Irradiation Damage in Solid Targets

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3rd High Power Targetry Workshop

OVERVIEW

- **Irradiation damage to carbon-based materials**
- **Irradiation effects on super-alloys**
- **Effects on conductivity**
- **Neutron irradiation**

Radiation effects on materials

Radiation damage results from interaction of bombarding particles and atoms of the solid in 3 ways:

- electronic excitations ➔ no damage, only thermalization
- Elastic collisions (transferring of recoil energy to a lattice atom) leading to displaced atoms (dpa) and the formation of interstitials and vacancies. These are mobile at elevated temperatures
- Inelastic collisions ➔ transmutation products (generation of gases, primarily He)

OVERVIEW - Radiation effects on materials

- **Microstructural changes due to displacement defects and gas elements in grain boundaries**
  - increase in yield strength (hardening) and loss of ductility
  - irradiation creep
  - swelling
  - loss of ductility at high temperature/reduction of fatigue lifetime

Accelerator Target Interests

Extensive radiation damage studies in search the ideal materials to serve as proton beam targets and other crucial beam-intercepting components of the next generation particle accelerators

Primary concerns:

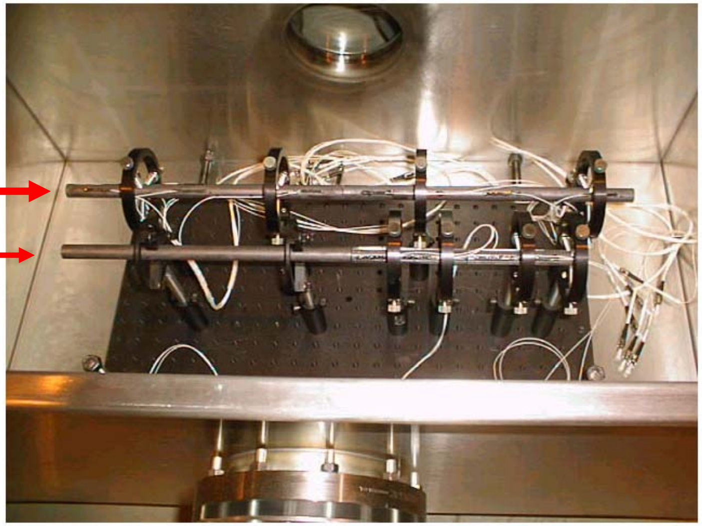
- Absorption of beam-induced shock
- premature failure due to fatigue
- radiation damage from long exposure

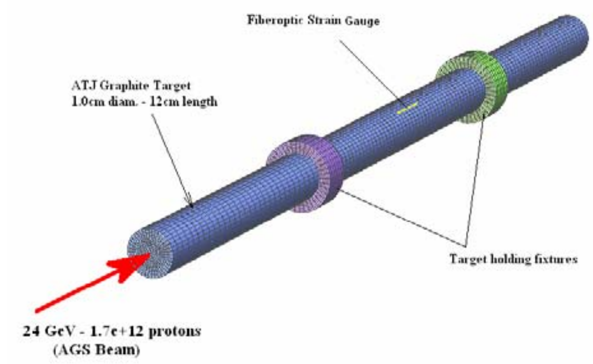
Anticipated condition cocktail far exceeds levels we have experience with

- while past experience (reactor operation; experimental studies) can provide guidance, extrapolation to conditions associated with multi-MW class accelerators will be very risky
- All one can do is inch ever closer to the desired conditions by dealing with issues individually

Irradiation damage to carbon-based materials

Beam Studies: Graphite & CC Composite at the AGS

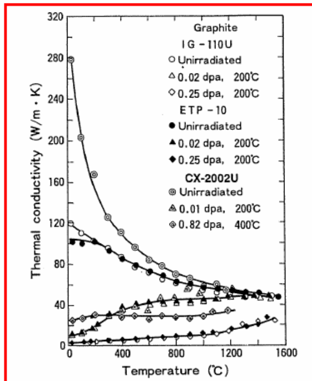




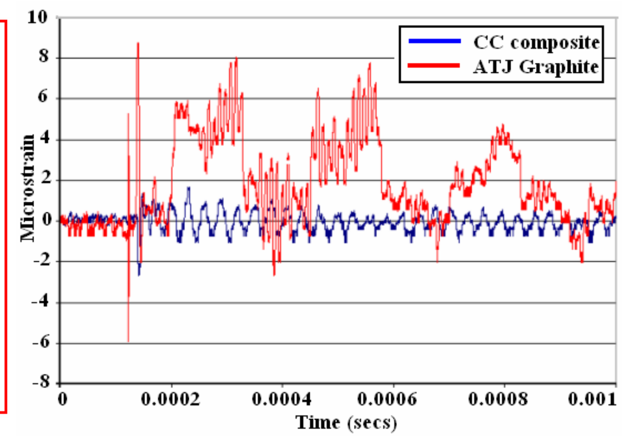
<u>The love affair with carbon composites</u>

Irradiation has a profound effect on thermal conductivity/diffusivity

CC composite at least allows for fiber customization and thus significant improvement of conductivity.

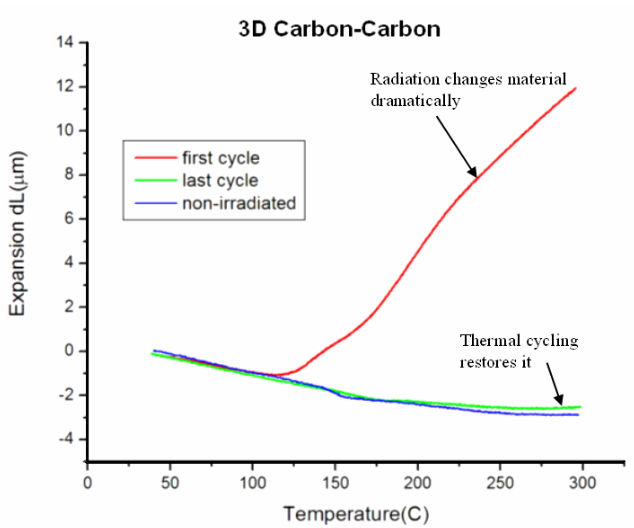


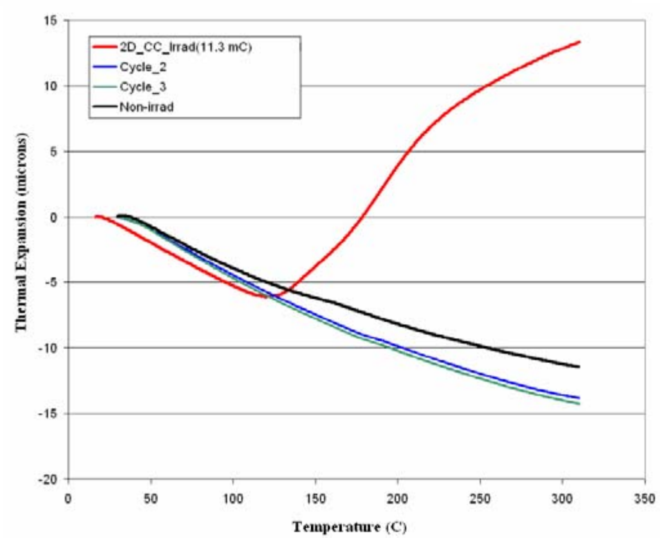
Thermal conductivity of neutron-irradiated graphites.

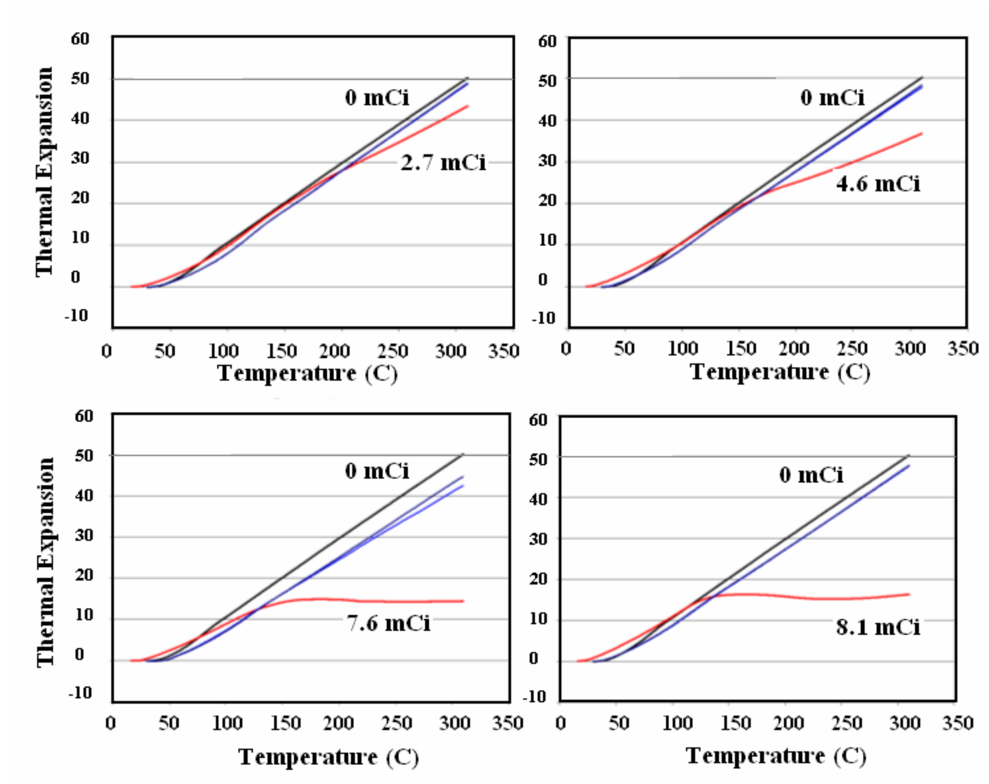


Yet to know for sure how carbon composites respond to radiation

Irradiation effects and “annealing” of carbon composites

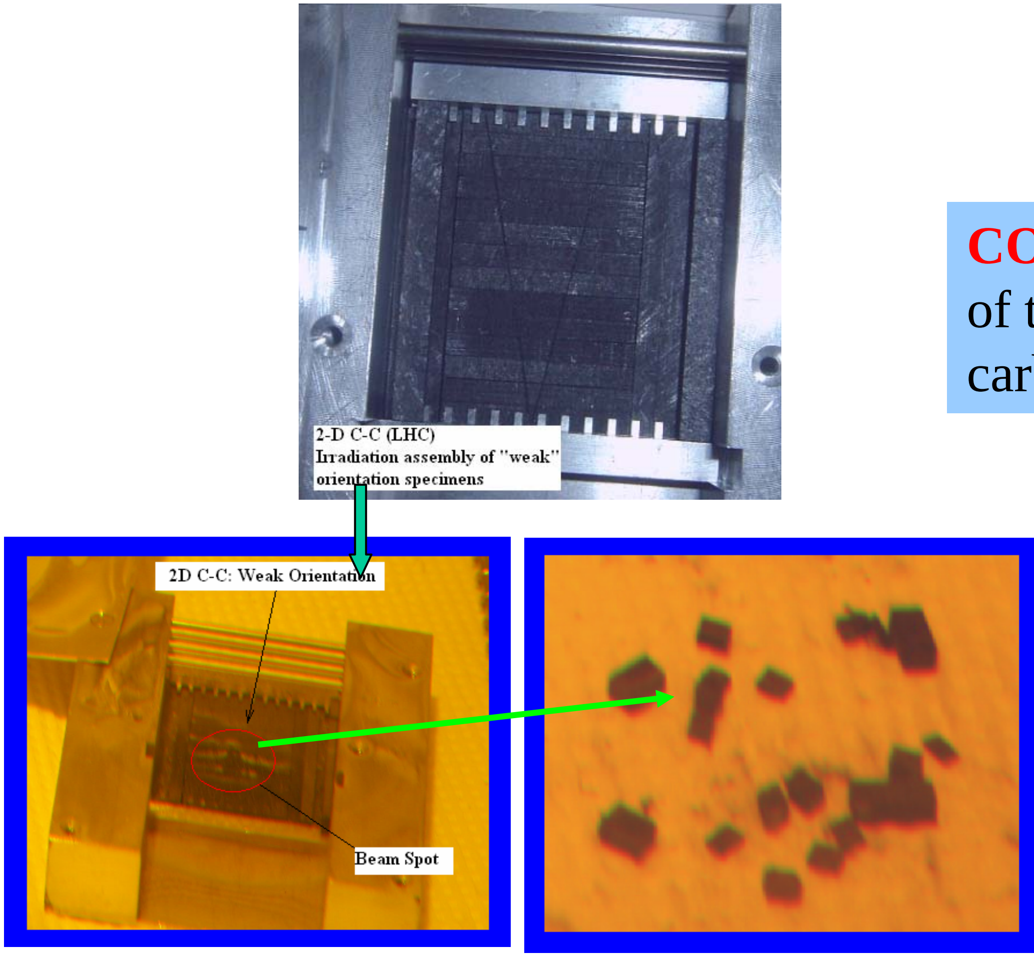






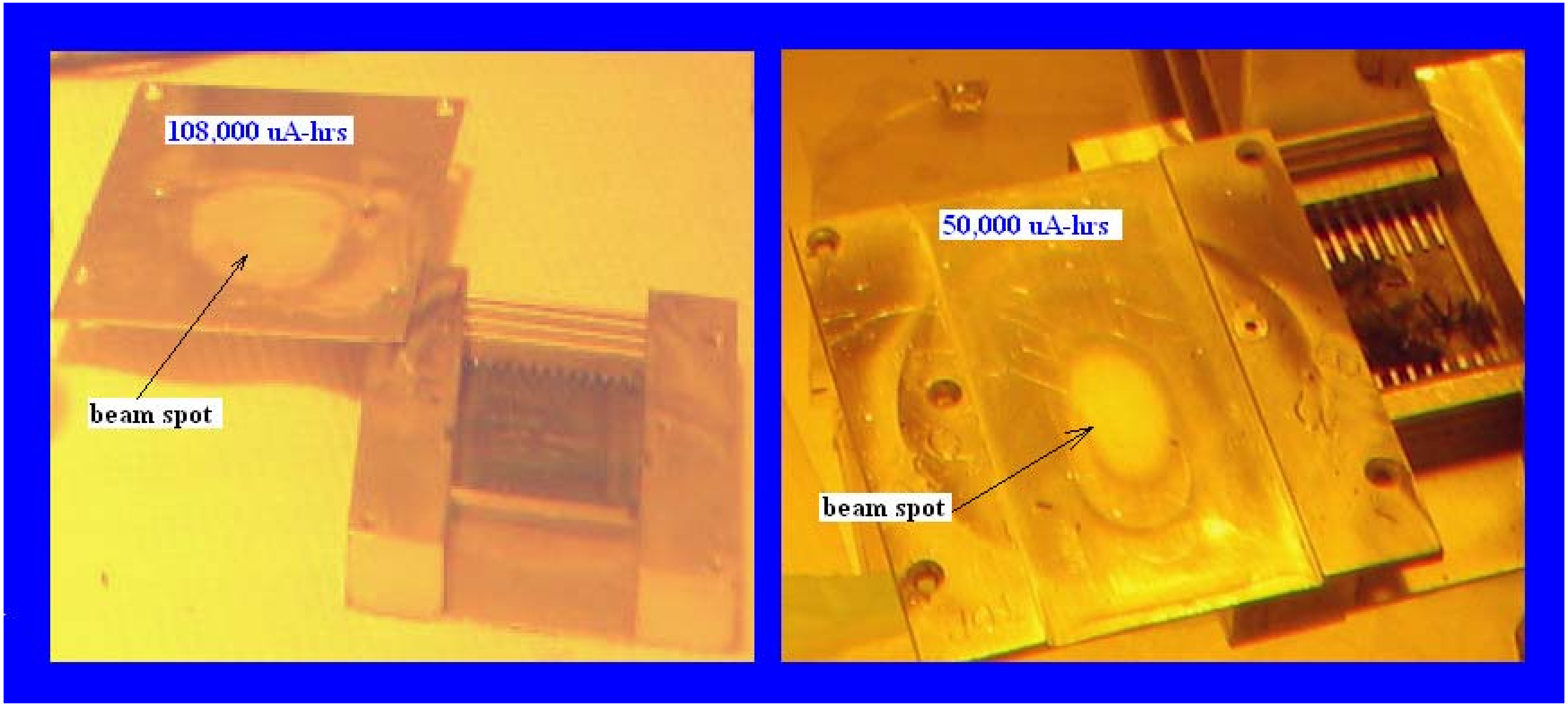
Signs of trouble !!

