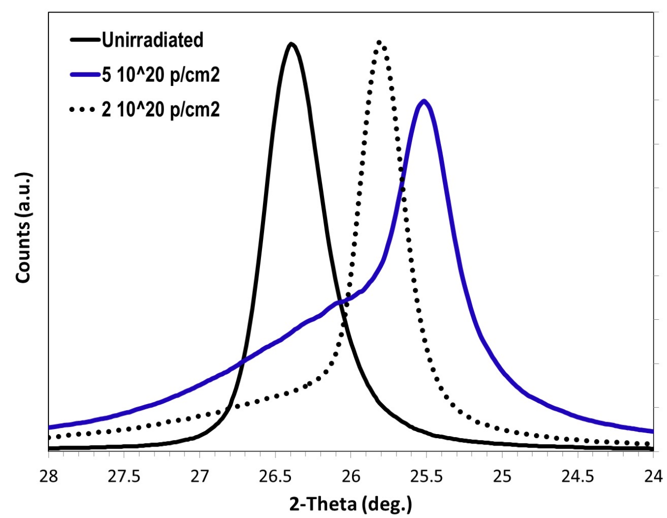


N. Simos, et al., "Solid Target Studies for Muon Colliders and Neutrino Beams," Nuclear Physics B, 155, pp. 288-290, 2006

N. Simos, H. Ludewig, et al., "Multi-MW accelerator target material properties under proton irradiation at Brookhaven National Laboratory linear isotope producer," *Physical Review Accelerators and Beams* (2018) 21 (5)

Correlating damage in GRAPHITE between neutrons and protons at BNL

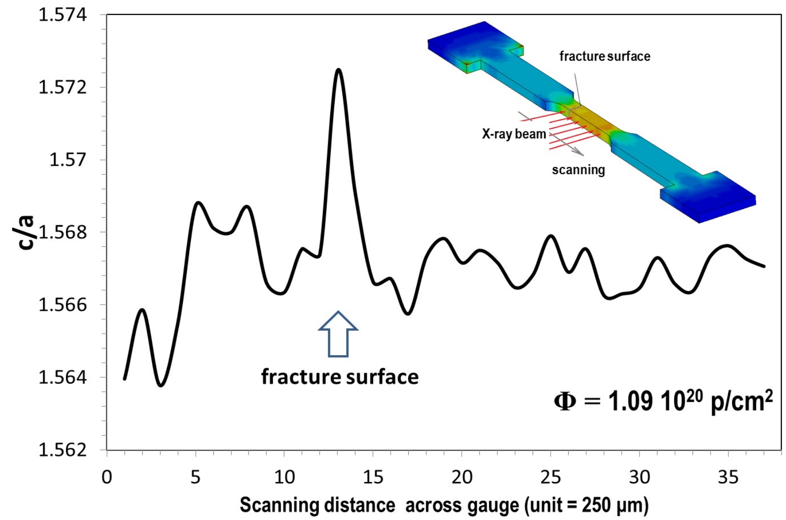


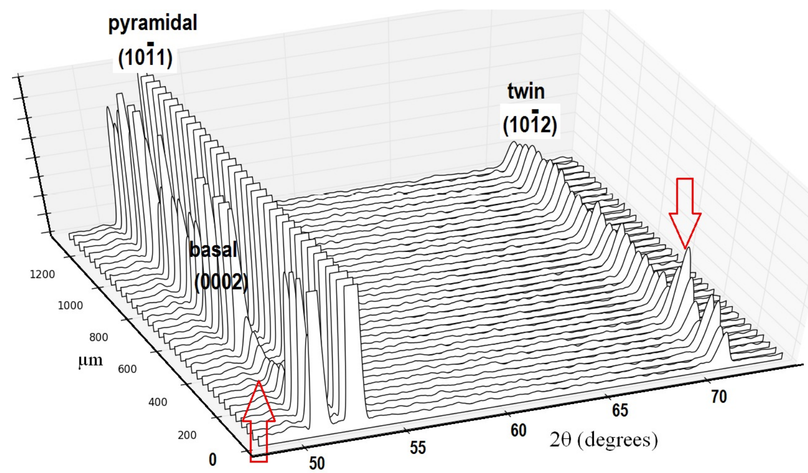


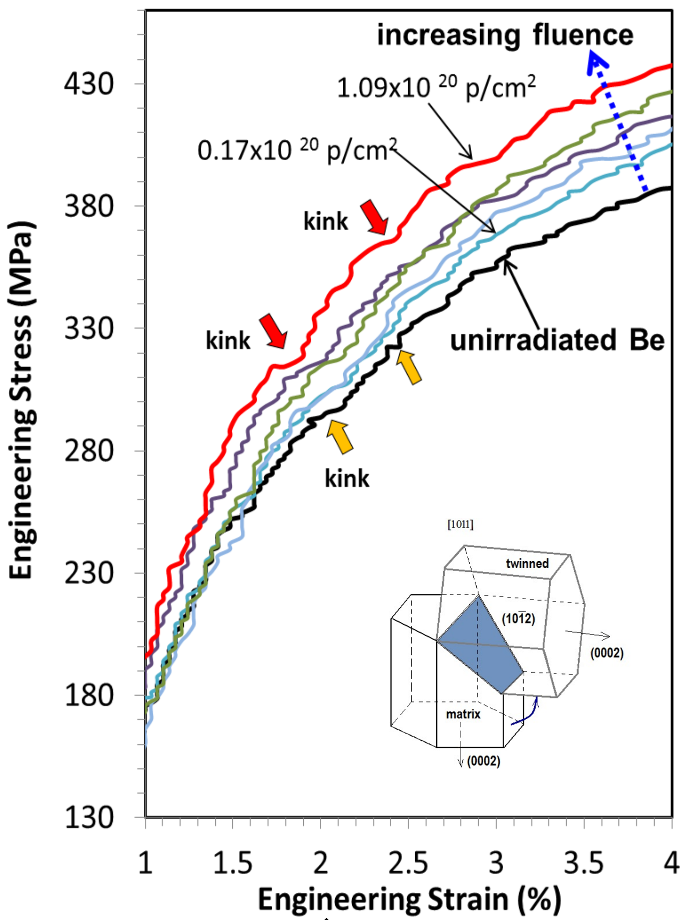
N. Simos, et al., "Proton Irradiated Graphite Grades for a Long Baseline Neutrino Facility Experiment," Physical Review Accel. and Beams 20, 071002 2017

