Irradiation damage in LHC beam collimating materials

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….. with contribution from a great number of colleagues including

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Background

R&D Studies prompted by interest in High Power Targets

– Short term exposure (thermo-mechanical shock)
– Long term exposure (radiation damage)

While dreaming of of a 4 MW proton driver

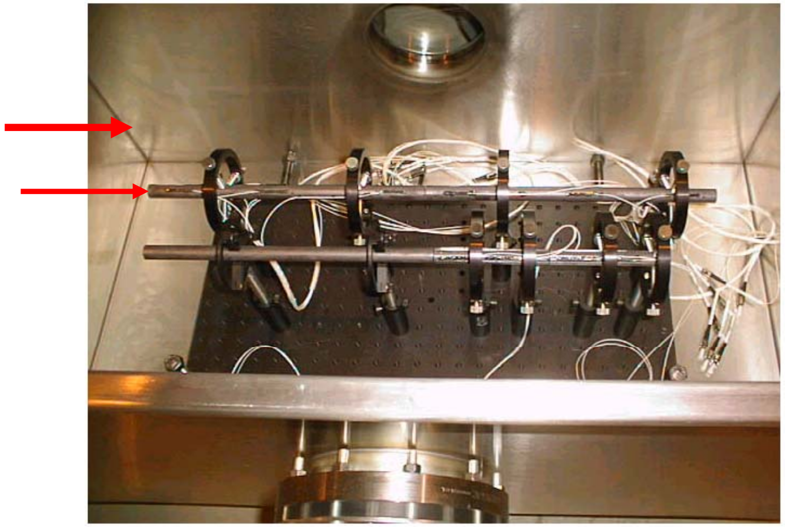
Radiation Damage on materials could very well be the LIMITING Factor !!

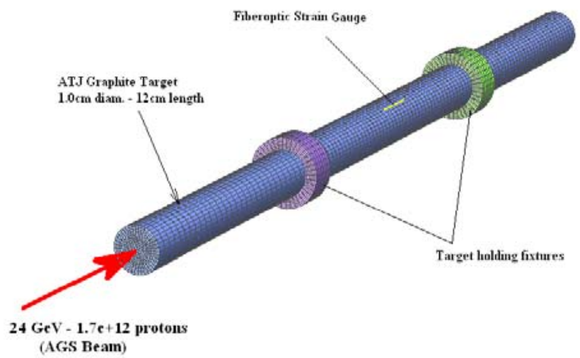
What does it mean for materials (microscopic & macroscopic terms) ?
generation of voids/dislocations ➔ changes in physical and mechanical properties
trapping of gases, swelling ➔ density reduction

Experience mostly from reactor neutron irradiation
Question: does radiation type matter?

In search of the wonder material ………➔

Beam Studies: Graphite & CC Composite at the AGS

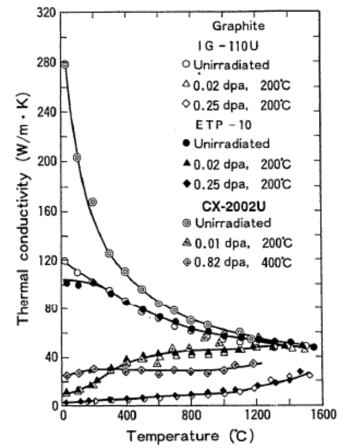




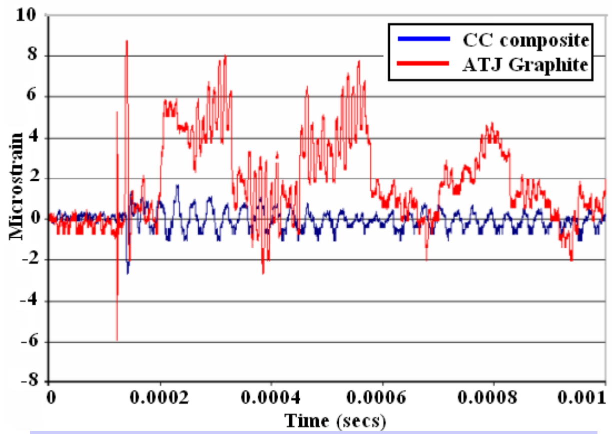
<u>WHY the love affair with CC in place of graphite?</u>

Irradiation has a profound effect on thermal conductivity/diffusivity

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

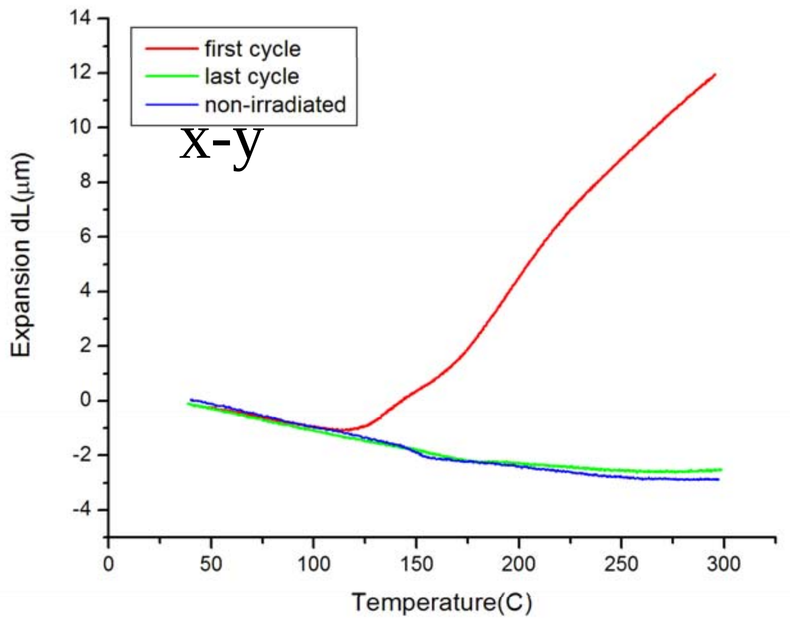


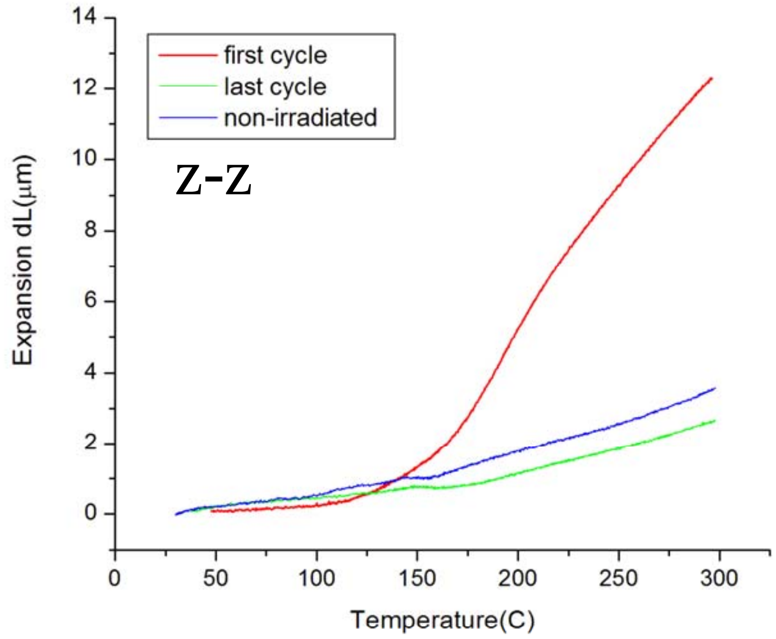
Thermal conductivity of neutron-irradiated graphites.