"weak" reinforcing fiber orientation

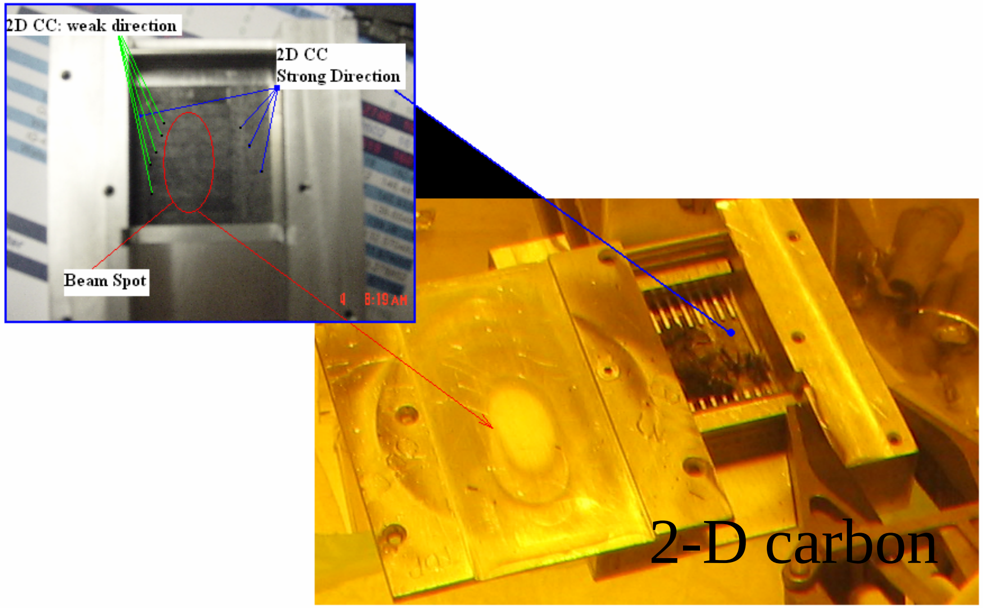


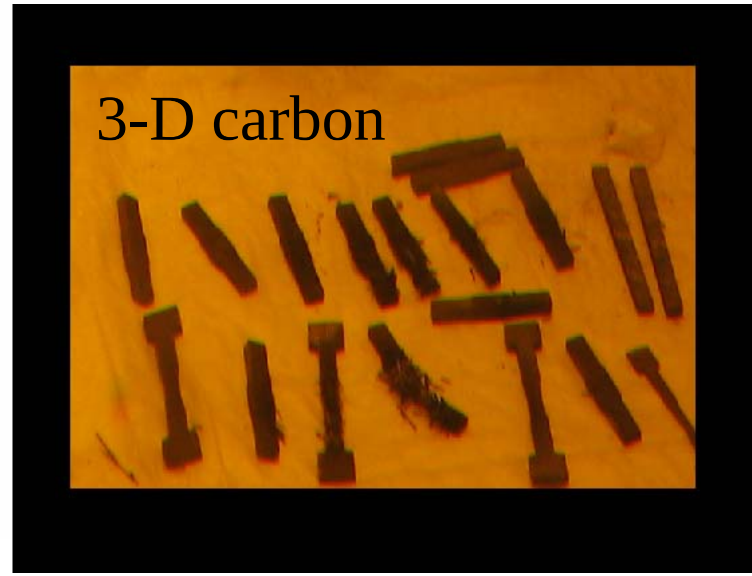
CONCERN: is damage characteristic of the 2-D structure or inherent to all carbon composites?

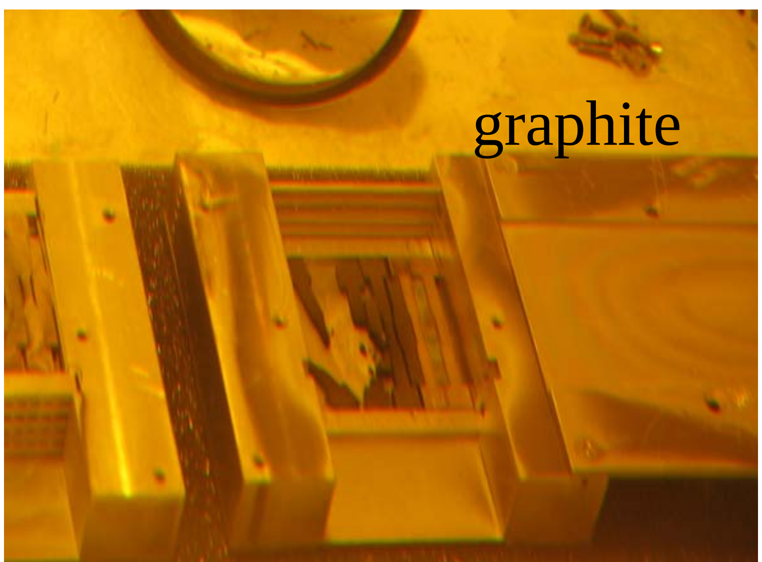
Follow-up Irradiation Phase for 2-D; 3-D Carbon composites and Graphite



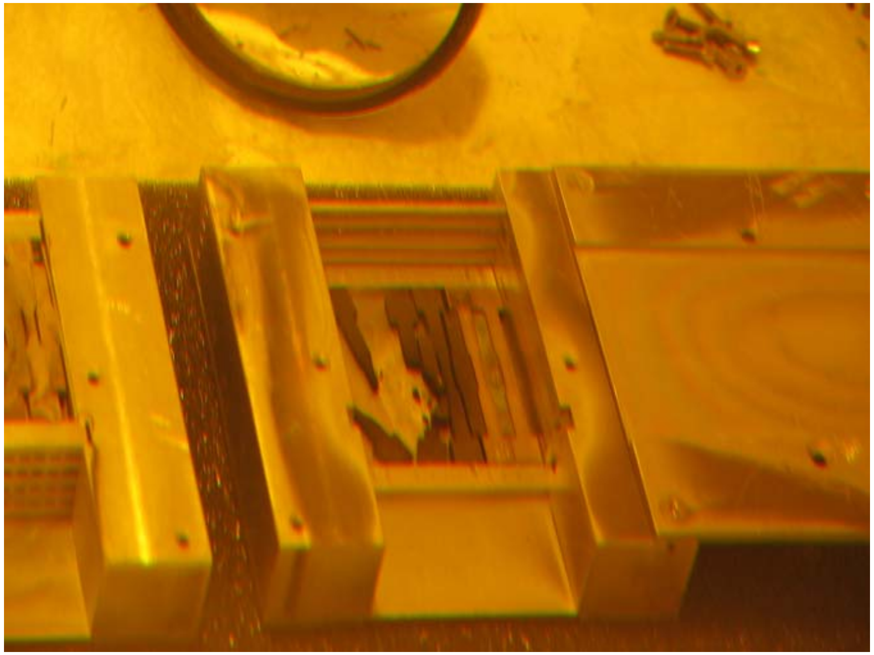
Condition of most heavily bombarded specimens after irradiation (fluence ~10^21 p/cm2)

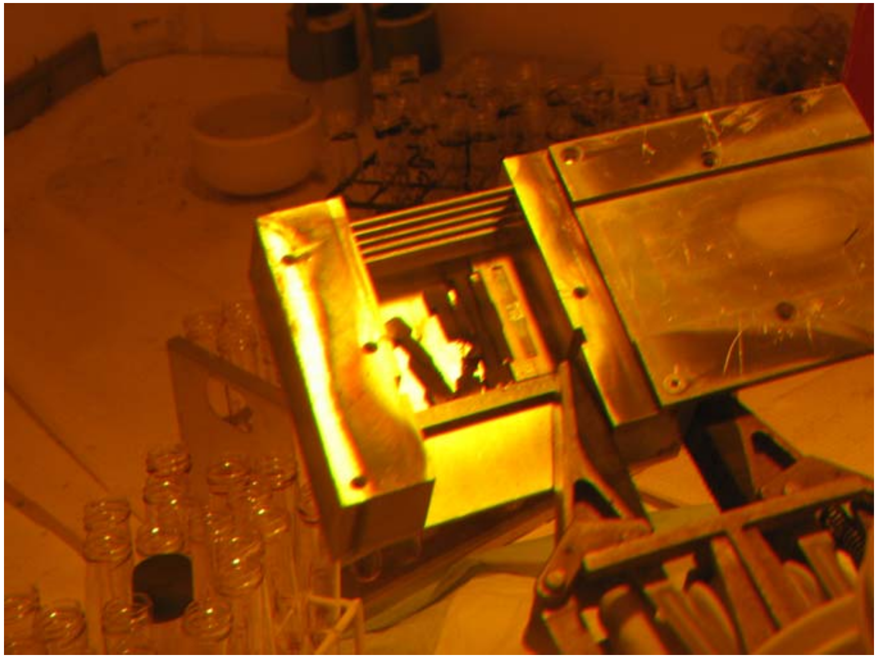






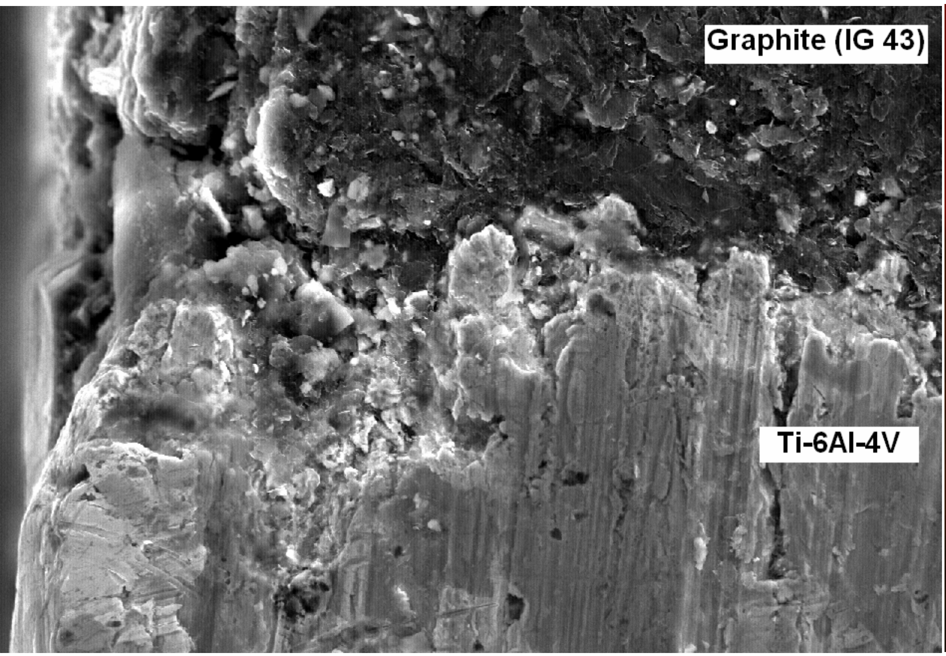
Damage in Graphite

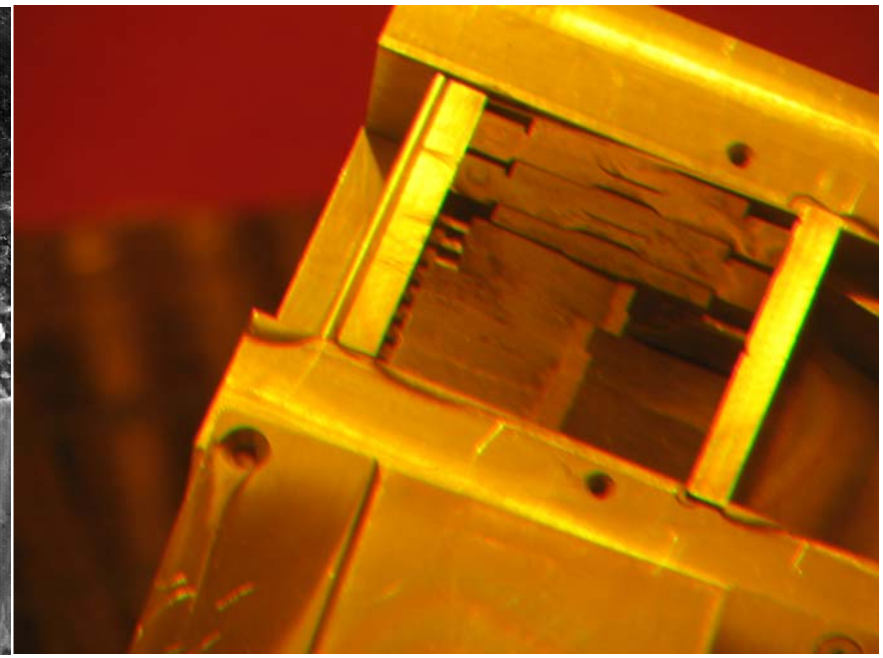




Graphite – Irradiation Effects on Bonding

While graphite has survived “quite” well in fission reactors (several dpa) it does not seem to endure the high proton flux (fluence ~ 10^21 p/cm2)





