Extreme Environments of Next Generation Energy Systems and Materials.

Can they “peacefully” co-exist?

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National Synchrotron Light Source II

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BNL Colleagues

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- **Committee members**

OVERVIEW

Overview of Energy Challenge

Materials in the mix

A historical BNL perspective

BNL Material Studies

Path to the future

Next Generation Energy Systems
What do we mean by that?

To meet the FUTURE energy demand energy systems we depend on:

- **conventional (coal, oil, gas)**
- **nuclear**
- **wind**
- **solar**
- **geothermal**
- **supercritical steam turbines**

MUST make leap to higher efficiency/reliability levels while achieving

maximum performance per unit of cost ➔ higher power output

e.g.

Costs less to build and operate a 1,200 MW than 2 x 600 MW nuclear plants

How do materials get in the mix?

Wind Power to overcome present limitations will need light-weight, extremely stiff materials (*not necessarily strong materials*)

Next Generation Turbines operating with **ultra-super-critical steam** (>700 C) must tolerate unprecedented oxidation attack

Next generation nuclear power (fission or fusion) will depend on materials that can withstand extreme radiation fluxes at very high temperatures

NO ONE-SIZE-FITS-ALL SOLUTION !!!

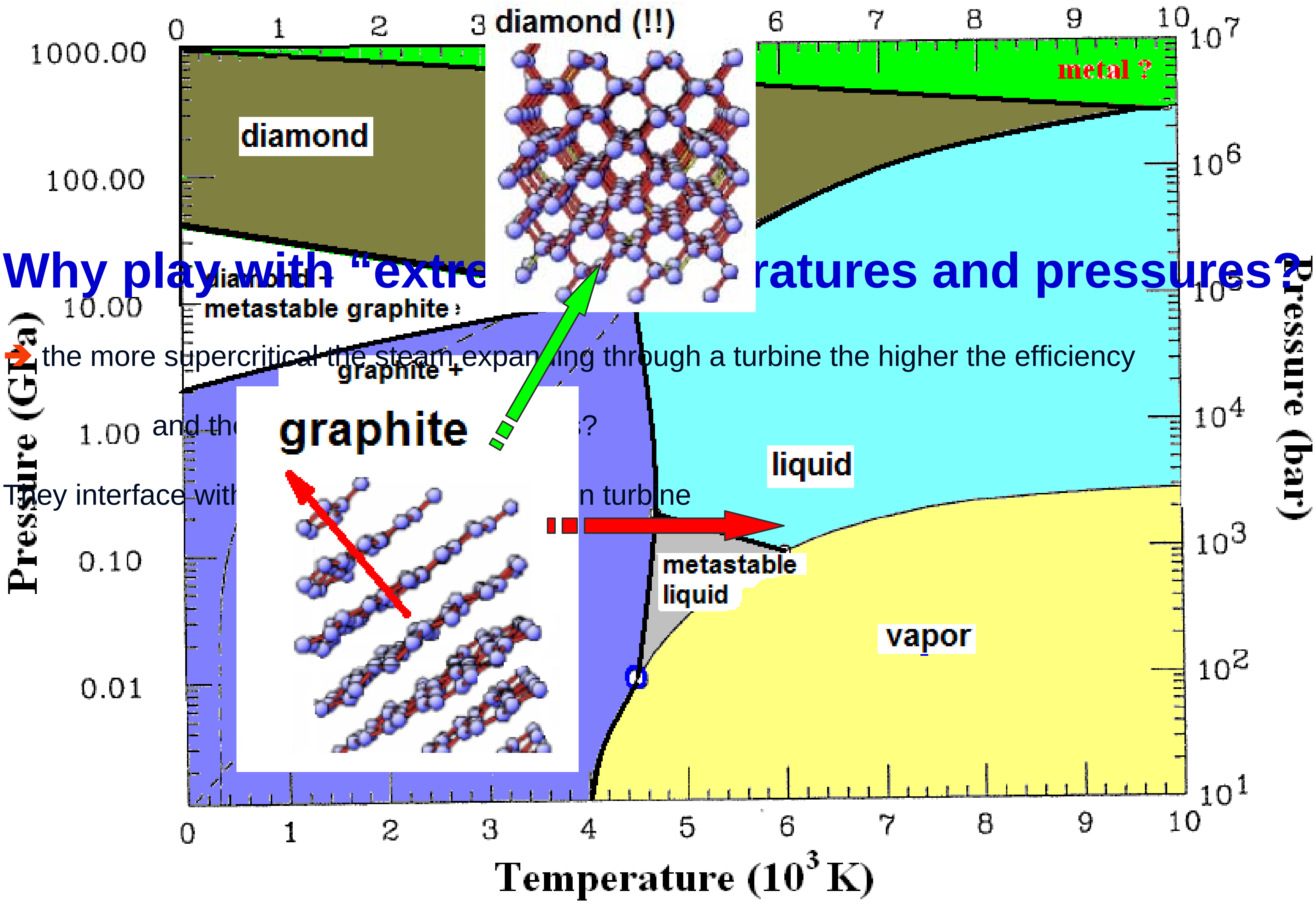
what happens when we push materials to extreme?

Why play with "extre ratures and pressures?

- the more supercritical the steam expanding through a turbine the higher the efficiency

and th ?

They interface with n turbine



How serious is the problem?

Just look at the oxidation of **tantalum**

Accelerated Ta Oxidation:

Present of a third element

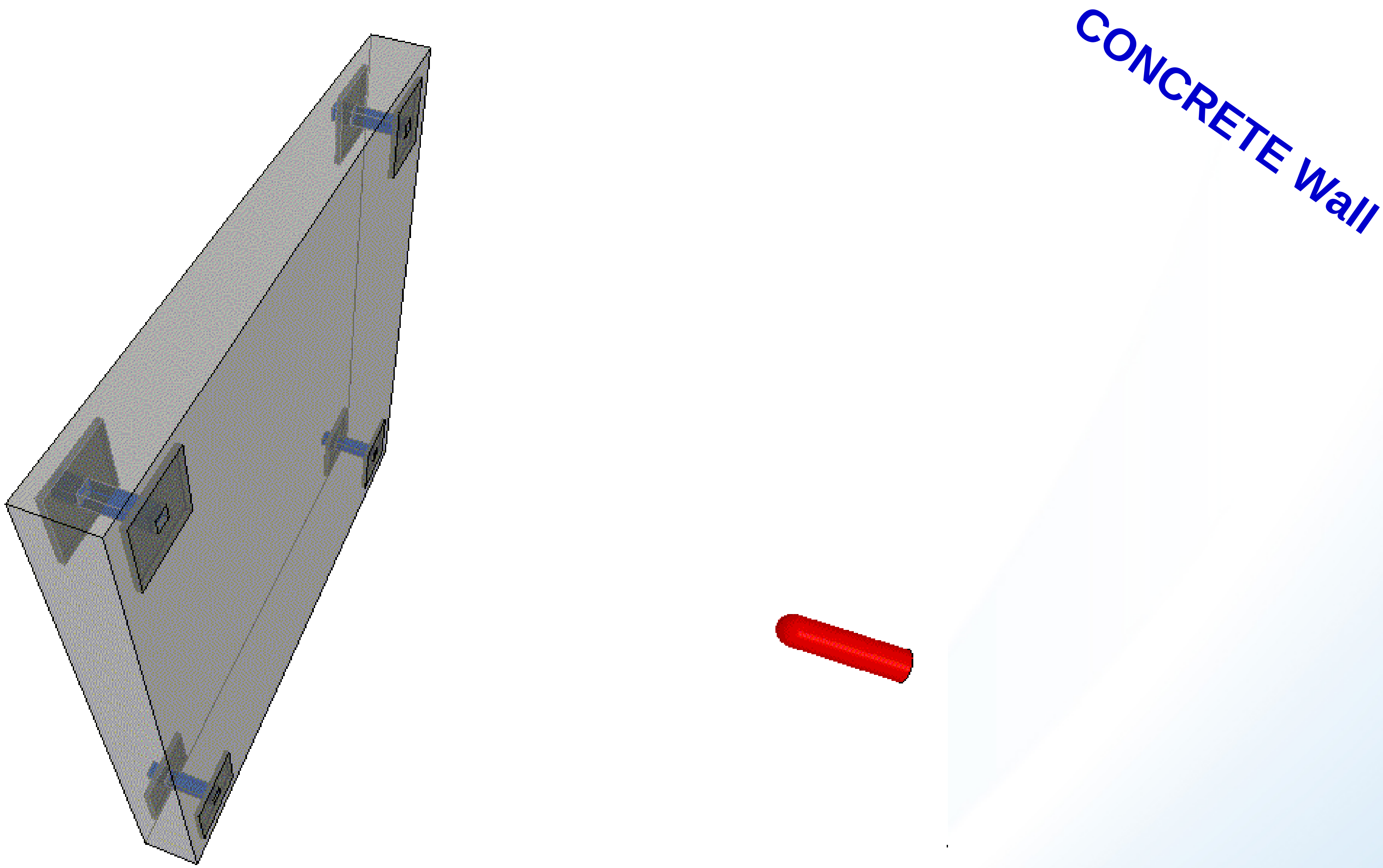
Radiation-induced oxidation acceleration ?

In an effort to make things stronger and more durable, 3 types of “enhanced” materials emerged, namely

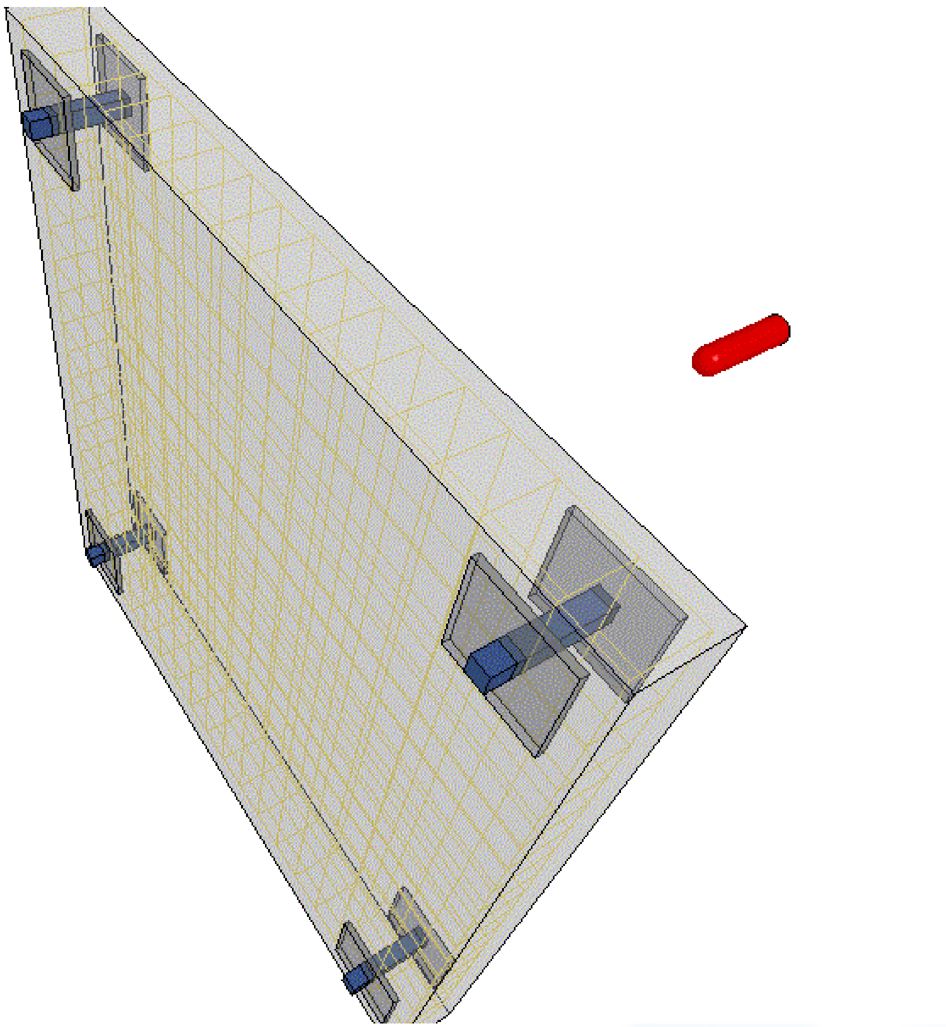
Super alloys .... What are they ?
[from Fe to steel (add carbon), to stainless, to super-alloys]

Composites - what are they? *materials meshed or “weaved” but acting together*

WHAT DO COMPOSITES OFFER?