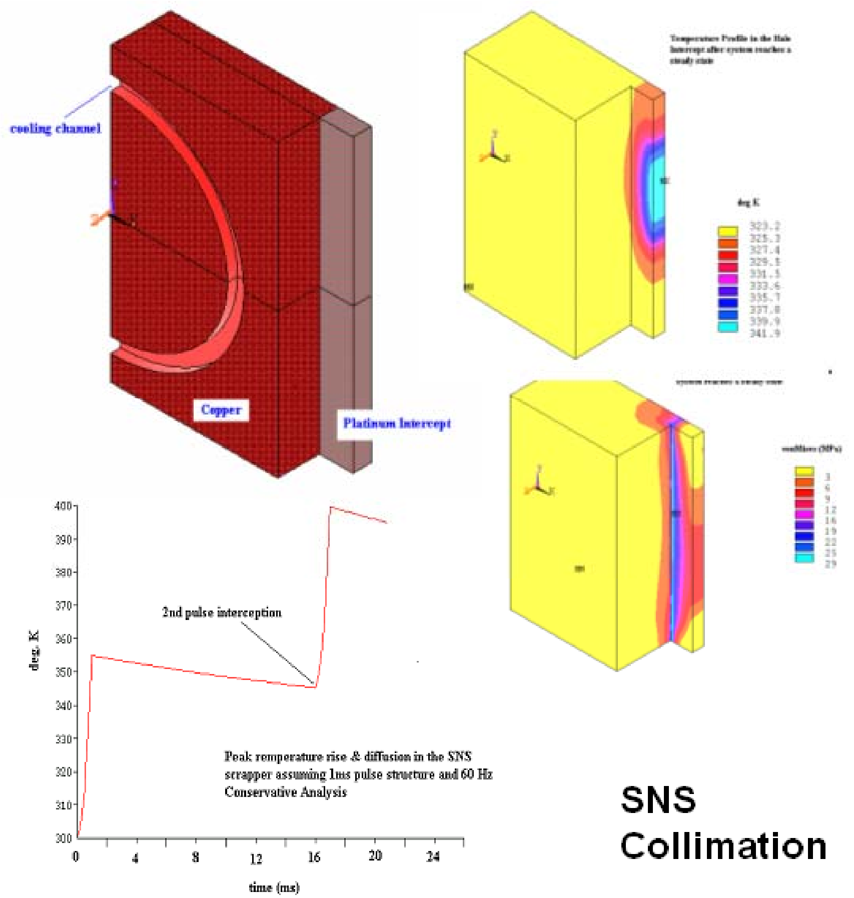
Yet to know for sure how carbon composites respond to radiation

Encouraging signs of 3D CC composite under modest irradiation levels "annealing" behavior with thermal cycling