HCP Beryllium (S 200F) at BNL

Microscopic analysis







Macroscopic closer view

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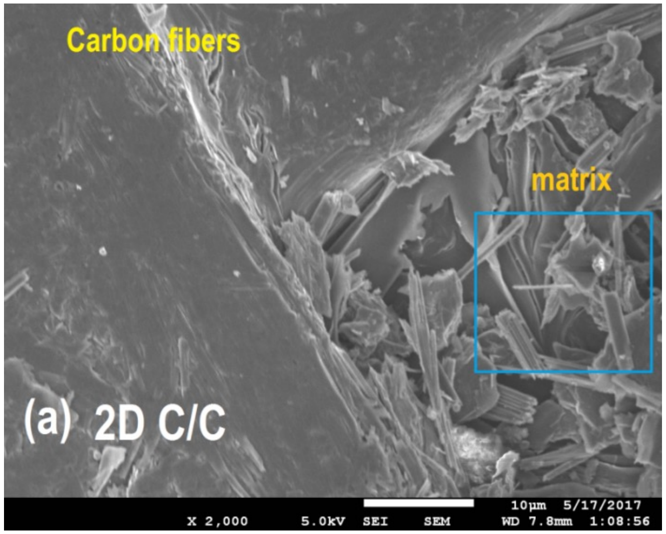
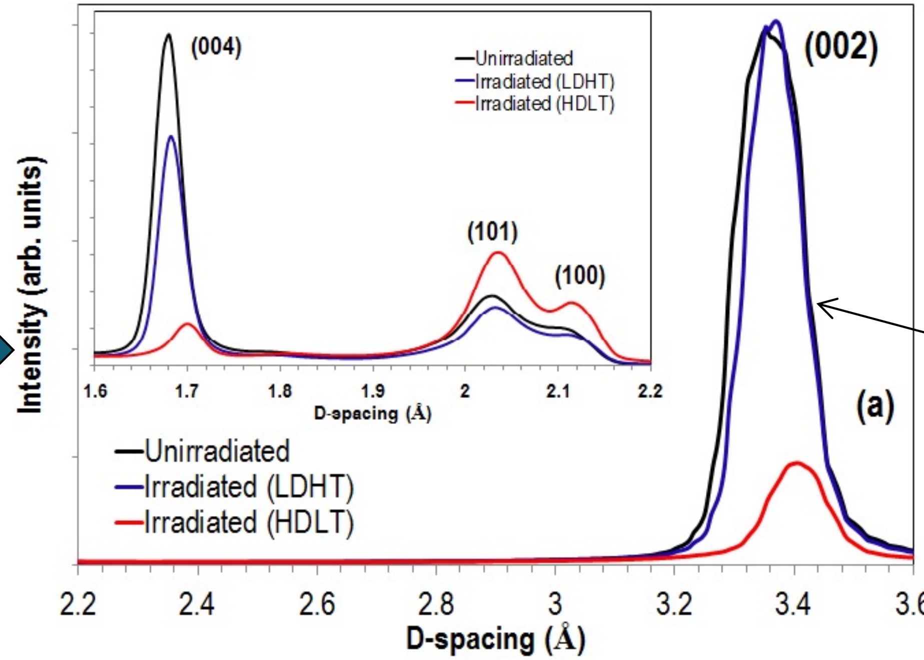
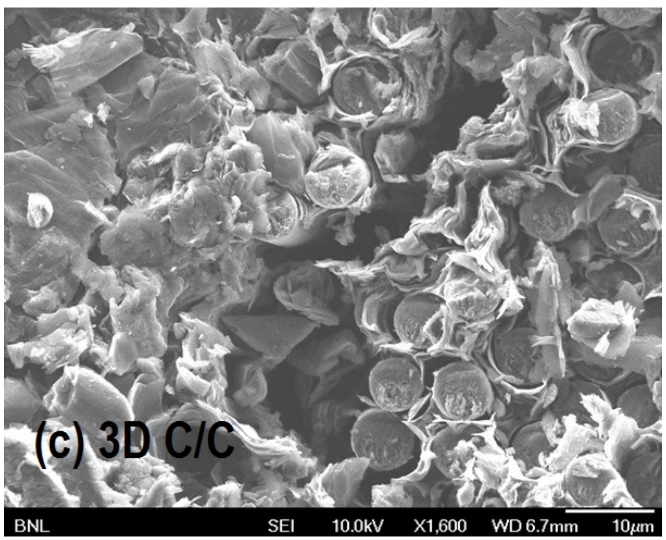
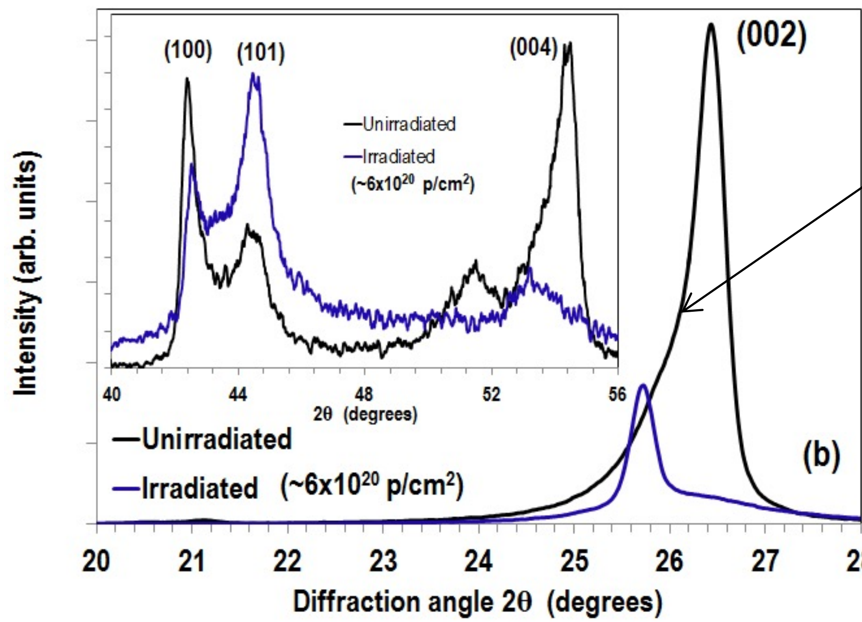
CFC Materials