Irradiation damage to carbon-based materials

Focus of Experimental Effort

Extensive research in fission reactors, BUT in accelerator setting such as the one used:

- Higher production rates for He, H
- Pulsed energy input (flux, temperature, stresses)
- Higher fluxes ➔ higher displacement rates
- Protons vs. neutrons

Explore the effects of proton/neutron flux on these materials with interesting macroscopic properties ➔

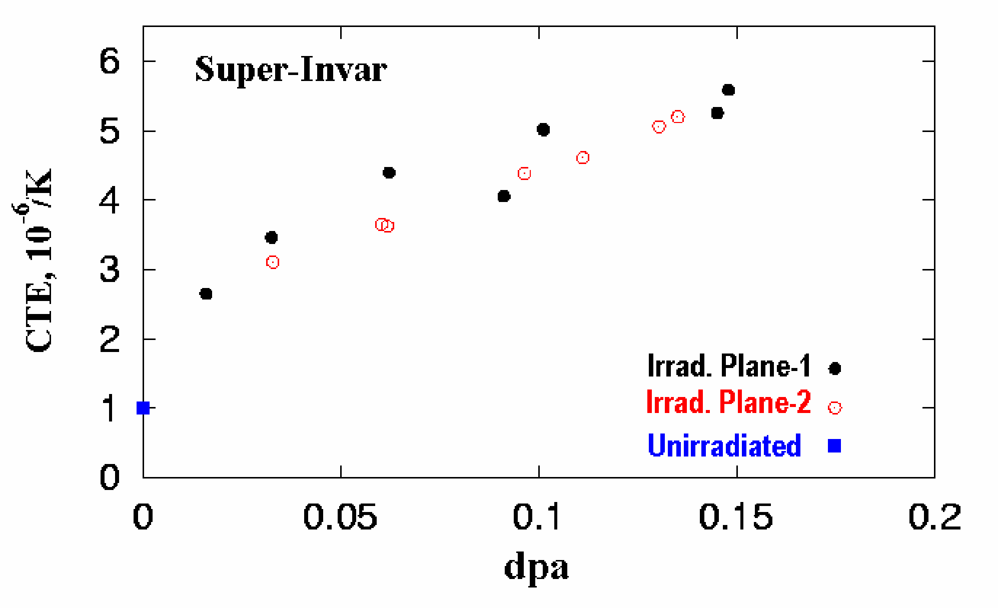
- super-alloys
- carbon composites
- graphite
- fused silica

Irradiation studies on super-Invar

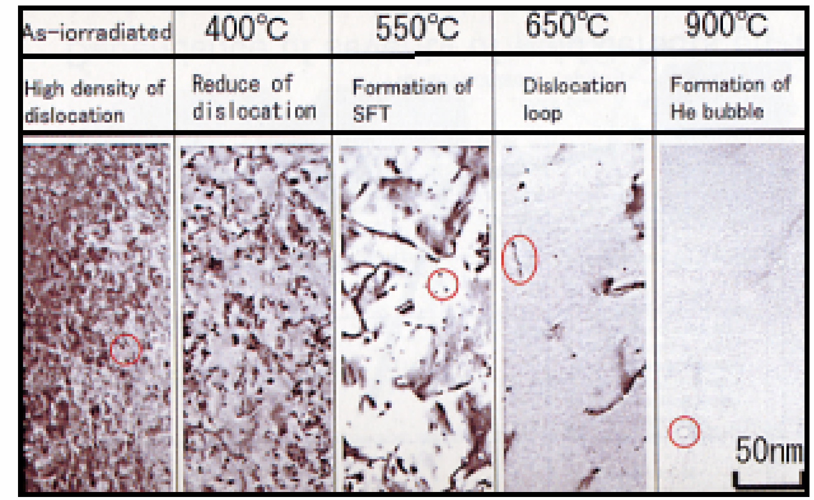
"invar" effect found in Fe-Ni alloys ➔ low CTE

- "inflection" point at around 150 C

Effect of modest irradiation



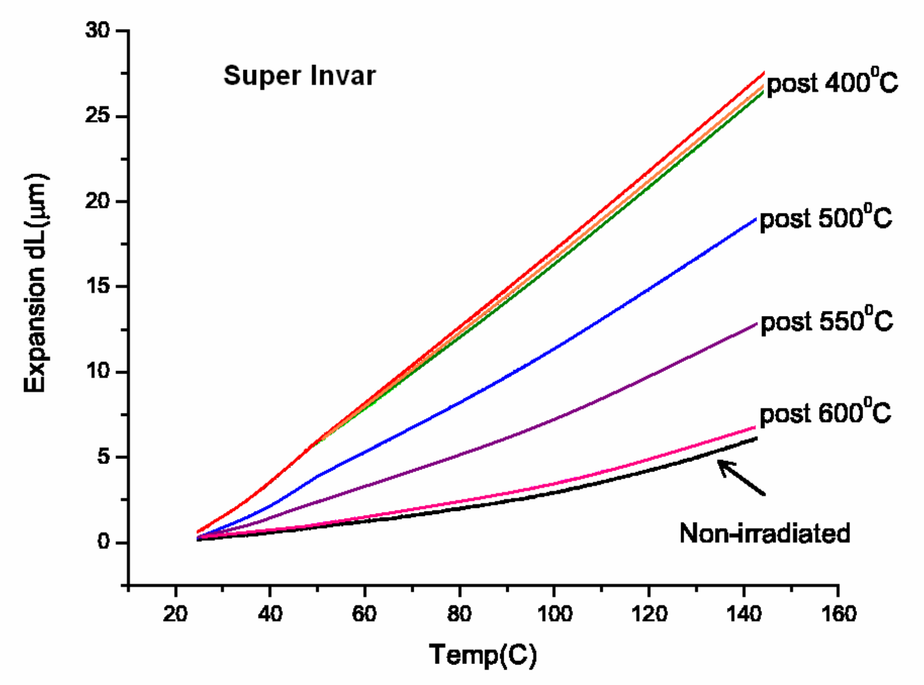
Annealing or defect mobility at elevated temperature



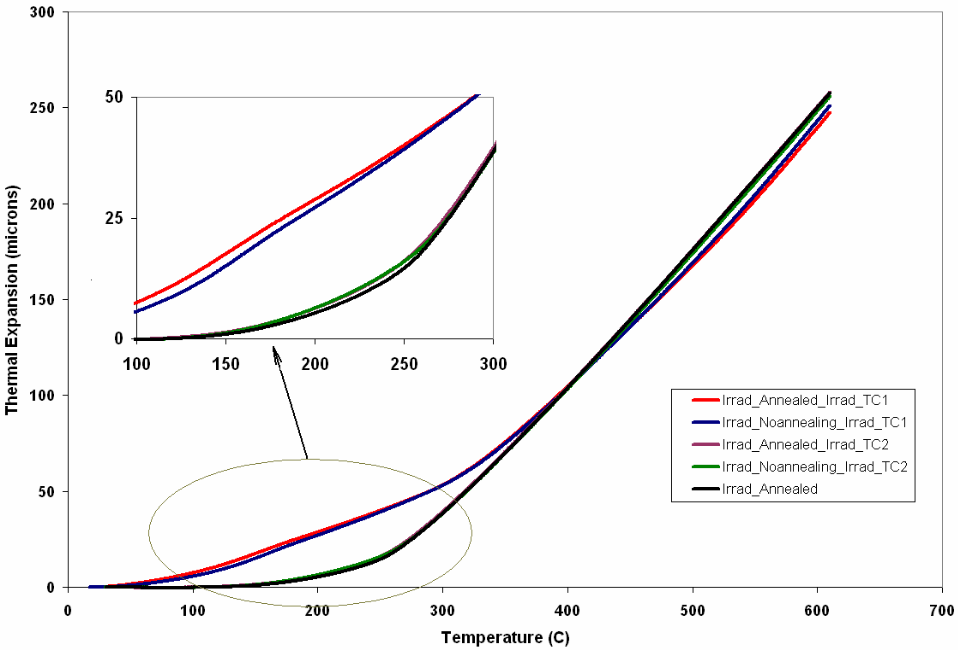
Y. Ishiyam et. al., J. Nucl. Mtrl. 239 (1996) 90-94

“annealing” of super-Invar

Following 1st irradiation

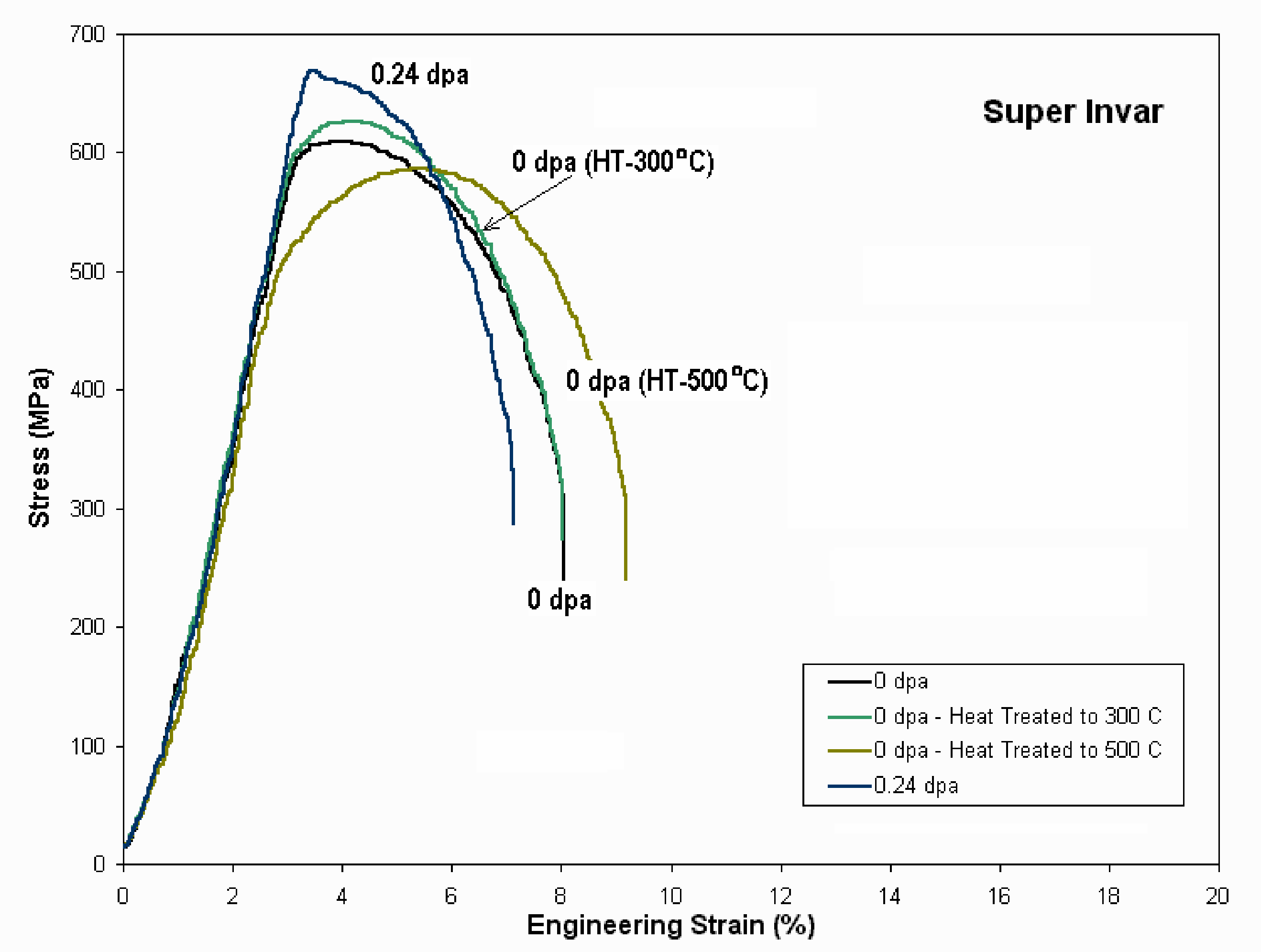


Following annealing and 2nd irradiation

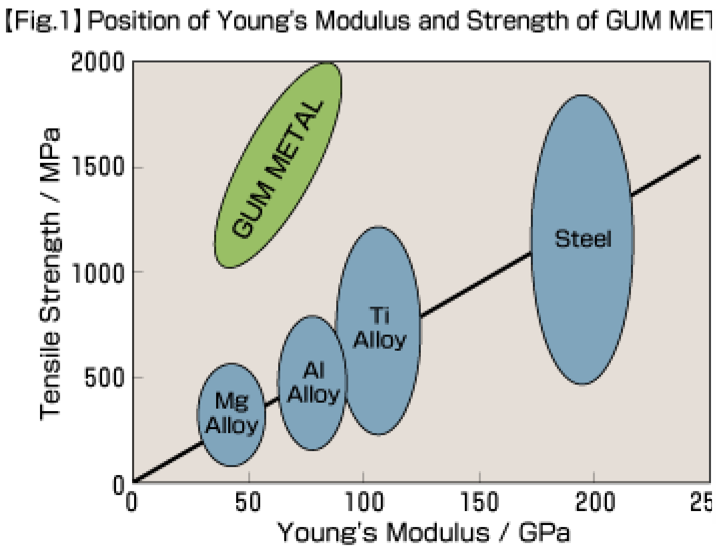


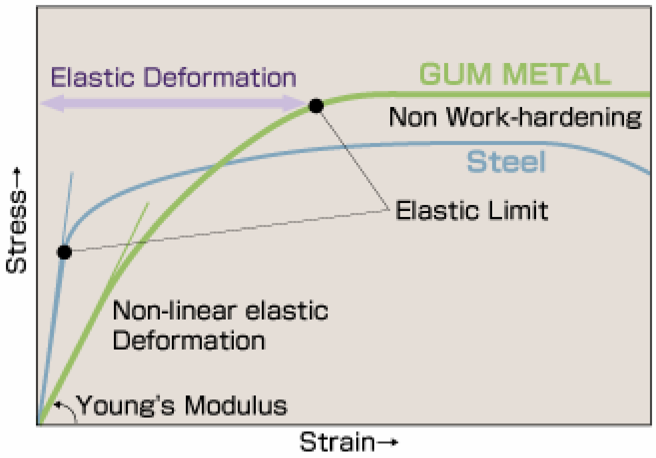
ONGOING 3rd irradiation phase: neutron exposure

