Irradiation and Structural Analysis Capabilities at Brookhaven National Laboratory:

A synergistic model of beam irradiation and synchrotron light source characterization to bridge the micro-macro characterization gap of radiation effects and damage

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BROOKHAVEN
NATIONAL LABORATORY

U.S. DEPARTMENT OF
ENERGY

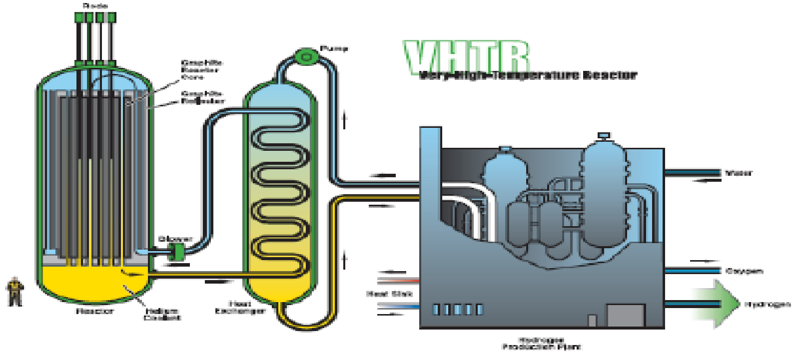
Nuclear (and other) Material Studies at BNL

At a glance:

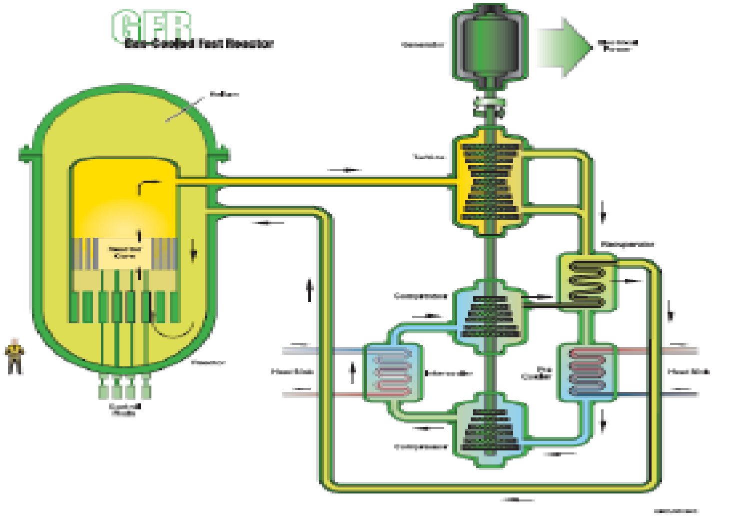
- Intense proton beam effects on target materials and beam windows
  - 24 GeV protons at AGS
- Radiation damage effects on particle accelerator materials and systems
  - Targets, beam windows and collimators
- Radiation damage effects on reactor materials
  - Graphites, Carbon-fiber and SiC/SiC composites, Be, W, Ta, Mo
  - Super-alloys (super-Invar, Gum metal, Ti_6Al_4V)
  - Dispersion strengthened Cu (fusion, LHC)
  - Nano-precipitated steels
  - Nano-structured coatings on reactor steels
  - Molten-salt/material interfaces (Inconel, Steels)
- Radiation effects on detectors and exotic systems
  - Rare earth magnets (synchrotron undulators)
  - CZT crystals
  - SiO_2 fibers
  - Ferrofluids

Nuclear Materials and Synchrotron Radiation Relationship

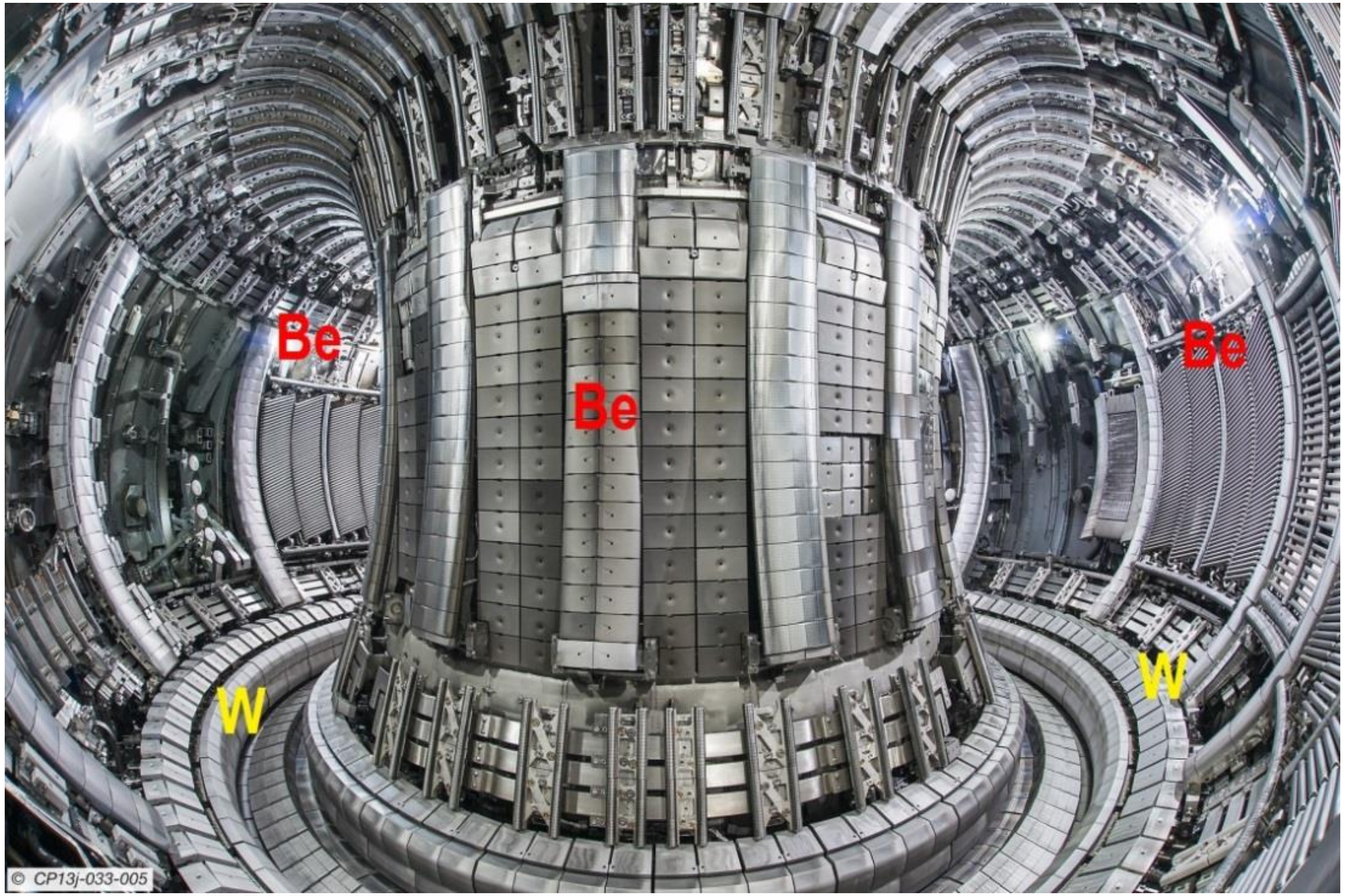
Advanced Reactor Concepts



Very high temperature reactor



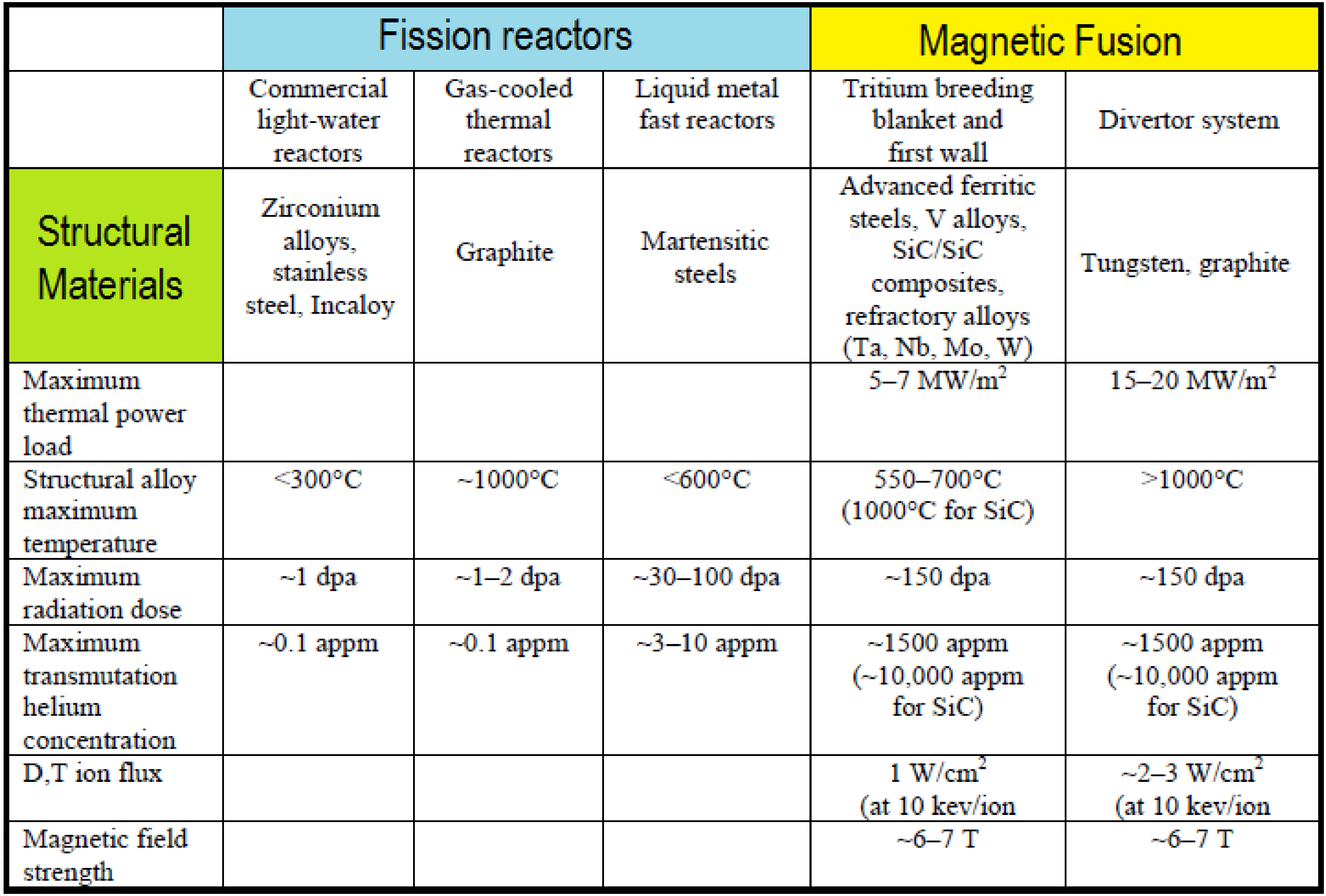
Gas-cooled fast reactor



N. Simos, “Composite Materials under Extreme Radiation and Temperature Environments of the Next Generation Nuclear Reactors", *Composite Materials*, Intech Publishers, ISBN 978-953-307-1098-3, 2011

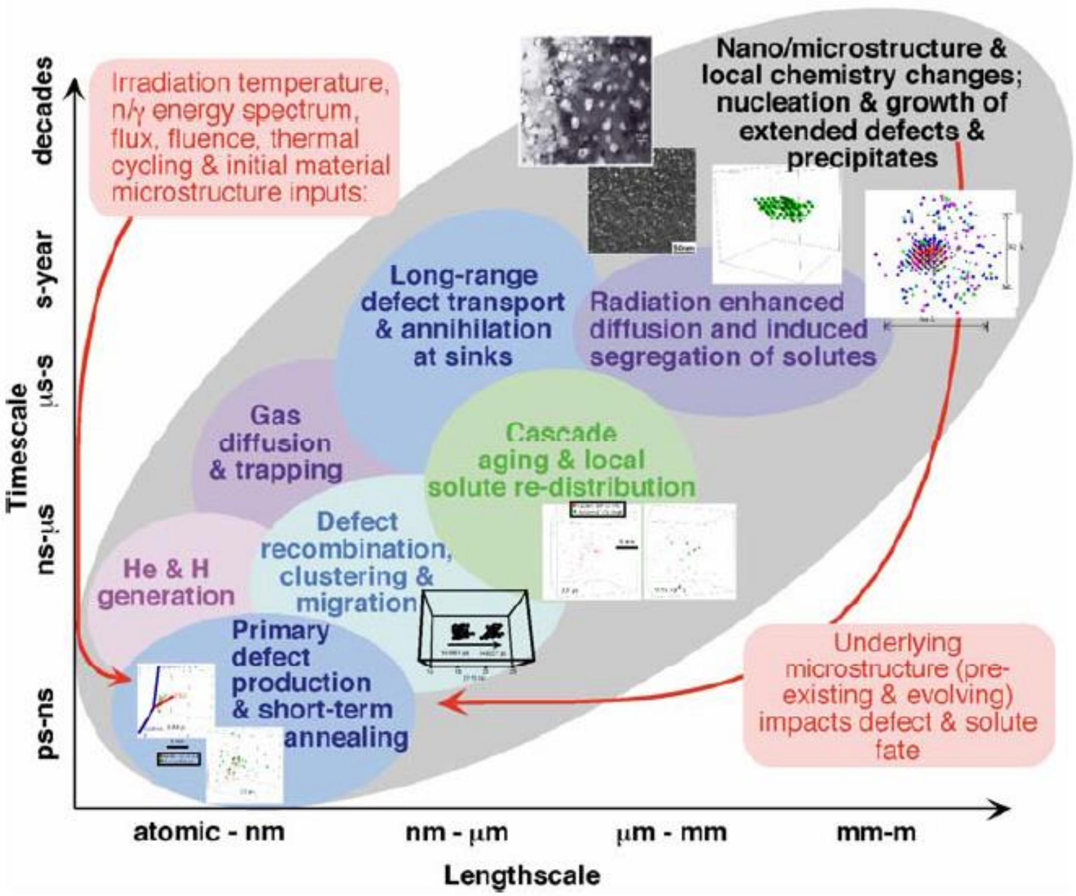
Extreme Environments for Structural Materials:

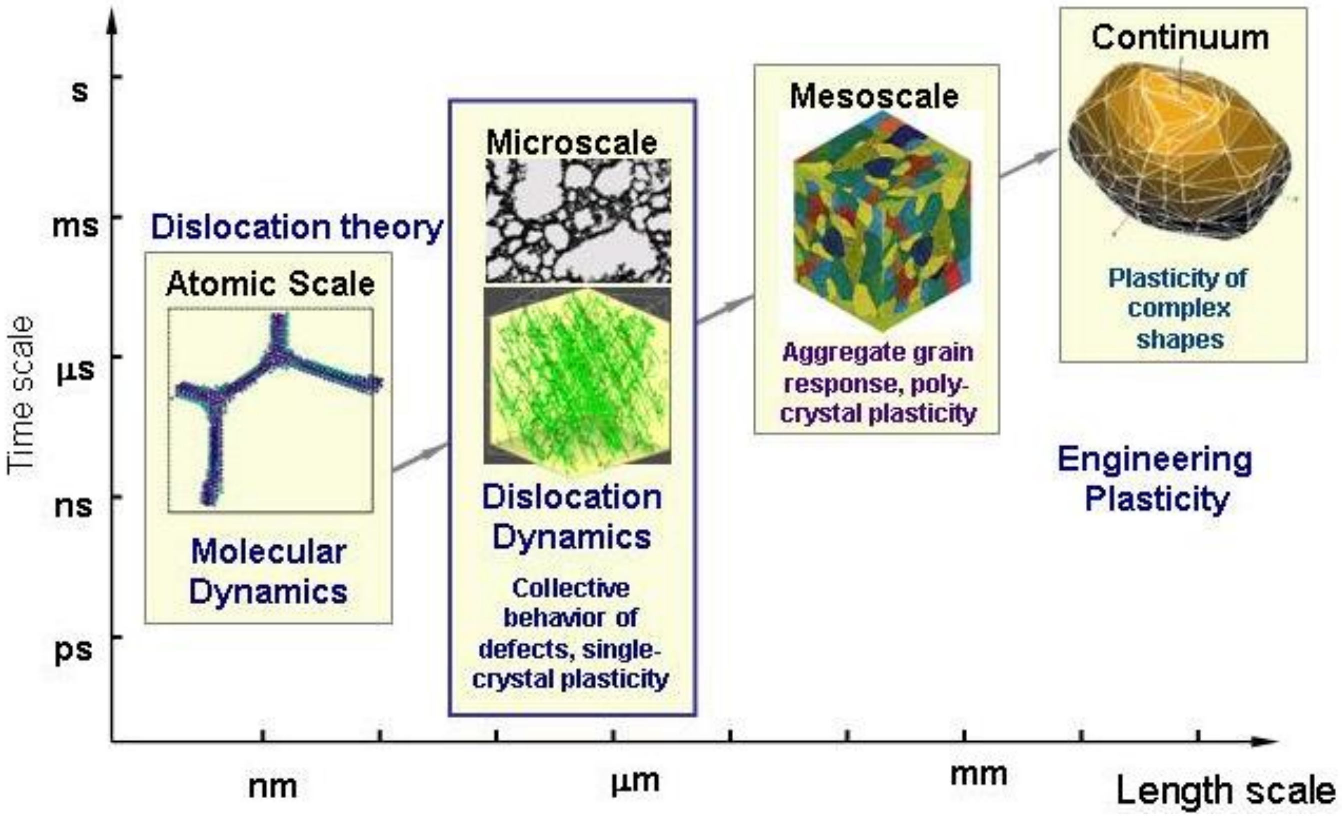
Fission Reactors and Magnetic Fusion Systems