Graphitization issue/comparison

N. Simos, et al., "Radiation damage and thermal shock response of carbon-fiber-reinforced materials to intense high-energy proton beams," Phys. Rev. Accel. Beams 19, 2016

Super Alloys

- The (α + β) Ti-6Al-4V alloy
- The β-titanium alloy **Gum metal** (Ti-21Nb-0.7Ta-2.Zr-1.2O)
- Super-Invar
- Inconel 625 and 718

Refractory Metals

- Tantalum
- Tungsten
- Molybdenum

LHC Collimation Materials

- Glidcop
- Mo-carbide-Graphite
- Copper-Diamond

Nuclear steels and nano-structured materials (coatings), including SiC, SiC/SiC

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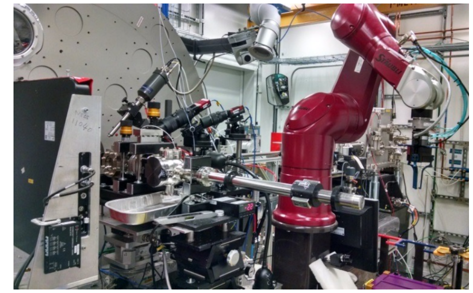
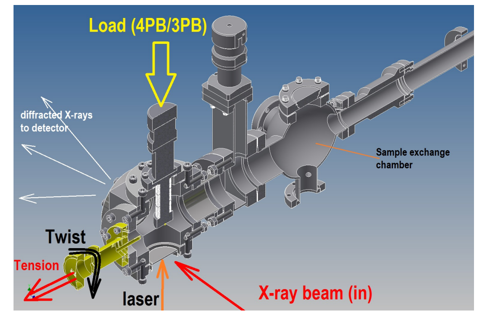
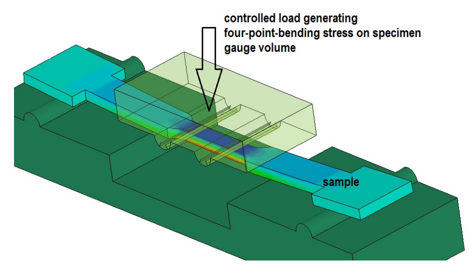
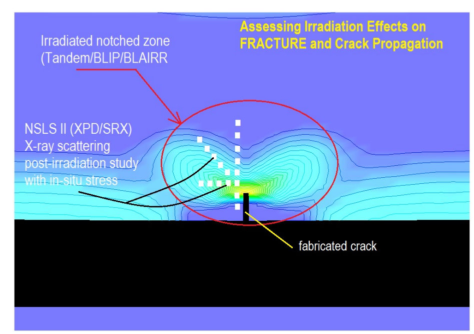
Enhancing EXTREME conditions during X-ray Characterization

- Under way with upcoming experiments at NSLS-II beamlines
- X-ray characterization under extreme, multi-dimensional stress states
- High energy X-rays and creep of irradiated materials
- High energy X-rays and fracture toughness/crack propagation
- High energy X-rays and high temperatures, aggressive environments









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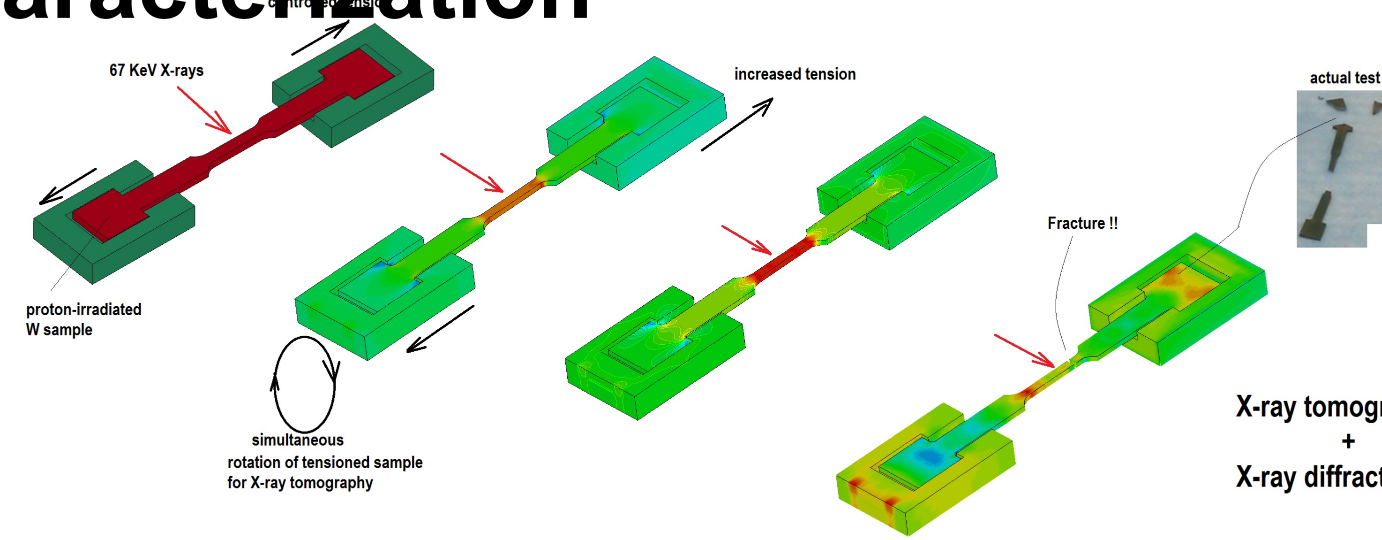
BNL Microstructural Analysis Capabilities - X-ray Characterization