Irradiation & temperature effects on Super-Invar

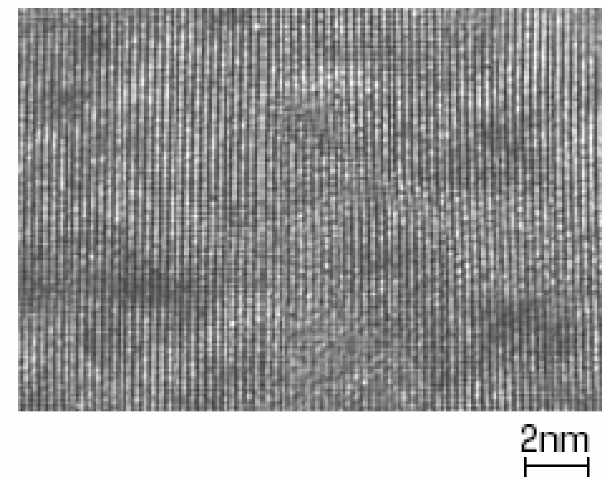


Studies of Gum Metal (Ti-12Ta-9Nb-3V-6Zr-O)



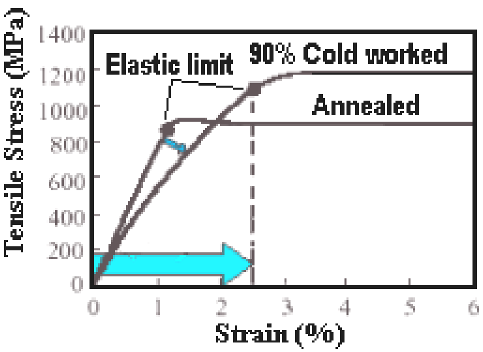


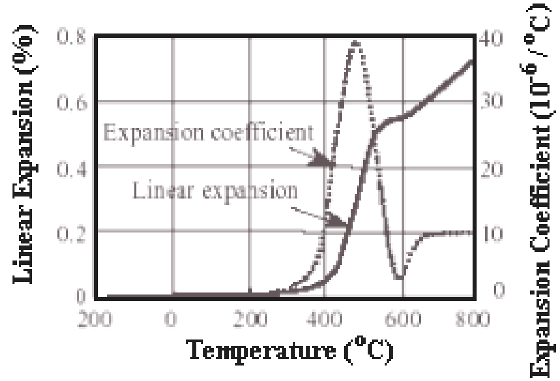
- **Super elasticity**
- **Super plasticity**
- **Invar property (near 0 linear expansion) over a wide temp range**
- **Elinvar property (constant elastic modulus over a wide temp range)**
- **Abnormality in thermal expansion "unrelated" to phase transformation**
- **It exhibits a dislocation-free plastic deformation mechanism**

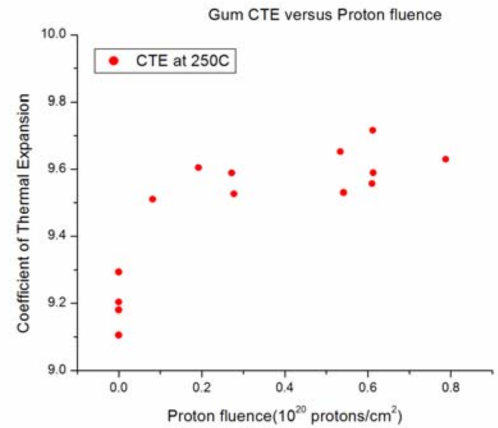


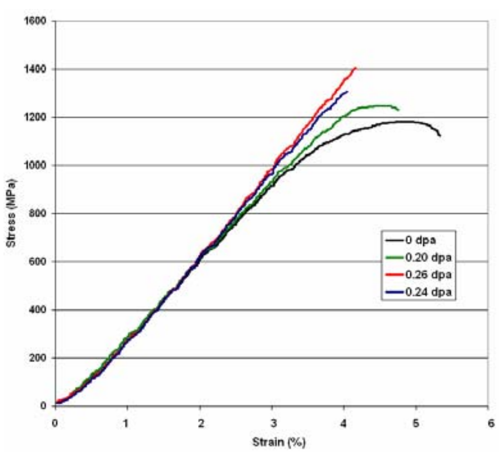
RESULT of cold-working !!!

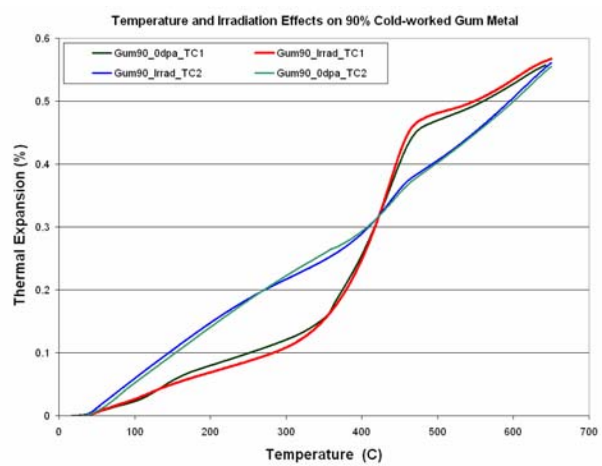
Effects of radiation and temperature on Gum metal

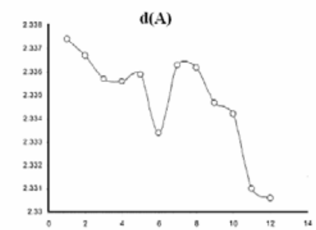


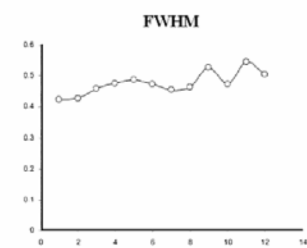


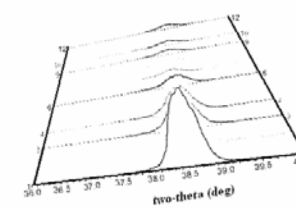




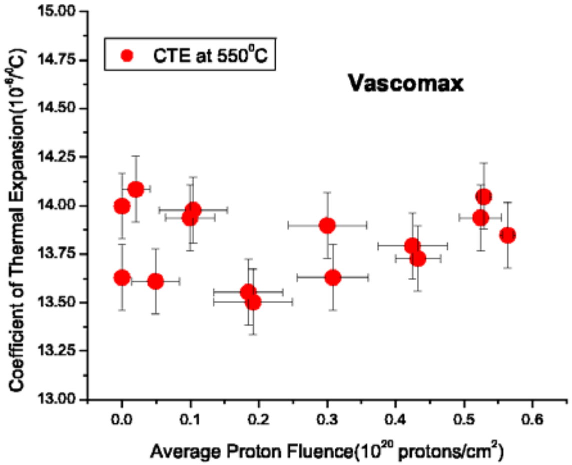


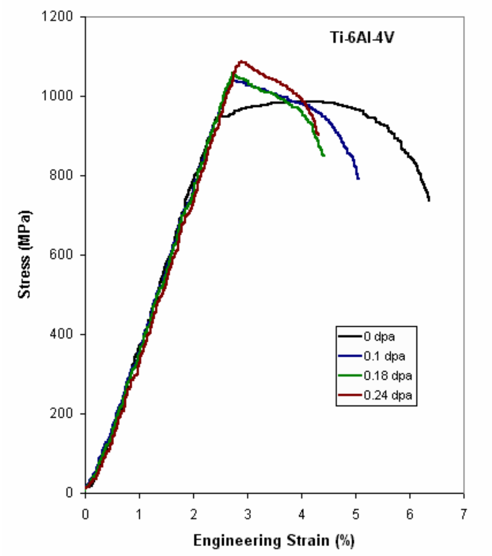


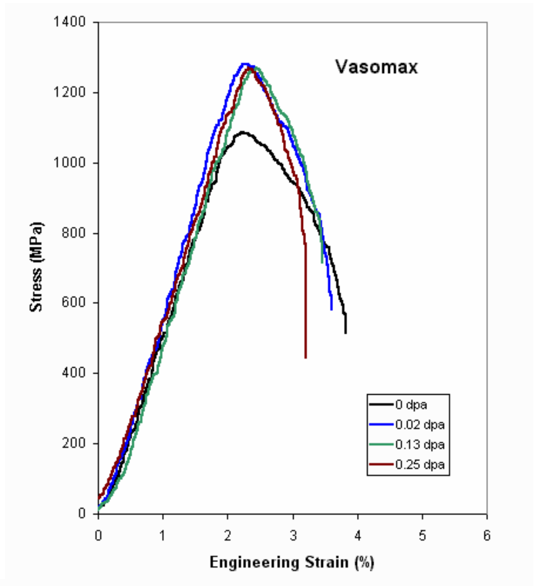


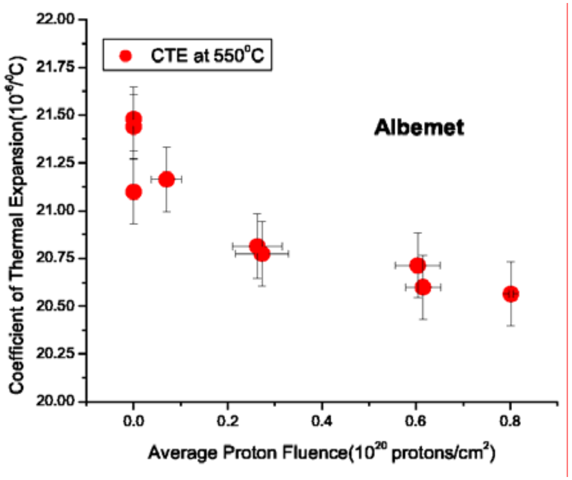


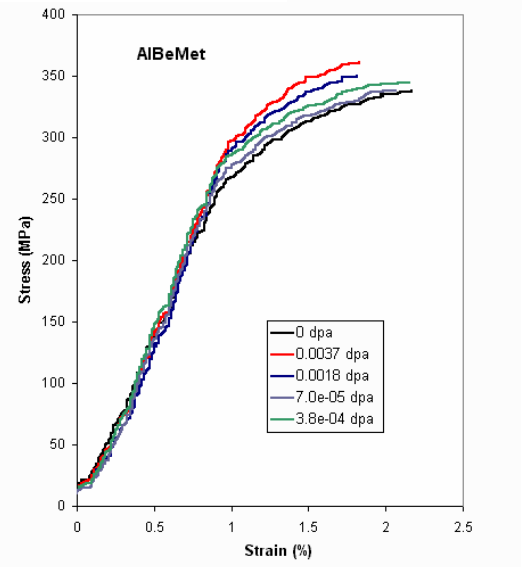
Radiation Damage Studies



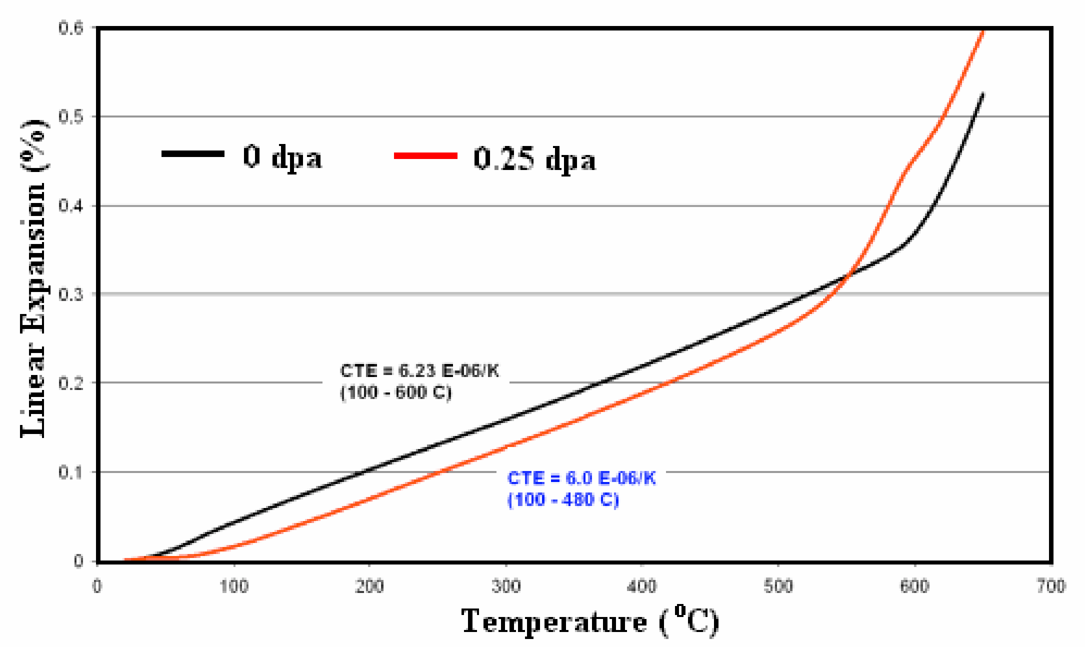


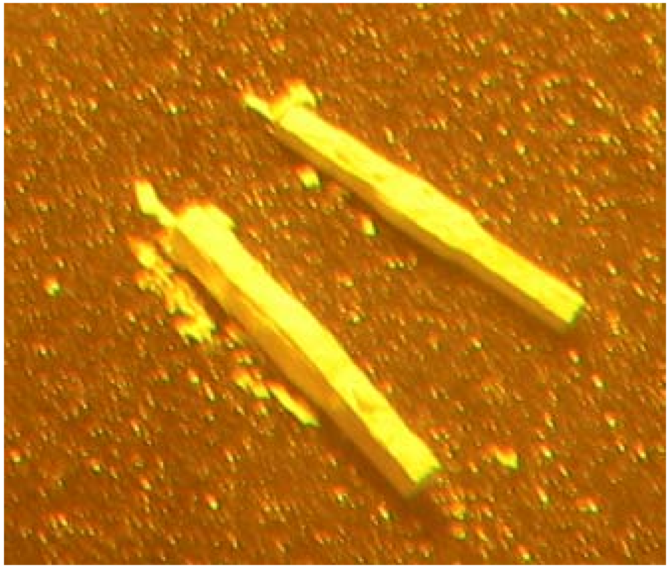






Irradiation effects on Tantalum



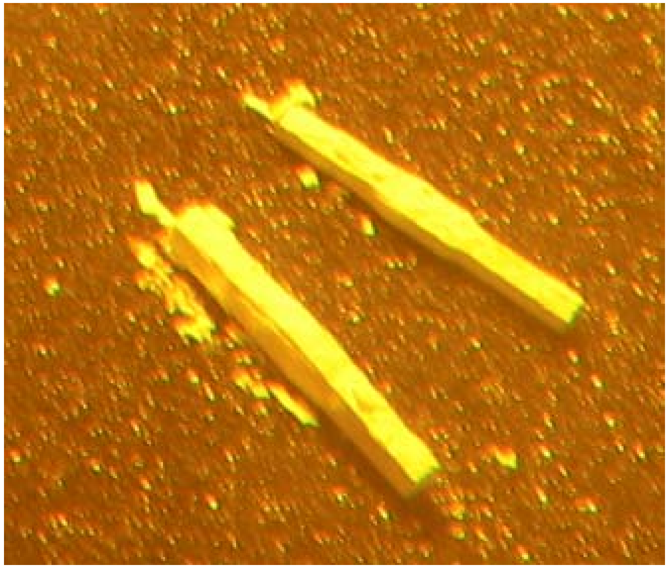


Interesting things observed in this experiments:

In the presence of carbon, heated tantalum T > 500C carbide phases are formed on surface. Carbon diffuses into the metal lattice. Reported by other investigators, diffusion takes place as individual atoms !