Animation of actual field test of a 240 m/s projectile impacting a wall



Super alloys .... What are they ?
[from Fe to steel (add Carbon), to stainless (add Cr), to super-alloys]

Composites - what are they? *materials meshed or "weaved" but acting together*

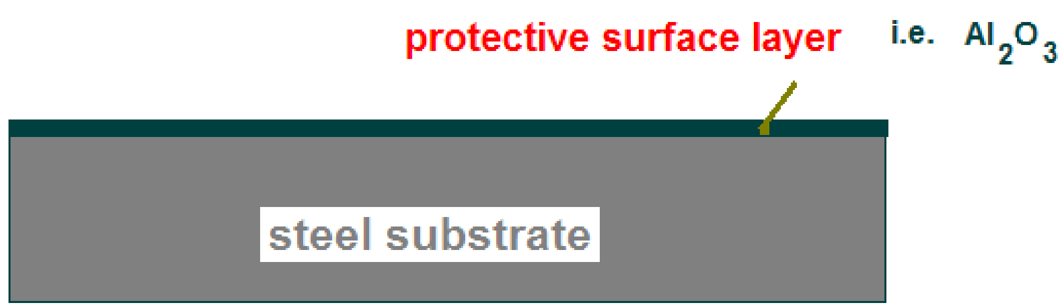
Nanostructured coatings

Protective surface layer bonded to substrate, made of nano-sized particles offering

Strain Tolerance

Wear Resistance

Resistance to oxidation, corrosion, erosion



BNL, Materials and Energy

BNL played important, even leading role in materials and energy

World-class research on graphite as nuclear reactor moderator, radiation damage of nuclear materials

Pioneered randomly packed, H-cooled, particle bed reactor exhibiting extremely high power density at extremely high temp. and pressures

World-recognized research in material behavior under aggressively corrosive environments

Leading research in the development of novel geothermal materials

Materials and "Next Generation Nuclear Energy"

Pursue of nuclear power since 40's formed basis for most developments in material science

Politically correct or not, it is here to stay and continue to be an important force towards the new generation materials

Adverse effects of radiation on materials

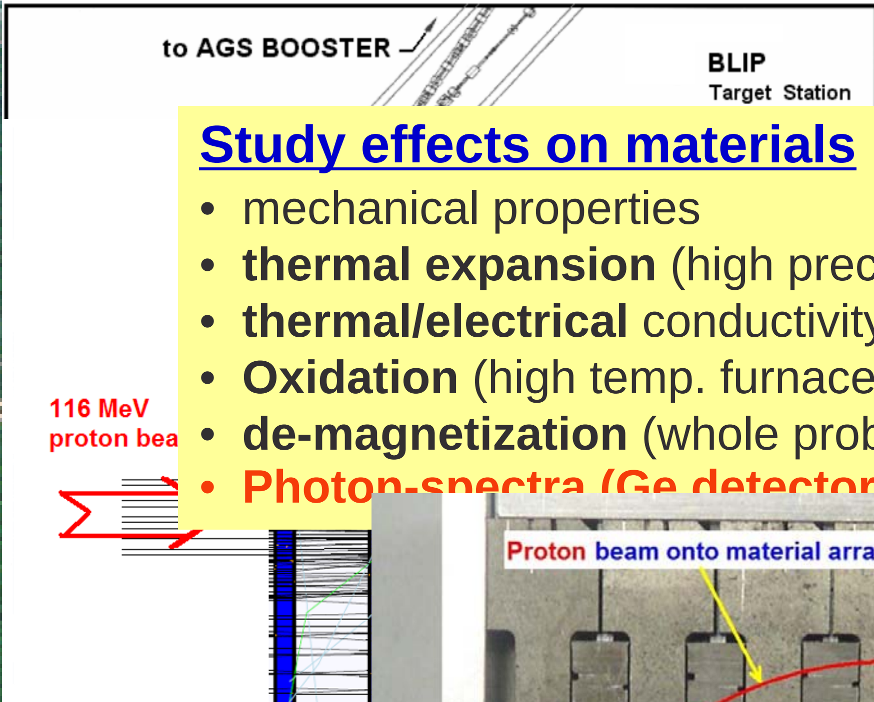
- How radiation interacts with matter
  - **electronic excitations** ➔ no damage, only thermalization
  - **elastic collisions** ➔ leading to displaced atoms
  - **inelastic collisions** ➔ transmutation products (i.e., H, He)

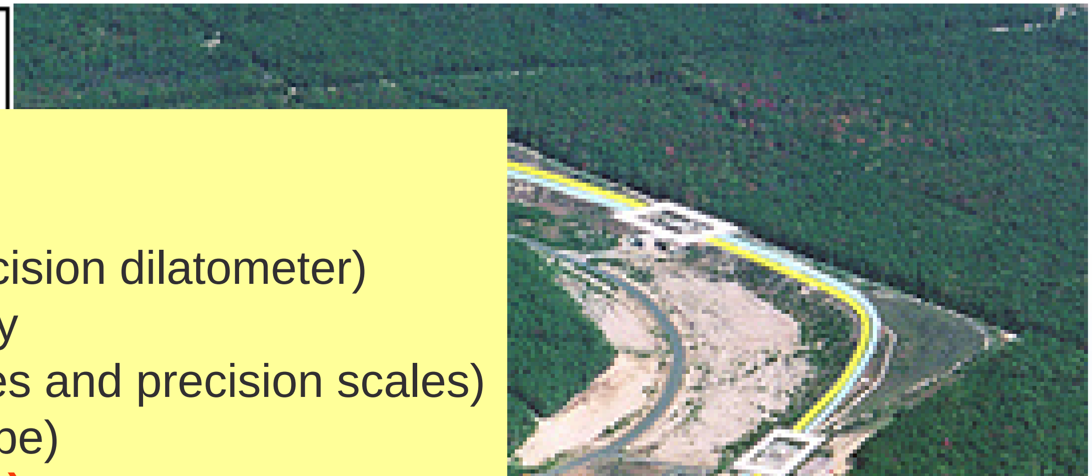
- Microstructural changes ➔ UNDESIRED macroscopic property changes
  - loss of ductility
  - swelling
  - fatigue lifetime reduction

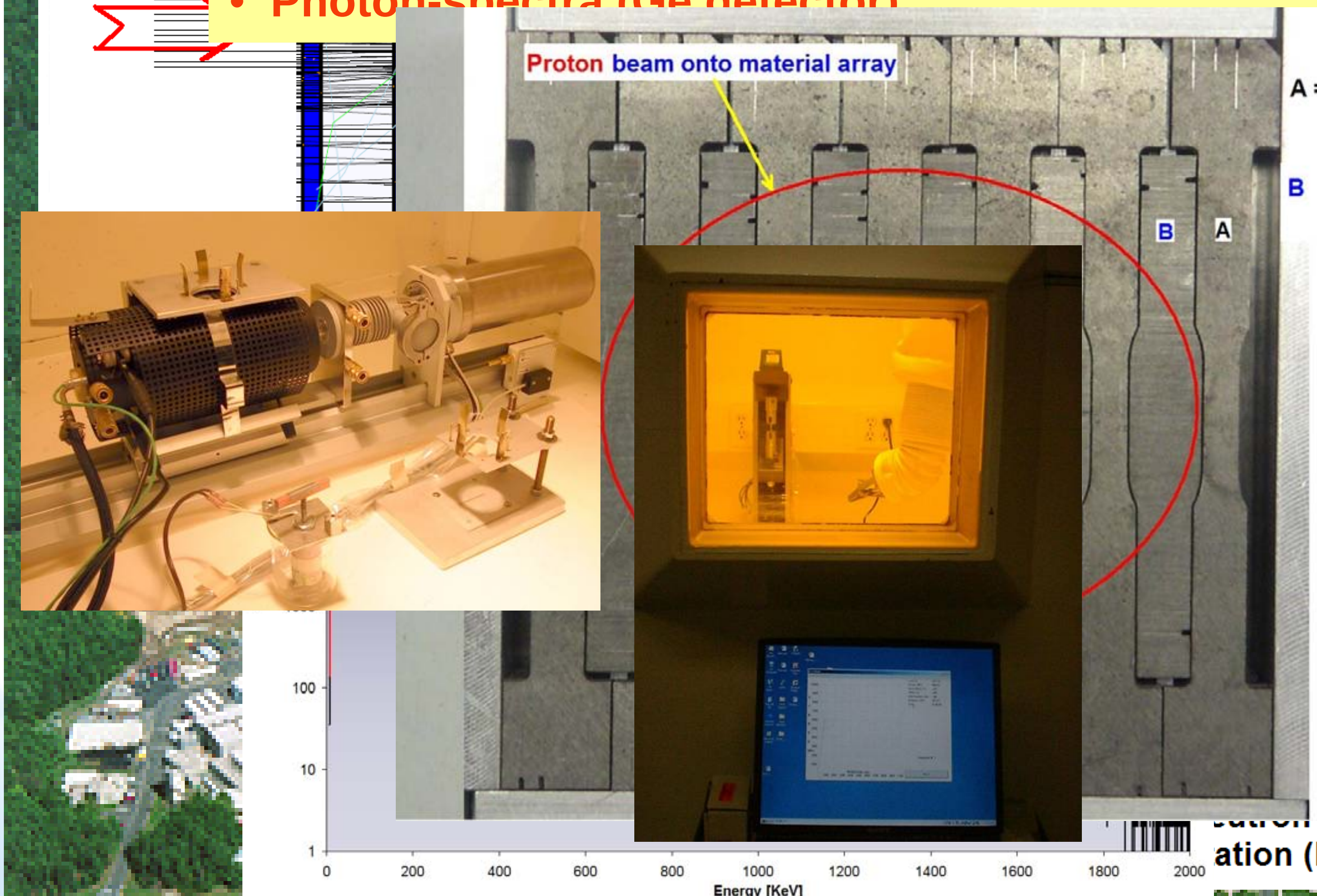
Effects on new super-alloys, composites and specially-coated materials studied using the BNL accelerator complex

Study effects on materials

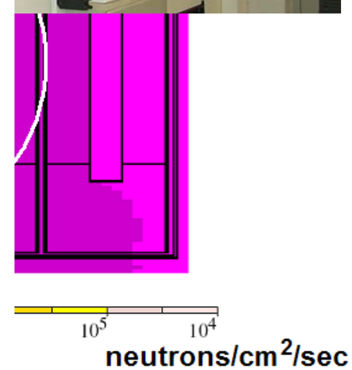
- mechanical properties
- **thermal expansion** (high precision dilatometer)
- **thermal/electrical** conductivity
- **Oxidation** (high temp. furnaces and precision scales)
- **de-magnetization** (whole probe)
- Photon-spectra (Ge detector)







Macroscopic analysis
L Hot Cells



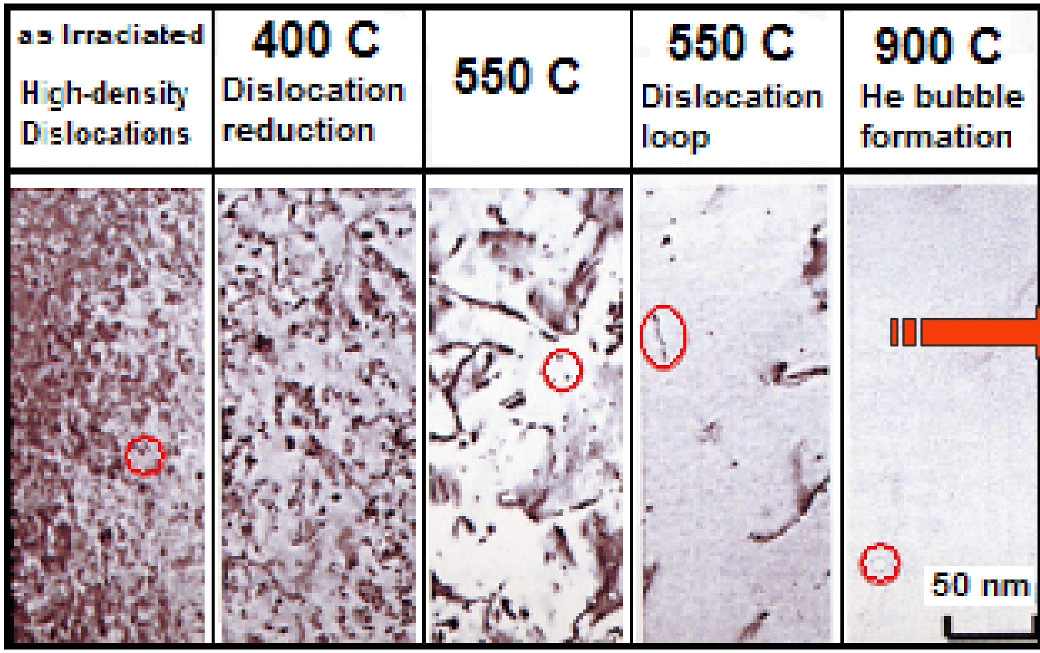
ation (by N. Mokhov, FNAL)

Super-alloys and radiation

While an extensive array of alloys were studied, results on some with intriguing behavior will be presented here

Irradiation = damage, BUT irreversible ?