	Fission reactors			Magnetic Fusion	
	Commercial light-water reactors	Gas-cooled thermal reactors	Liquid metal fast reactors	Tritium breeding blanket and first wall	Divertor system
Structural Materials	Zirconium alloys, stainless steel, Incaloy	Graphite	Martensitic steels	Advanced ferritic steels, V alloys, SiC/SiC composites, refractory alloys (Ta, Nb, Mo, W)	Tungsten, graphite
Maximum thermal power load				5–7 MW/m^2	15–20 MW/m^2
Structural alloy maximum temperature	<300°C	~1000°C	<600°C	550–700°C (1000°C for SiC)	>1000°C
Maximum radiation dose	~1 dpa	~1–2 dpa	~30–100 dpa	~150 dpa	~150 dpa
Maximum transmutation helium concentration	~0.1 appm	~0.1 appm	~3–10 appm	~1500 appm (~10,000 appm for SiC)	~1500 appm (~10,000 appm for SiC)
D,T ion flux				1 W/cm^2 (at 10 kev/ion	~2–3 W/cm^2 (at 10 kev/ion
Magnetic field strength				~6–7 T	~6–7 T

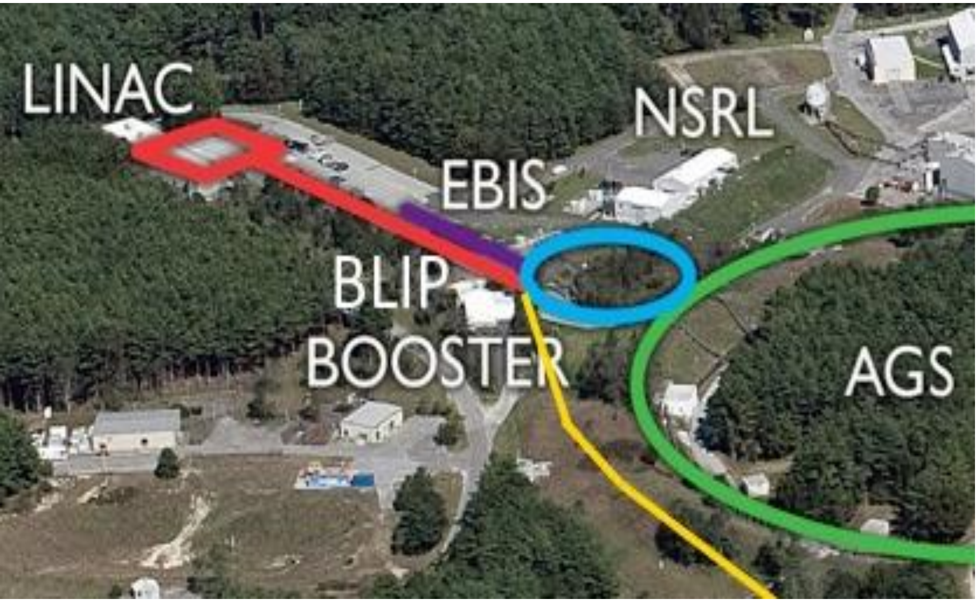
Challenges of Connecting Scales: Materials in Extreme Conditions

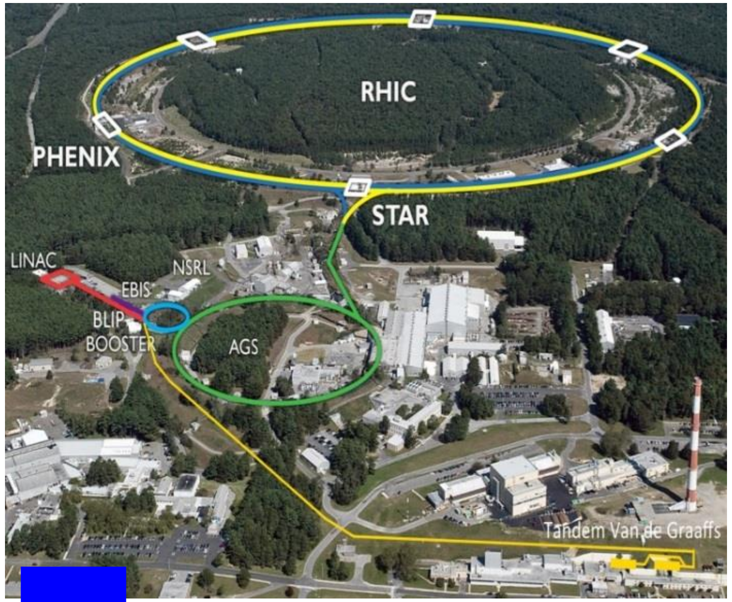




⇨ The unique position of HiRadMat to help advance the field

Synergies with the BNL Accelerator Complex





Collider Complex

NSLS II Synergy

BLIP Irradiation Capabilities

Multiple proton energies 66-200 MeV
    Good beam current (165µA +)
    Beam rastering
    RUN cycle (Dec. – July)

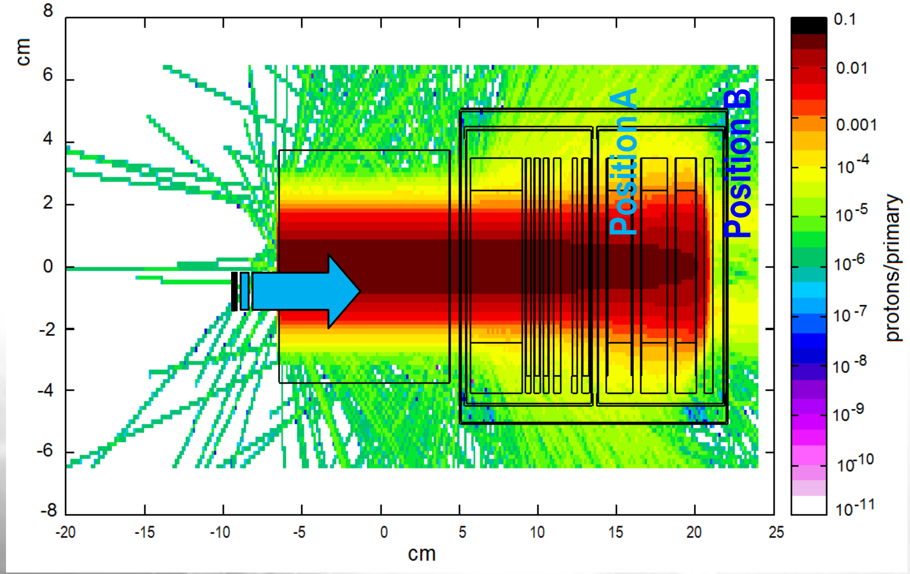
Operates in-tandem with Isotope production and RHIC (no dedicated beam time needed)

Fully operational hot cell laboratory & infrastructure

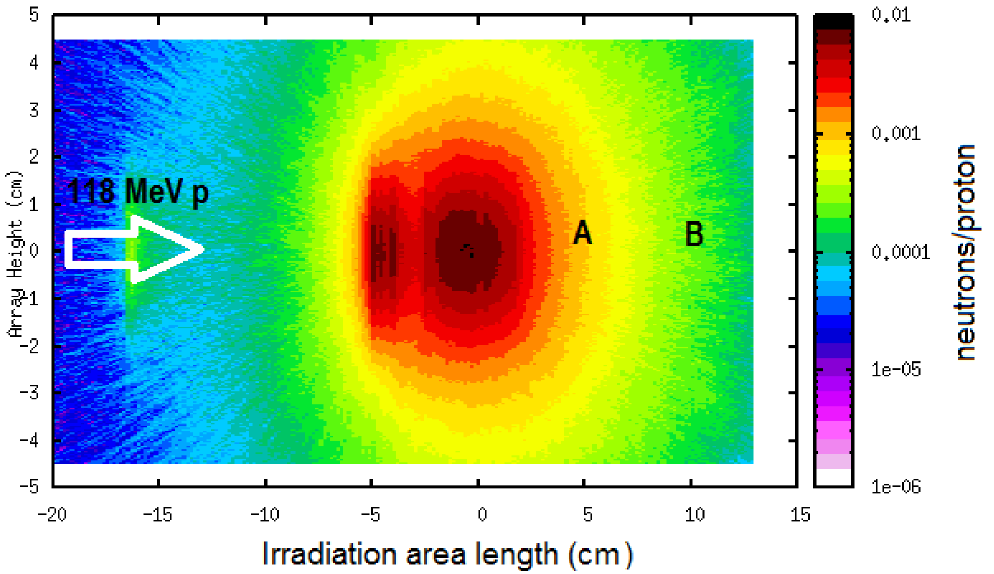
Availability of nuclear instruments/technical expertise

Can operate as neutron spallation source

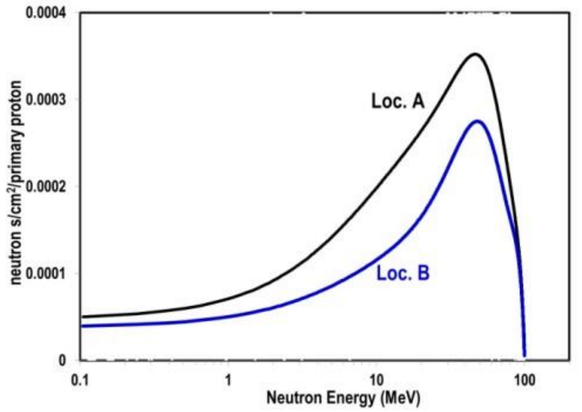
Mode I: Irradiation with BNL Linac protons (up to 200 MeV)



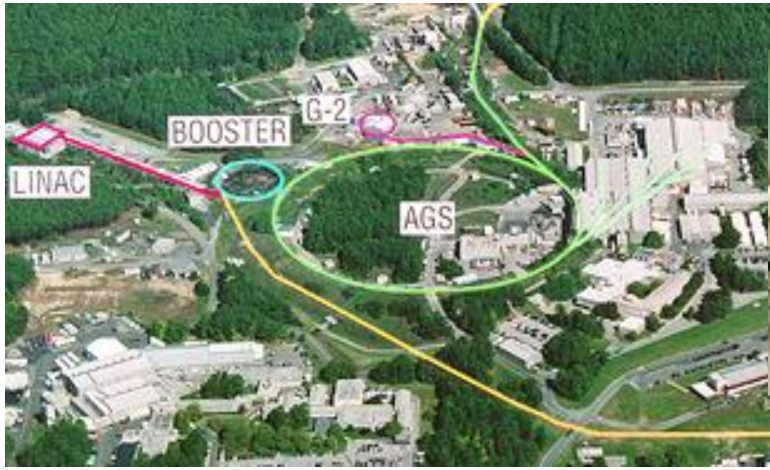
Mode II: Target endstation as a Neutron Source



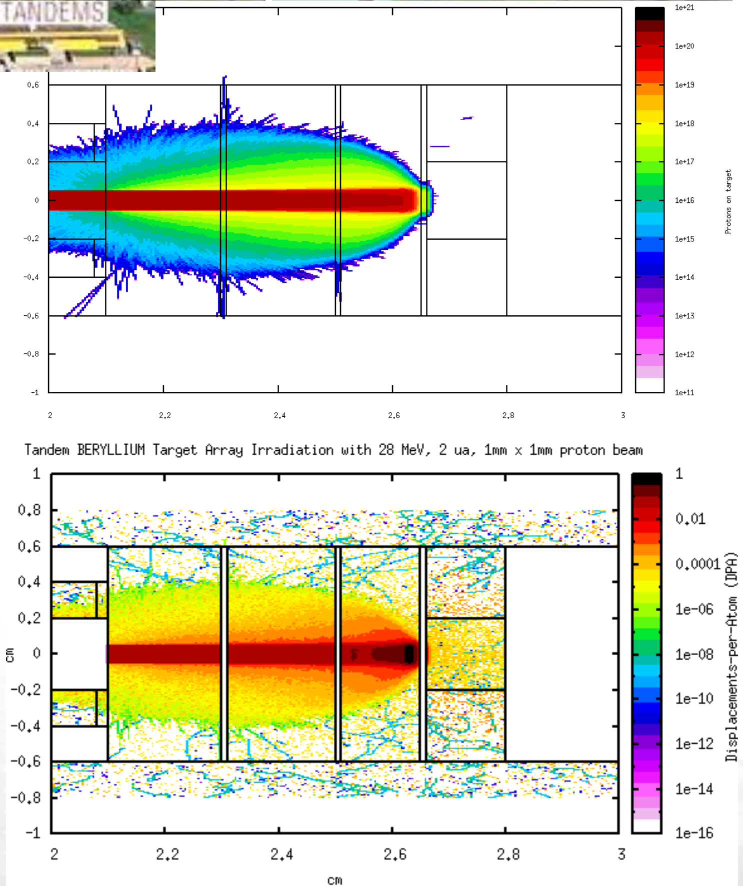
Fusion spectrum similarities



Tandem van de Graaff Capabilities

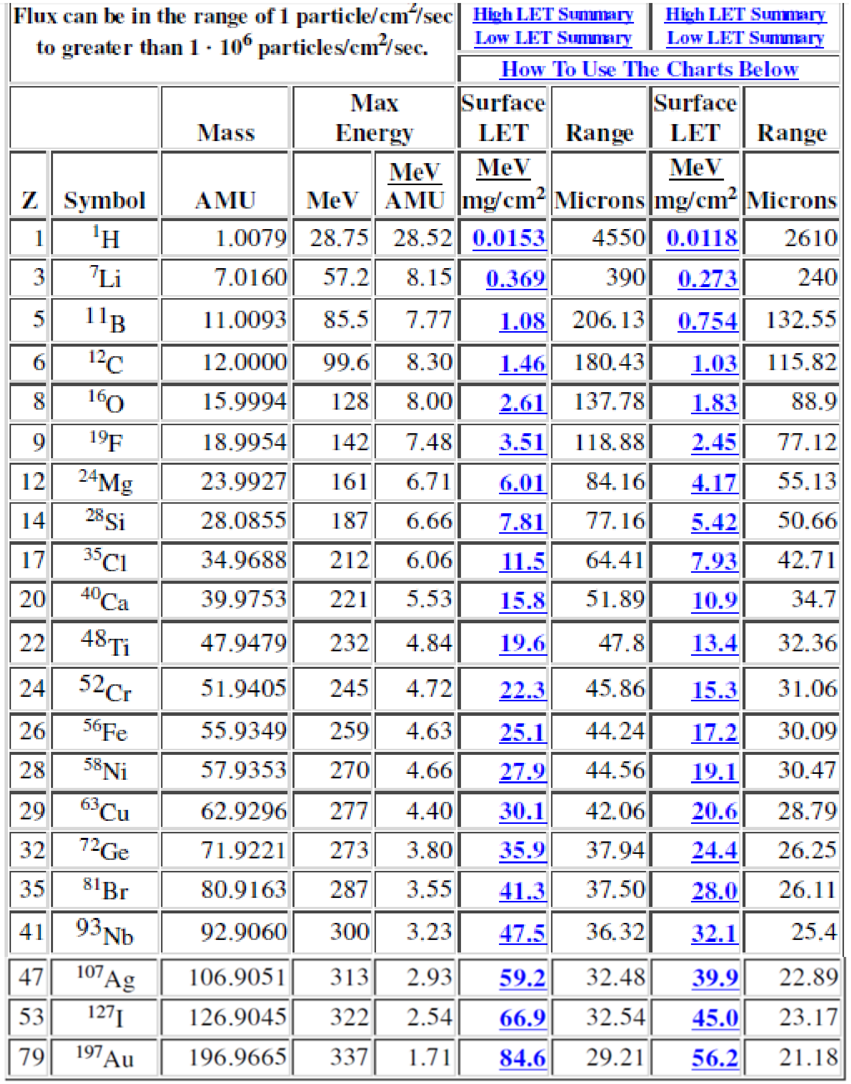


Target Irradiation Beamline



Tandem BERYLLIUM Target Array Irradiation with 28 MeV, 2 ua, 1mm x 1mm proton beam

Ions Available at Tandem



Flux can be in the range of 1 particle/cm²/sec to greater than $1 \cdot 10^6$ particles/cm²/sec.