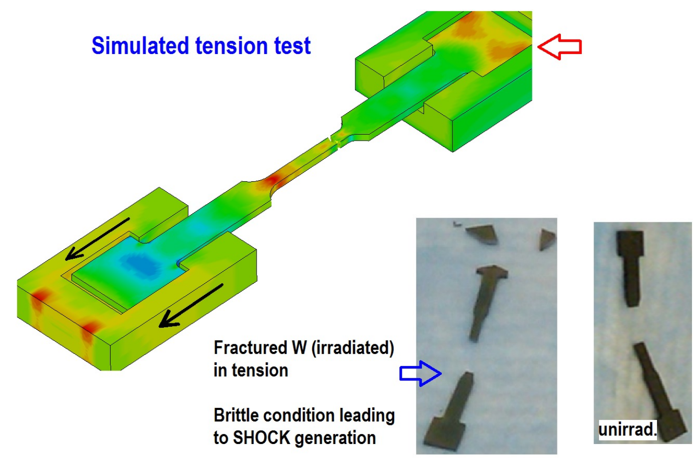
X-ray tomography
+
X-ray diffraction

XPD-D Beamline
NSLS-II, BNL

X-ray Diffraction, X-ray tomography, small angle scattering with **in-situ** multidirectional loading.
Including 3-point, 4-point bending

Tension (to fracture), compression and twisting in addition to the 4-point and 3-point bending

ENABLES observation of the microstructural evolution of the IRRADIATED bulk samples as the material is taken to its limits and eventual fracture.



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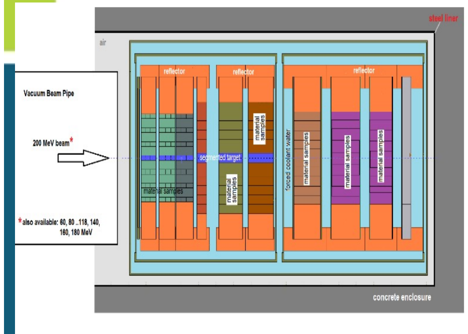
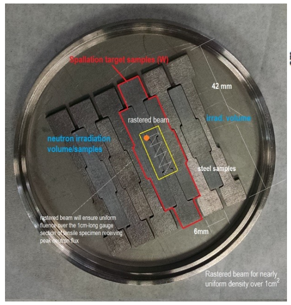
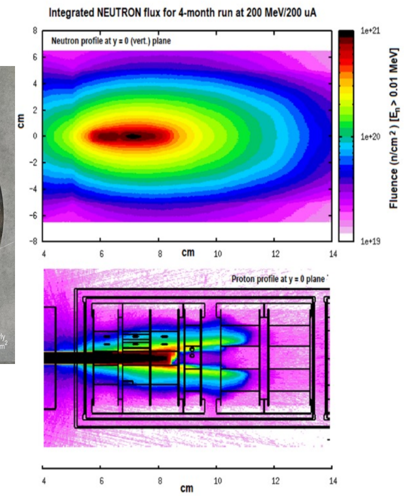
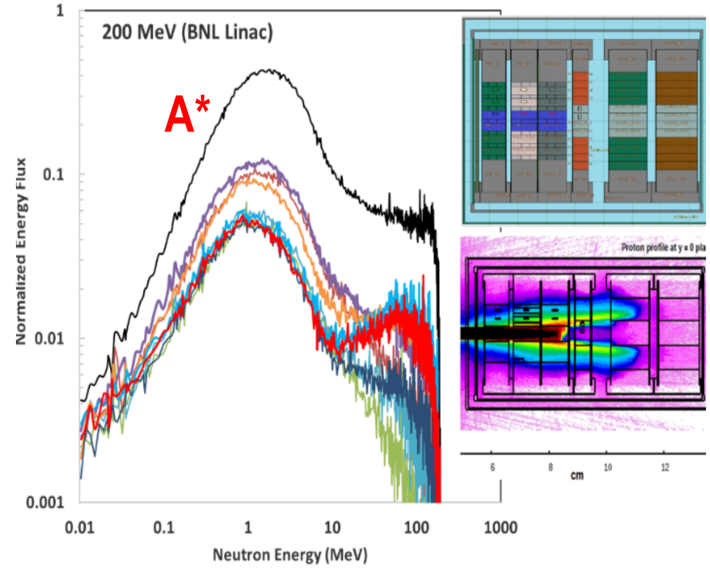
Forward – Spallation Process optimization for fission/fusion reactor materials