Annealing or defect mobility at elevated temperature



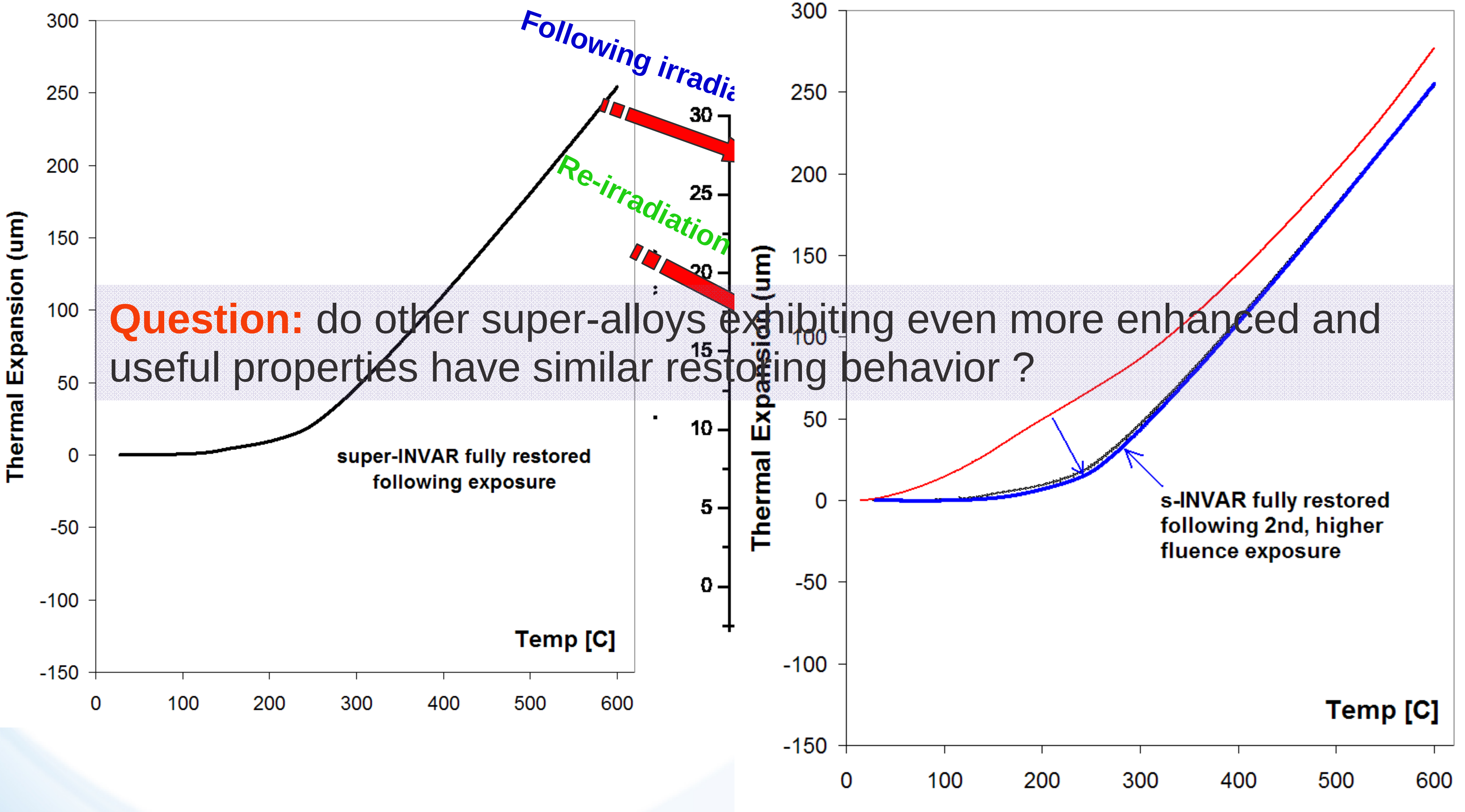
Y. Ishiyama et al., J. Nucl. Mtrl. 239, 1996

Observed Behavior:

upon re-irradiation defect density increases and damage accelerates !!

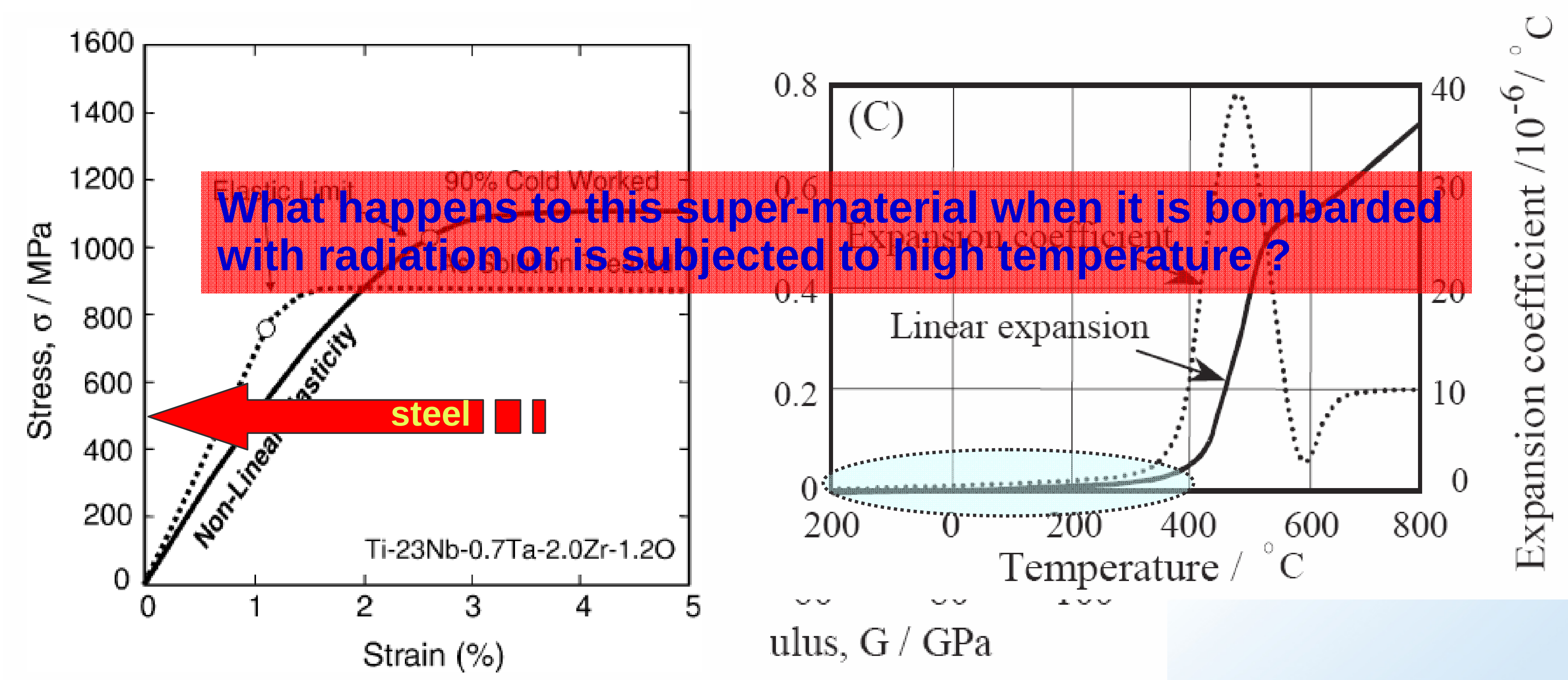
Of interest are alloys exhibiting extremely low thermal expansion

Super-INVAR (33% Ni, 0.05% C, 3.2%Co, Fe balance)



Question: do other super-alloys exhibiting even more enhanced and useful properties have similar restoring behavior ?

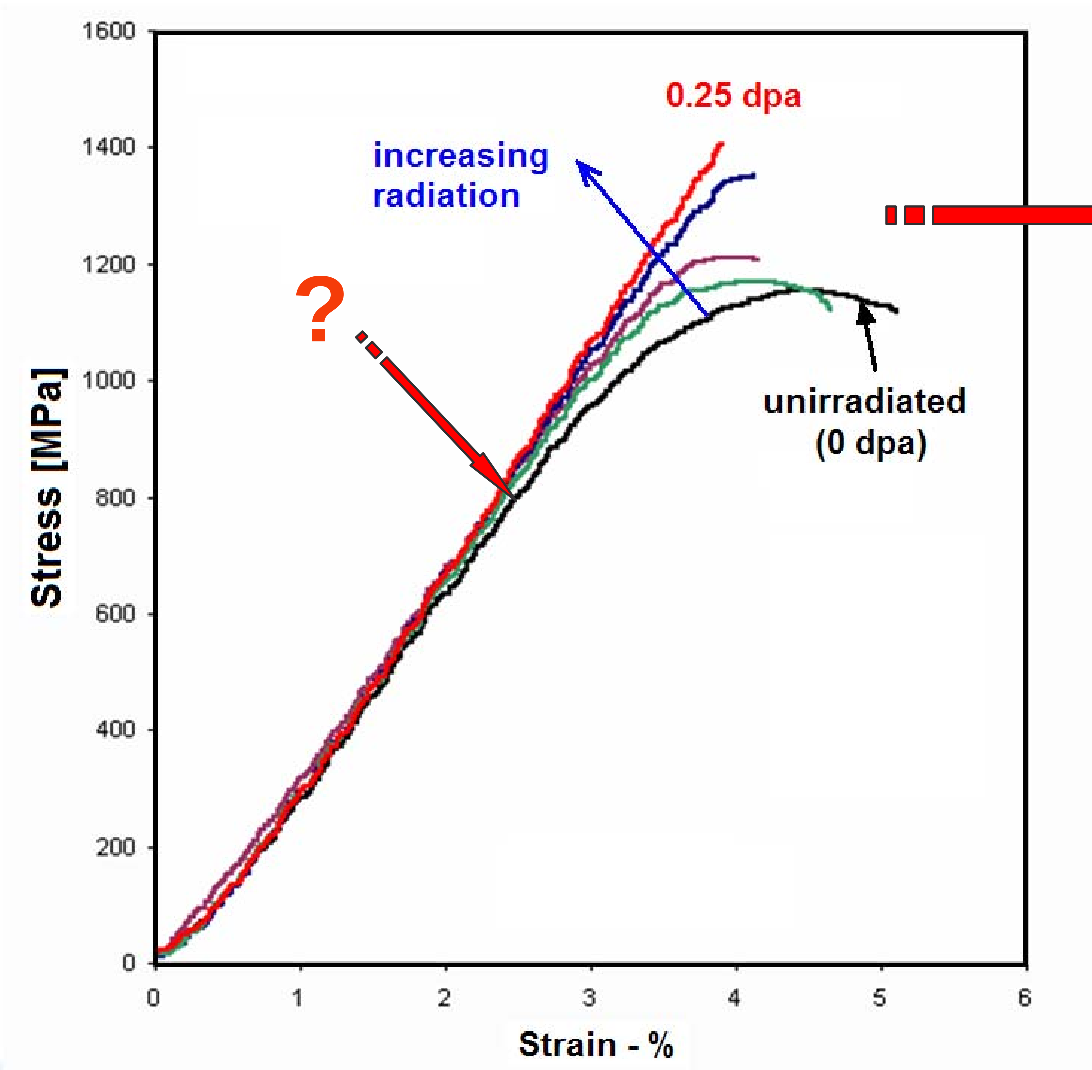
Ti-12Ta-9Nb-3V-6Zr-O or “gum” metal “Wonder Material ??”