High LET Summary
Low LET Summary

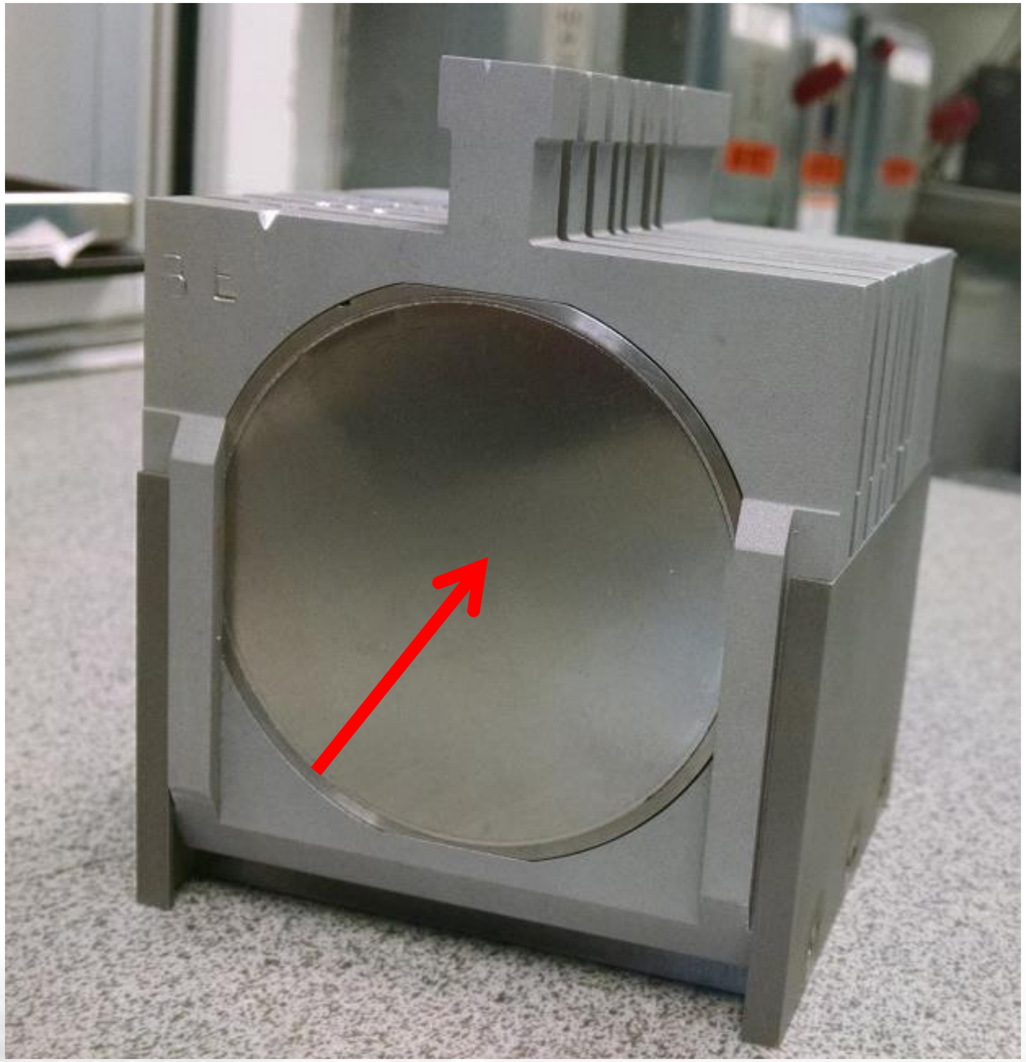
High LET Summary
Low LET Summary

How To Use The Charts Below

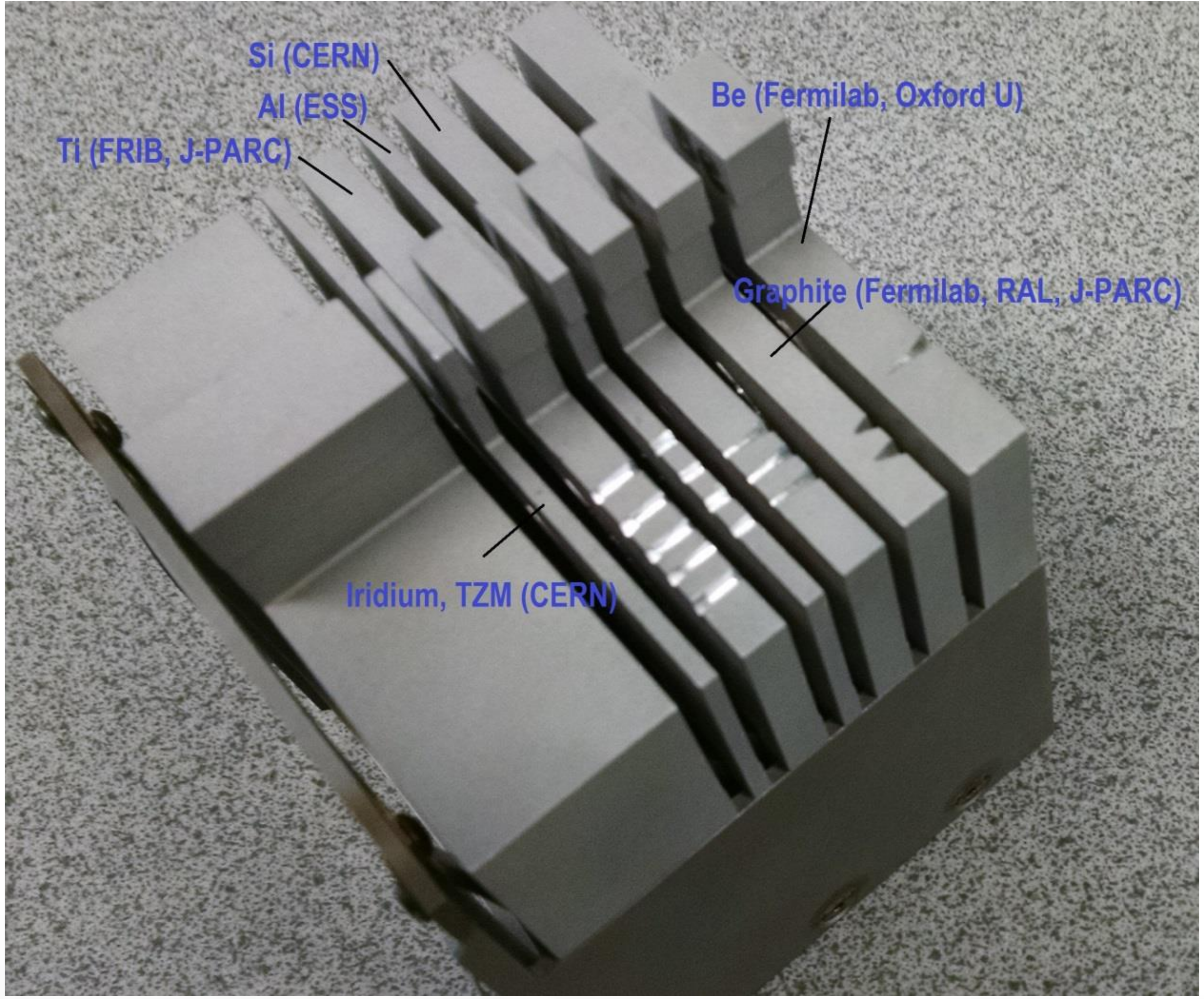
		Mass	Max Energy		Surface LET	Range	Surface LET	Range
Z	Symbol	AMU	MeV	MeV/AMU	MeV/mg/cm²	Microns	MeV/mg/cm²	Microns
1	^{1}H	1.0079	28.75	28.52	0.0153	4550	0.0118	2610
3	^{7}Li	7.0160	57.2	8.15	0.369	390	0.273	240
5	^{11}B	11.0093	85.5	7.77	1.08	206.13	0.754	132.55
6	^{12}C	12.0000	99.6	8.30	1.46	180.43	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

Irradiation Damage Experiments

Aim: reach proton fluence levels that approach threshold or operational goal



Target Array in Beam



Nuclear Material Studies at BNL

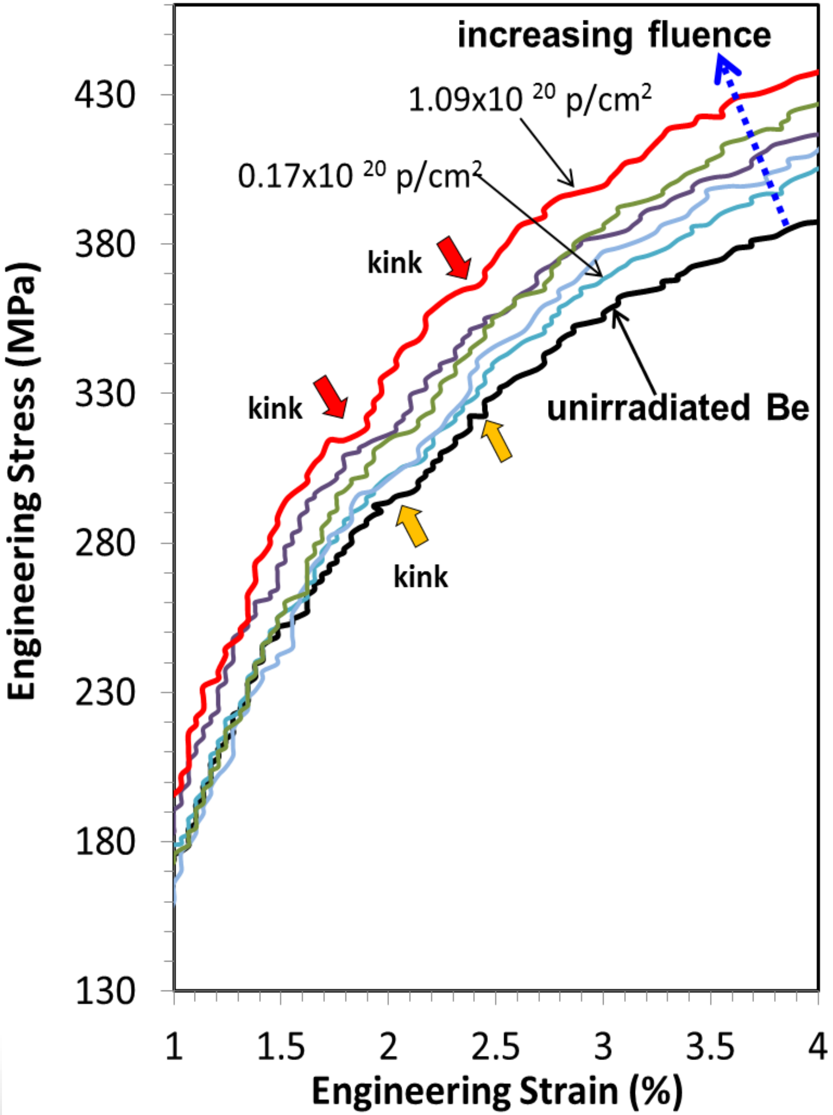
Radiation damage effects

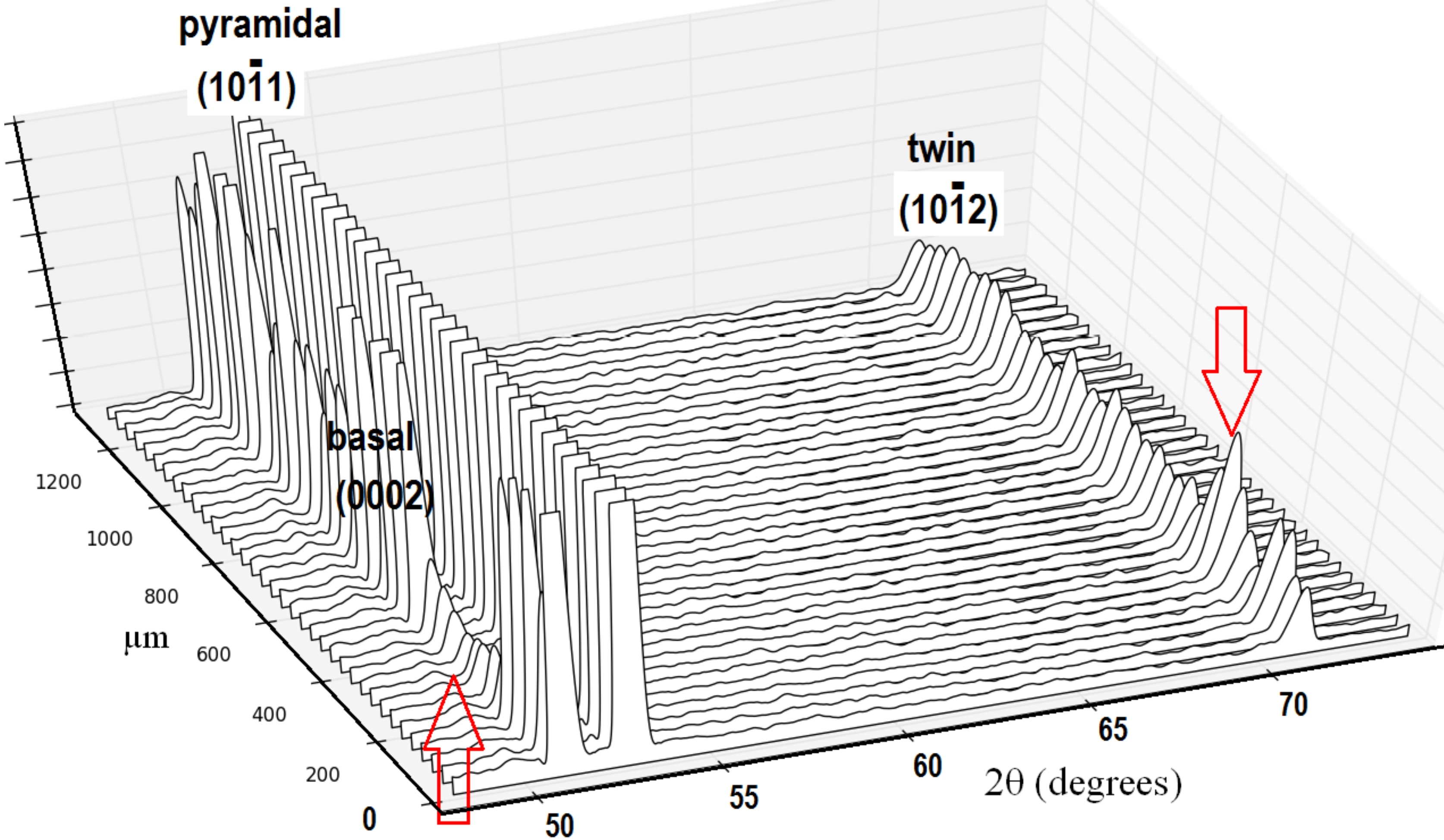
Linking macrostructure to radiation-induced lattice defects

Focus on:

- Gr, h-BN, Be
- Super-alloys
- Dispersion strengthened Cu (fusion, LHC)
- Nano-precipitated steels