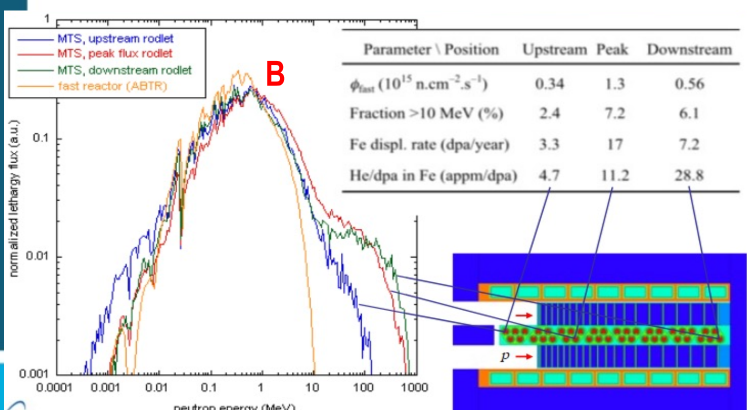




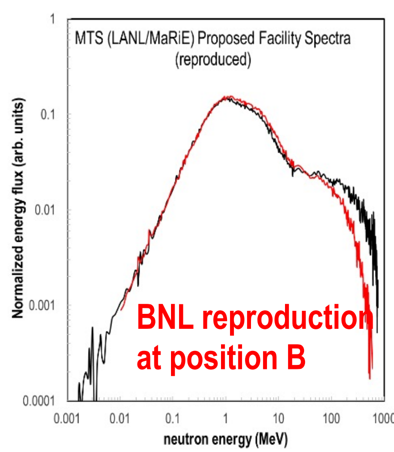


Neutron energy spectra generated by the 200 MeV protons of the BNL beam at various irradiation locations within the irradiated volume

Reproduction of the MaRIE (LANL) produced neutron spectra using 800 MeV LANCE protons prior to completing the BNL option study.



Parameter \ Position	Upstream	Peak	Downstream
ϕ_{fast} (10^{15} n.cm^{-2}.s^{-1})	0.34	1.3	0.56
Fraction >10 MeV (%)	2.4	7.2	6.1
Fe displ. rate (dpa/year)	3.3	17	7.2
He/dpa in Fe (appm/dpa)	4.7	11.2	28.8

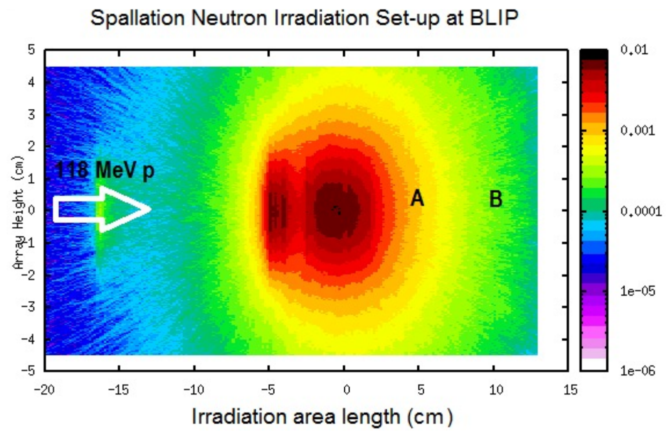


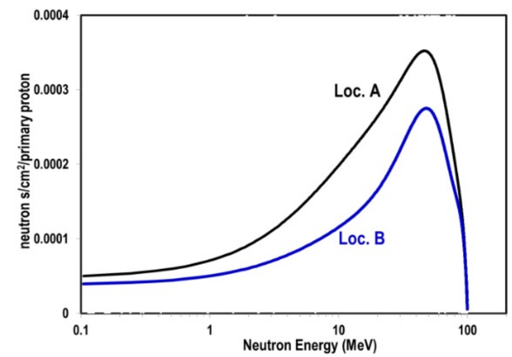
BNL, due to the potential of arranging the irradiated (fast neutron) material volume very close to the spallation target (W) CAN in the closest position match both the spectra and flux (trace **A***)

Spallation target can be studied as accelerator material under proton (200 MeV) flux.

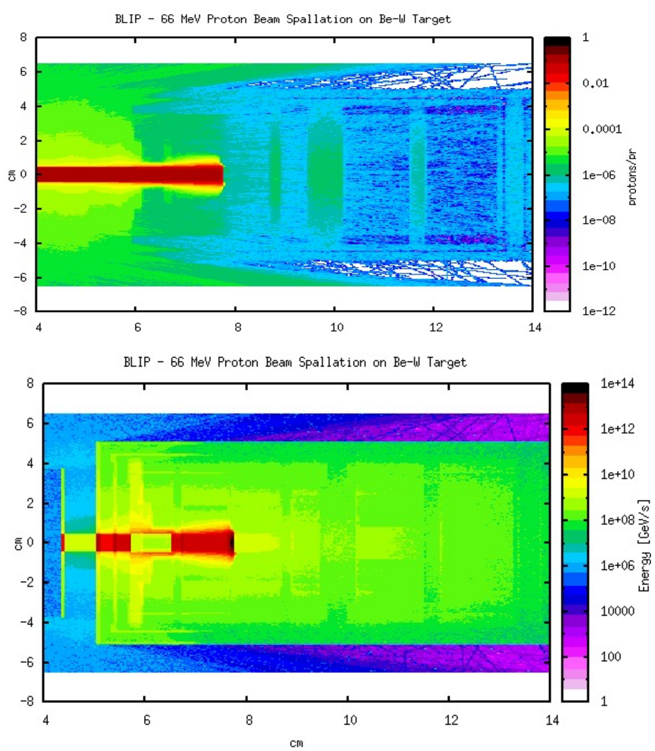
Forward: Fast Neutron Spectra for Fusion Reactor Materials