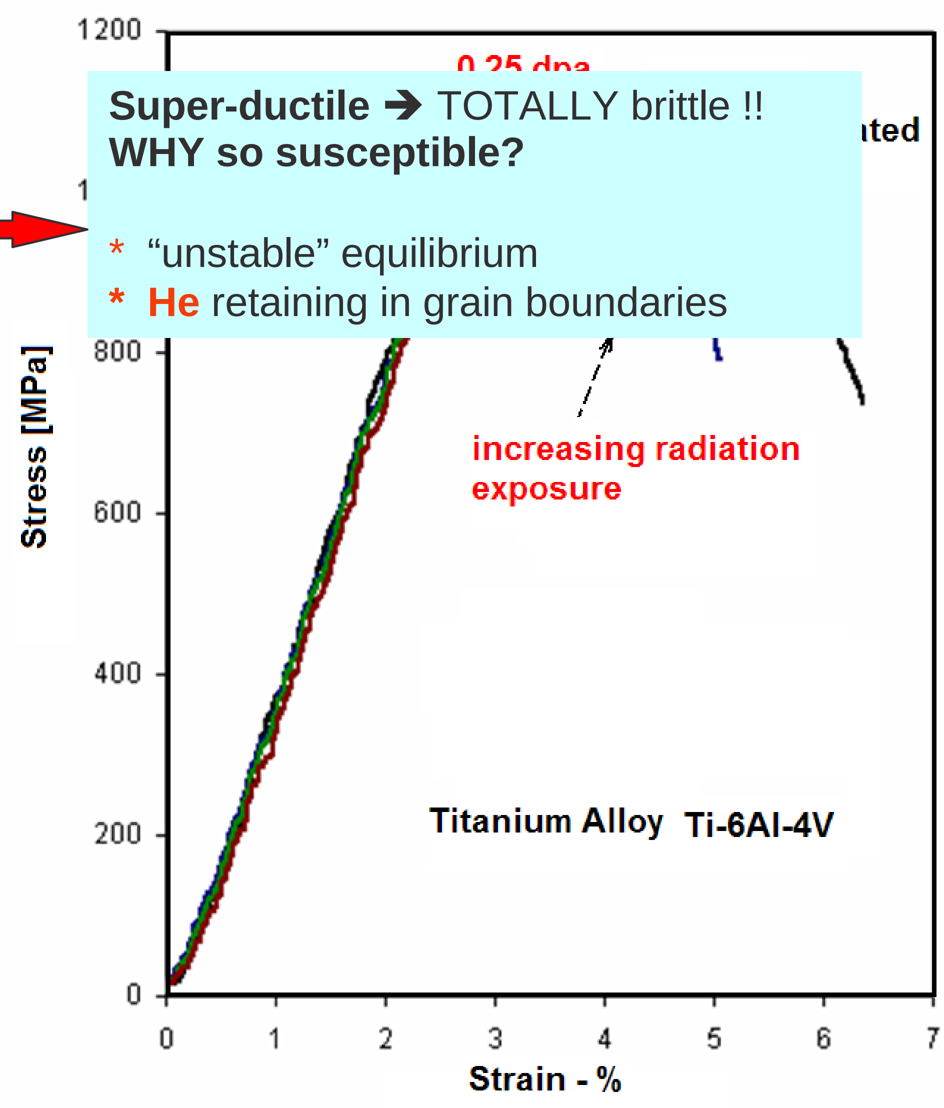


What happens to this super-material when it is bombarded with radiation or is subjected to high temperature ?

T. Saito, et al., Multifunctional Alloys Obtained via a Dislocation-Free Plastic Deformation Mechanism, Science, 300 (2003) 464

Radiation effects on Mechanical Properties of Gum Metal

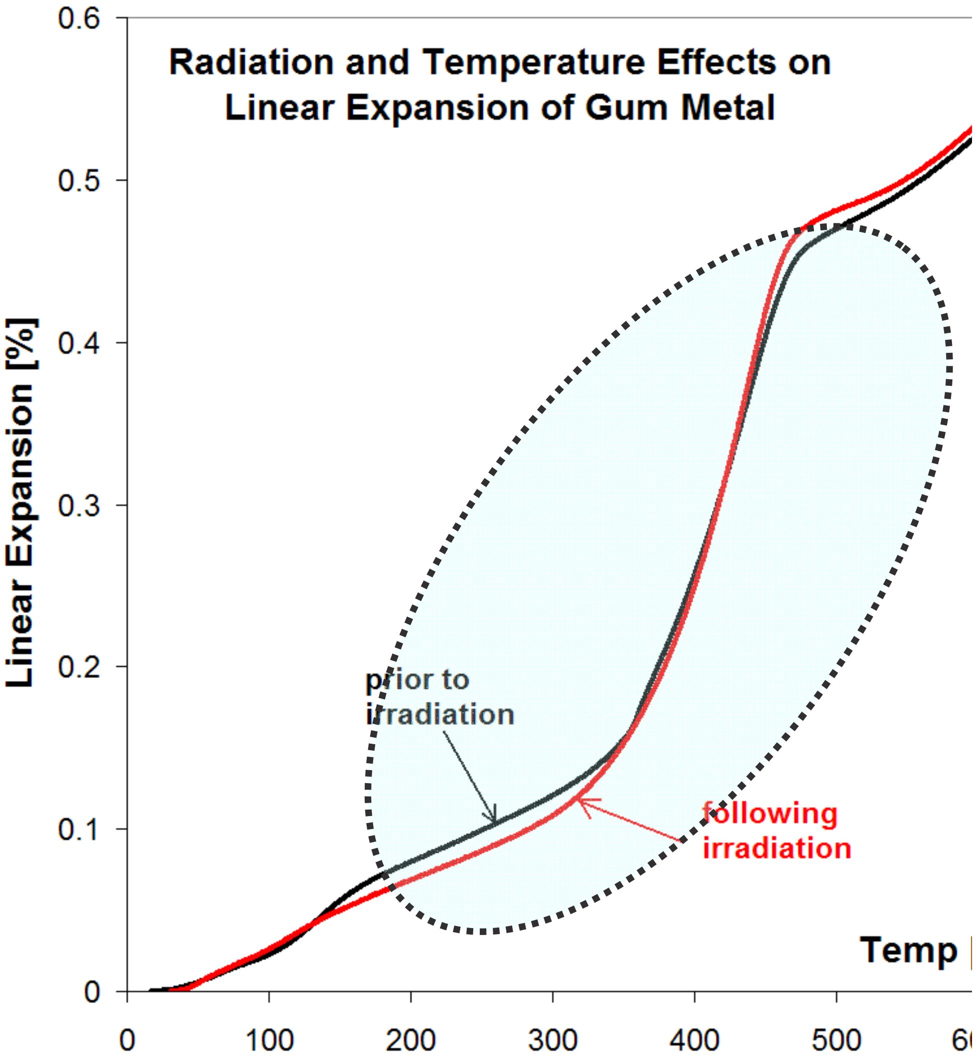


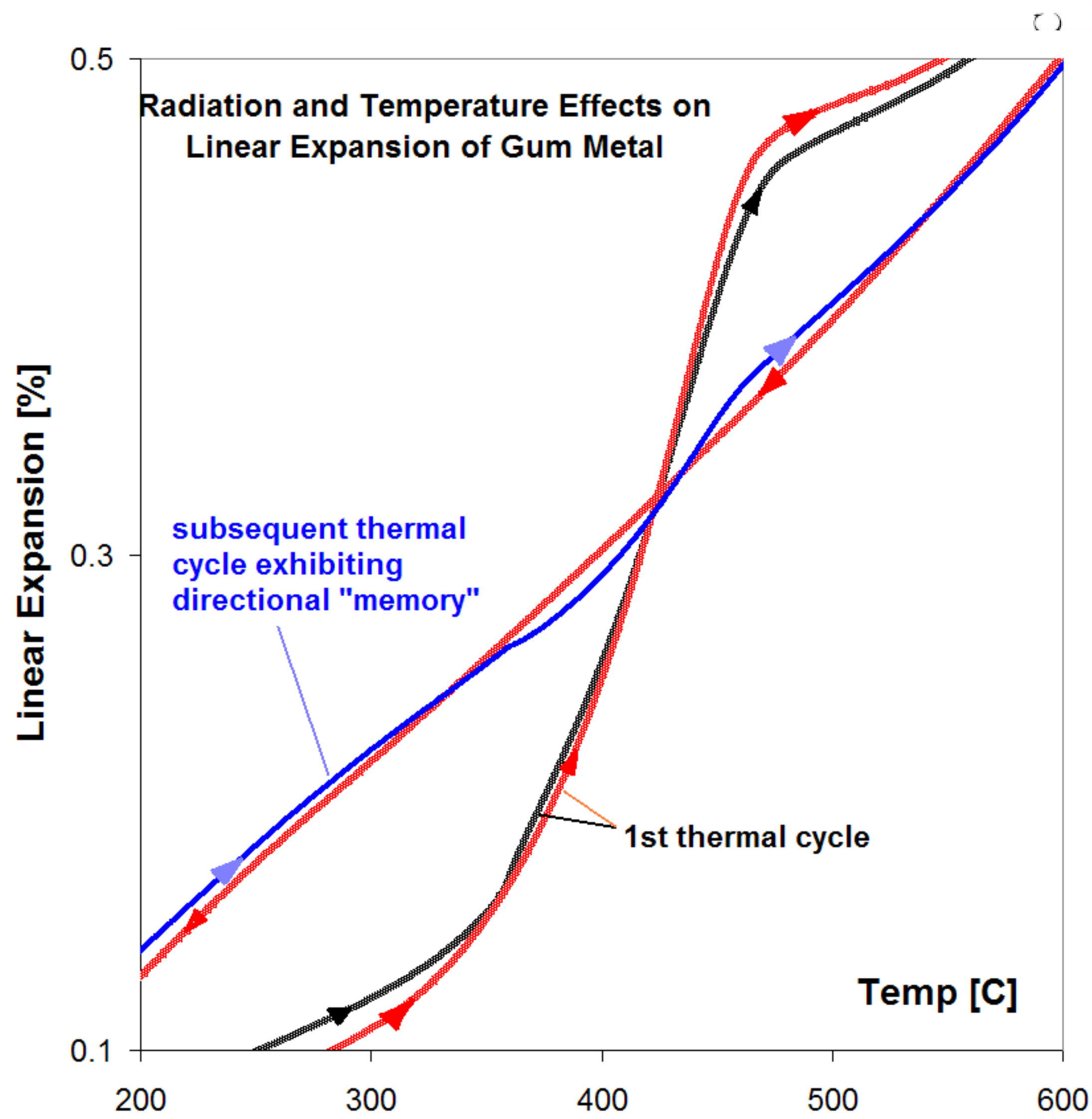


Super-ductile ➔ TOTALLY brittle !!
WHY so susceptible?

* "unstable" equilibrium
* **He** retaining in grain boundaries

Unique gum metal linear expansion behavior





Carbon Composites and Graphite

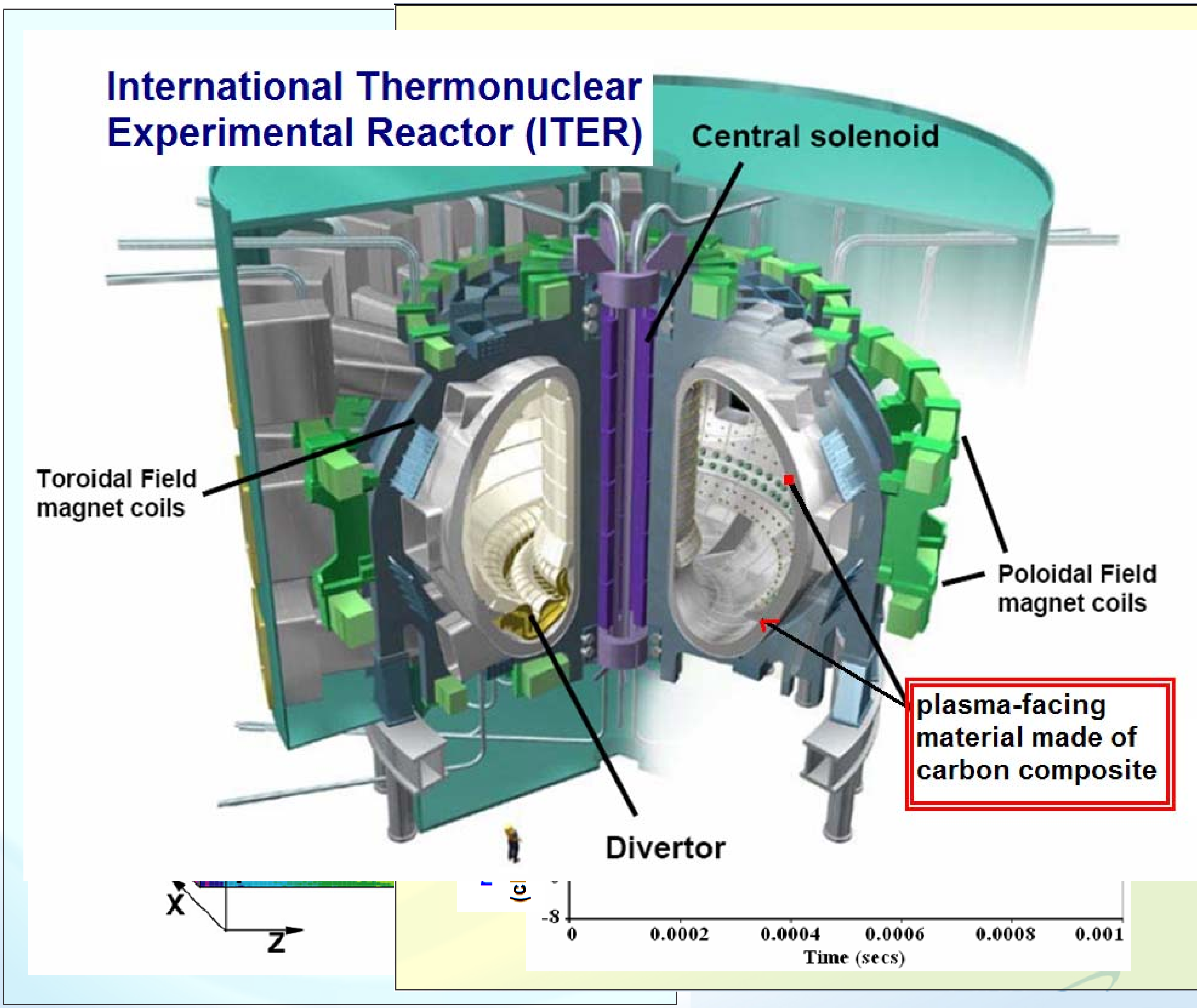
Graphite closely linked with nuclear energy's past ..... Carbon fiber composites = future?