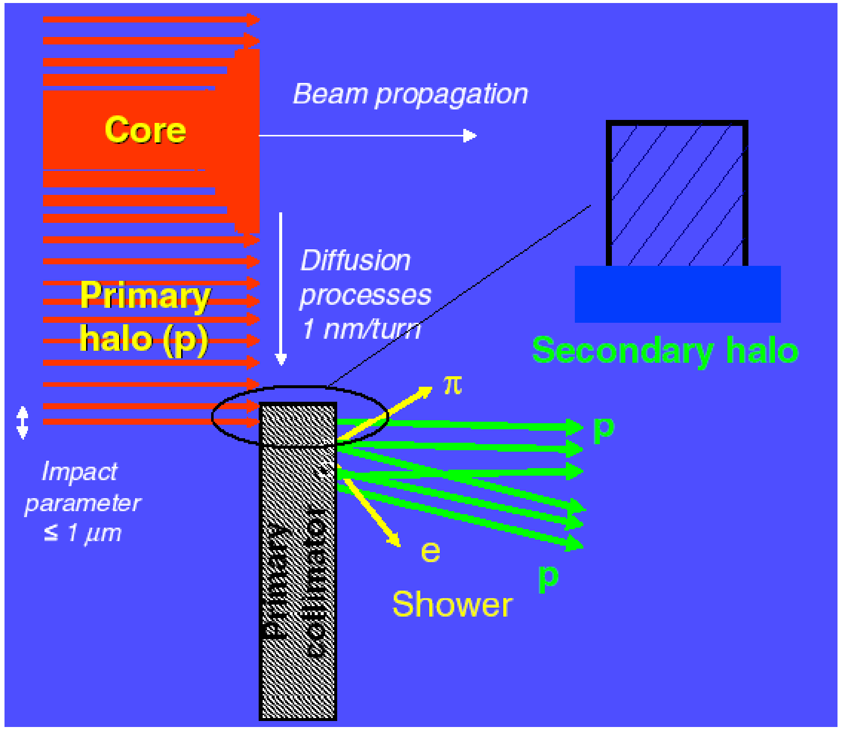


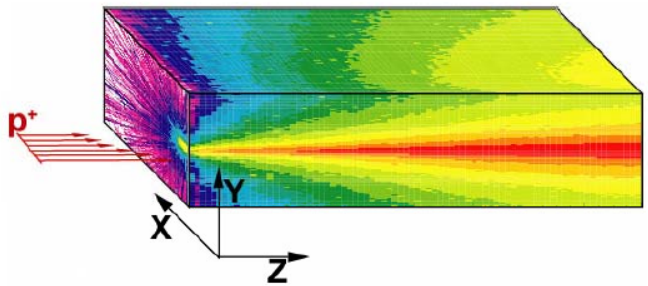


And along came the SNS & LHC Collimators



SNS Collimation

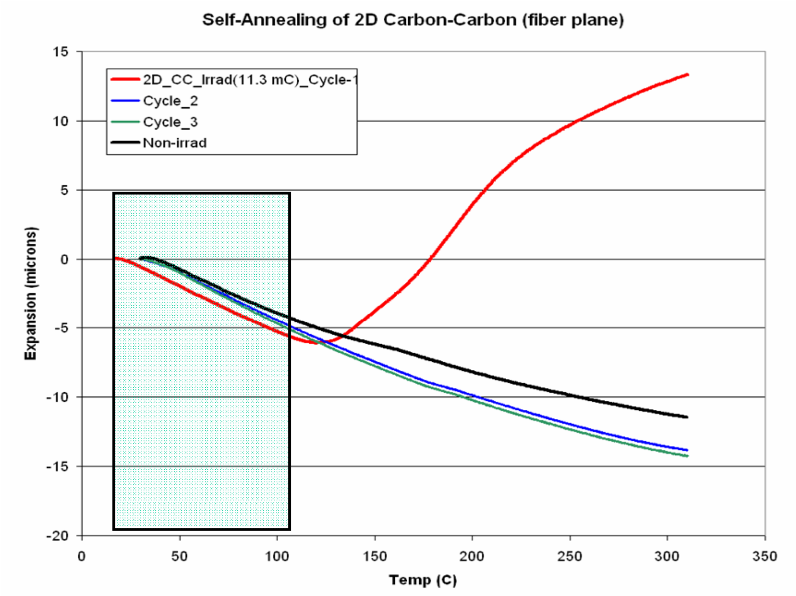




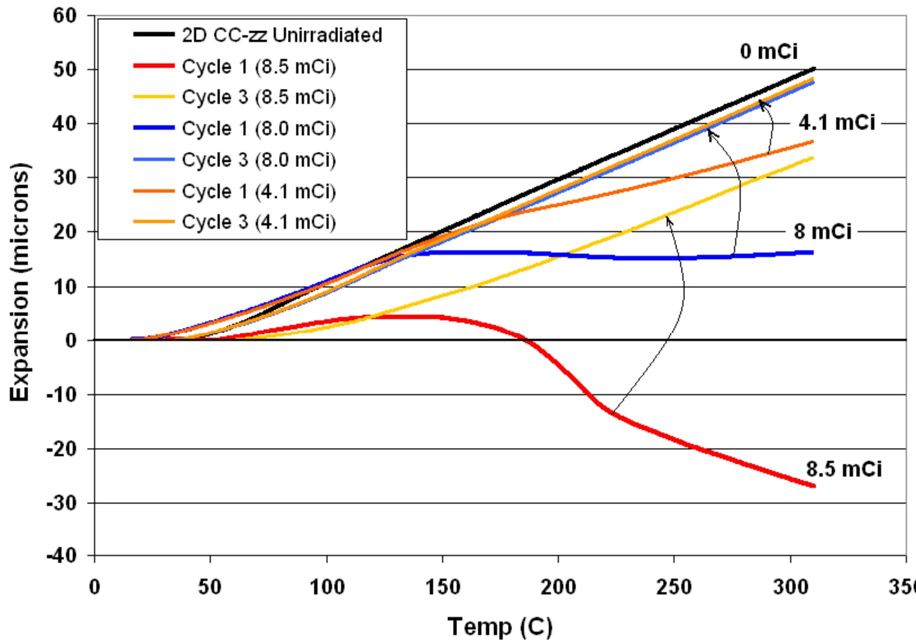
Annealing behavior also exhibited by 2D Carbon !

(fluence ~ 10^20 protons/cm2)

Fiber (strong) direction

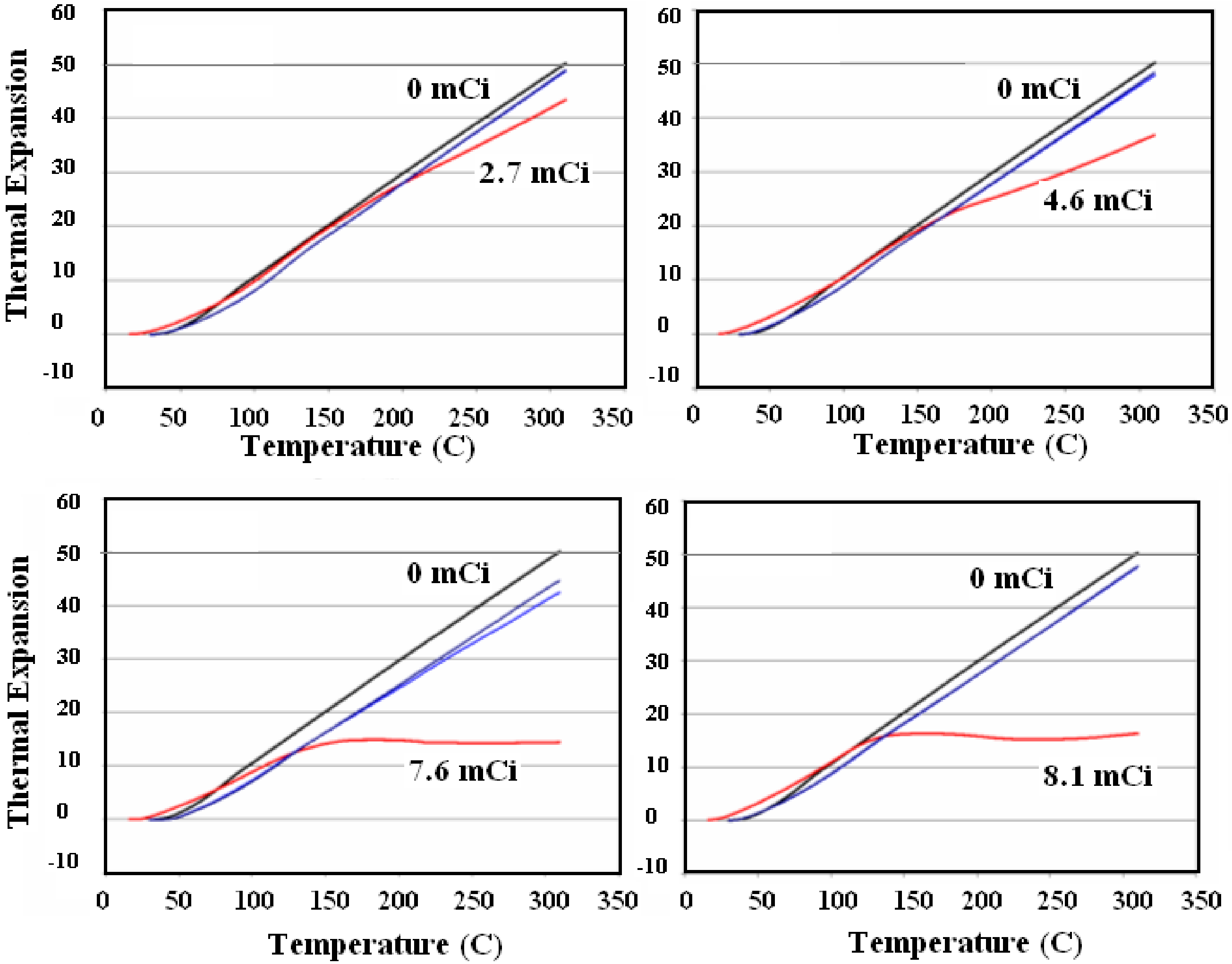


Weak direction (orientation normal to fibers)



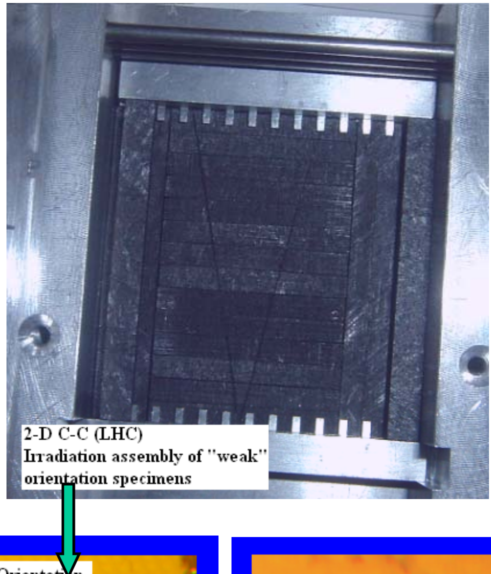
- **Non-irradiated shown in BLACK**
- **Effects of irradiation (captured in 1st post-irradiation thermal cycle) shown in RED**
- **Rest are additional thermal cycles that restore material through annealing**
- **Also shown are specimen activations in mCi**
- **Worth noting is the similar annealing behavior of specimens with same activation**

LHC 2-D carbon composite along its weak direction

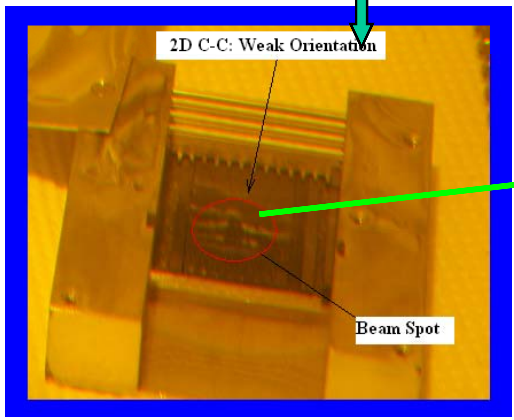


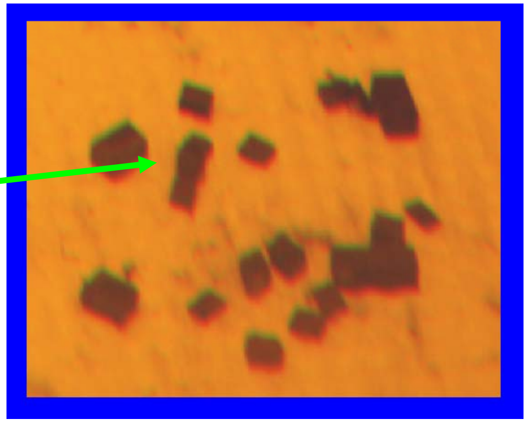
Signs of trouble !!