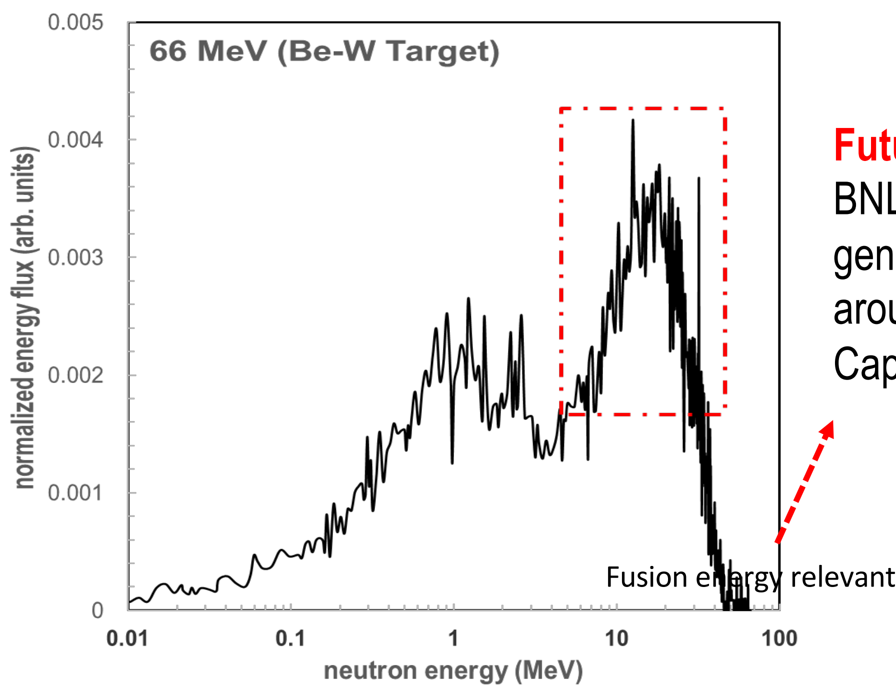
Current capability in irradiating with fast neutrons (constrained by isotope production with beam at 118 MeV, thus fast spectra at 0-degree downstream peaking at ~30 MeV)





Future (explored): Proton beam at 66 MeV with W-Be spallation target





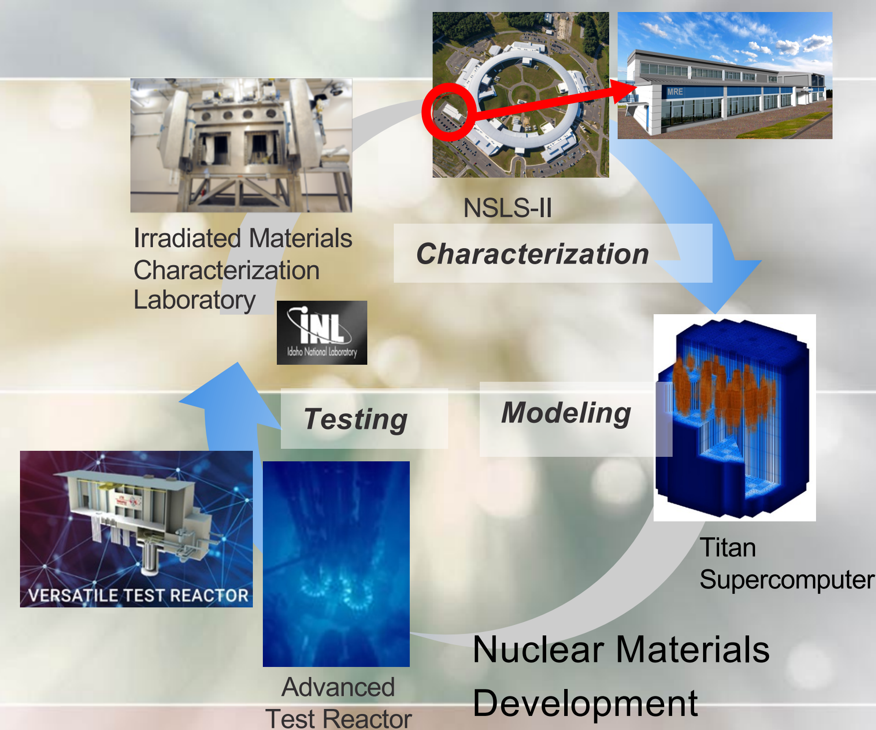
Future capability of the BNL Linac/BLIP to generate spectra peaking around 14 MeV!! Capability stemmi

Section Break

Materials in Radiation Damage

Materials in Radiation Environment

A unique opportunity identified by INL and BNL to enhance DOE mission delivery



Nuclear Materials Development Cycle

Providing a critical tool for Post Irradiation Examination of materials and actinide chemistry in support of the DOE mission to address America's nuclear energy and security challenges