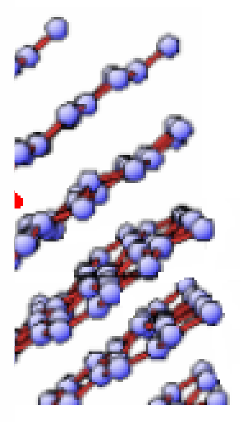
...erators NOT reactors

Grap... chan...

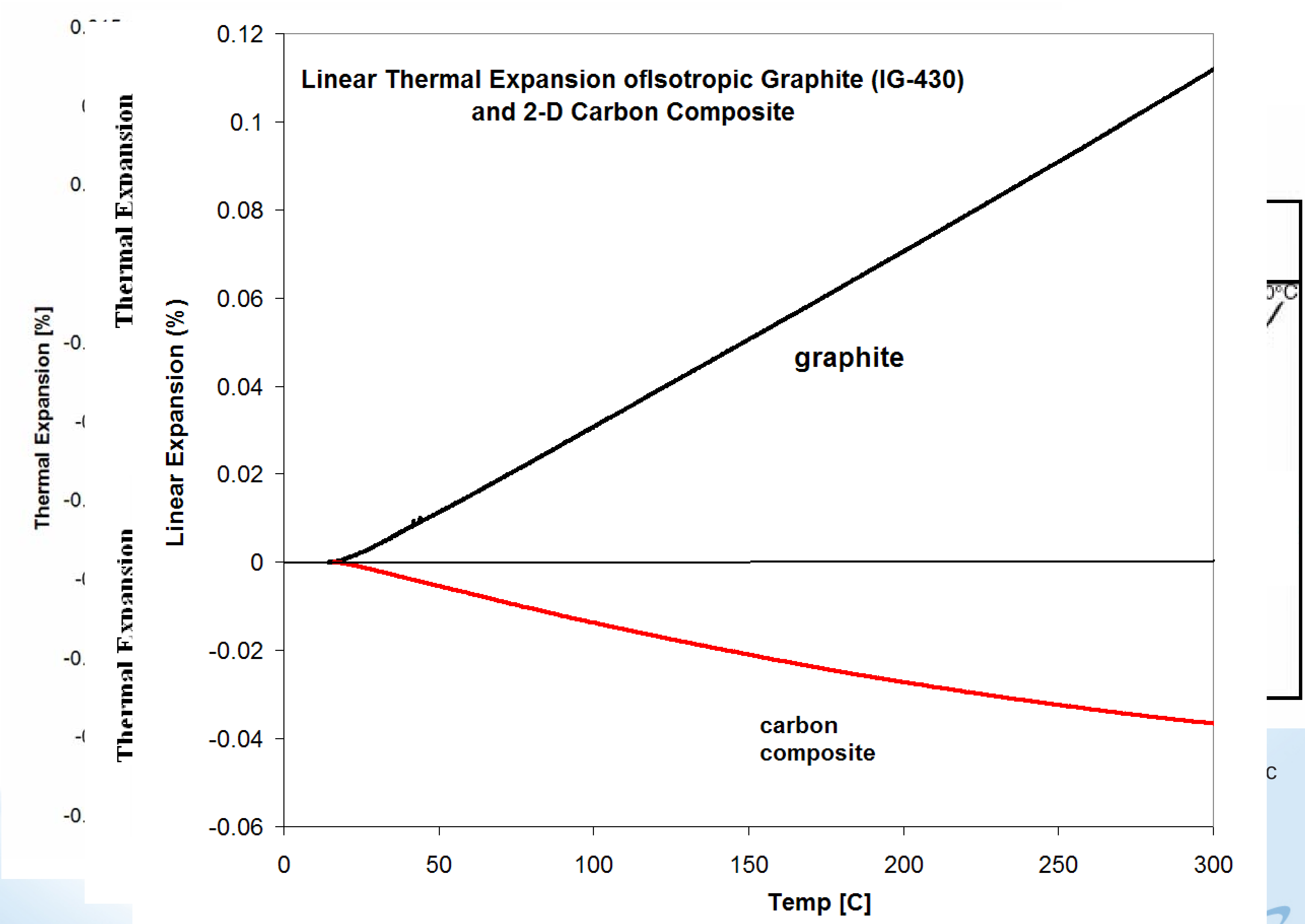
...nal

...ite



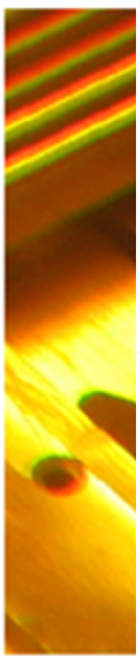


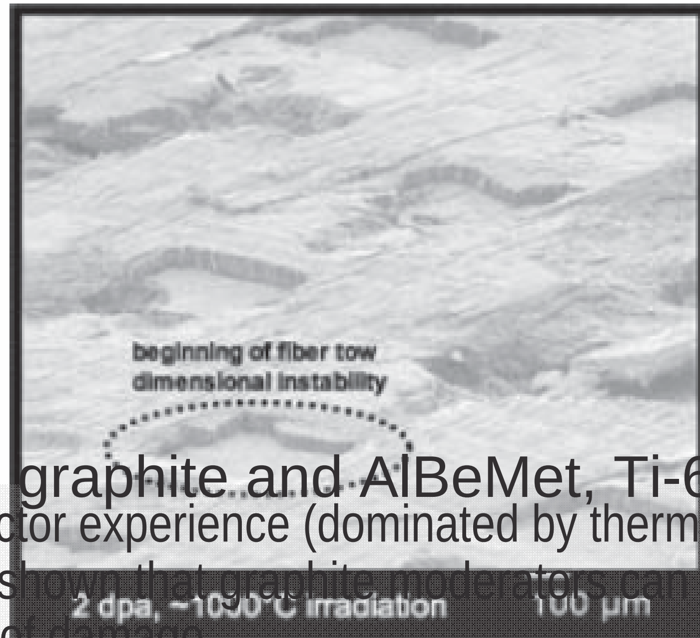
Graphite and carbon-carbon composites



While things seemed promising with carbon fiber composites

A THRESHOLD PROTON FLUENCE OF ~10^{21} protons/cm^2 HAS EMERGED





J-P. Bonal, et al., Graphite, Ceramics and Ceramic Composites for High-Temperature Nuclear Power Systems, MRS Bulletin, V. 34, 2009

Good news so far ➔ isotropic graphite and AlBeMet, Ti-6Al-4V

Reactor experience (dominated by thermal neutron flux) has shown that graphite moderators can withstand tens of dpa of damage

Premature degradation result of:

radiation rate?

or thermal neutrons vs. energetic protons ?

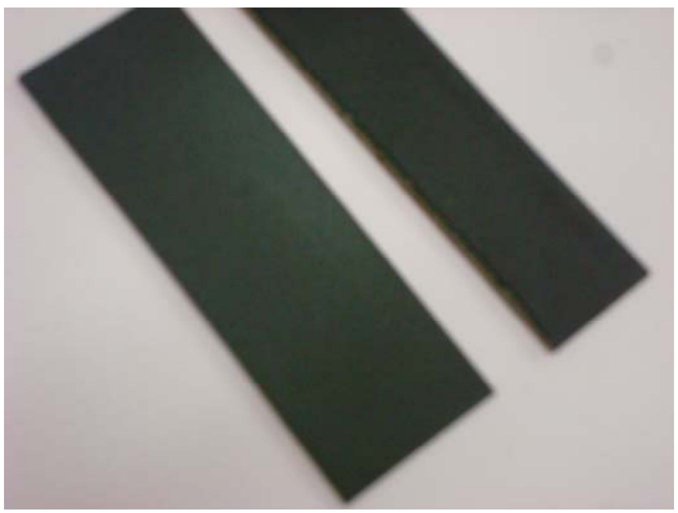
Nanostructured COATINGS under Extremes

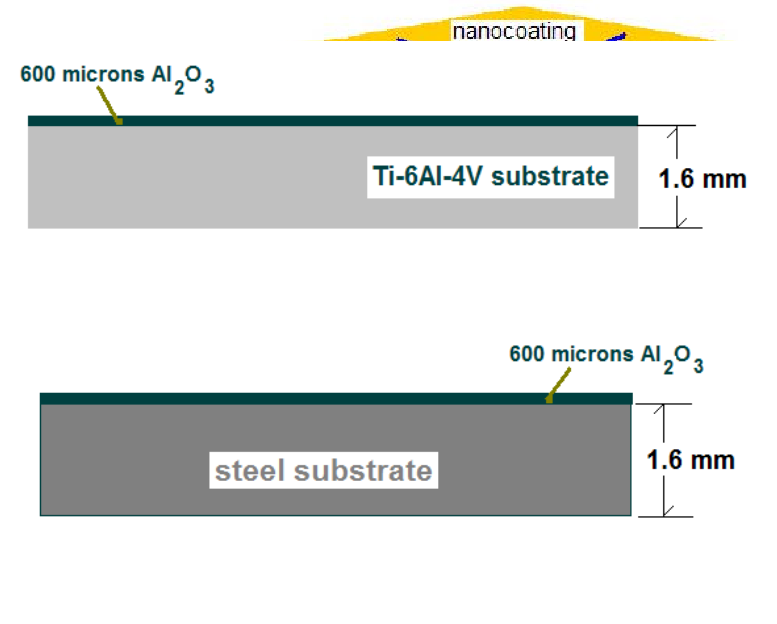
Matching of the thermal expansion coefficients is crucial

Lets see what happens to these nano-coated materials under extreme temperatures

Wh

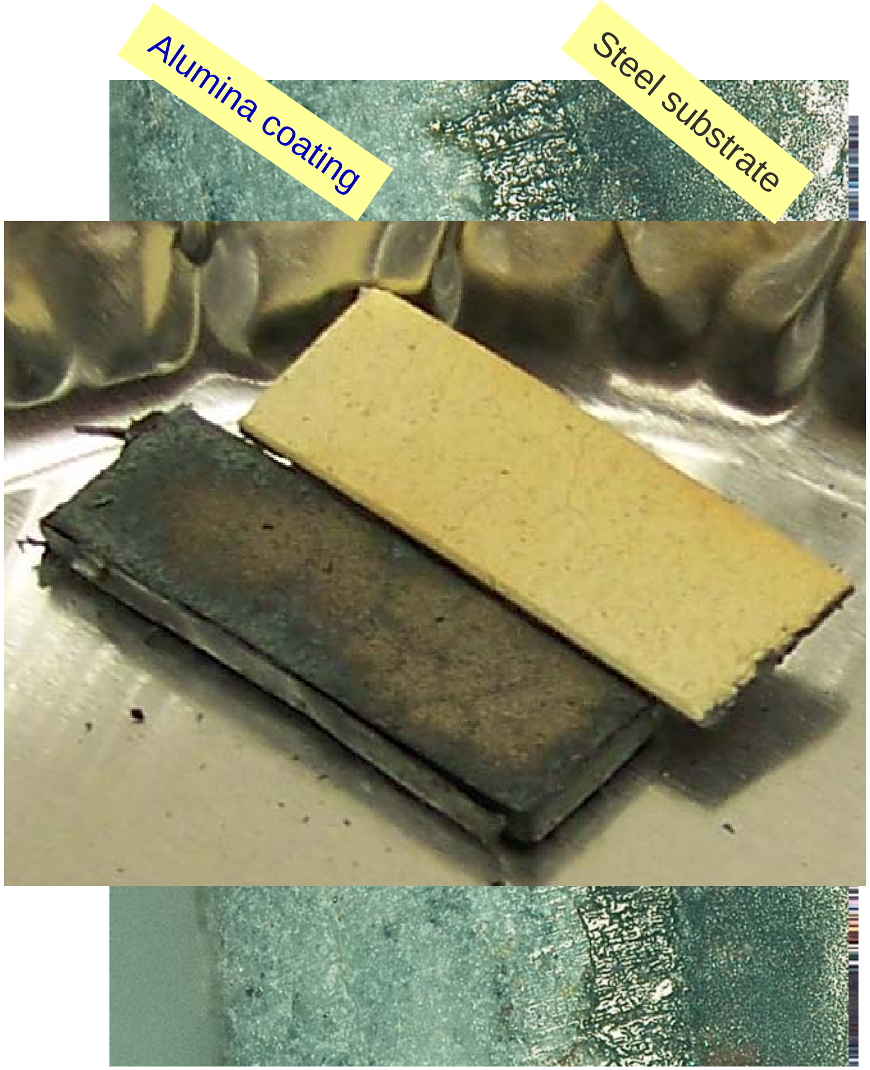
and especially radiation or chemical stimuli change the CTE differently ?