"weak" reinforcing fiber orientation

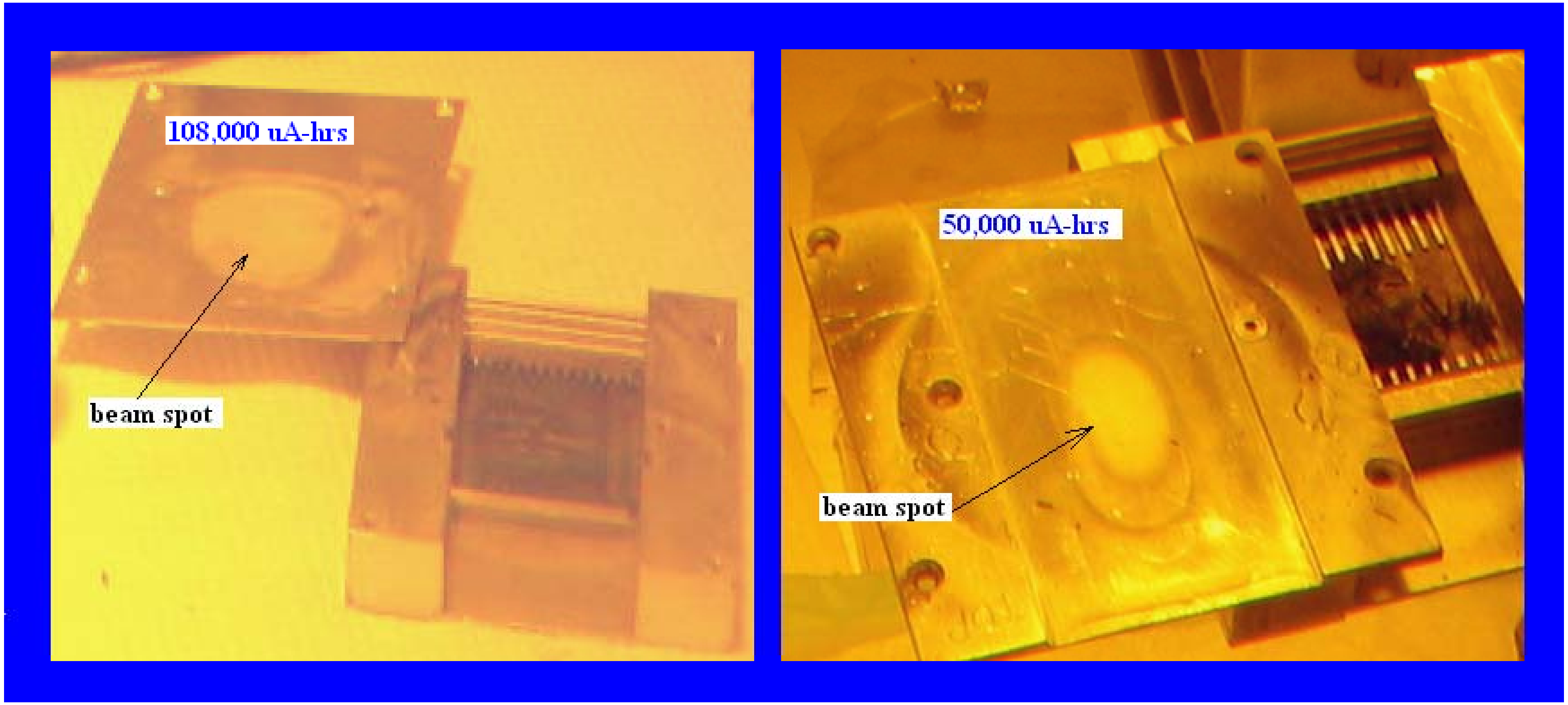


CONCERN: is damage characteristic of the 2-D structure or inherent to all carbon composites?