November 19, 2020

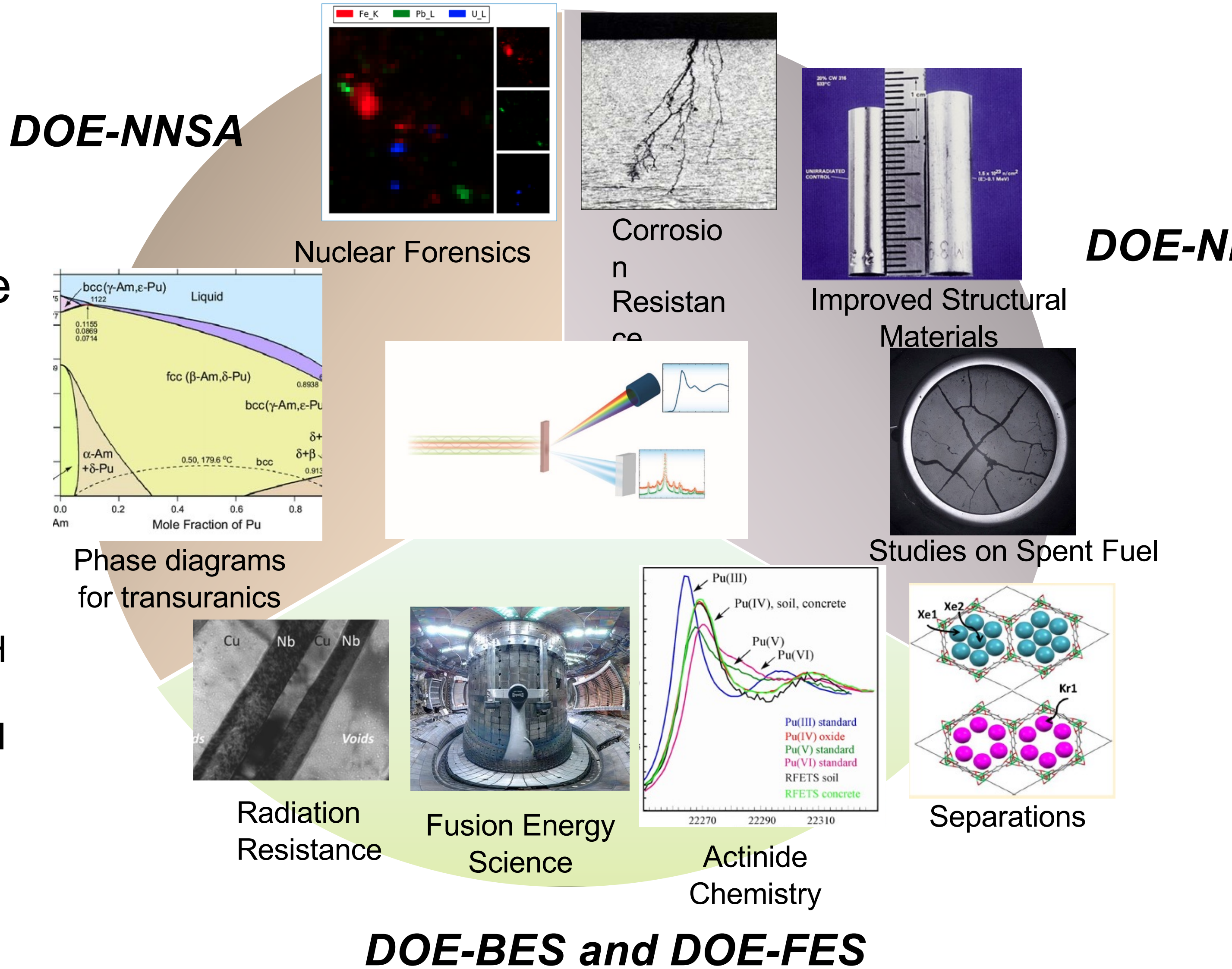
Idaho National Laboratory

BROOKHAVEN NATIONAL LABORATORY

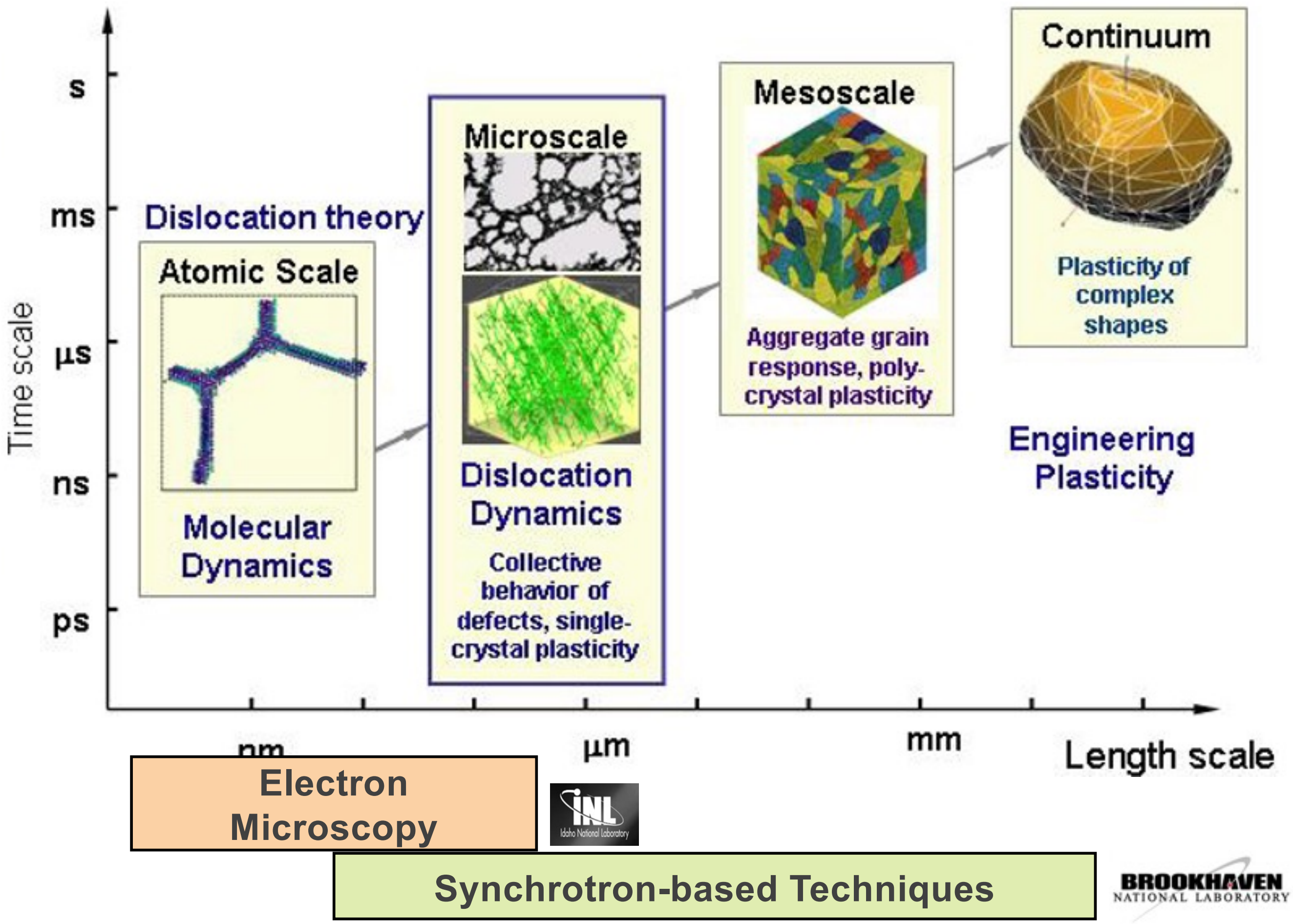
MRE

Addressing Questions Across the Mission of the Entire DOE

- High x-ray energy
- High photon flux
- Separate building
- Separate access and ESH envelope from NSLS-II
- Operated as a radiological facility