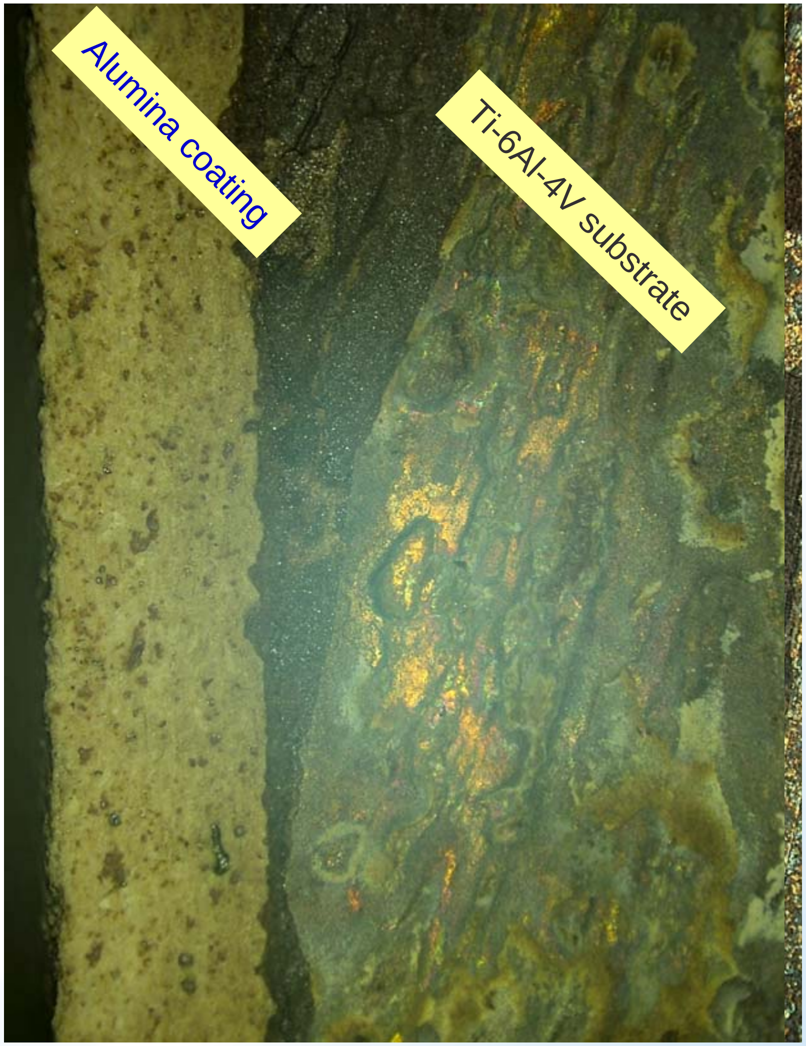




Nano-coated materials provided by Prof. Tsakalakos, M. Croft and colleagues at Rutgers U.