Beryllium Deformation – Correlating Macroscopic with Lattice Strain





N. Simos, et al, "Proton irradiation effects on beryllium - A macroscopic assessment," Journal of Nuclear Materials, Vol. 479, 489-503, 2016

N. Simos, et al, "High-temperature annealing of proton irradiated beryllium – A dilatometry-based study," Journal of Nuclear Materials 477, 2016

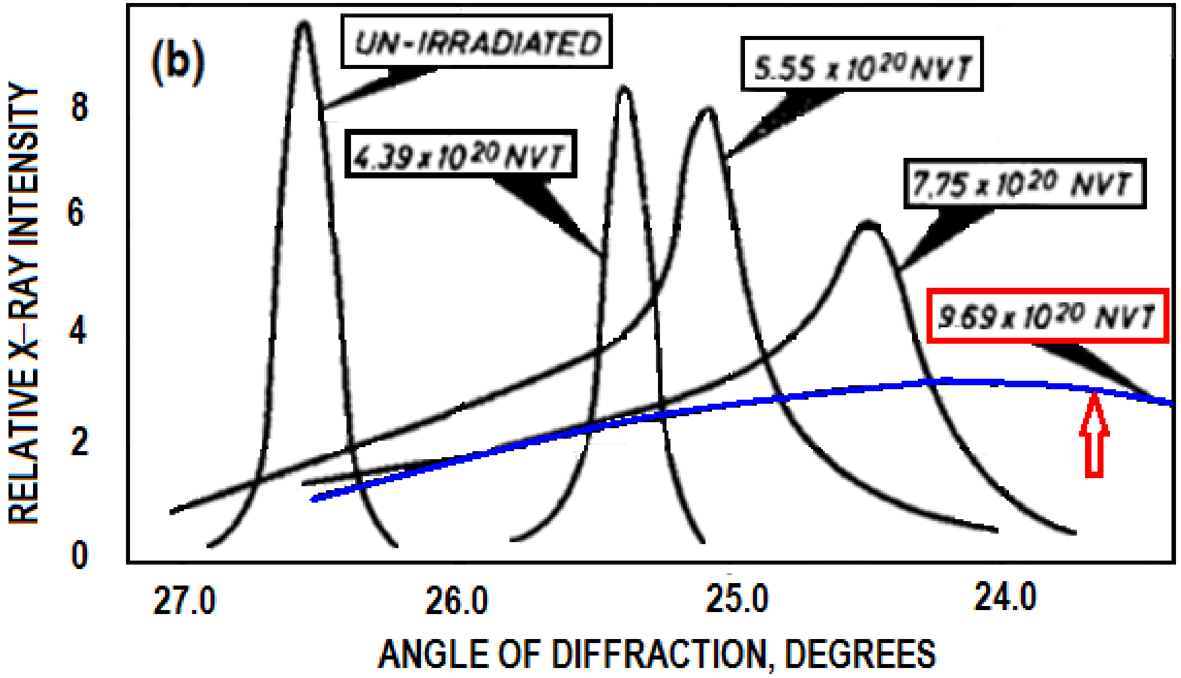
N. Simos, M. Elbakhshwan, et al, "X-ray diffraction studies of 145 MeV proton-irradiated AlBeMet 162," Nuclear Materials and Energy, Vol. 8, 8-17, 2016

N. Simos, M. Elbakhshwan, et al, "X-ray Diffraction, Annealing and Oxidation studies of Proton-irradiated Beryllium," Transactions of the American Nuclear Society, 2017

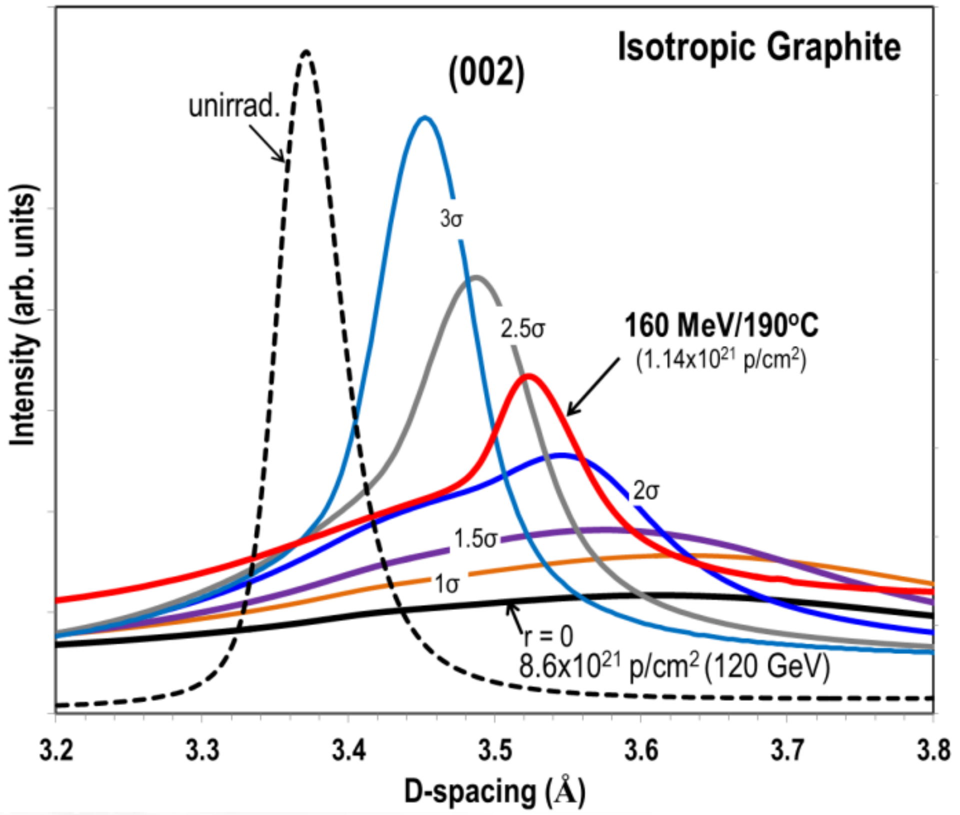
Graphite Irradiation Damage Studies

Proton-neutron damage correlation with the help of NSLS-II

Neutron Damage



Proton Damage

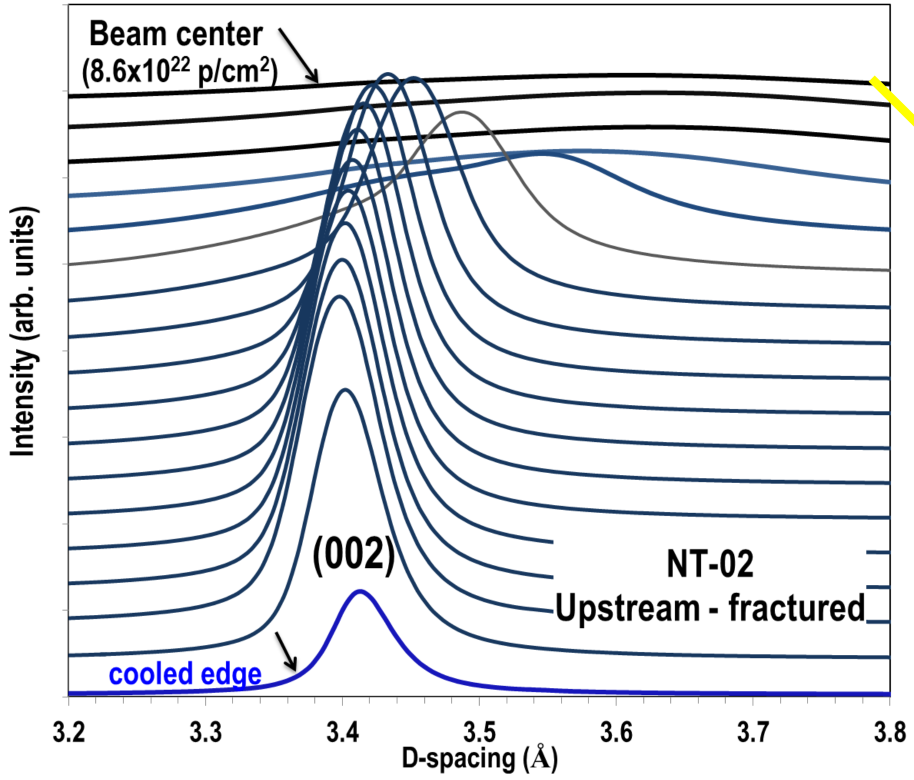


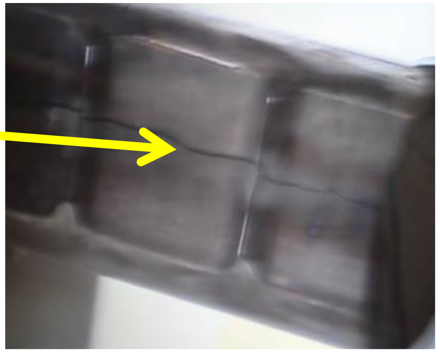
N. Simos, et al., “Proton Irradiated Graphite Grades for a Long Baseline Neutrino Facility Experiment,” Ph. Review Accelerators and Beams 20, 071002 2017

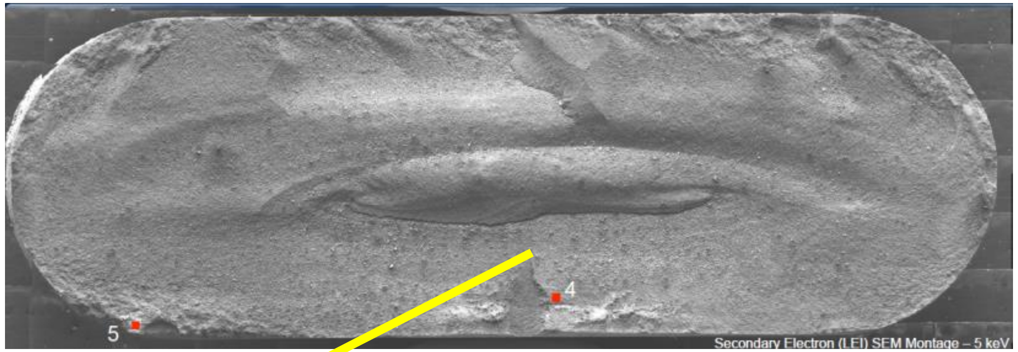
120 GeV NuMI Target Meets World's Brightest X-ray beam at NSLS-II

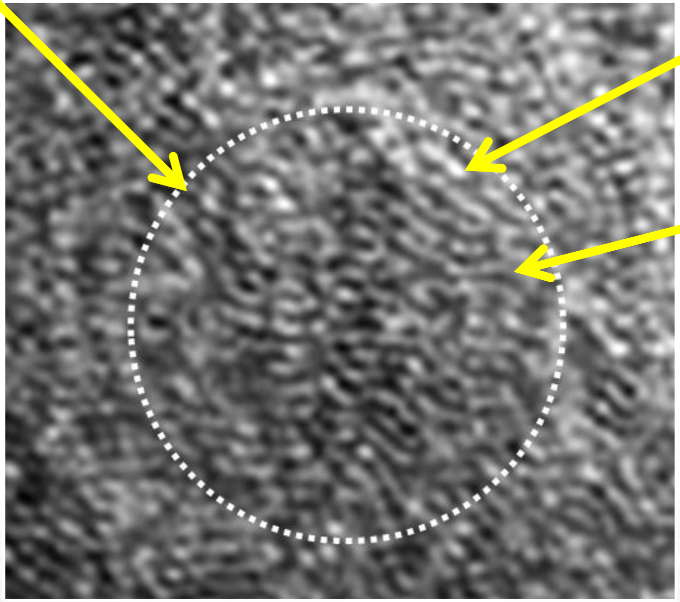
6.1 x10^{20} protons delivered to NT-02 target resulting in a peak fluence of ***8.6×10^{21} protons/cm^2***

Fracture surface









Graphite fragmentation into nano-crystallites

Correlation of X-ray and electron microscopy in IDENTIFYING the state of NuMI target at FAILURE

N. Simos, et al., “120 GeV neutrino physics graphite target damage assessment using electron microscopy and high-energy X-ray diffraction,” Phys.Rev.Accel.Beams 22, 041001, 2019

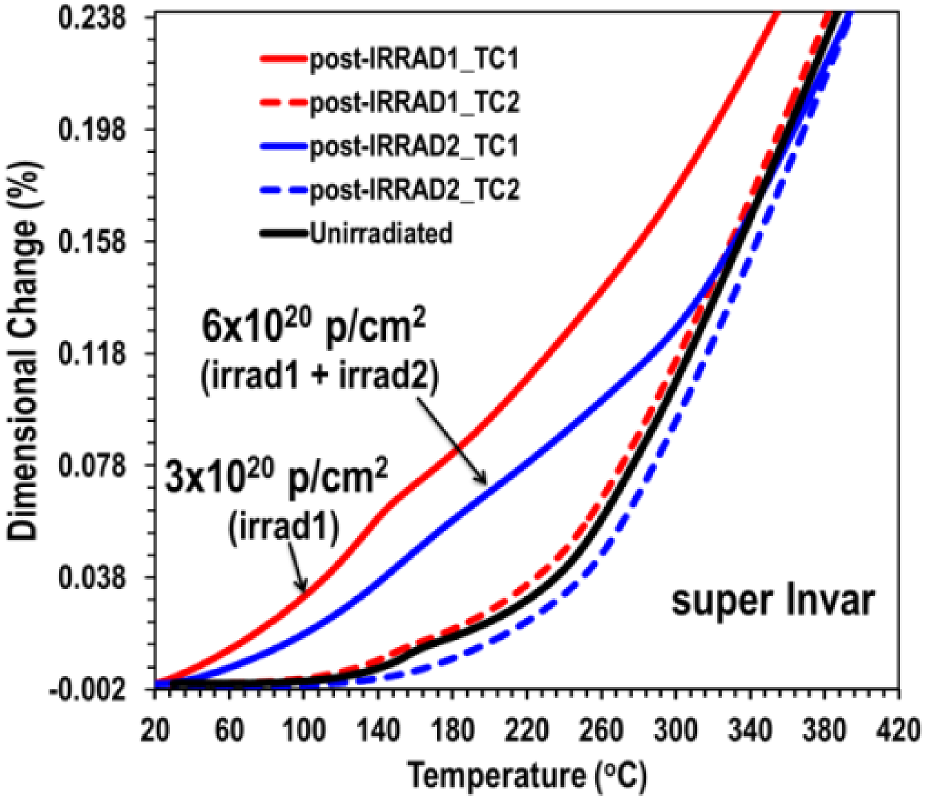
Using the BNL Accelerator Complex to Study Super-alloys & Novel Materials

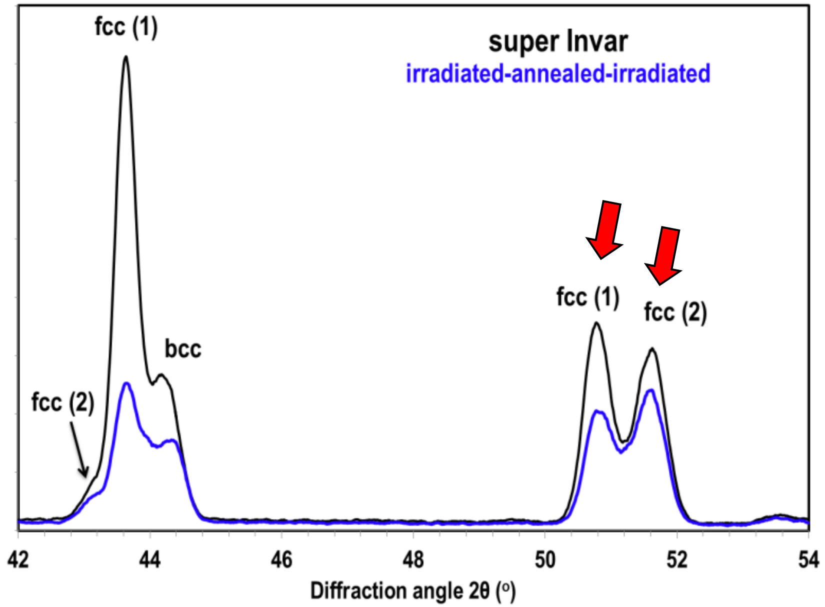
- The (α + β) Ti-6Al-4V alloy
- Super-Invar
- The β-titanium alloy **Gum metal**