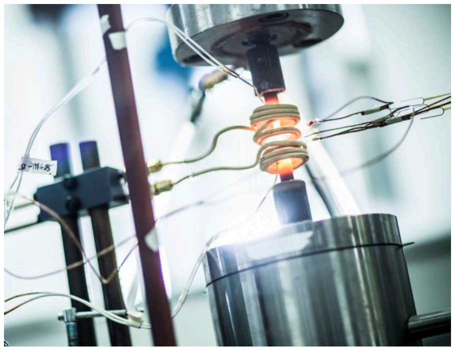
Complementary tools for PIE



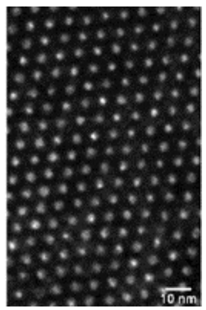
- NE Materials Research Challenges involve a range of processes with length scales spanning orders of magnitude
- Electron microscopy and synchrotron techniques provide a complementary tool set to address these challenges

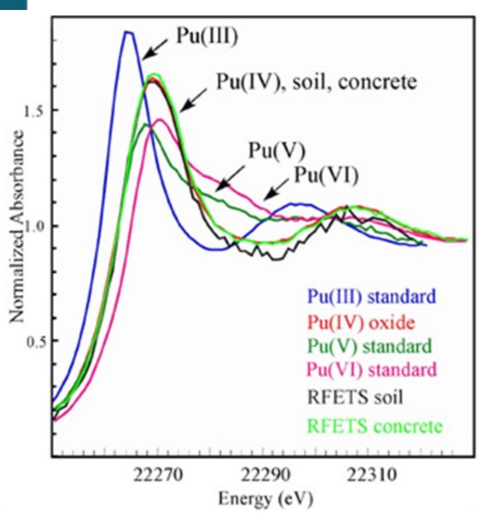
MRE Expands Scope of SC Research on Radioactive Materials

In situ experiments with actinides



Nanopatterning due to radiation damage

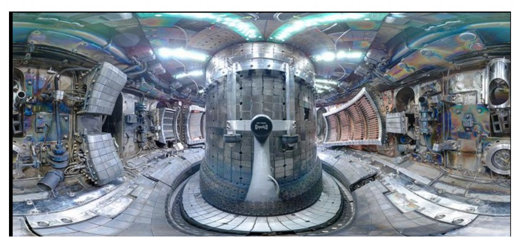


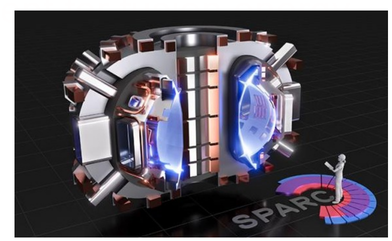


Spectroscopy of actinides

<u>DOE-SC research interests where cutting-edge characterization of radioactive materials is critical to success</u>

- Formation of self-organized microstructures
- Role of grain boundaries in irradiation response
- Design of radiation-resistant alloys
- Crack initiation
- Actinide chemistry / *f*-electron challenge
- Actinide-ligand bonding
- Interaction of actinides at interfaces (liquid-liquid and liquid-solid)
- Advanced materials for waste forms
- Materials degradation in complex environments across broad timescales
- Aqueous chemistry far from equilibrium due to ionizing radiation





Looking Forward at BNL

- Utilizing the potential of NSLS II and establish/complete the spectrum of extreme conditions at the beamlines (high temperature, high and complex stress states, fatigue, oxidation/corrosion kinetics)
  - In-situ multi-dimensional stress capabilities with X-rays adding to the 3- and 4-point bending to include, Tension to failure, Compression, Torsion, High temperature, Oxidizing and other environments within the chamber

  X-ray Tomography, Small Angle Scattering
  and with upcoming HEX beamline: EDXRD and X-ray imaging once HEX beamline is commissioned

- Bring into the suite of characterization capabilities electron microscopy for irradiated materials.
  - The introduction of scanning electron microscopy (SEM) in the TPL laboratory is currently under study in coordination with the BNL Center of Functional Nanomaterials (CFN), a capability that will enhance the characterization of materials at TPL.

- LINAC/BLIP upgrade: reached 205 μA current ➔ UPGRADE goal 300 μA
- Materials in Radiation Environment

Brookhaven National Laboratory

Novel materials, alloys and composites for next generation reactors and/or accelerators require assessment under extremes. Key to such assessment is the ability for post-irradiation characterization of materials of interest

BNL over the decades has maintained infrastructure for macroscopic characterization (hot cells, etc.)

Availability of the NSLS-II synchrotron with high energy X-rays and the commissioned techniques at the beamlines provide an excellent means of micro-characterizing BLIP irradiated materials.

While currently Electron Microscopy has been integrated into the characterization process only for unirradiated materials under extremes (at Center of Functional Nanomaterials facility)

Protons and other **ions** as surrogates to emulate the damaging effects of fast neutrons have been used at BNL . Also, BNL Linac/BLIP has provided to-date modest means to increase availability of **fast neutrons** to test materials for fast reactors
Proposal is moving forward at BNL to utilize the 200 MeV Linac and the 300 μA peak current it can deliver after its upgrade (peak current achieved to-date 200+ μA) for usable fast neutron spectra for fission and fusion materials

MRE facility will allow for more through testing of irradiated materials.

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Questions?