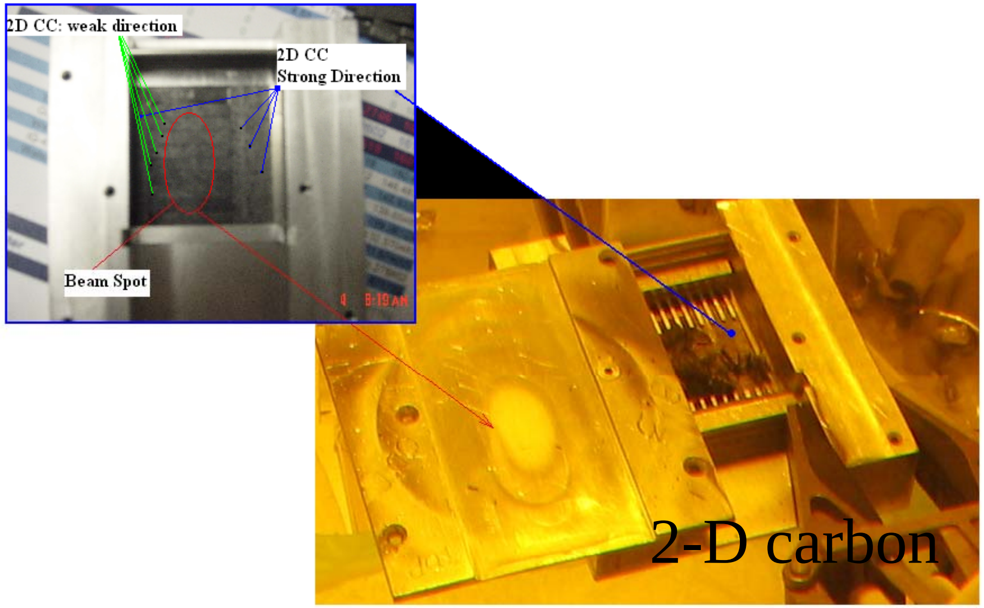


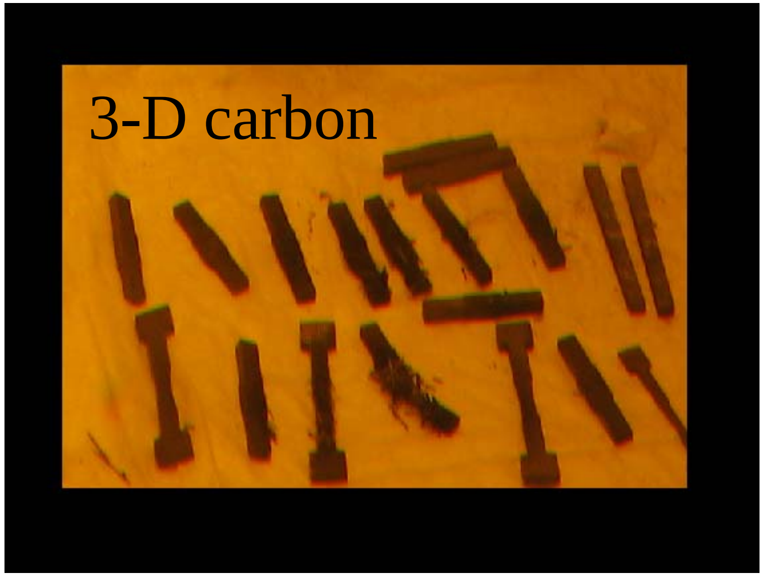


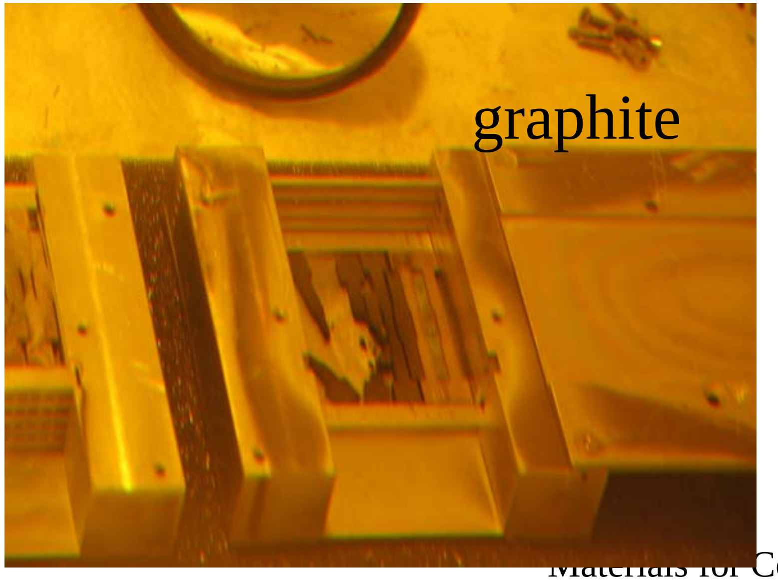
Follow-up Irradiation Phase for 2-D; 3-D Carbon composites and Graphite



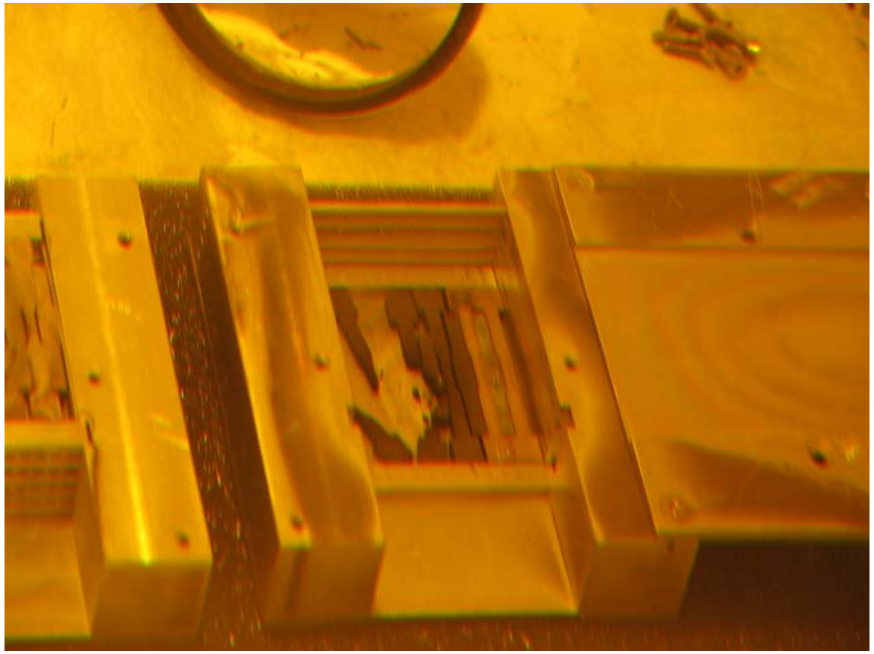
Condition of most heavily bombarded specimens after irradiation (fluence ~10^21 p/cm2)