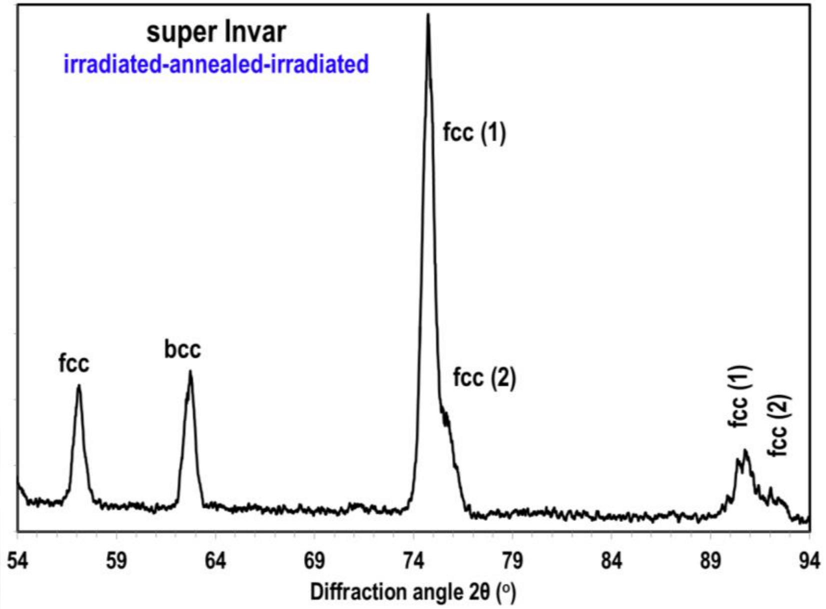
  (Ti-21Nb-0.7Ta-2.Zr-1.2O)

Simos et al., Multi-MW accelerator target material properties under proton irradiation at Brookhaven National Laboratory linear isotope producer, *PHYSICAL REVIEW ACCELERATORS AND BEAMS* 21, 053001 (2018)

Magnetostriction, Annealing and fcc Phases in Super-Invar



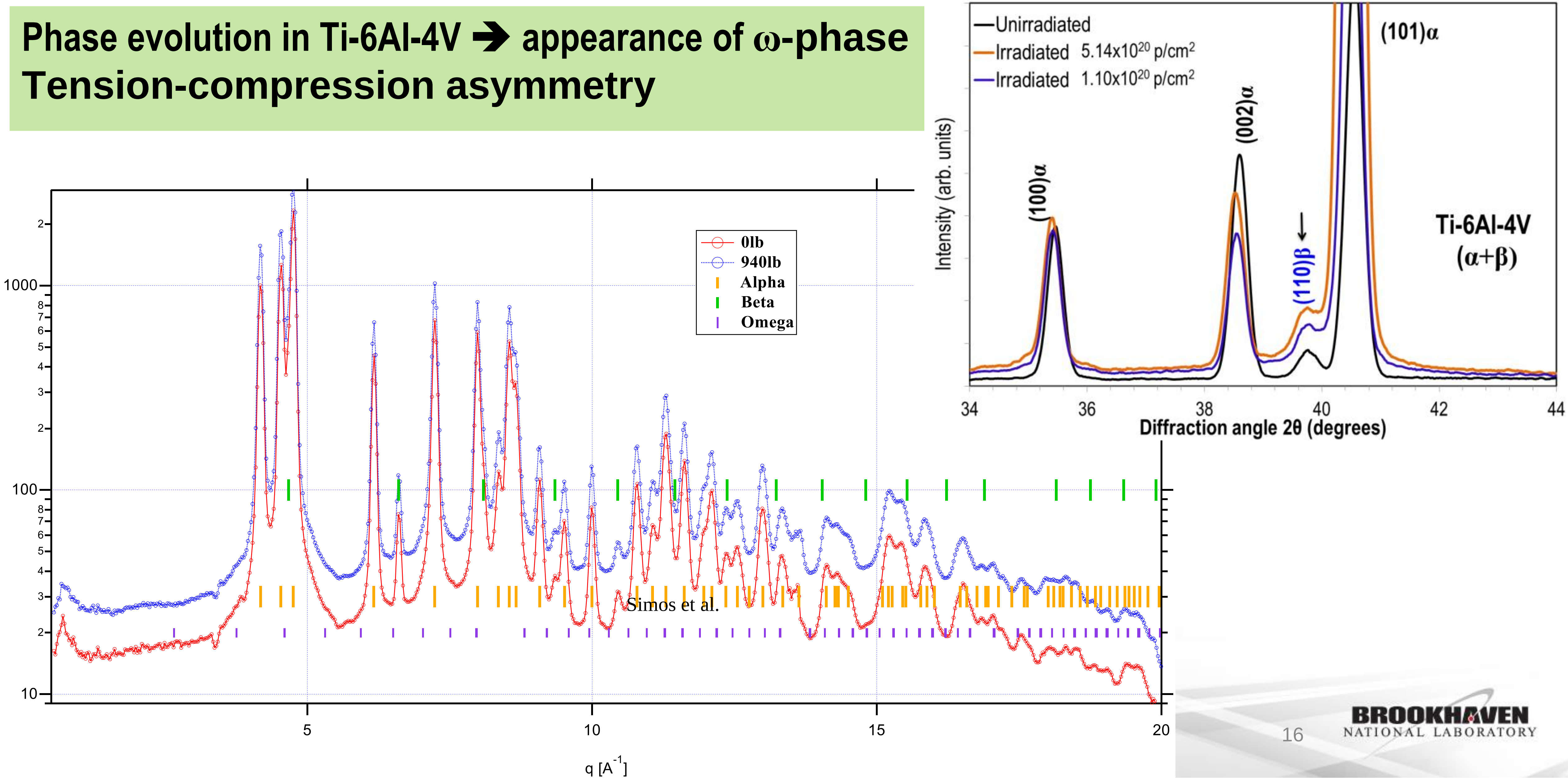




- CC phases (Ni-rich and Fe-rich) stable following irradiation and annealing !!
- X-ray beam, at NSLS II to reveal presence of 2nd fcc (paramagnetic) phase

Radiation Effects on Microstructure and Phase Stability in Ti-6Al-4V

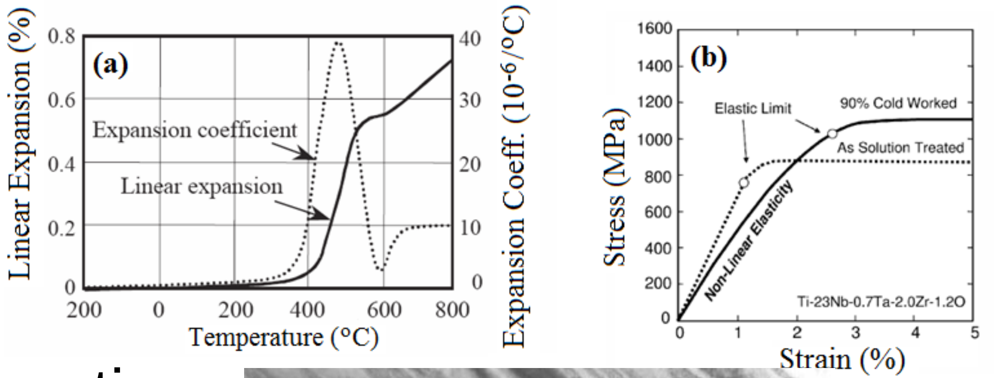
Phase evolution in Ti-6Al-4V ➔ appearance of ω-phase
Tension-compression asymmetry



Simos et al.

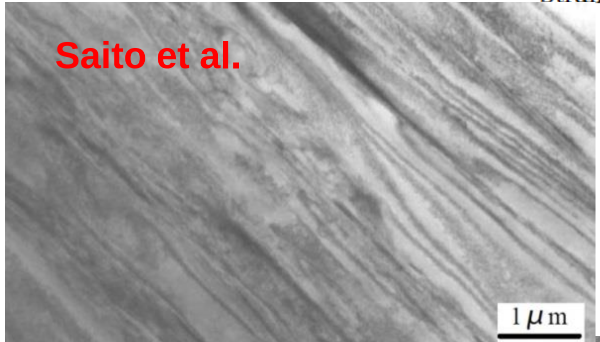
β-type MULTIFUNCTIONAL alloys Ti-21Nb-2Ta-3Zr-1.2O (Gum Metals)

- Gum metals, exhibit extraordinary properties
  - Super-elasticity
  - Super-plasticity
  - Low elastic modulus
  - High strength

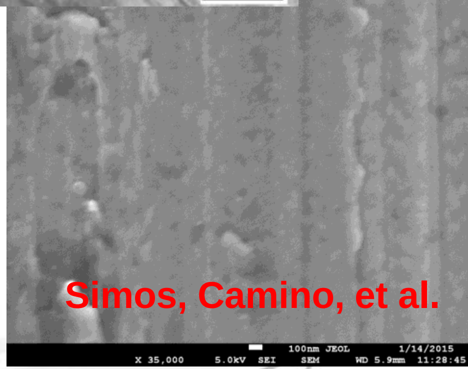


- Debate as to mechanism responsible for its deformation:
  - Martensitic transformations ?

  or
  - Unconventional localized lattice distortions (dislocation-free plastic deformation)
- Stress & thermally-induced martensite transformations and their role in super-elasticity and super-plasticity of the multifunctional Ti-21Nb-2Ta-3Zr-1.2O have been explored
- Radiation-induced phase evolution

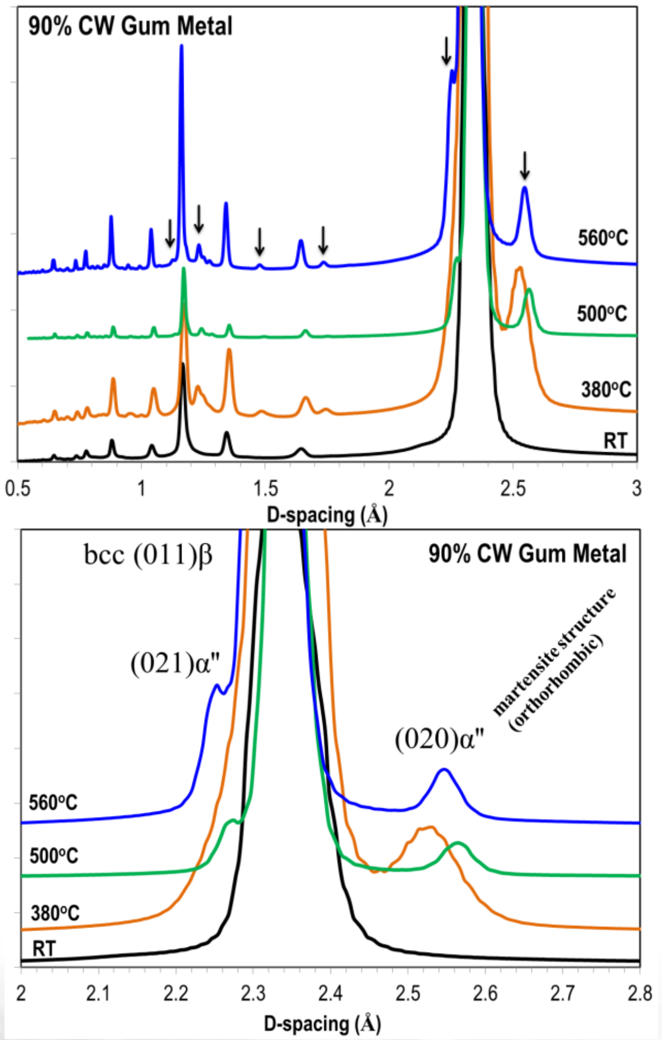


Saito et al.

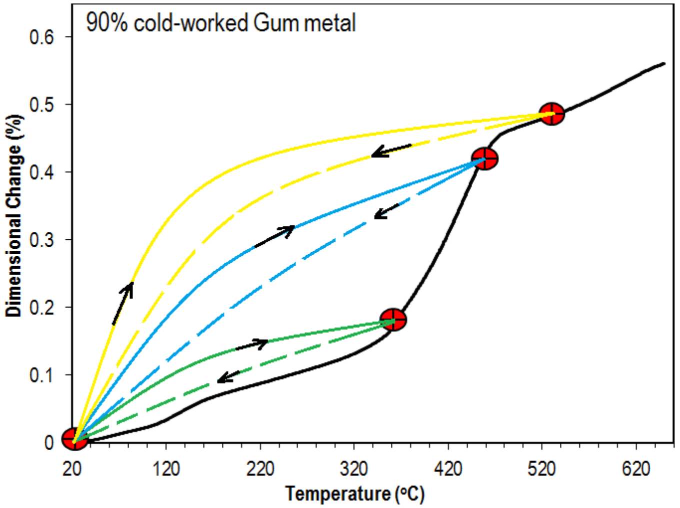


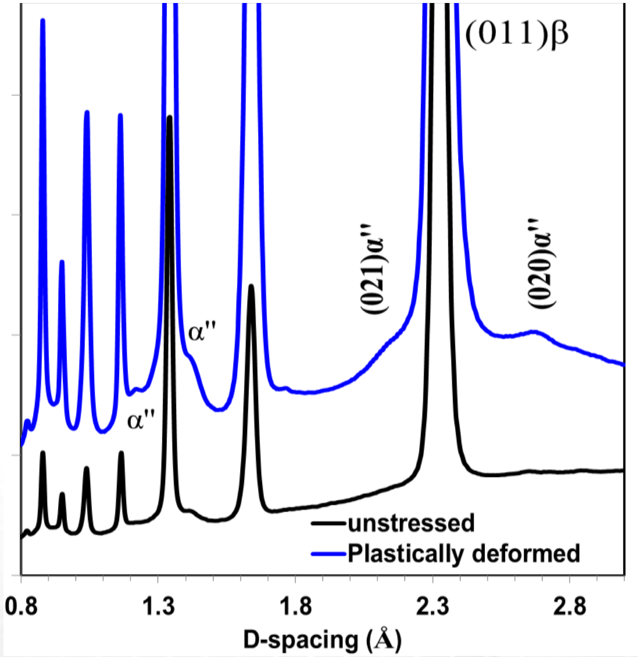
Simos, Camino, et al.