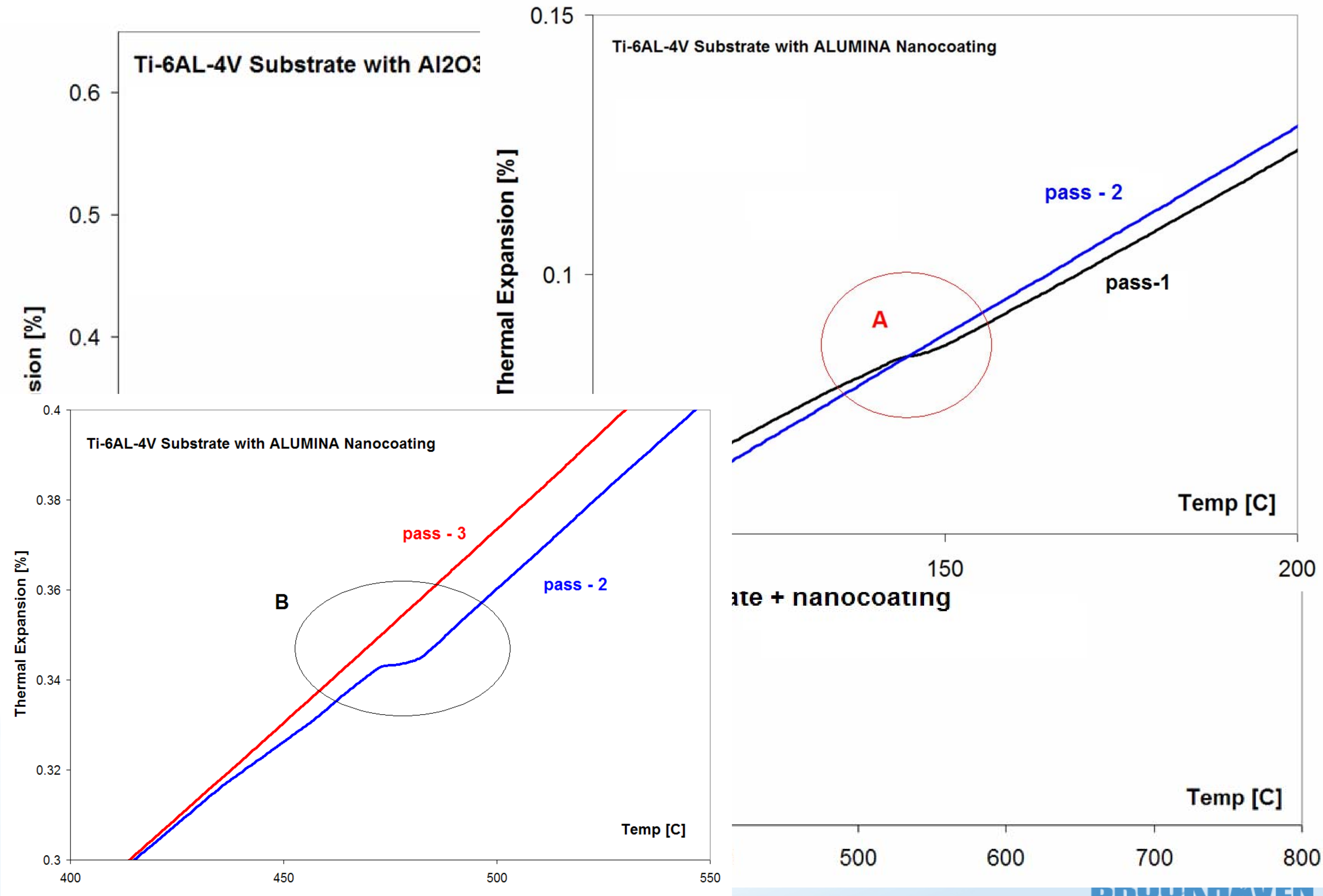
Nanocoatings and high temperatures



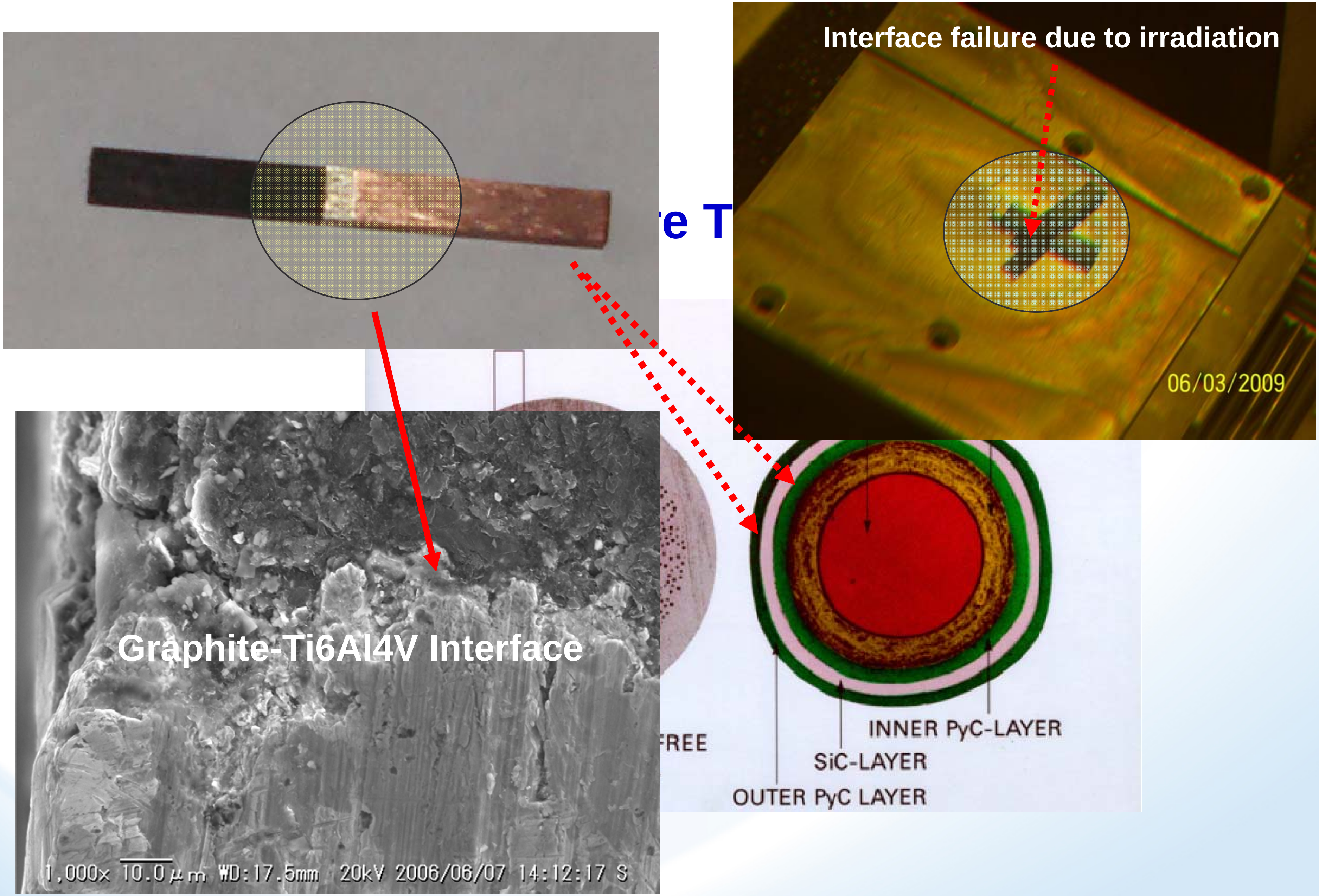


Temp = 1300 C

Nanocoatings and high temperatures



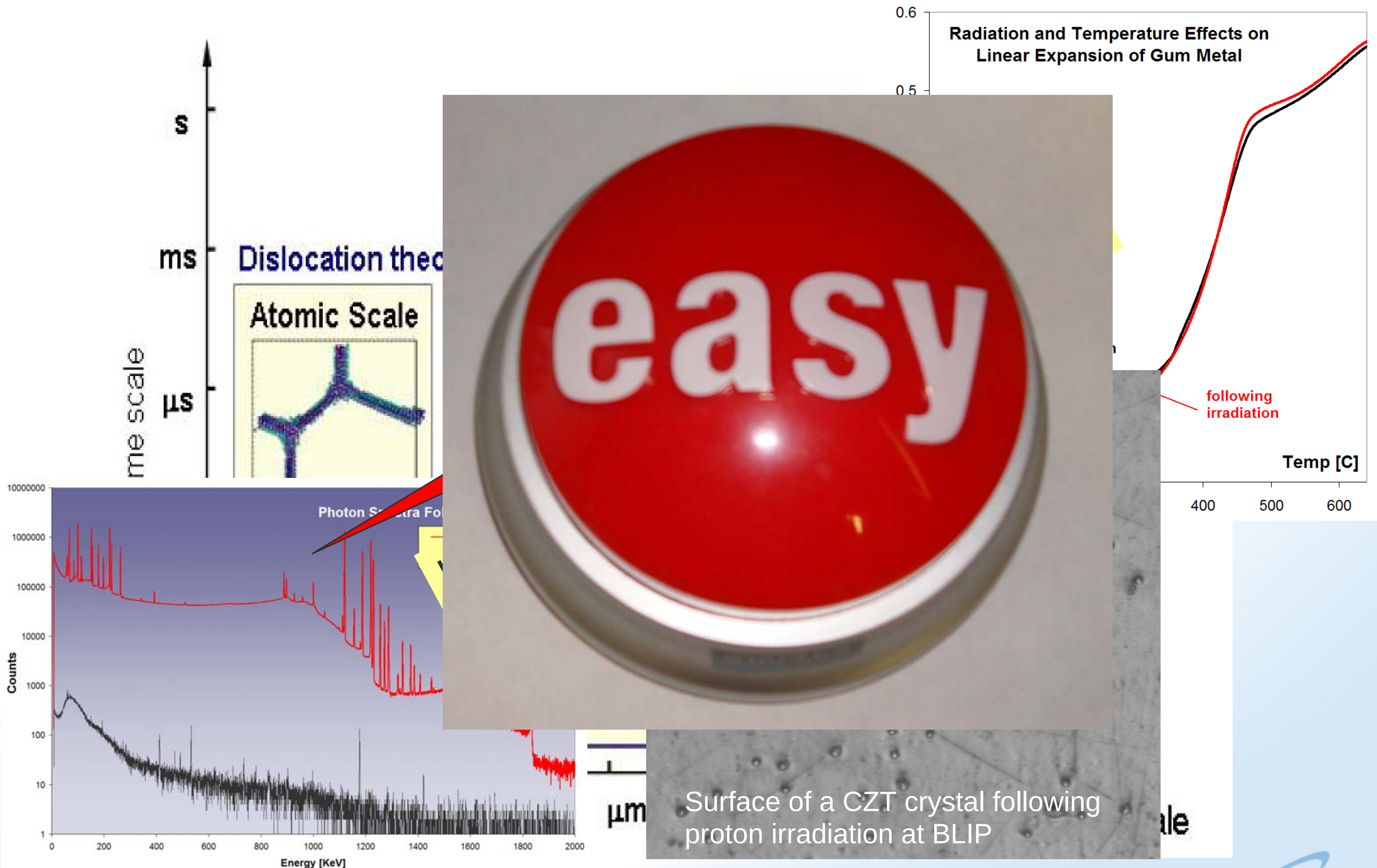
Radiation effects on special bonds/interfaces of dissimilar materials



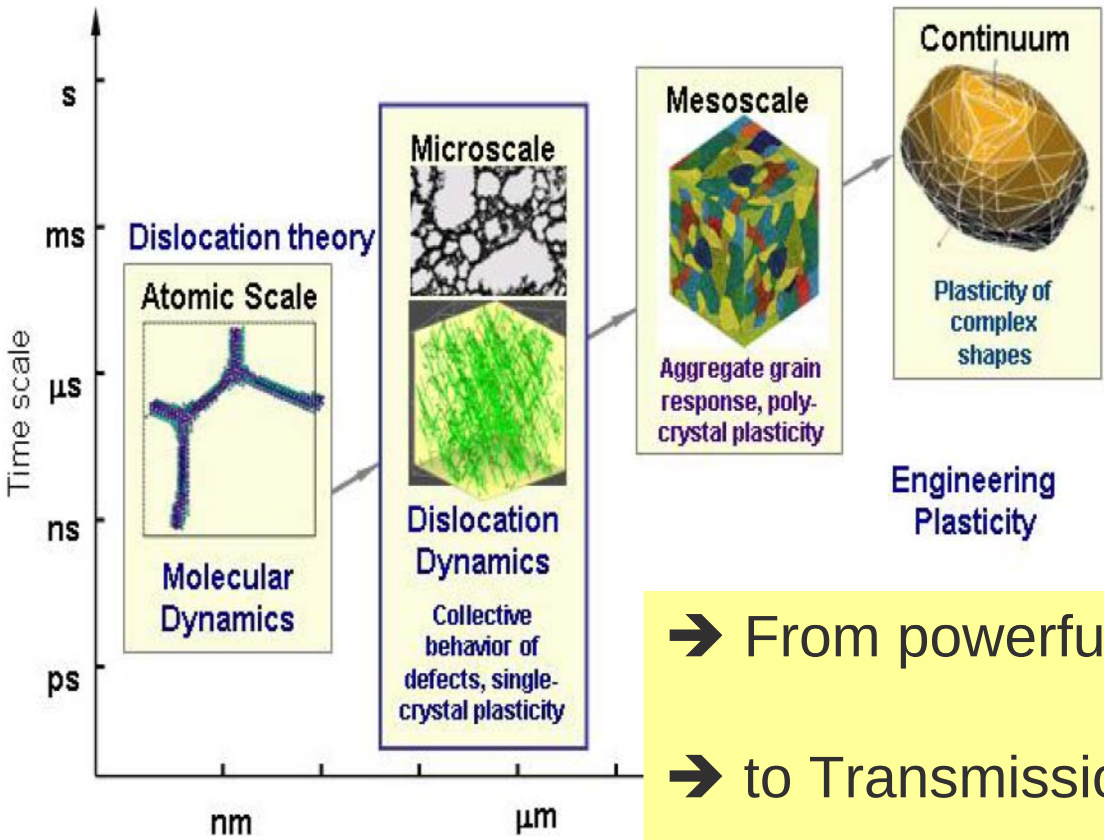
Characterization of Materials

and role of next generation probes

Characterization ...... The bridging of the scales CHALLENGE



(“Report of the Basic Energy Sciences Workshop on Basic Research Needs for Advanced Nuclear Energy Systems”)



pic scale ORIGINATES in ro-structure

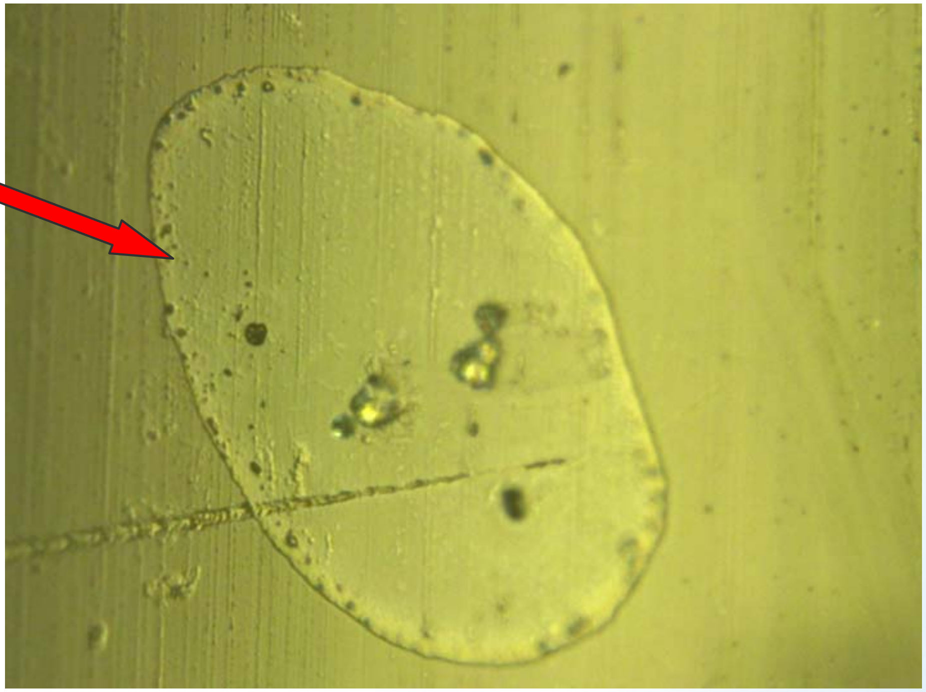
es” that allow us to view what ed to extremes:

ng phase transformations

- ➔ From powerful optical microscopes (10,000x)
- ➔ to Transmission Electron Microscopes (TEM)
- ➔ to X-ray scattering (phase and strain mapping)
- ➔ to molecular dynamics simulations (**???**)

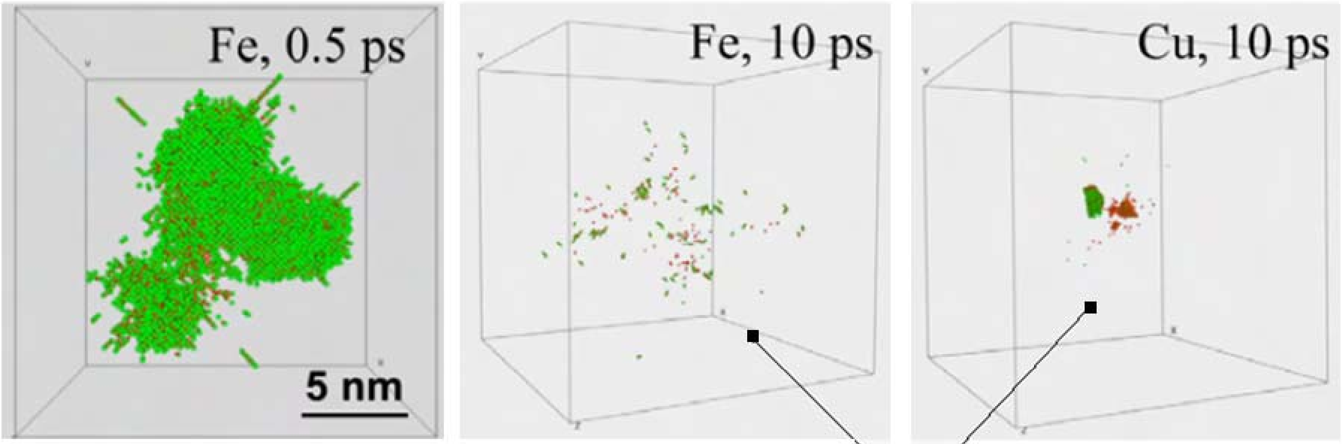
Molecular Dynamics and Reality

Fragment track and thermal spike on the surface of fused silica bombarded with energetic particles



MOLECULAR DYNAMICS SIMULATION

Atomic Dsisplacement Cascade

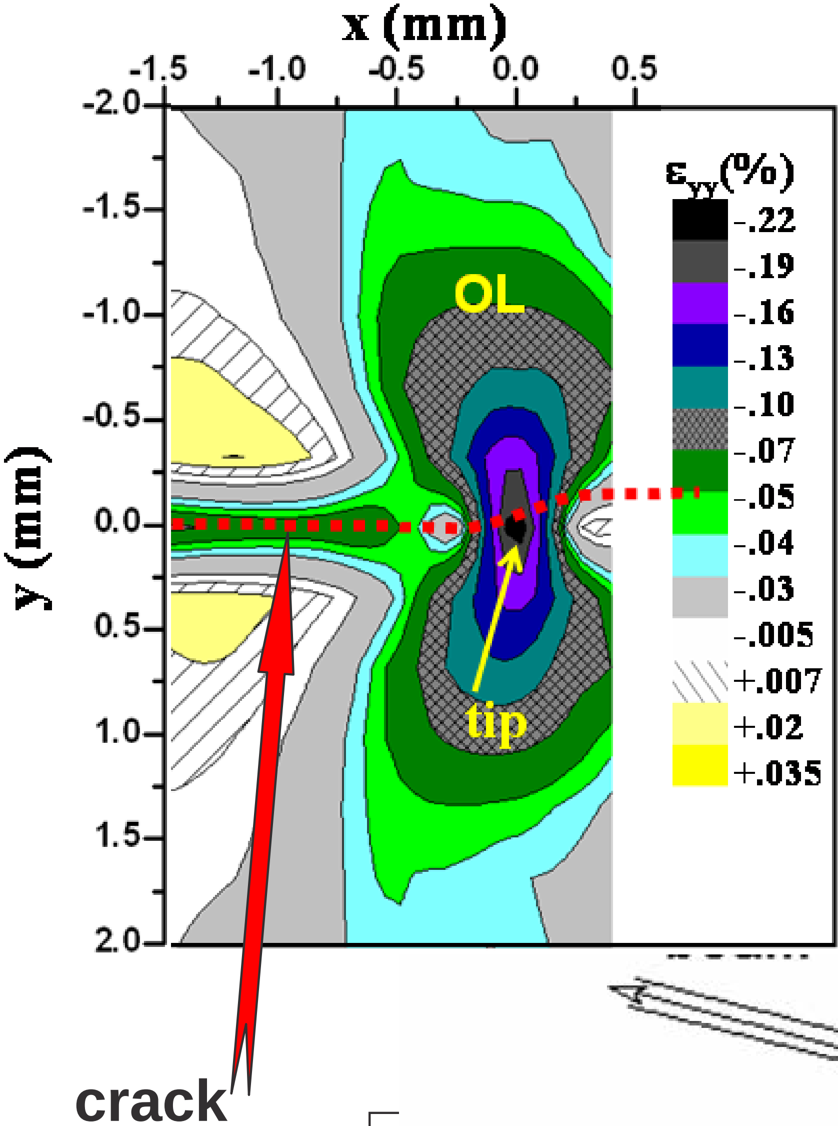


peak of displacement event

end of displacement cascade ("thermal spike")