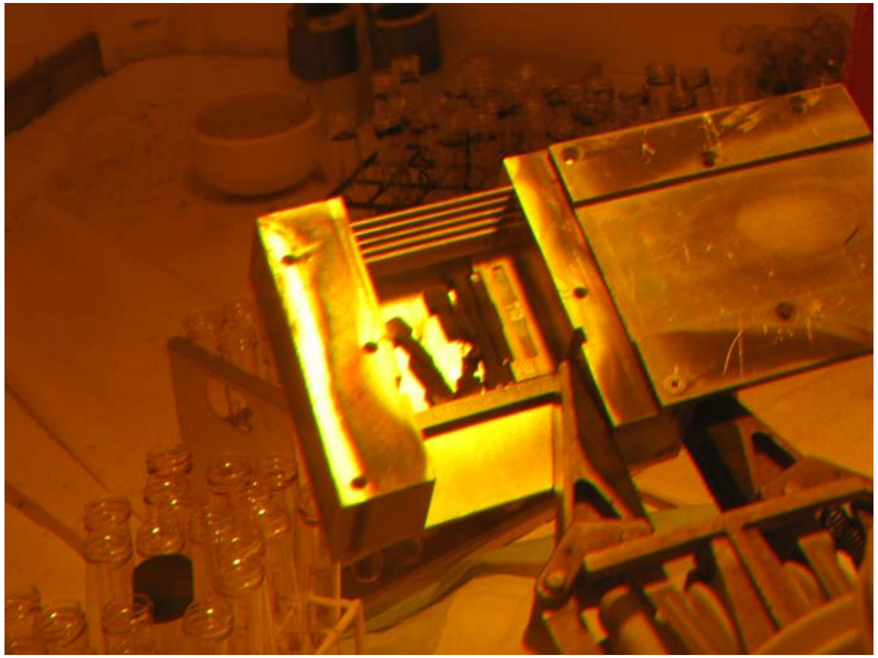






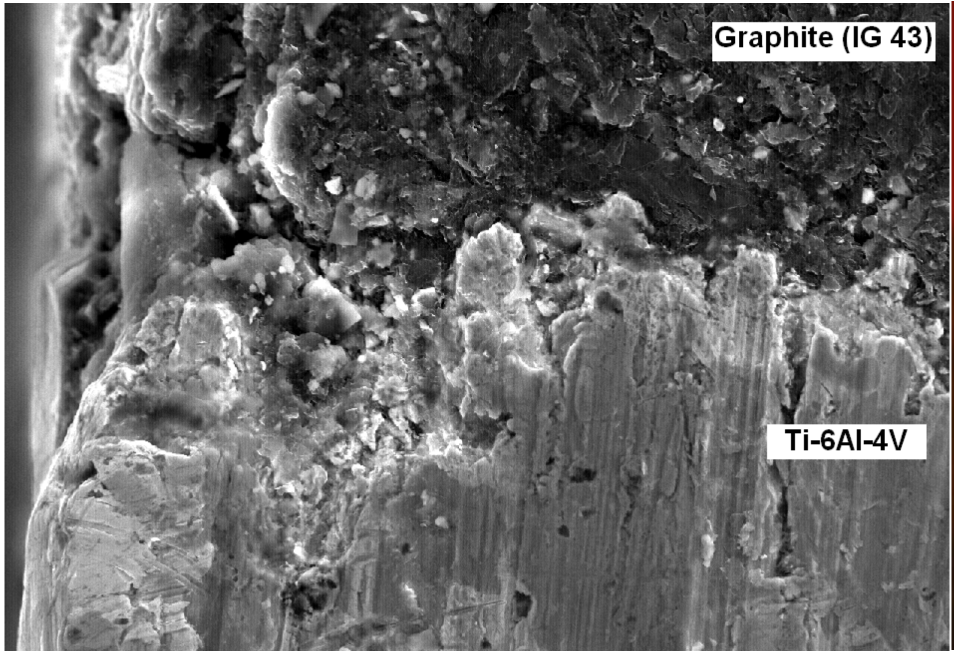
Damage in Graphite

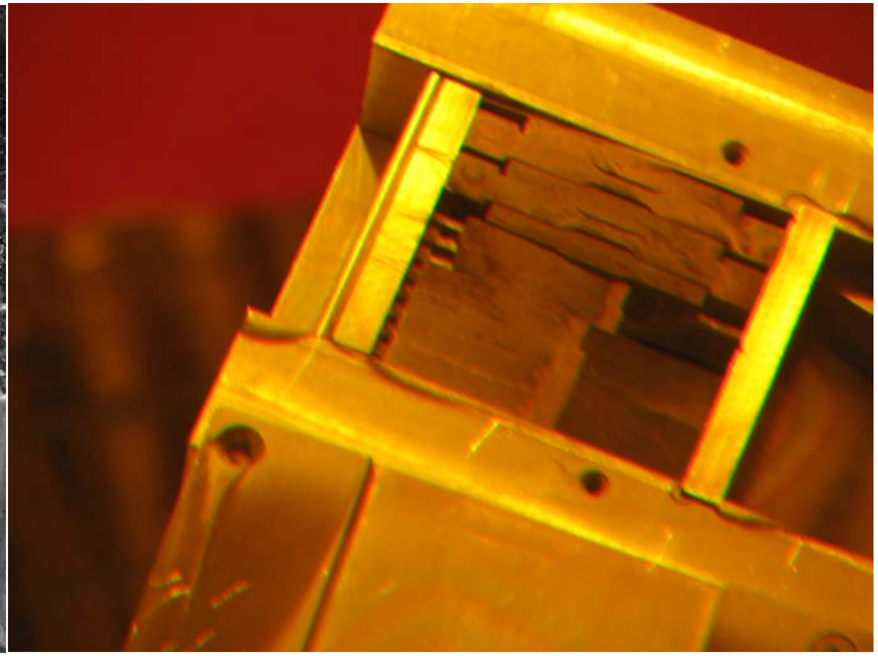




Graphite – Irradiation Effects on Bonding

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)





Collimation Irradiation Damage Studies – Exploring other materials

LHC-relevant Materials

PRIMARY

- **Copper (annealed)**
- **Glidcop_15AL – Cu alloyed with .15% Al (axial cut and transverse cut)**