Ti-21Nb-2Ta-3Zr-1.2O: Temperature, Strain and Radiation-induced Phase Transitions

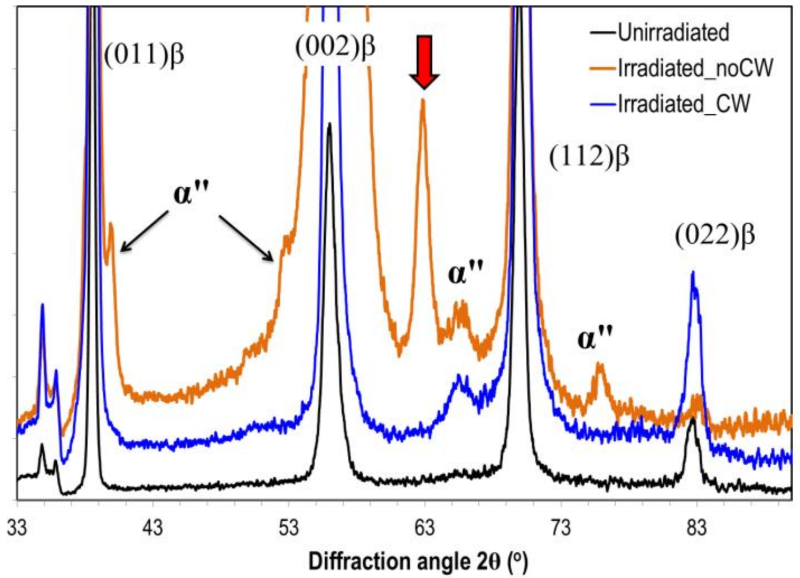


Phase transformation with temperature





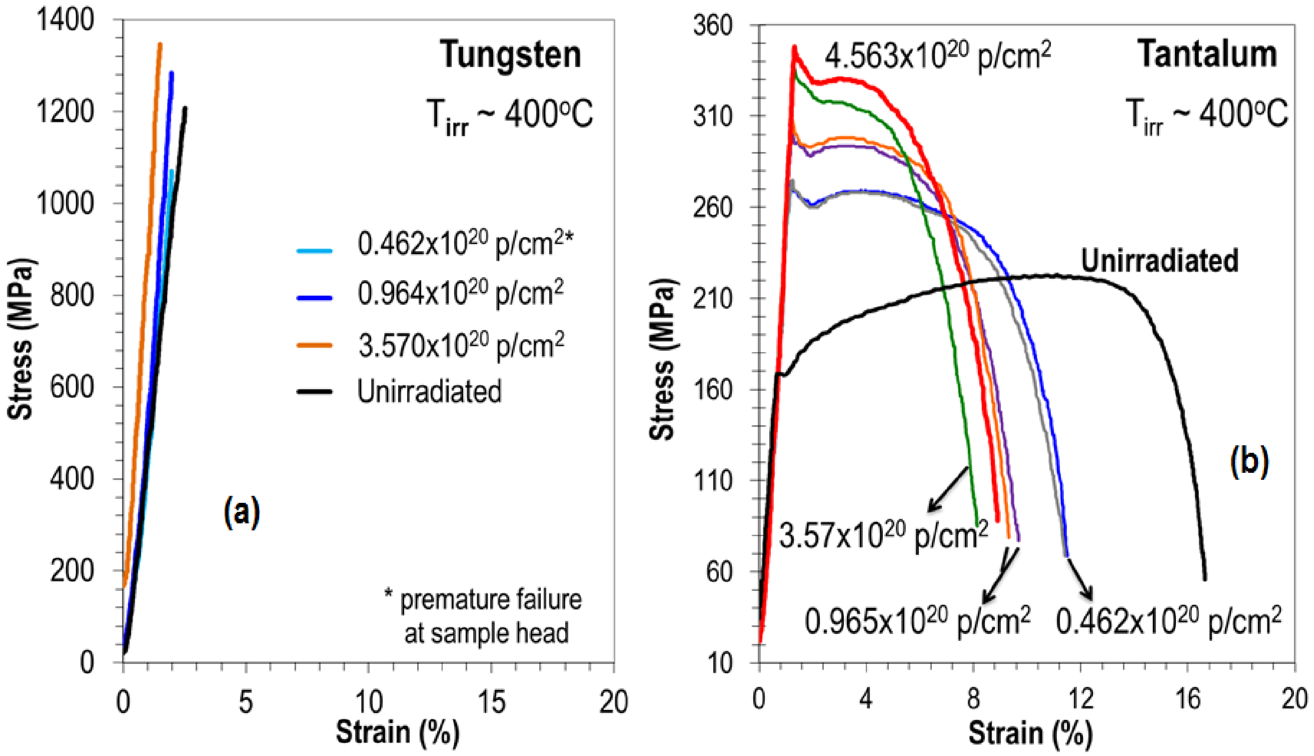
Phase transformation during plastic deformation

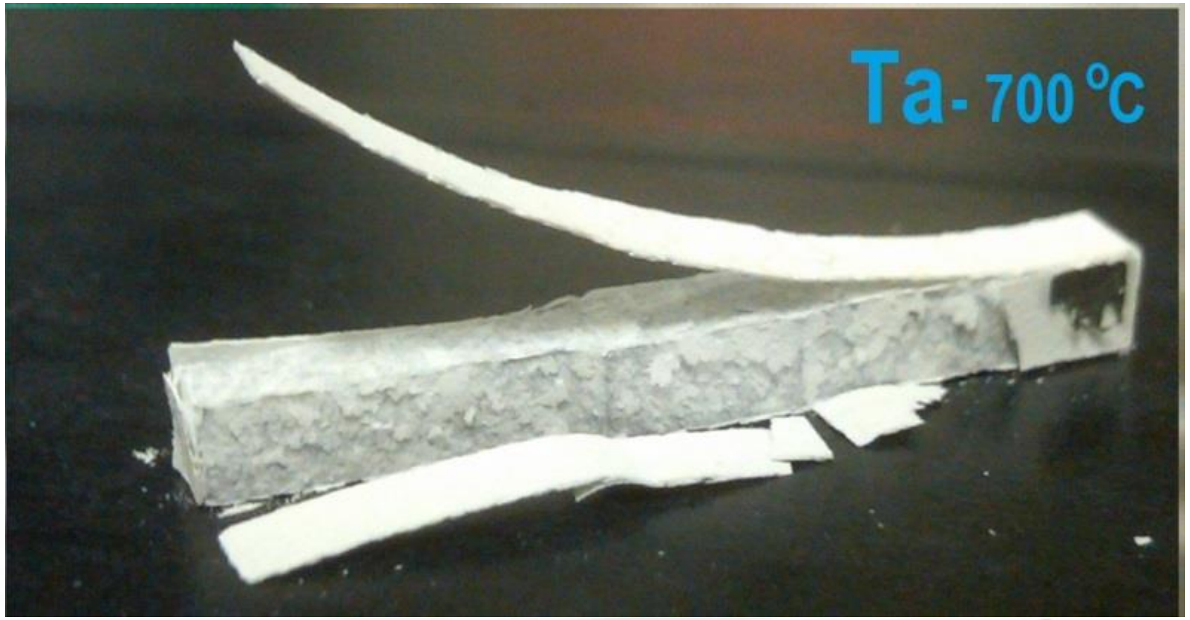


Phase evolution following irradiation

Studies of Refractory Metals (W; Ta: Mo)

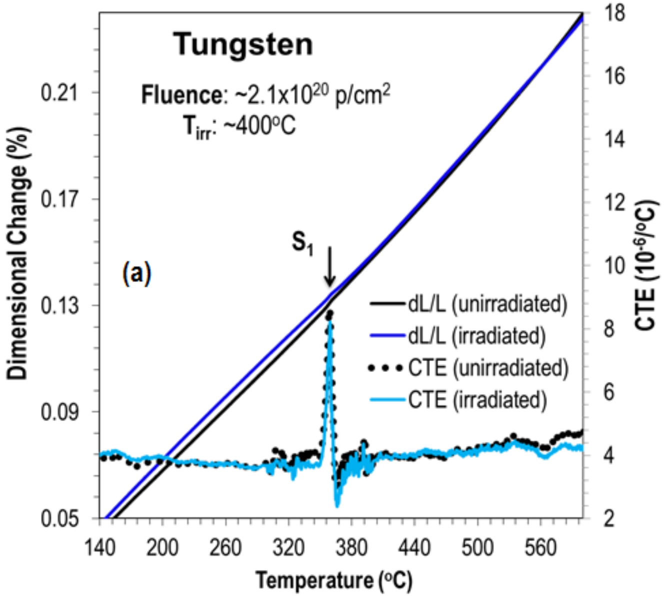
- Fusion applications
- Spallation target

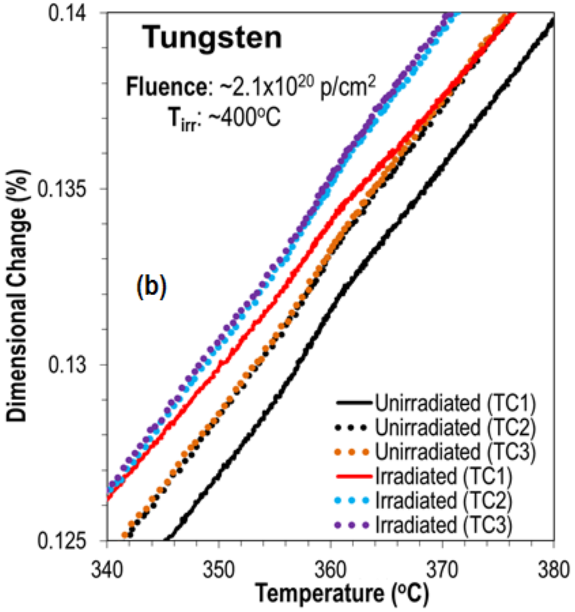


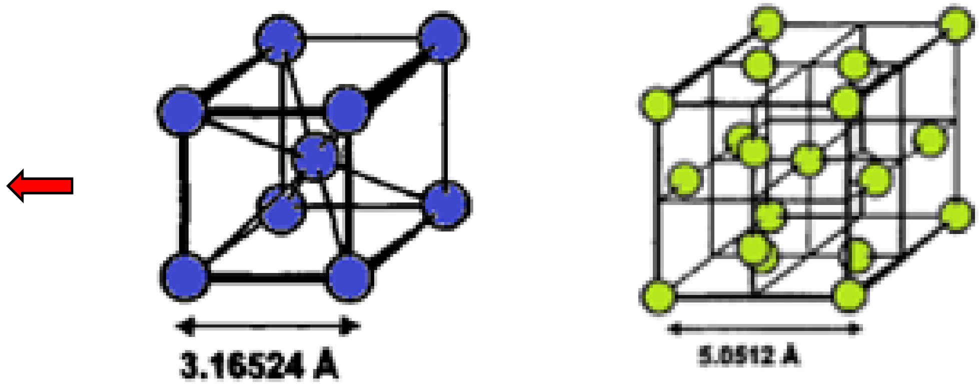


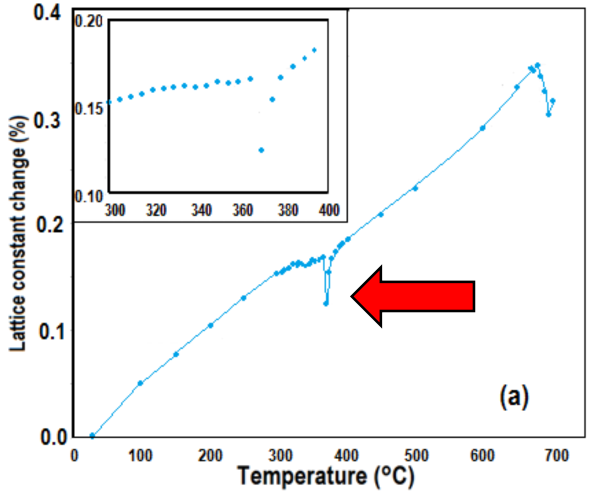
Simos et al., Multi-MW accelerator target material properties under proton irradiation at Brookhaven National Laboratory linear isotope producer, *PHYSICAL REVIEW ACCELERATORS AND BEAMS* 21, 053001 (2018)

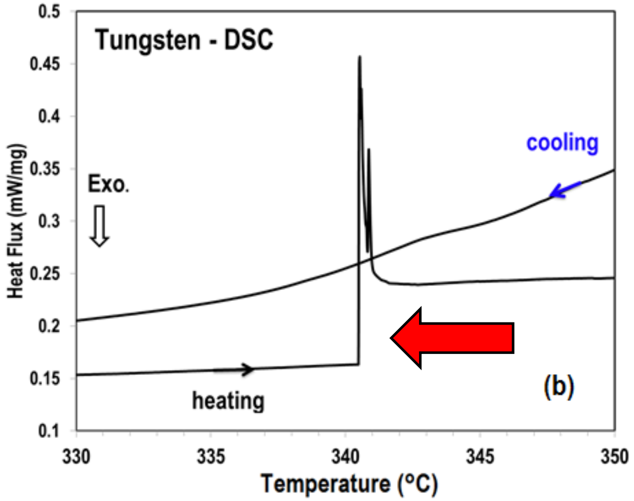
Observed “anomalies” – W or WO3 ?

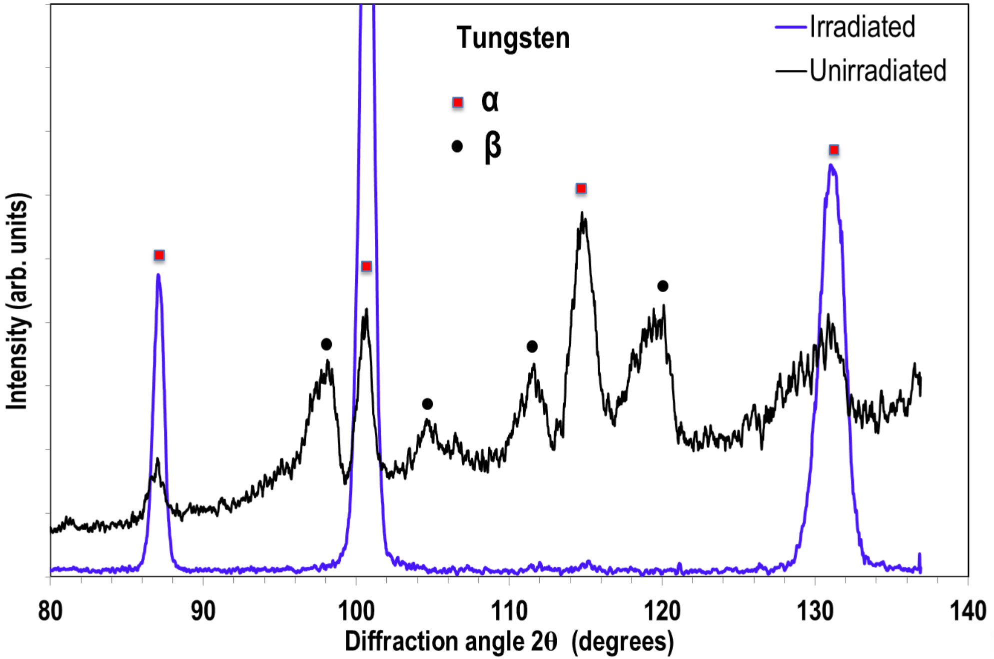












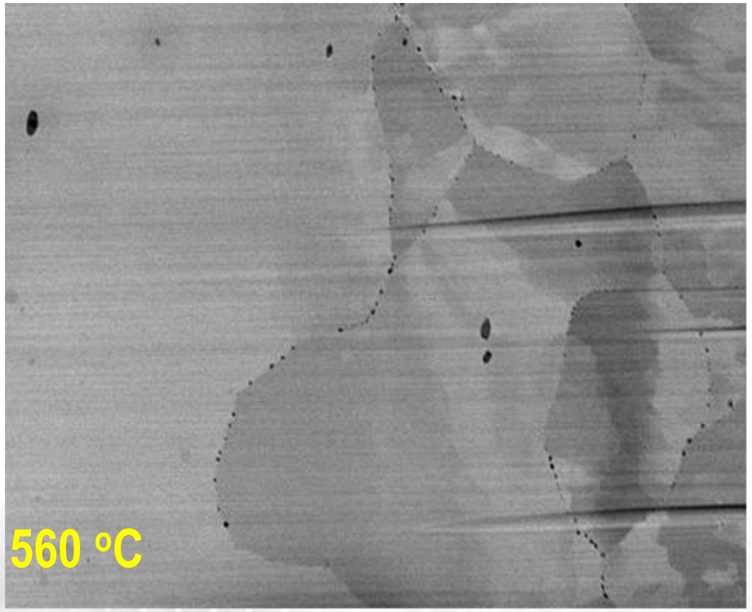
Nuclear Steels: Dispersion Strengthened, Nano-structured Coatings

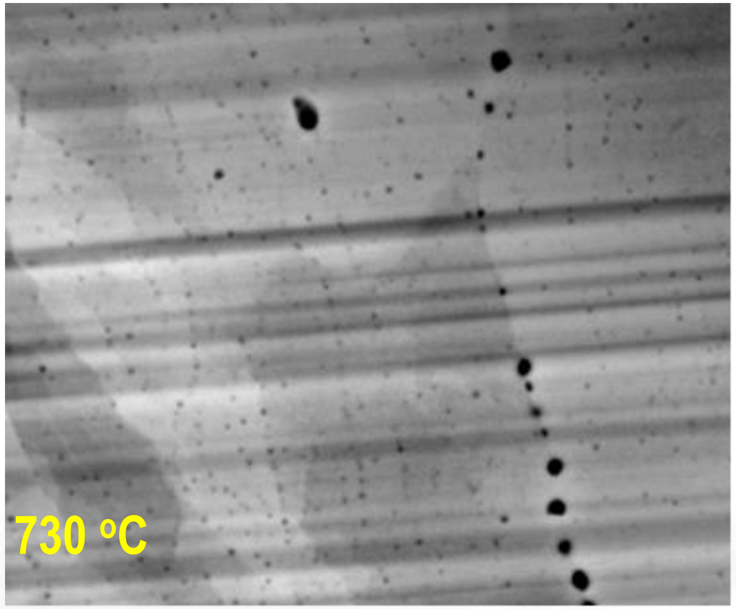
Precipitates in steel and their kinetics