BUT that did not explain the severe decomposition experienced. It is suspected that tantalum reacts with silicon in the presence of a 3rd component reacting with it. Threshold temperature observed is 550 C.

Interaction of Tantalum with radiation and temperature environments

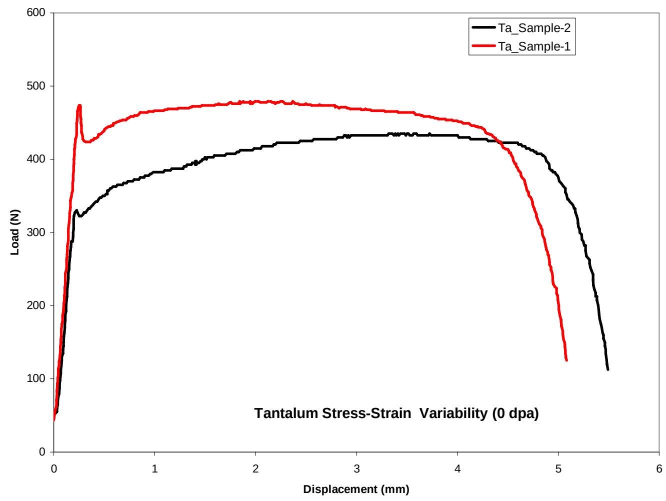


Possible Explanation:

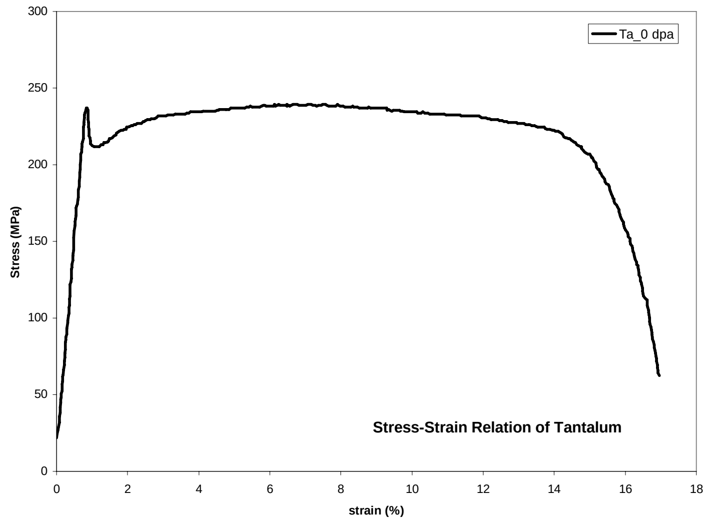
In the case of carbon and the formation of carbides, the carbon atom is small and can be accommodated by the lattice

In the case of silicon, however, its atom is closer in size to that of tantalum

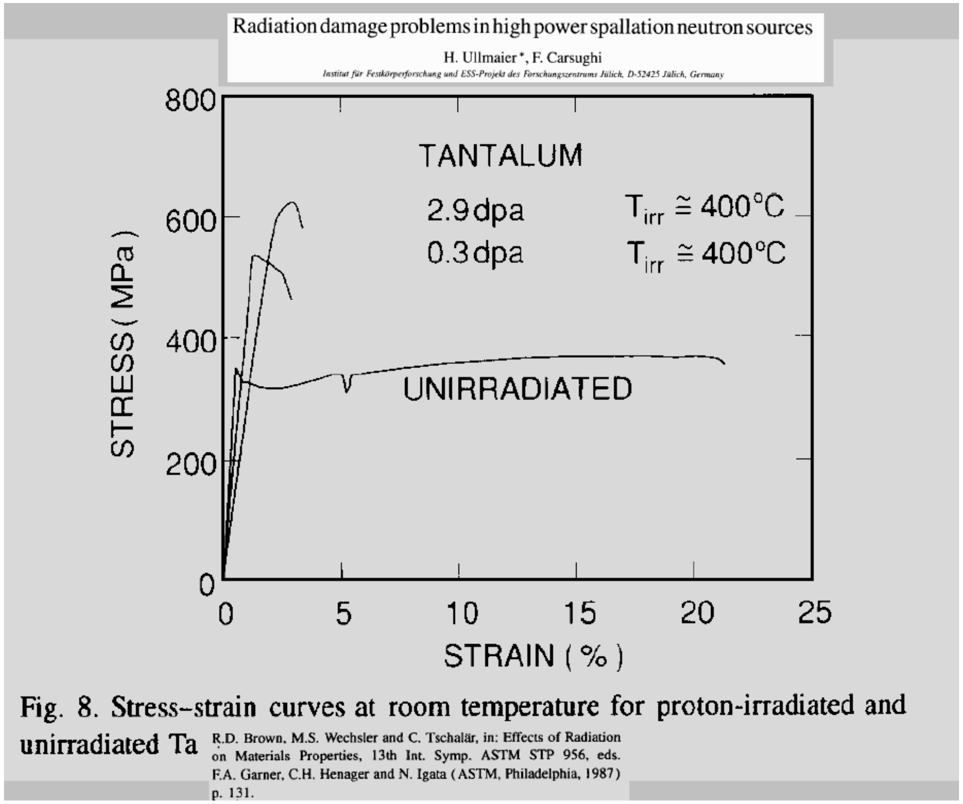
Tantalum



Ta_Sample-2
Ta_Sample-1
Tantalum Stress-Strain Variability (0 dpa)
Load (N)
Displacement (mm)
600
500
400
300
200
100
0
0
1
2
3
4
5
6

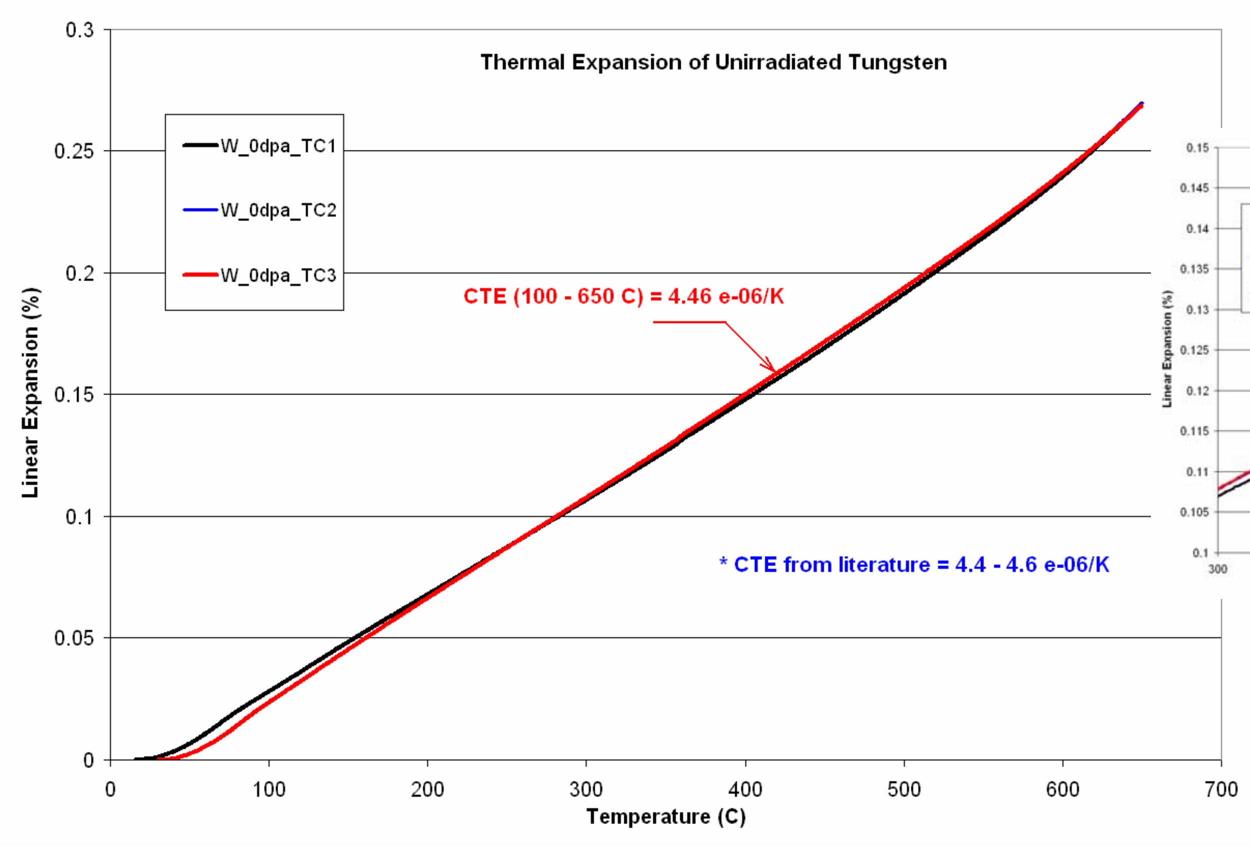


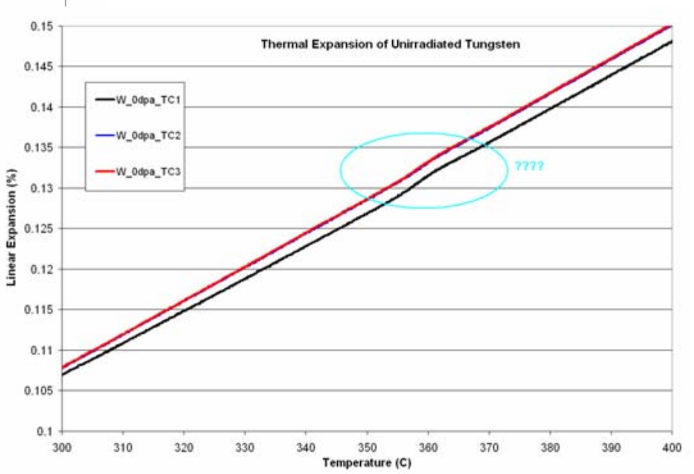
Ta_0 dpa
Stress-Strain Relation of Tantalum
Stress (MPa)
strain (%)
300
250
200
150
100
50
0
0
2
4
6
8
10
12
14
16
18



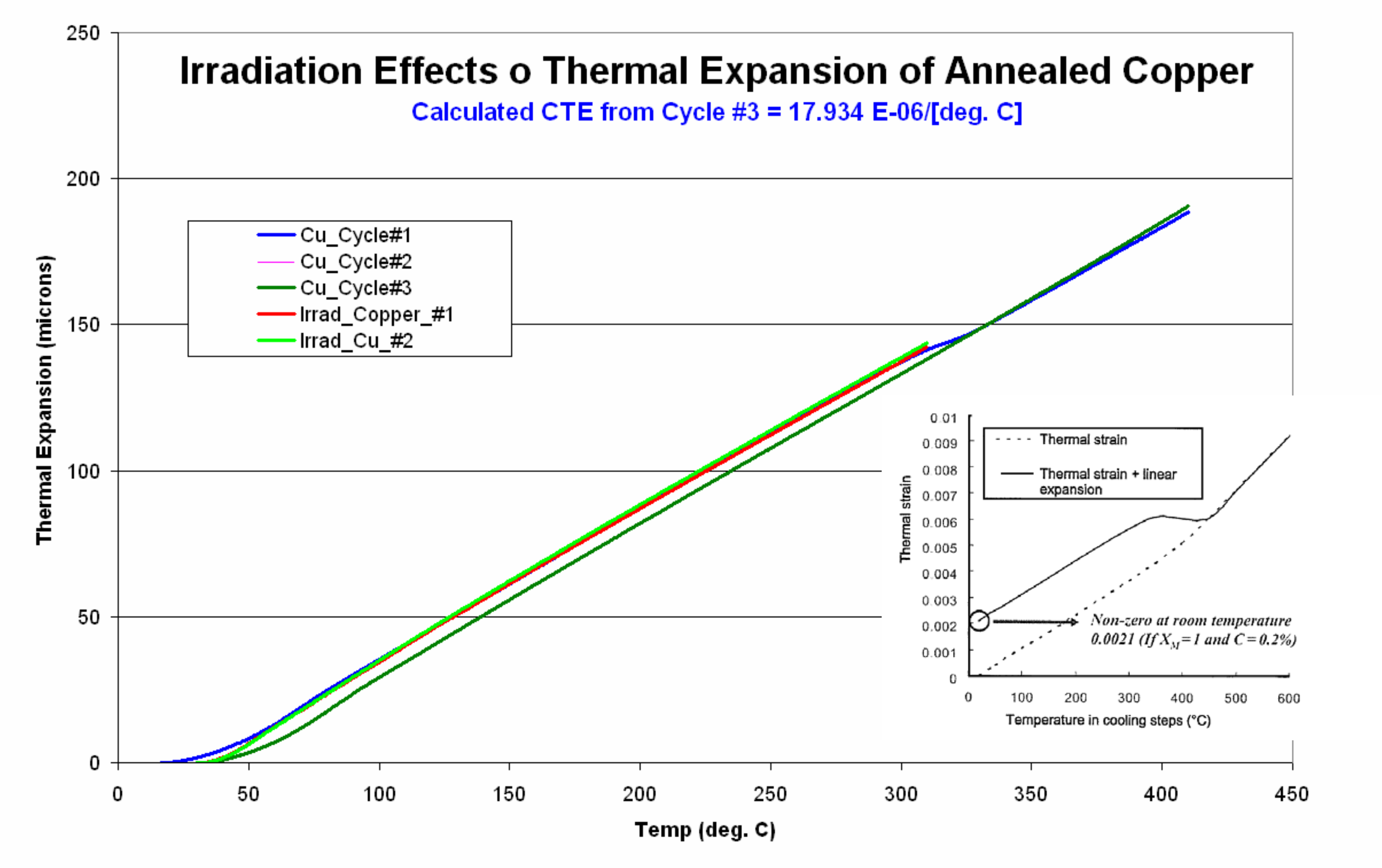
Radiation damage problems in high power spallation neutron sources
H. Ullmaier*, F. Carsughi
Institut für Festkörperforschung und ESS-Projekt des Forschungszentrums Jülich, D-52425 Jülich, Germany
TANTALUM
2.9 dpa
0.3 dpa
T_irr ≅ 400°C
T_irr ≅ 400°C
UNIRRADIATED
STRESS (MPa)
STRAIN (%)
800
600
400
200
0
0
5
10
15
20
25
Fig. 8. Stress–strain curves at room temperature for proton-irradiated and unirradiated Ta
R.D. Brown, M.S. Wechsler and C. Tschalär, in: Effects of Radiation on Materials Properties, 13th Int. Symp. ASTM STP 956, eds. F.A. Garner, C.H. Henager and N. Igata (ASTM, Philadelphia, 1987) p. 131.