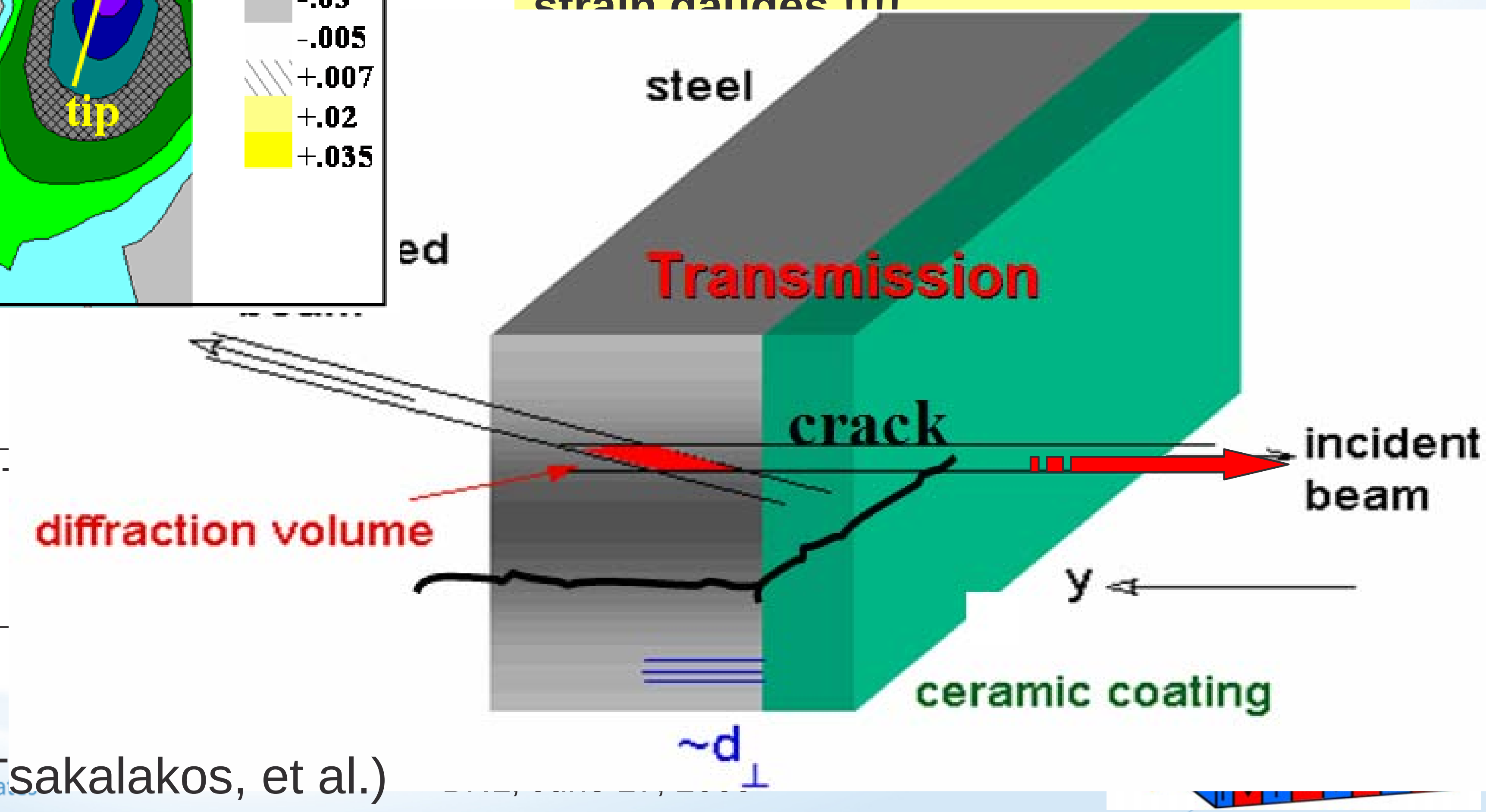
Characterization of Materials at NSLS

STRAIN MAPPING
Energy Dispersive Diffraction Mode



$$E_{hkl}\ [\text{in keV}] = \frac{6.199}{d_{hkl}\sin\theta} \Rightarrow \varepsilon = \frac{\Delta d}{d_0}$$

Like having imbedded inter-atomic strain gauges !!!!



(courtesy, T. Tsakalakos, et al.)

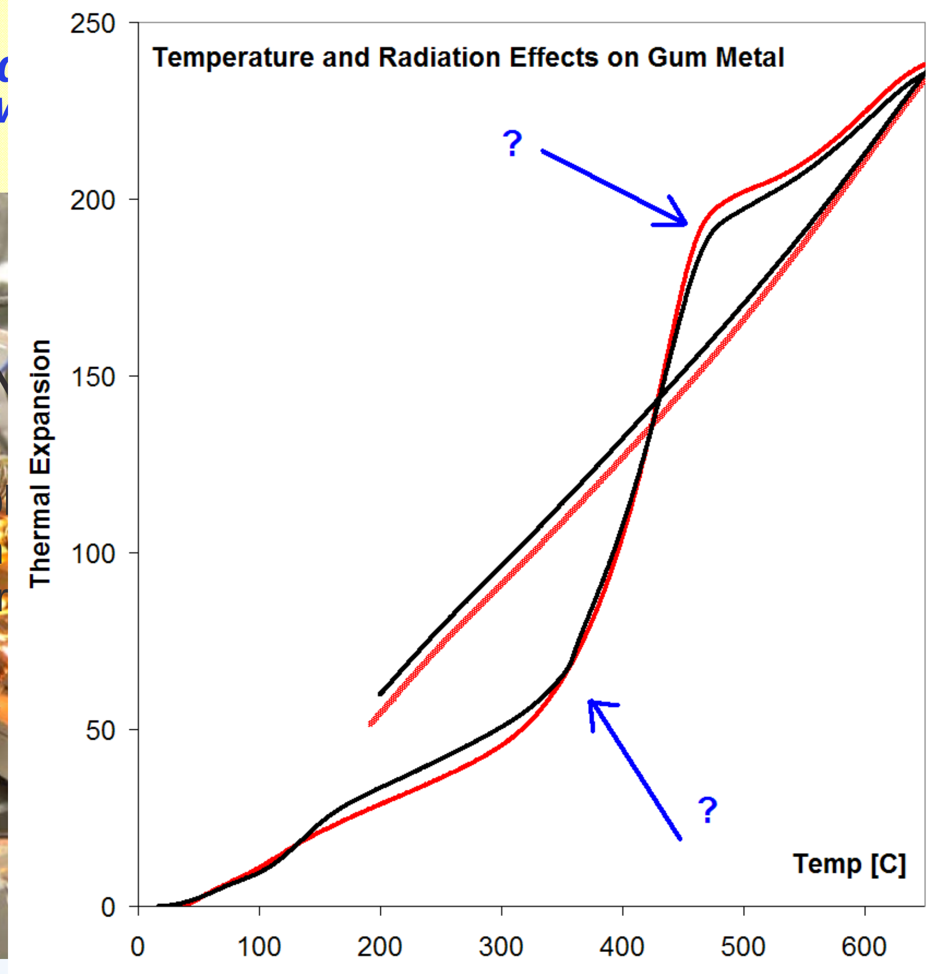
High Temperature Characterization of Advanced Materials and Nitride Fuels using X-ray Powder Diffraction and Pair Distribution Functions

L. Ecker, L. Ehm, N. Simos, and Chi-Chang Kao [BNL]; Ken Czerwinski, UNLV

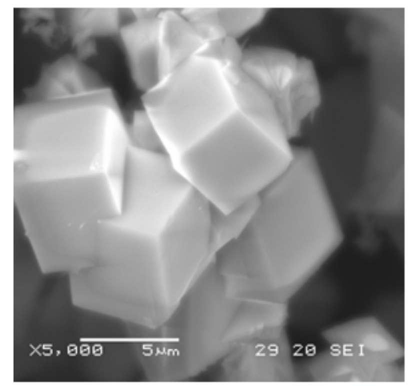
- ***Observe high-temperature fuel synthesis AND in-situ material phase transformations***
  - ***powder diffraction experiments up to 2000 C at NSLS***
- ***Use high-temperature c… structure follov…***
- ***Cr…***

Determine kinetics for UN…

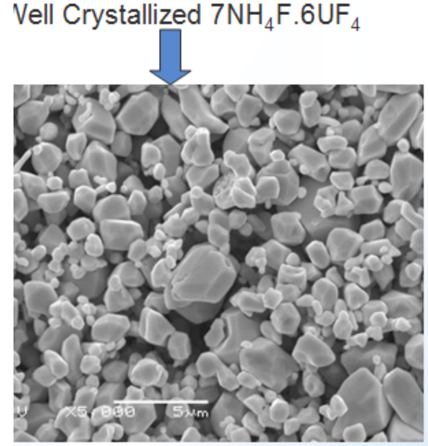
Uranium-nitrogen made of depl… nuclear fuel because high high… conductivity, high density and r…



rans-uranics with Nitride Fuels



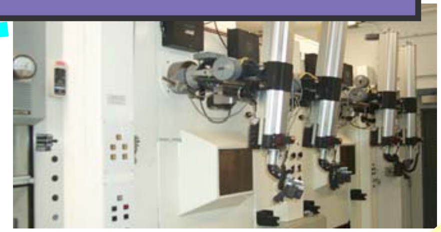
Vell Crystallized $7NH_4F.6UF_4$



…inski, University of Nevada, Las Vegas
-New, Lower Temperature Nitride Fuel Synthesis

Envisioned Synergistic Model at BNL

Irradiation & macroscopic assessment



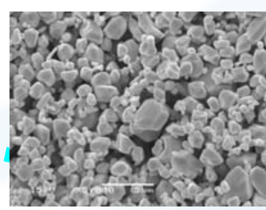
Visualization of damage

(X-ray probing/strain mapping)

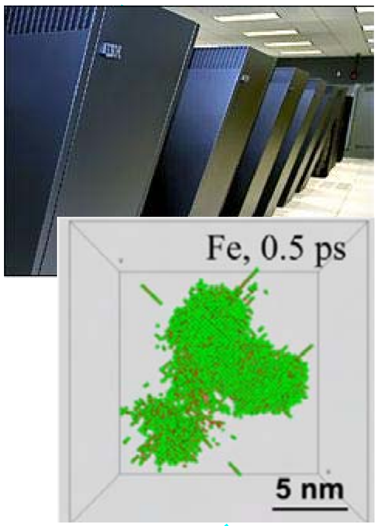
Light Source

Re-engineering of

nano- /micro-structure at CFN



o Molecular Dynamics
o Monte-Carlo analysis



Are we envisioning this in a vacuum?

NO, there are positive signs ....

Movement within US DOE to capture the moment and use its scientific
in

As

Co
the

BNL not standing on sidelines:

"White Paper - Materials in Extreme Environments ",
L. Ecker, G. Greene, N. Simos

Characterization of Advanced Materials under Extreme Environments for Next Generation Energy Systems Workshop, BNL, Sept. 25-26, 2009

SO, CAN THEY CO-EXIST?

MAYBE NOT THE ONES WE THOUGHT ALL ALONG !

Long road ahead to achieve **reliability** and **efficiency** goals that are intertwined with the advancement of materials

THANK YOU !