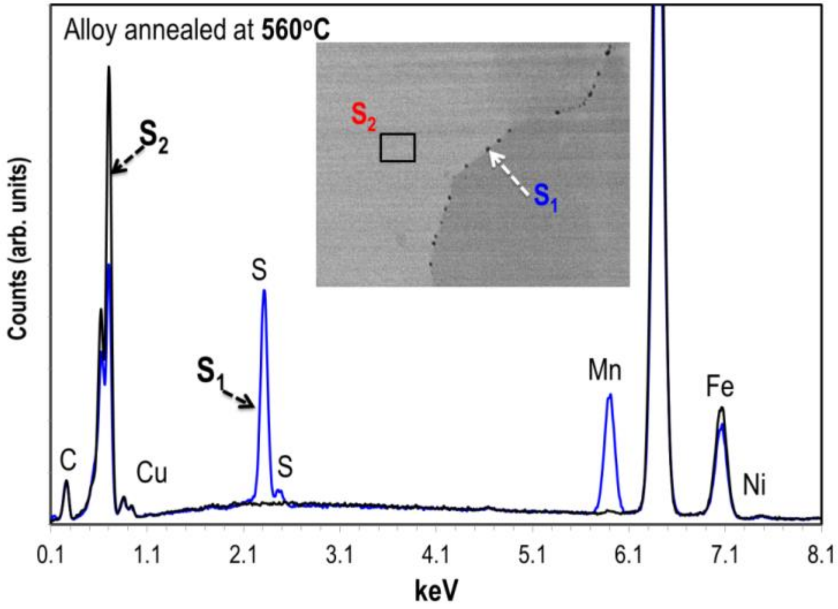
CRP = copper-rich precipitates (**more Cu** than other solutes: Mn, Ni, P, Si)
MNP = manganese-nickel-rich precipitates (more **Mn-Ni** than Cu)
LBPs = late blooming phases (Great Fear)

LBPs: Phases that give rise to sudden an unexpected increase in embrittlement

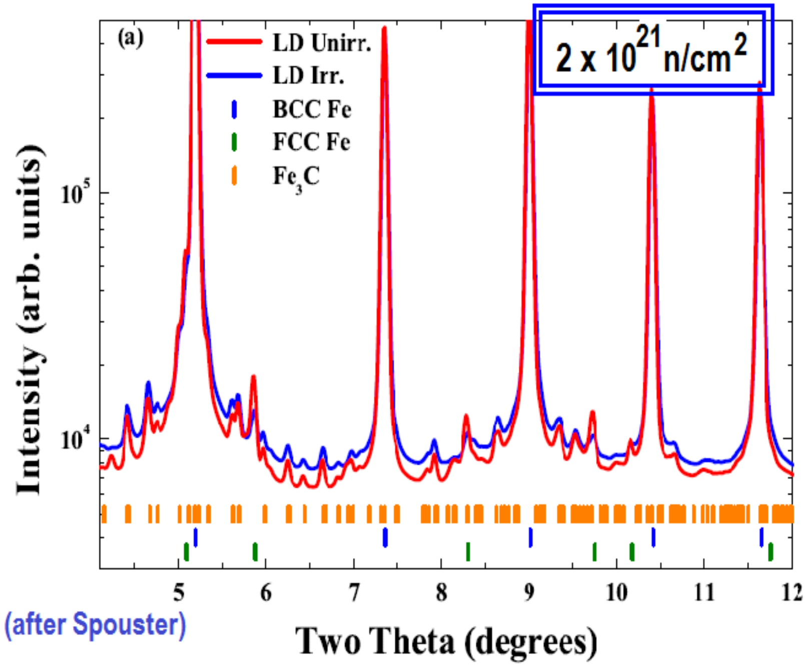
- long incubation period
- rapid growth thereafter







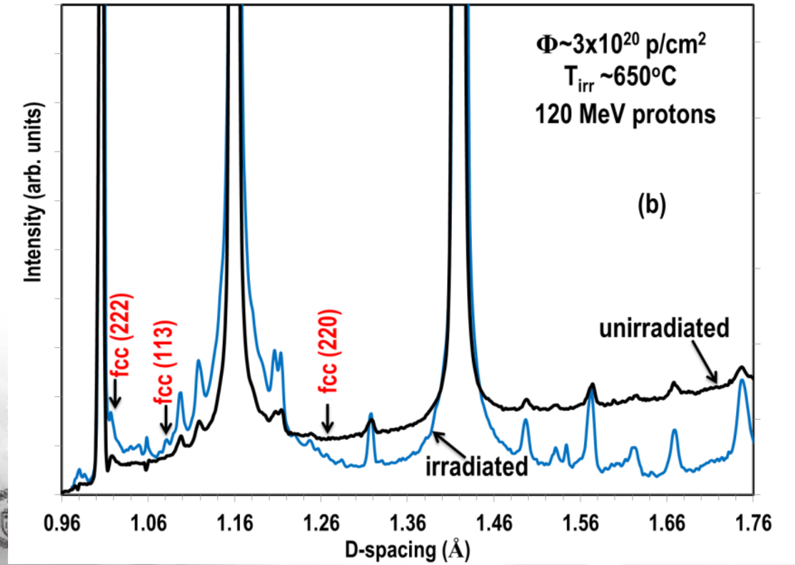
Addressing the “Great Fear” in Pressure Vessel Reactor Steels

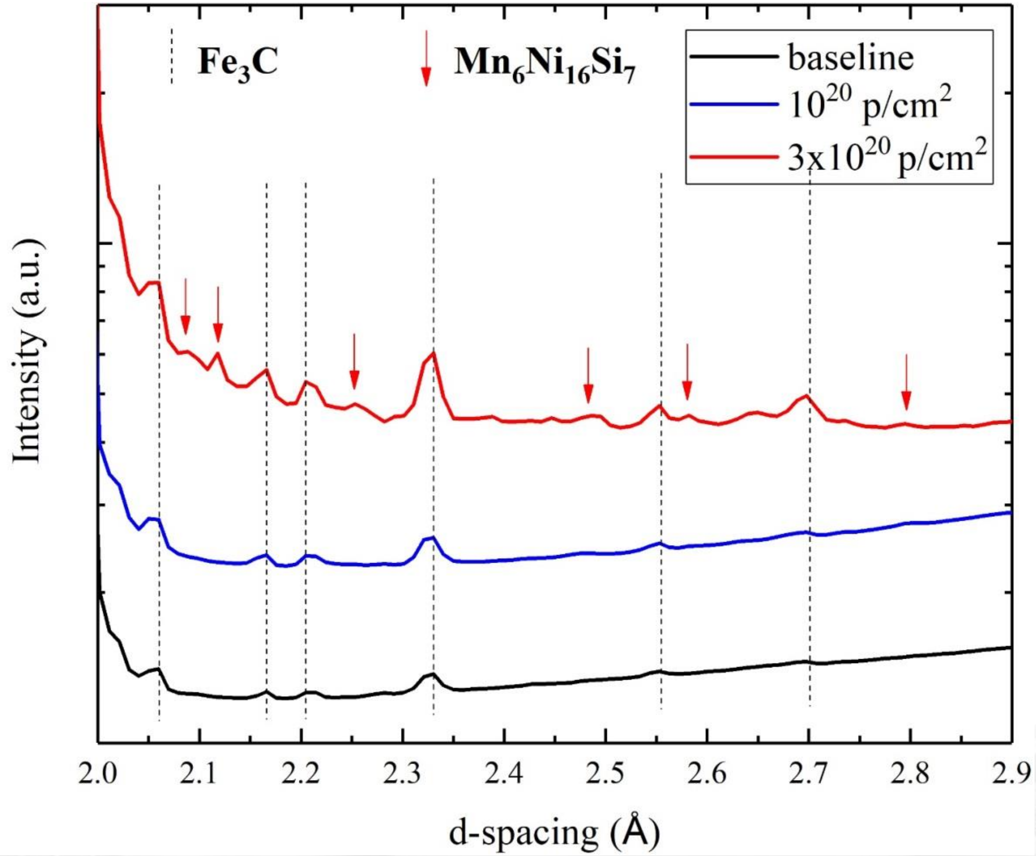


(after Spouster)

Precipitates in steel and their kinetics:

Under higher energy particle (fast neutron/proton) is “Great Fear” realized much earlier and these phases are not late blooming but rather early blooming?

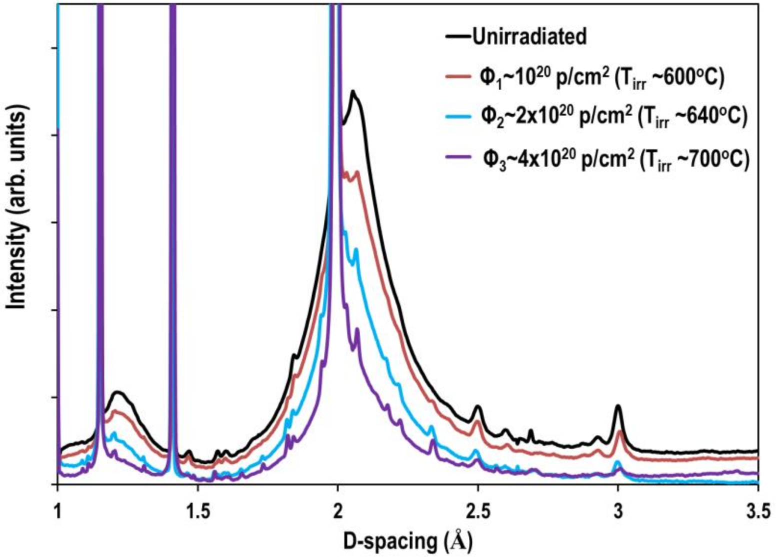


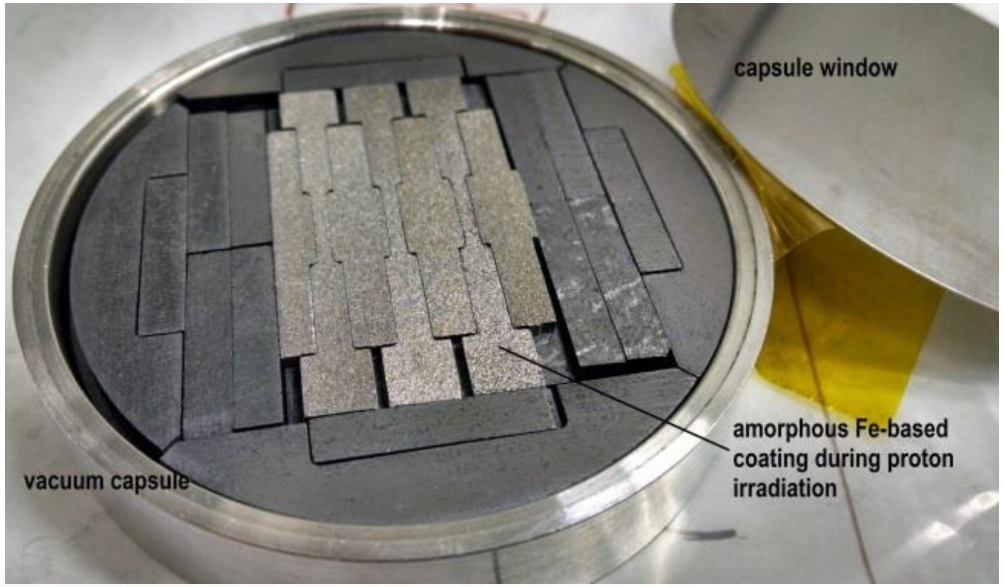


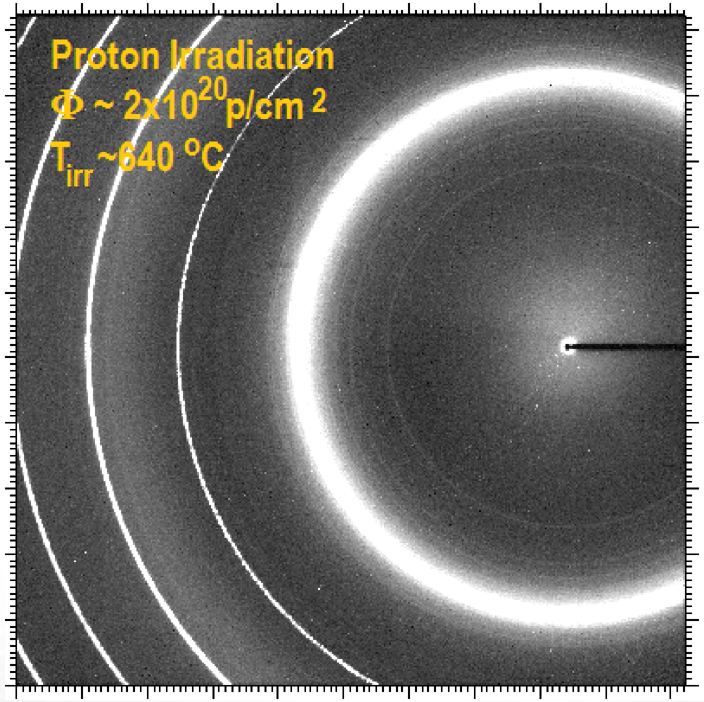
BROOKHAVEN
NATIONAL LABORATORY

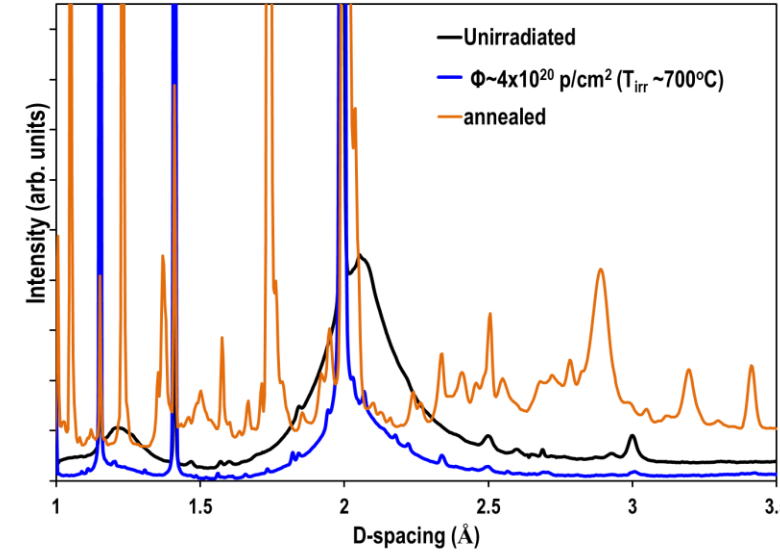
Nano-structured Fe-based Coatings on Steel

- BNL studies demonstrated the remarkable ability of nano-structured coatings to remain amorphous under intense proton irradiation.