Tungsten

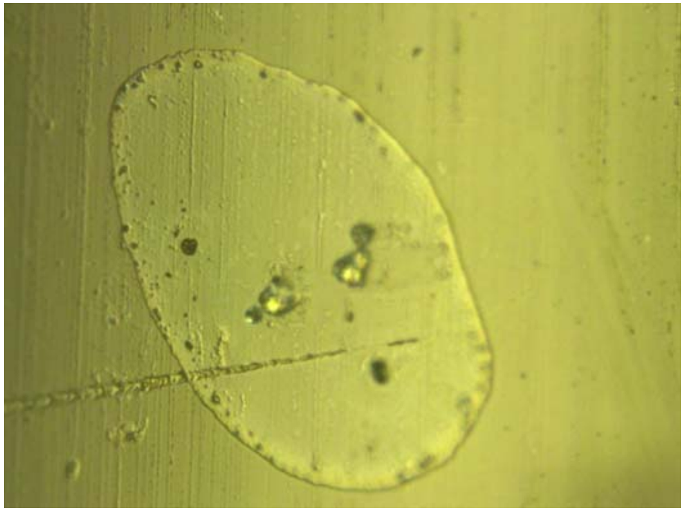

Thermal Expansion of Unirradiated Tungsten
W_0dpa_TC1
W_0dpa_TC2
W_0dpa_TC3
CTE (100 - 650 C) = 4.46 e-06/K
* CTE from literature = 4.4 - 4.6 e-06/K
Linear Expansion (%)
Temperature (C)
0
0.05
0.1
0.15
0.2
0.25
0.3
0
100
200
300
400
500
600
700

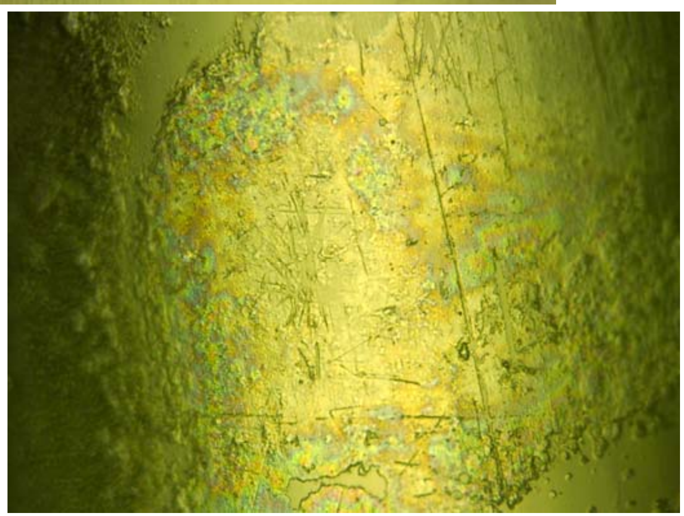

Thermal Expansion of Unirradiated Tungsten
W_0dpa_TC1
W_0dpa_TC2
W_0dpa_TC3
????
Linear Expansion (%)
Temperature (C)

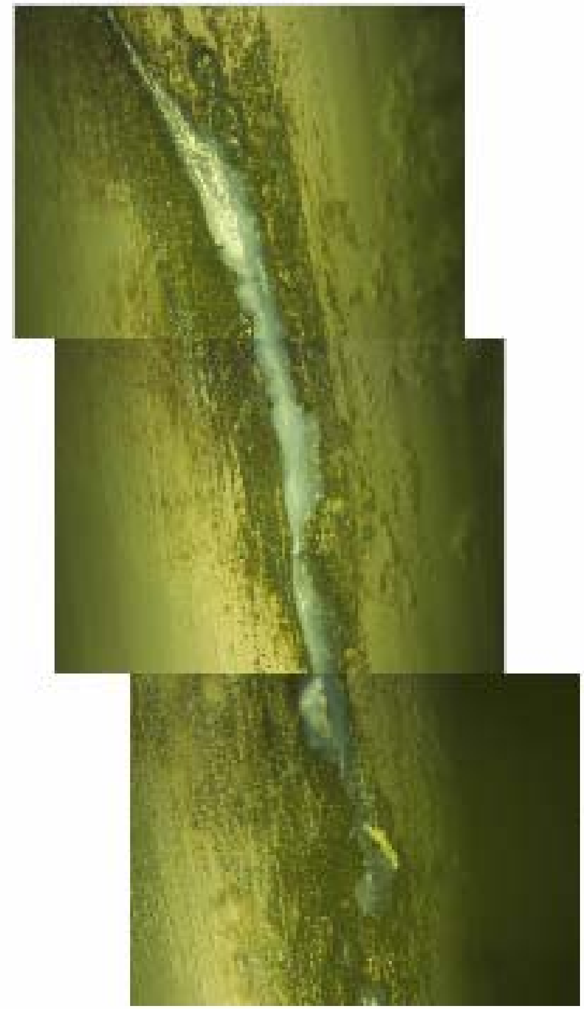
Irradiation Effects on Copper
(fluence ~ 10^21 protons/cm2)



Fused Silica

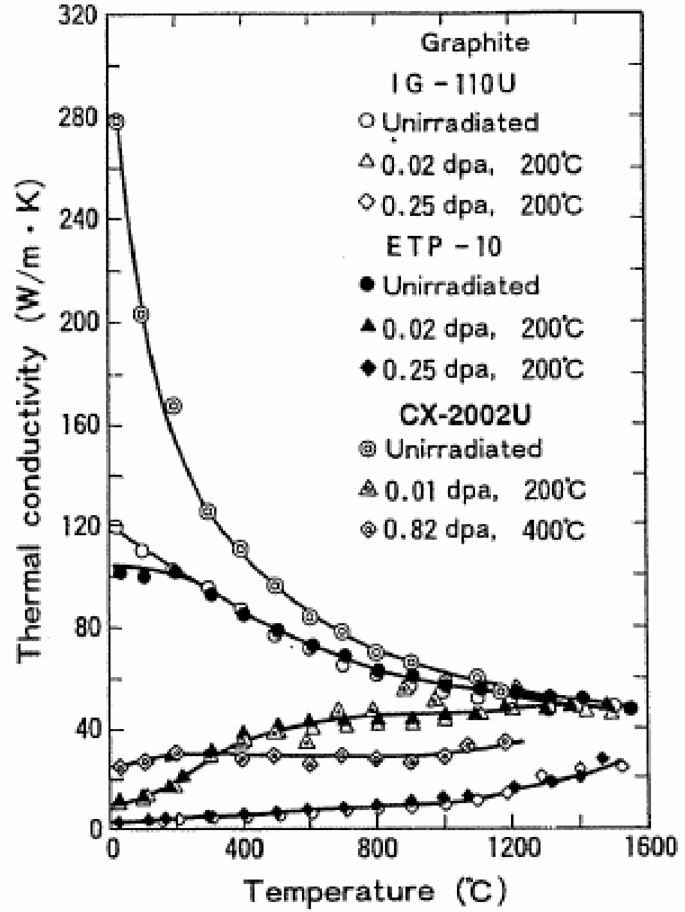






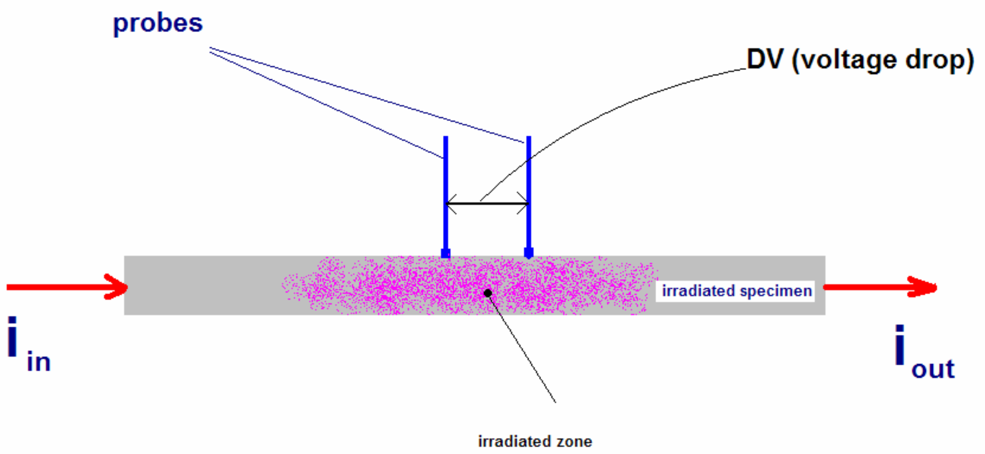
Irradiation damage to carbon-based materials

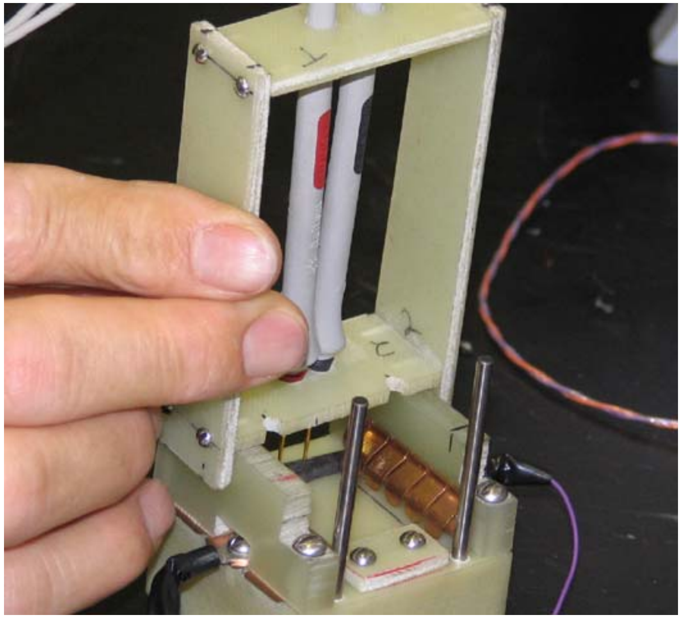
Results such as these causes us to stop and take notice…..

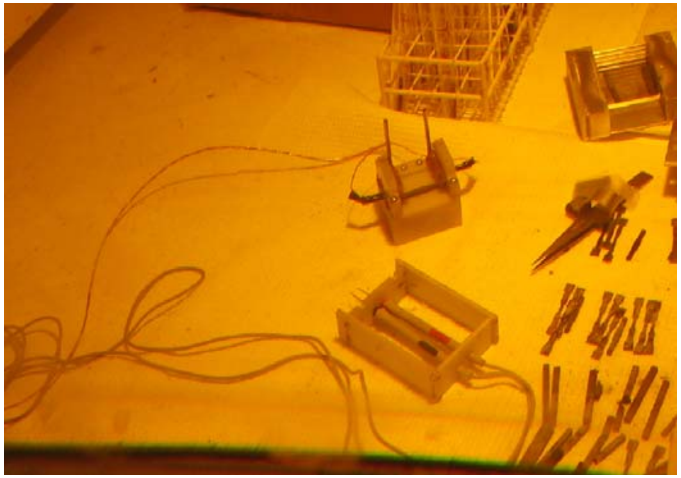


Thermal conductivity of neutron-irradiated graphites.

Electrical resistivity → Thermal conductivity







Some VERY preliminary results

3-D CC (~ 0.2 dpa) conductivity reduces by a factor of 3.2

2-D CC (~0.2 dpa) measured under irradiated conditions (to be compared with company data)

Graphite (~0.2 dpa) conductivity reduces by a factor of 6

W (1+ dpa)	→	reduced by factor of ~4
Ta (1+ dpa)	→	~ 40% reduction
Ti-6Al-4V (~ 1dpa)	→	~ 10% reduction
Glidcop	→	~ 40% reduction

Neutron Irradiation

Irradiation Exposure COMPLETED in June 2007

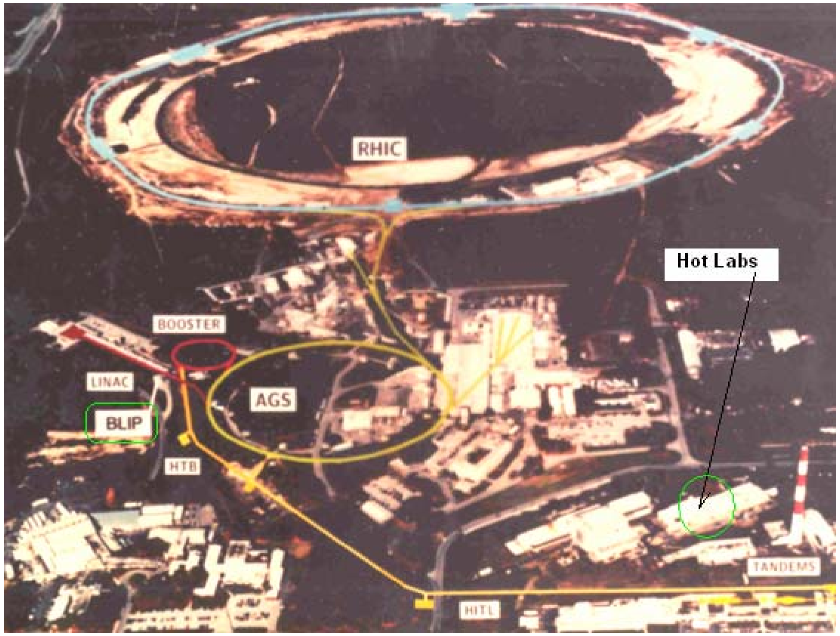
Materials include:

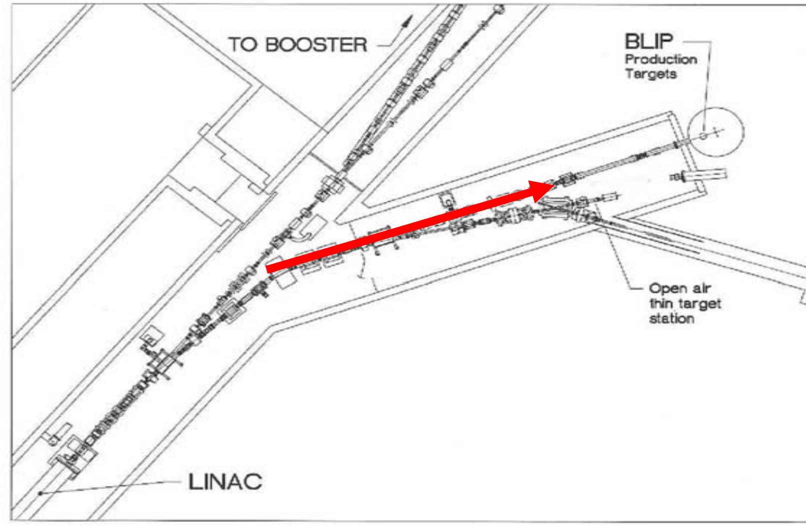
- Ta
- Copper/Glidcop
- Isotropic graphite (IG-430)
- Super-Invar/Gum metal
- Ti-6Al-4V (including nano-deposited alumina film)

Materials are in a “cool-down” phase

MARS analyses performed

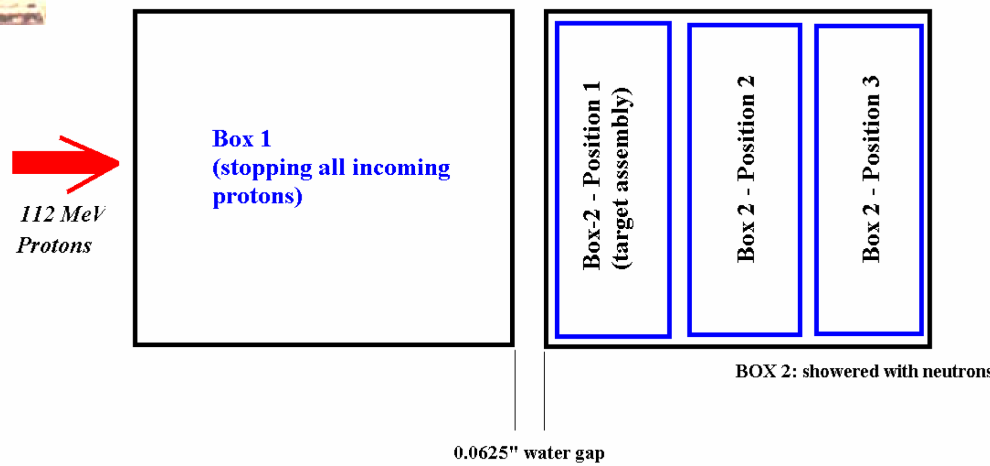
Irradiation Studies using the BNL Accelerator Complex

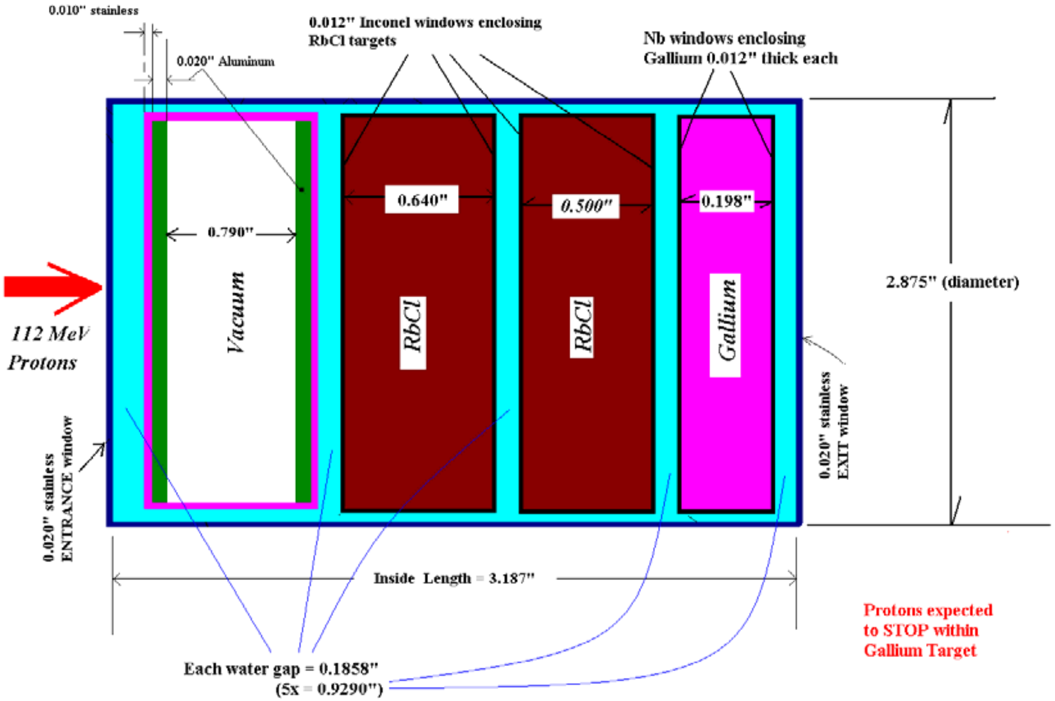


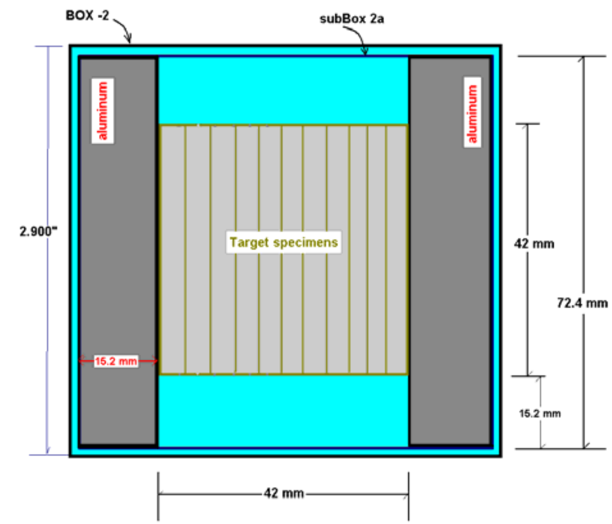


Schematic of BLIP Beam Line

Target Lay-out

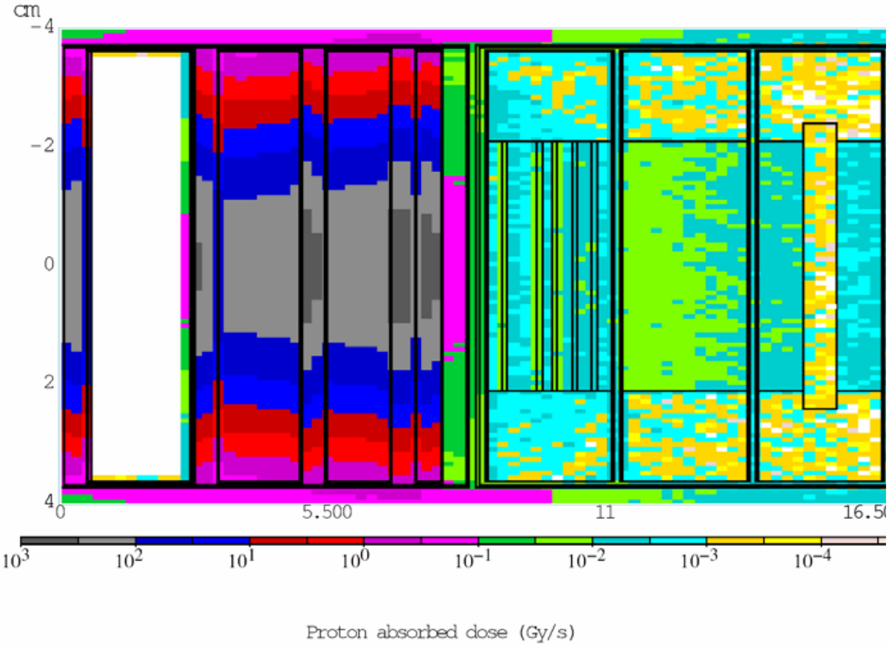


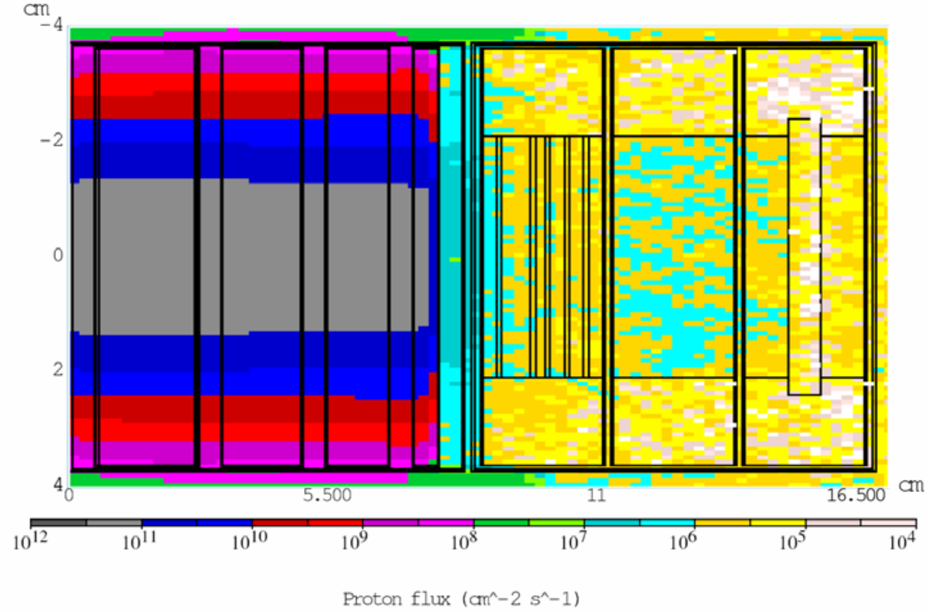




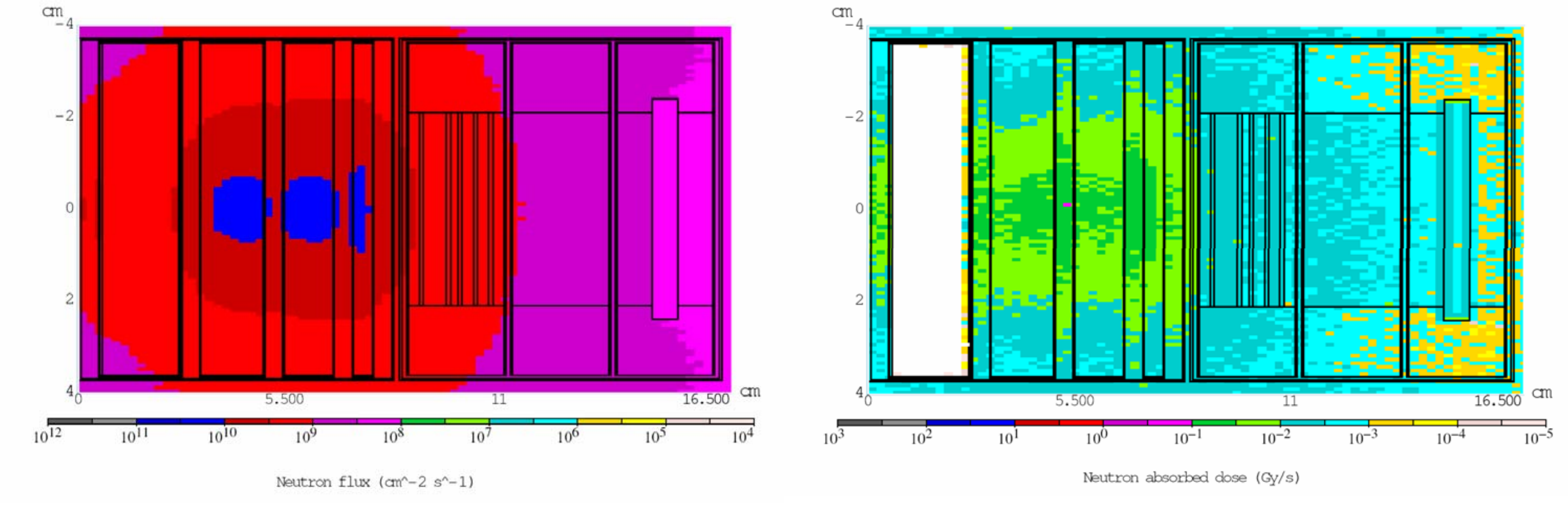
BOX 1: contains isotope production targets which are expected to stop all protons and generate a neutron flux downstream