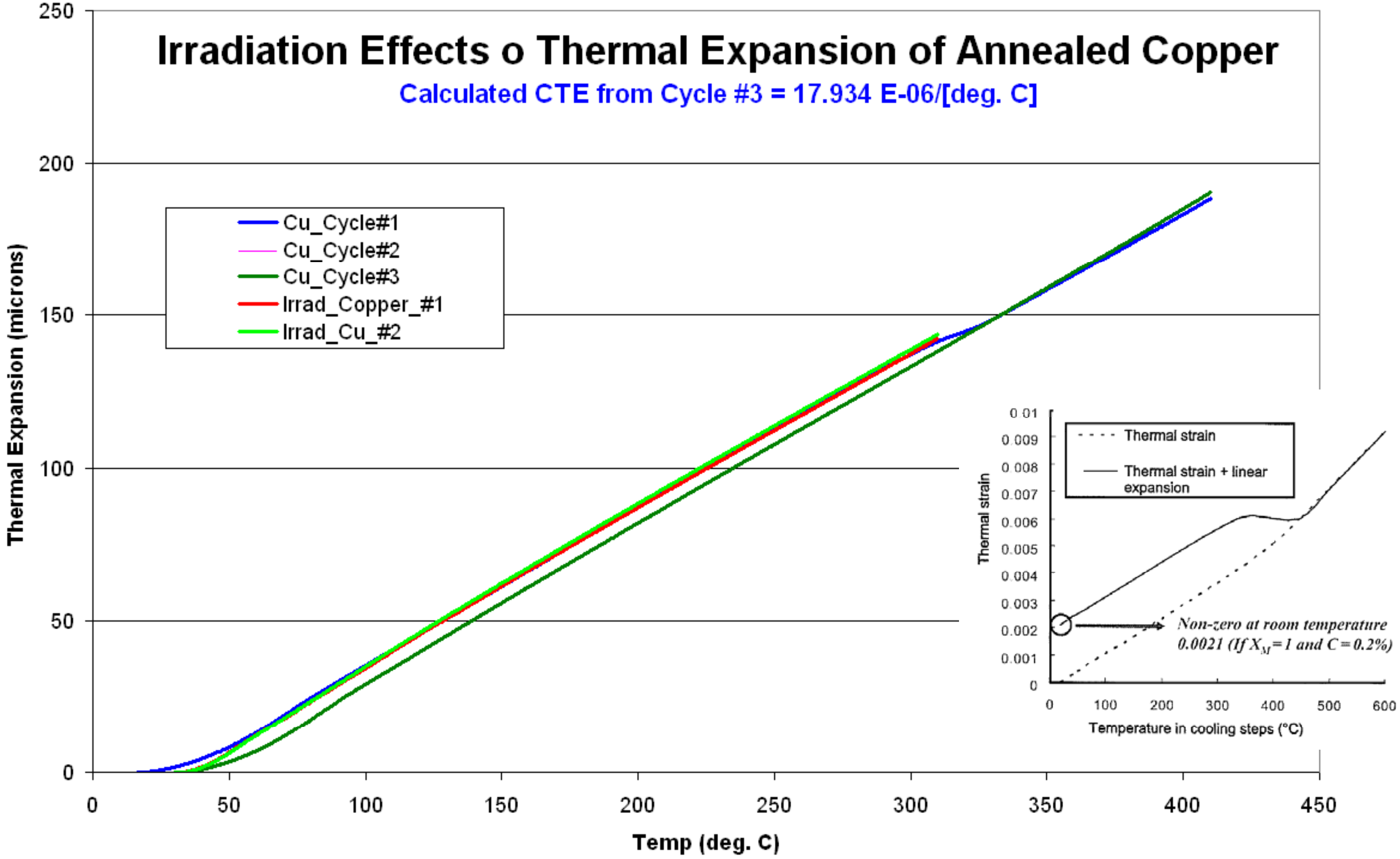
SECONDARY

- **Super-Invar**
- **Toyota "Gum Metal"**
- **Graphite (IG-430 "isotropic")**

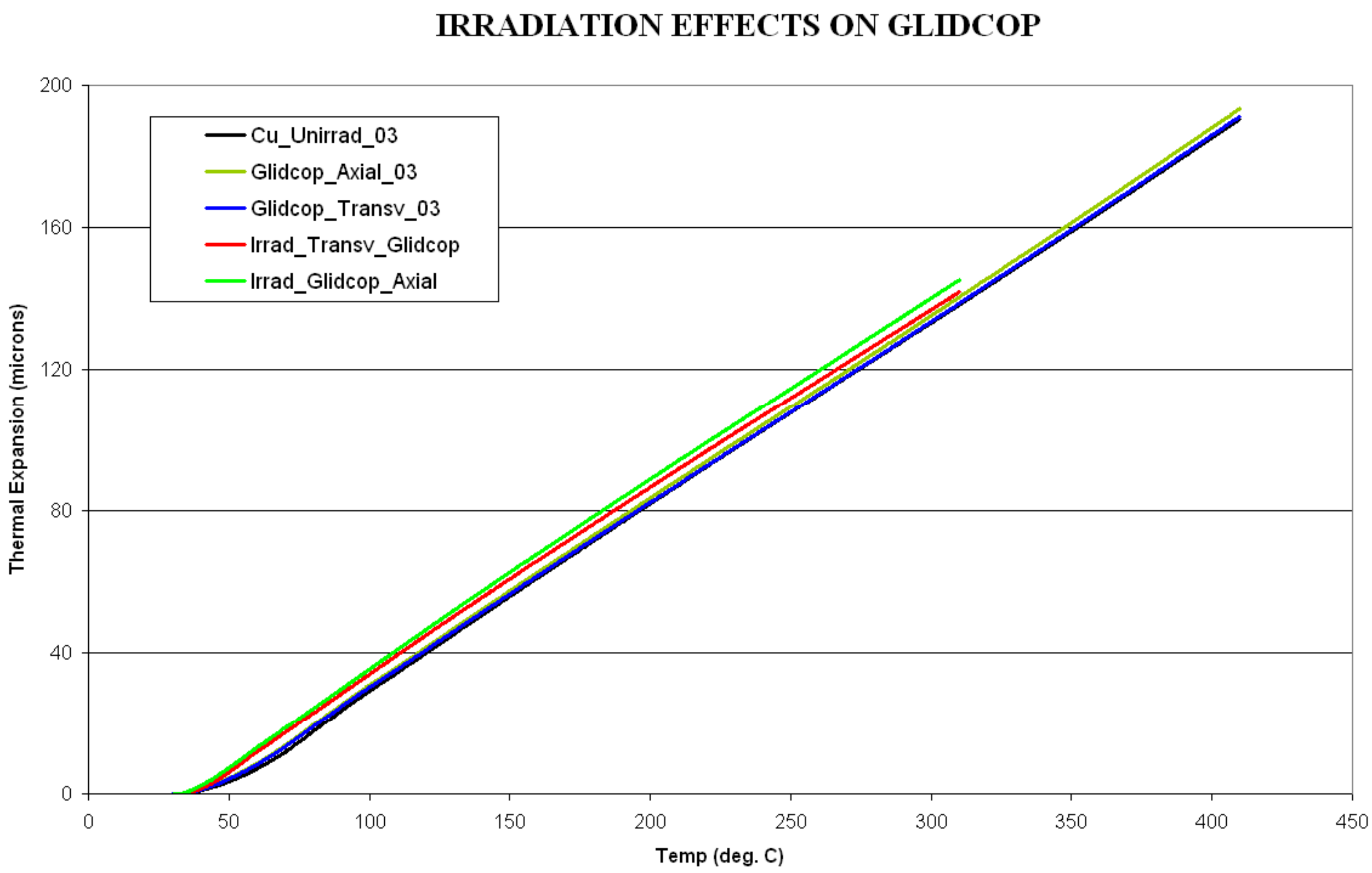
ALSO candidates under consideration

- **Ti Alloy (6Al-4V)**
- **Tungsten**
- **Tantalum**
- **Low-Z alloy - AlBeMet**

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



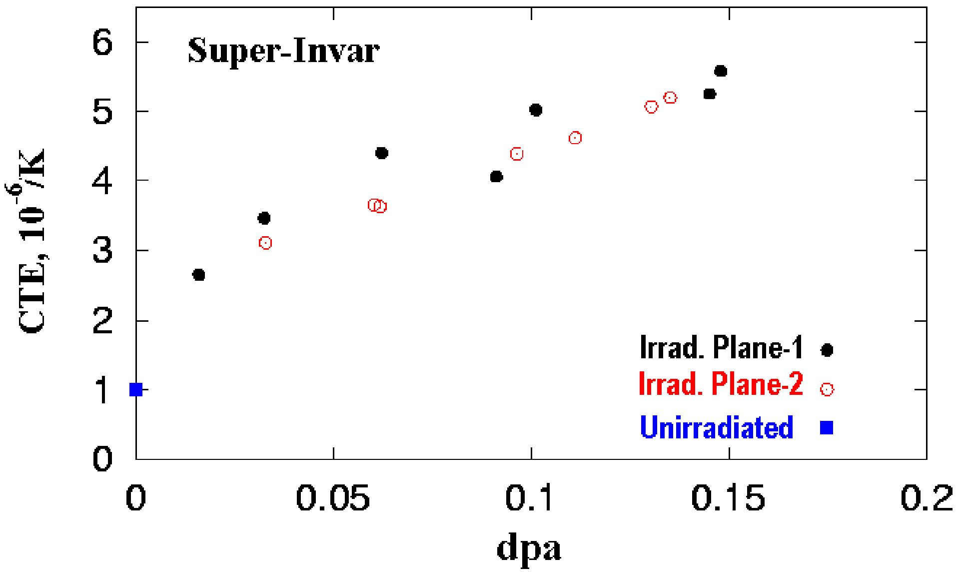
Irradiation Effects on Glidcop
(fluence ~ 10^21 protons/cm2)



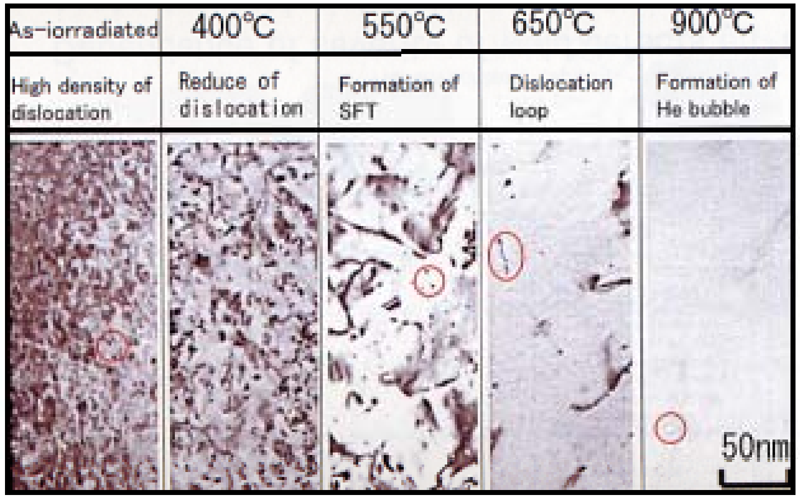
Irradiation studies on super-Invar

- “invar” effect found in Fe-Ni alloys ➔ low CTE
  - “inflection” point at around 150 C

Effect of modest irradiation



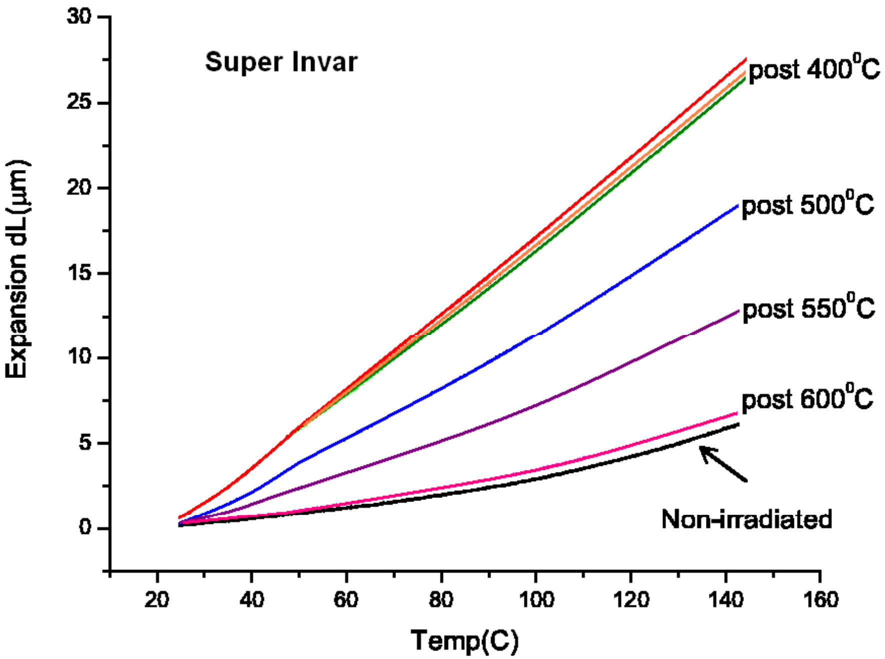
Annealing or defect mobility at elevated temperature