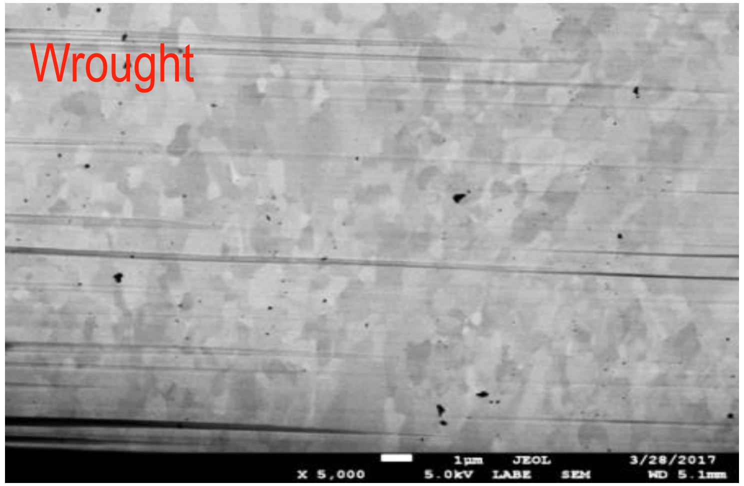


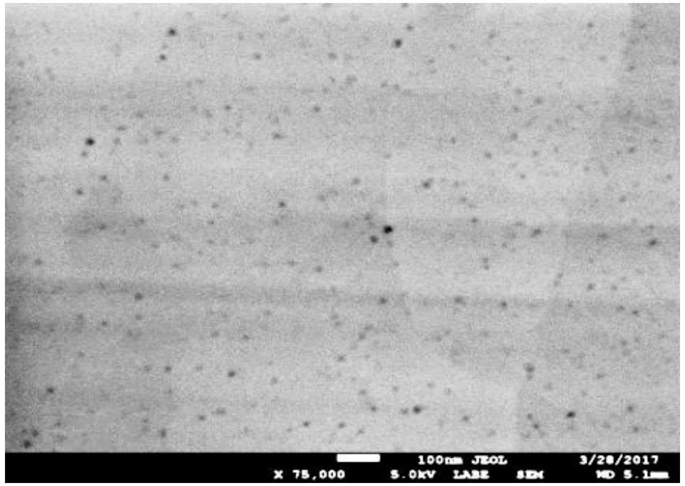


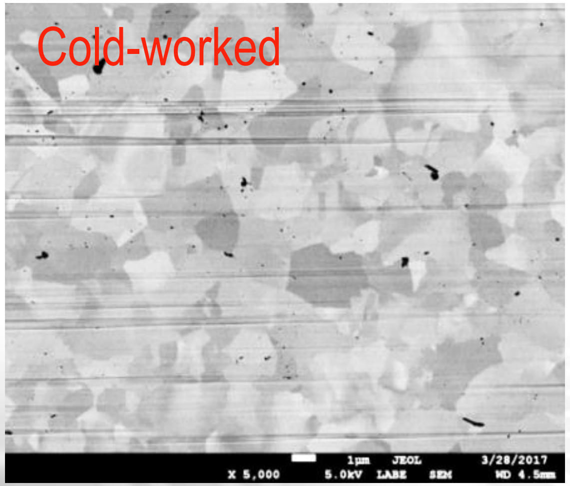


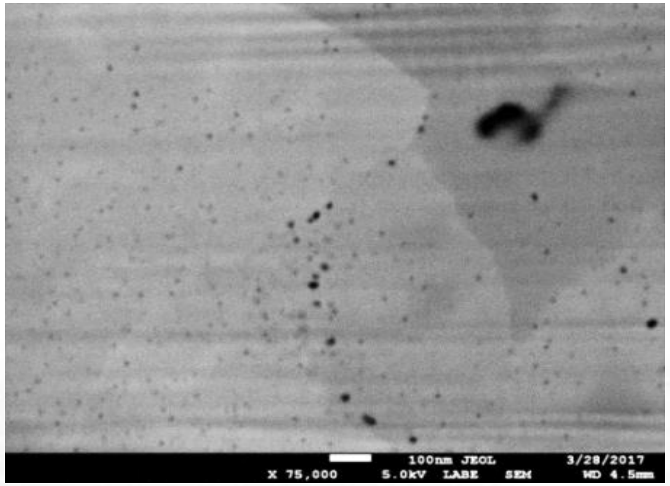
Oxide-dispersion-strengthened Copper Alloys (GlidCop Al15)

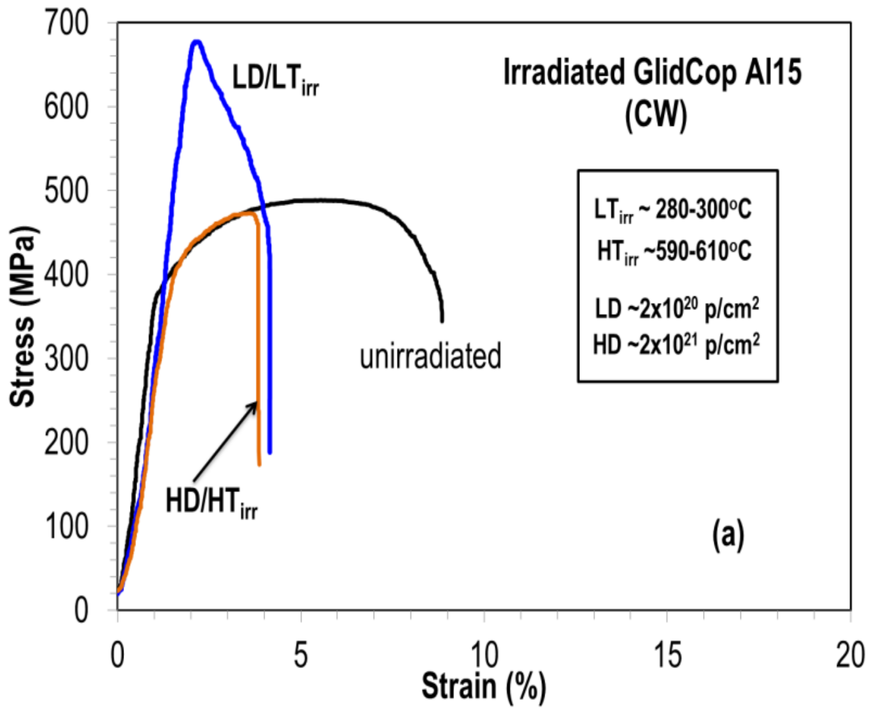
- From LHC applications (collimators) to Fusion reactor considerations

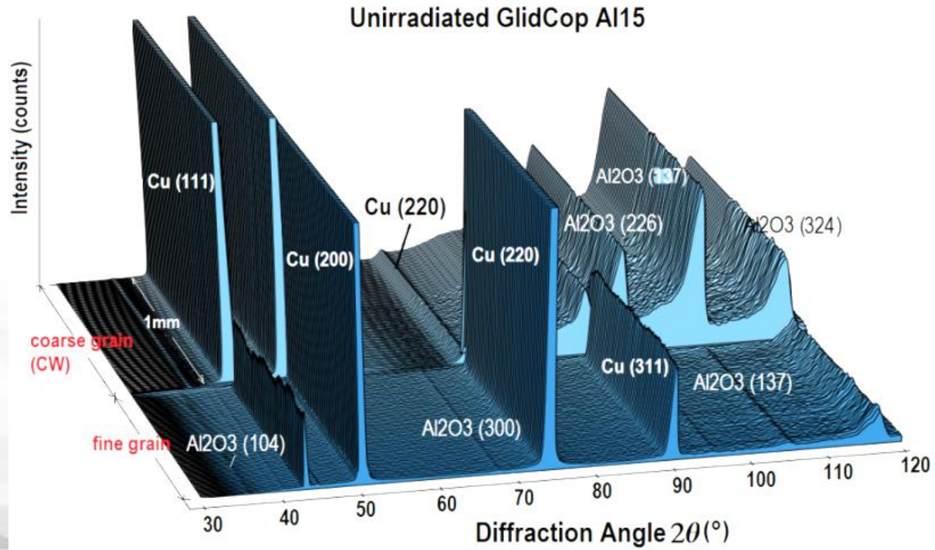








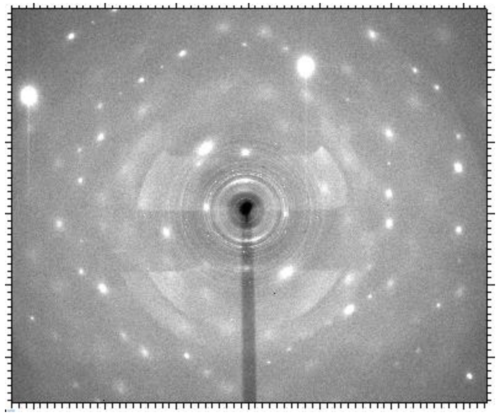


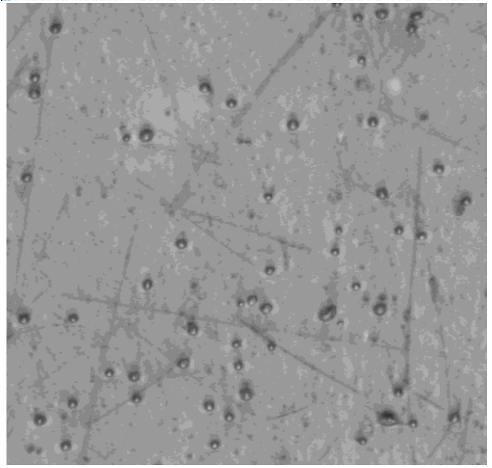


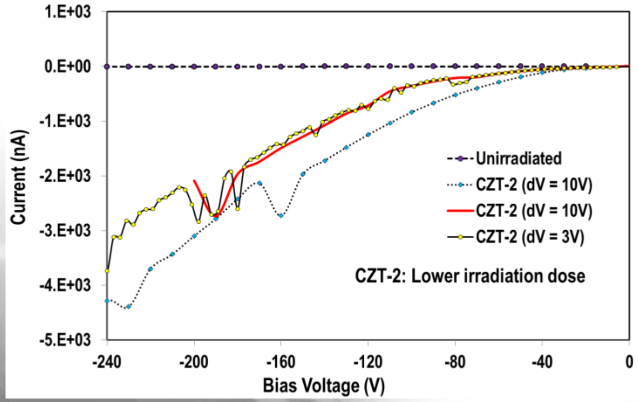
Using BNL accelerator complex to study detector materials, etc.

- Rare earth magnets
- CZT crystals
- SiO2 fibers
- Ferrofluidics

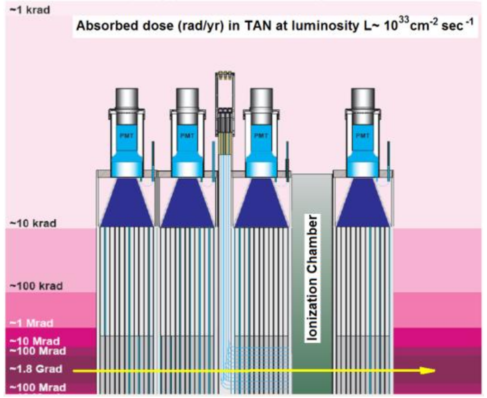
CZT crystals

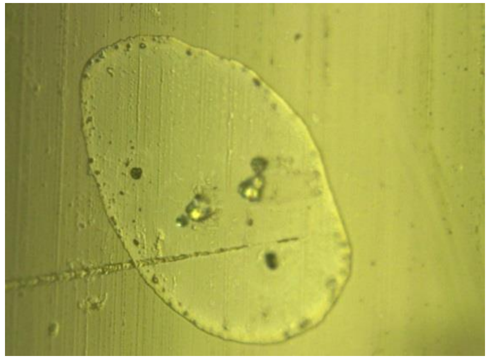


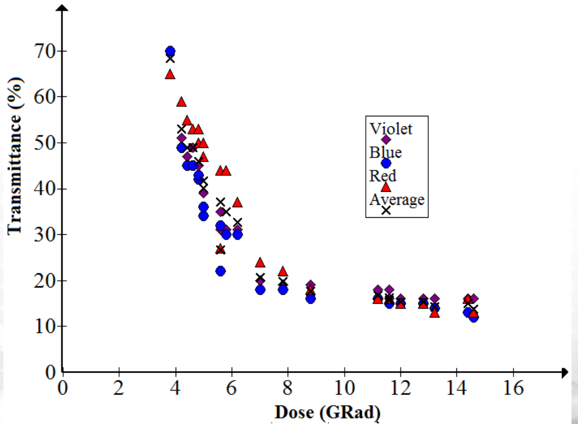




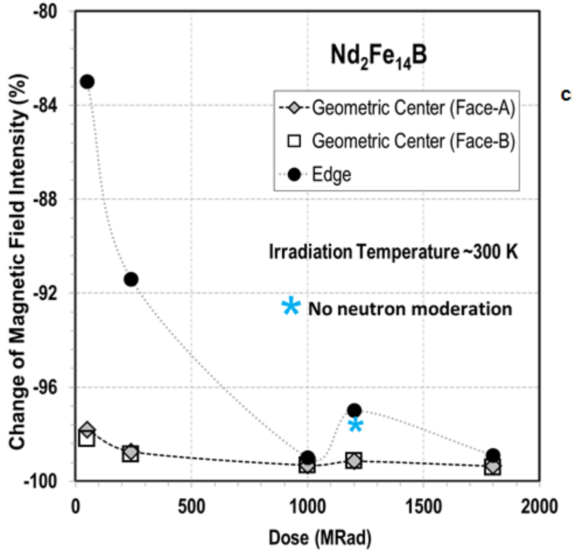
SiO$_2$: LHC 0-degree calorimeter

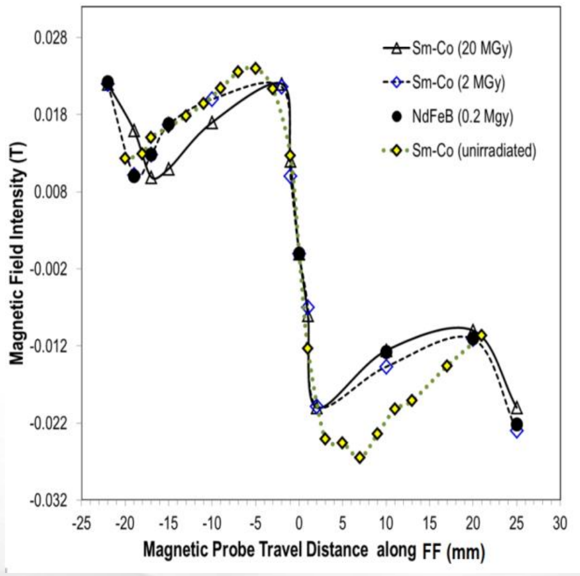






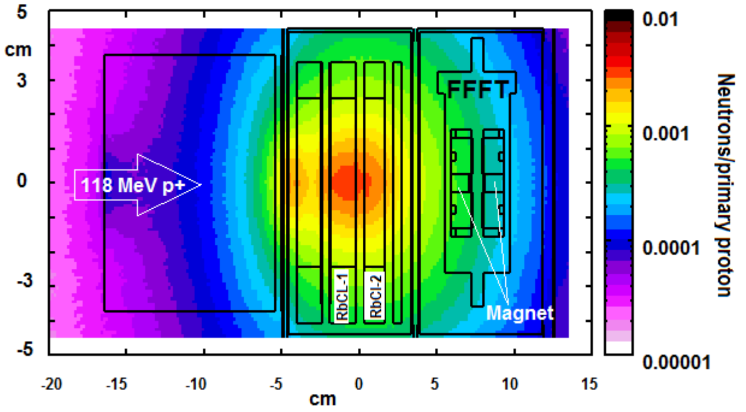
Rare-earth magnets

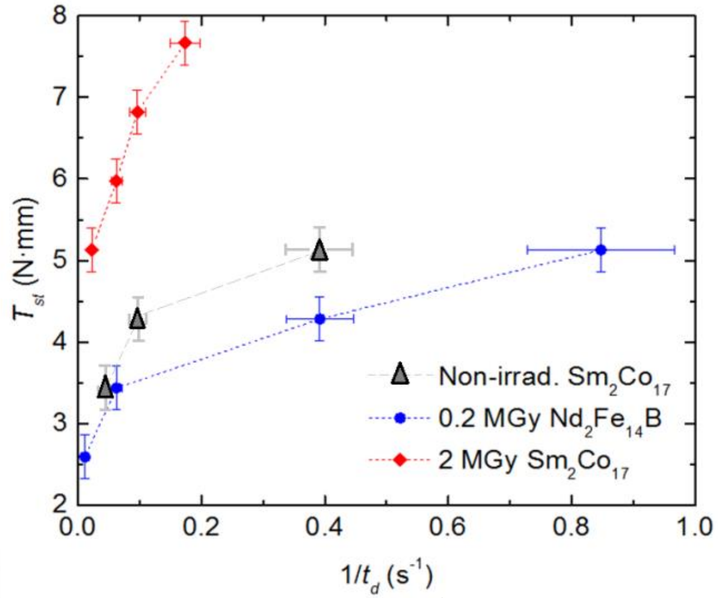




Ferrofluidics

Performance Degradation of Ferrofluidic Feedthroughs in a Mixed Irradiation Field





FF static torque vs. the inverse of displacement time ($1/t_d$) following rotational speed cycles up to 5,000 rpm

Summary

- The novel materials, alloys and composites required for next generation reactors and accelerator applications require evaluation under extreme conditions
  - The suite of tools available with the BNL accelerator complex enable such assessments
- Predicting material lifetimes in likely future environments remains a formidable challenge
  - Detailed studies of the structural evolution of materials under a range of conditions can substantially improve our ability to anticipate material performance
- The availability of fast neutron sources with high fluence for materials tests is very limited
  - Our knowledge of how materials evolve and damage under **thermal neutrons** cannot be extrapolated to their response to **fast neutrons** for fast reactors
  - Using **protons** or heavy **ions** as surrogates to emulate the damaging effects of fast neutrons is an ongoing debate and research
  - *BNL's combination of irradiation and x-ray characterization tools provides a powerful route to studying relationship between proton and fast neutron damage through detailed study of the evolution of materials at the microstructural level*

The BNL Team looks forward to continued collaboration with the HiRadMat effort to provide the next-generation materials our future facilities require

Thank you for your attention!