Neutron Irradiation Studies using the BNL Accelerator Complex
PROTON Flux & Dose

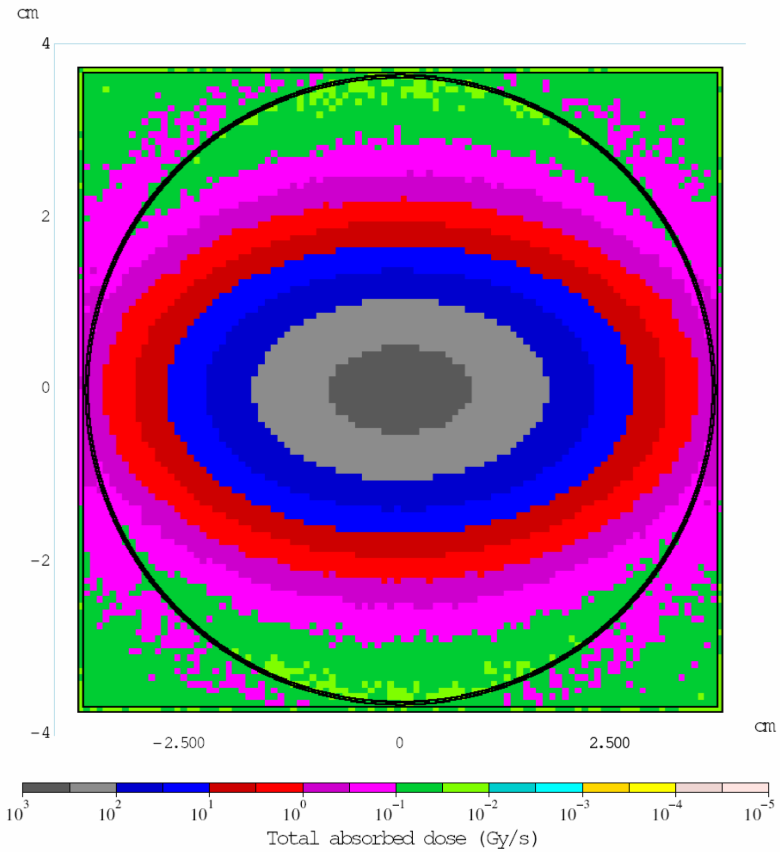


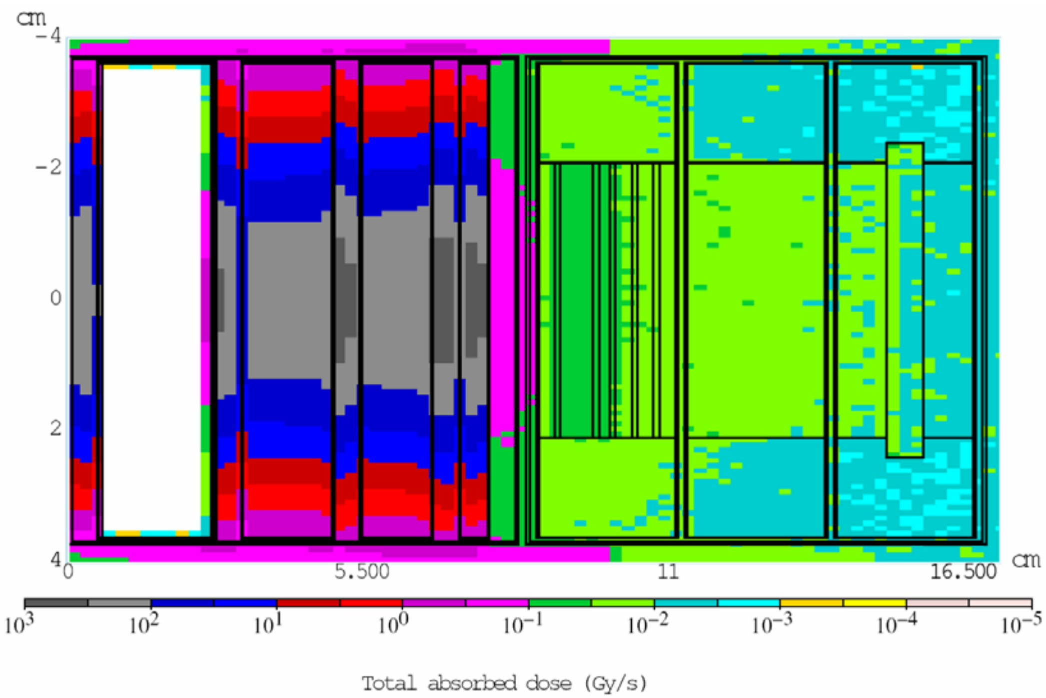


Irradiation Studies using the BNL Accelerator Complex
NEUTRON Flux & Dose

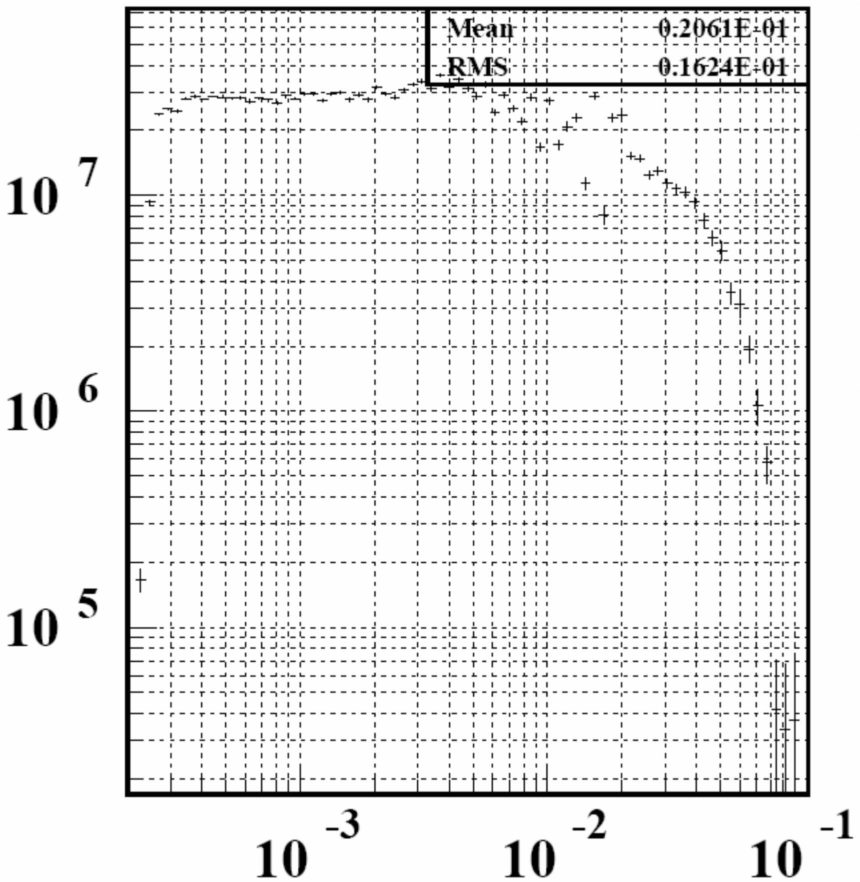


Irradiation Studies using the BNL Accelerator Complex
TOTAL Absorbed Dose

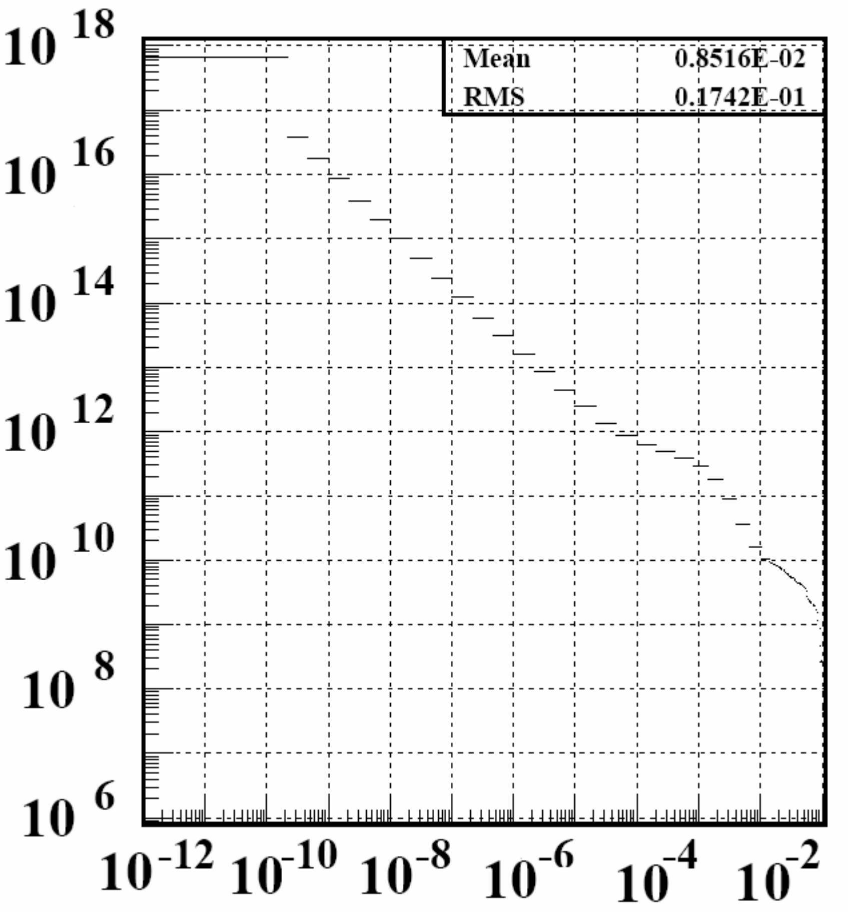




Irradiation Studies using the BNL Accelerator Complex
Spectra

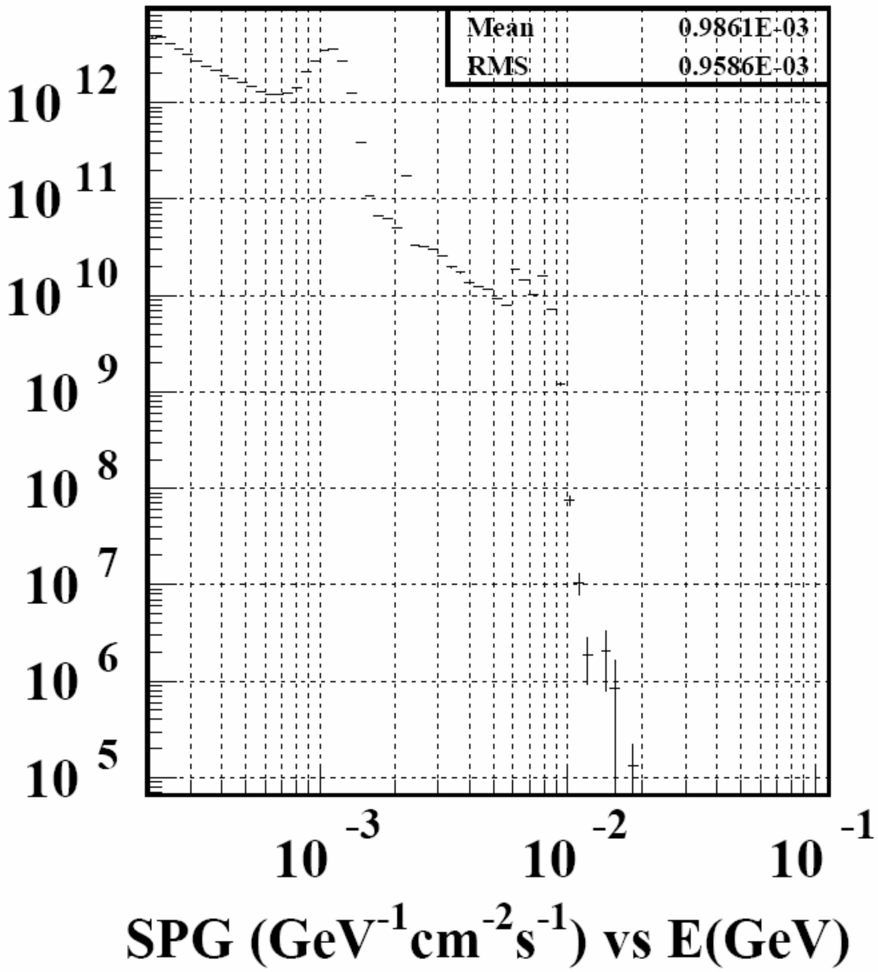


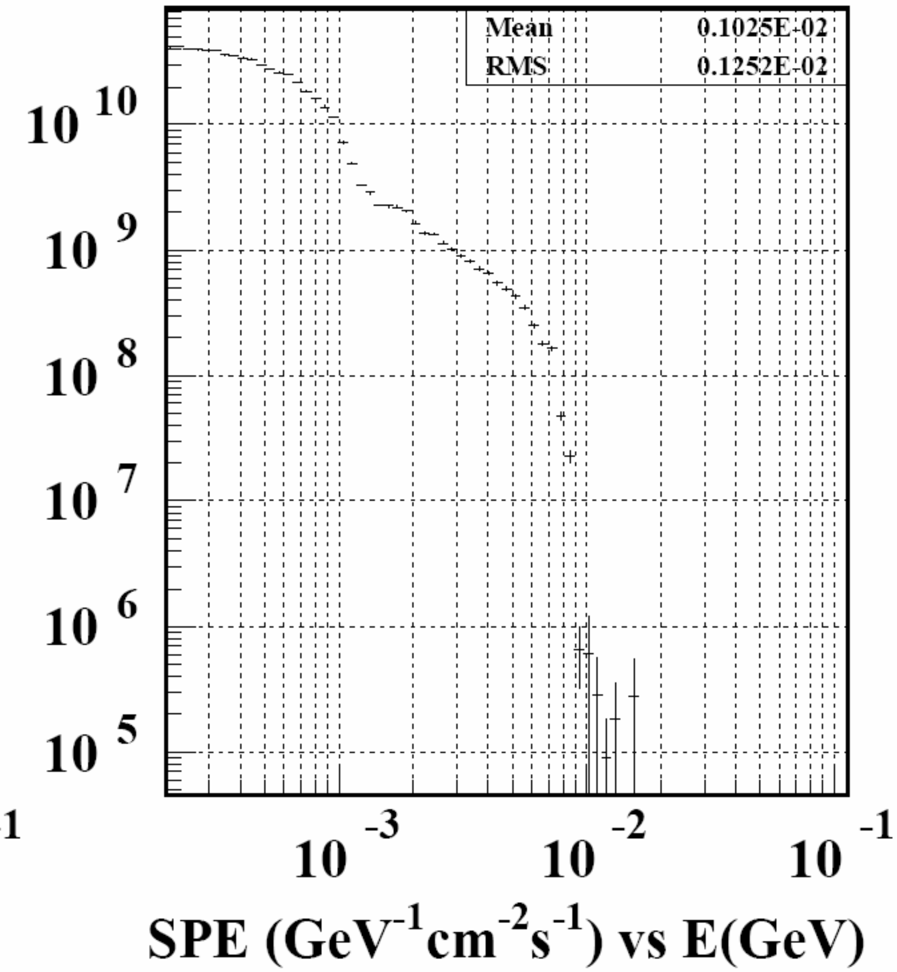
SPP ($GeV^{-1}cm^{-2}s^{-1}$) vs E(GeV)



SPN ($GeV^{-1}cm^{-2}s^{-1}$) vs E(GeV)

Irradiation Studies using the BNL Accelerator Complex
Spectra





SUMMARY

- **Information to-date is available from low power accelerators and mostly from reactor (neutron irradiation) experience. Extrapolation is RISKY**

- **Establishing relationship between neutron and proton damage will render useful the library of data from the neutron community. Effort under way at BNL looking at both neutron and proton damage**

- **Advancements in material technology (alloys, smart materials, composites) provide hope BUT must be accompanied by R&D for irradiation damage**

- **Experimental activities addressing one problem at a time (cannot have cocktail all at once …) are a must**