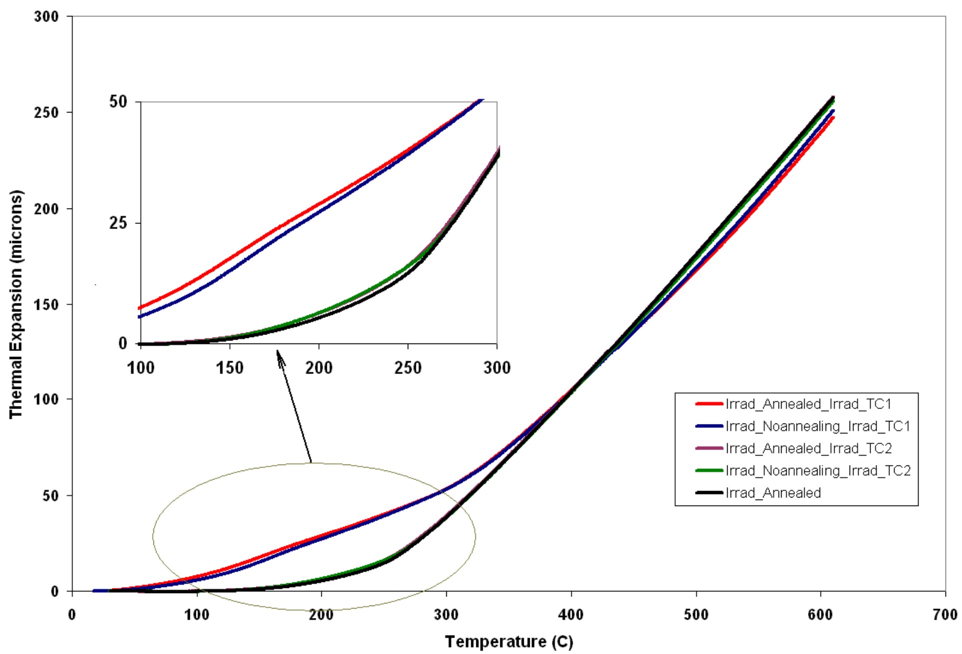
Y. Ishiyam et. al., J. Nucl. Mtrl. 239 (1996) 90-94

“annealing” of super-Invar

Following 1st irradiation

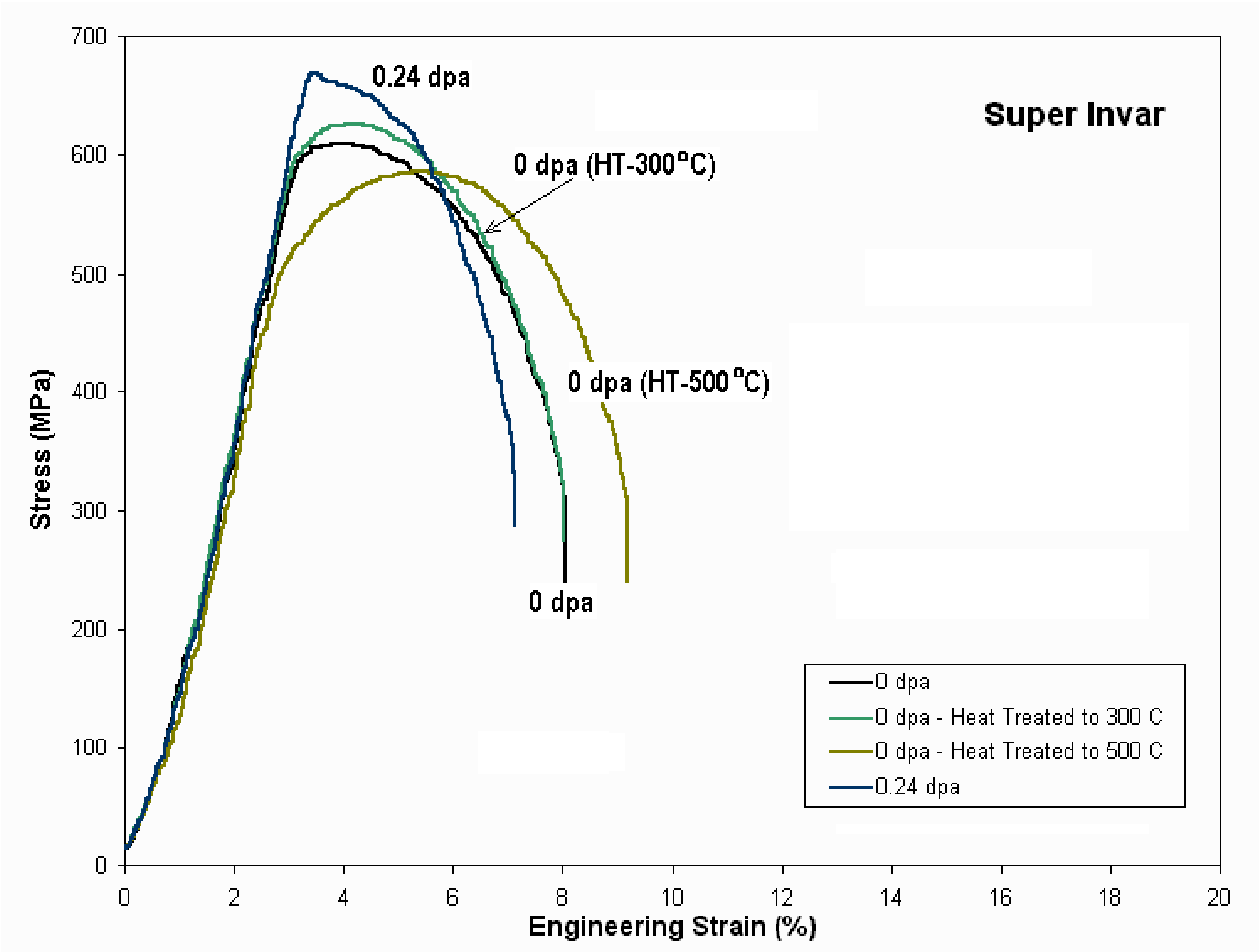


Following annealing and 2nd irradiation



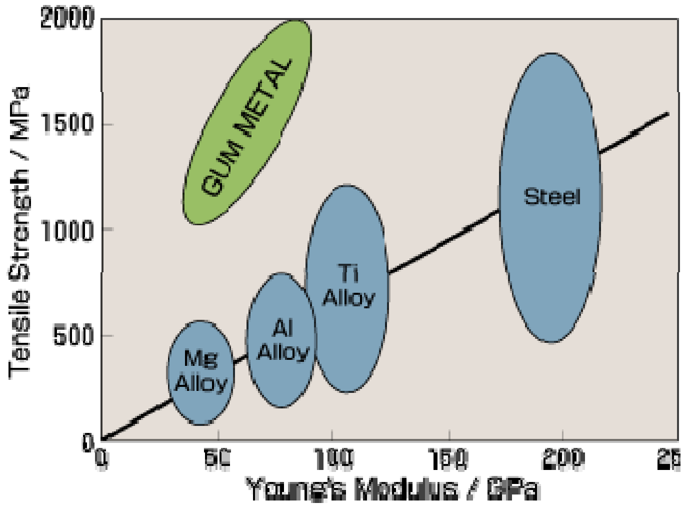
ONGOING 3rd irradiation phase: neutron exposure

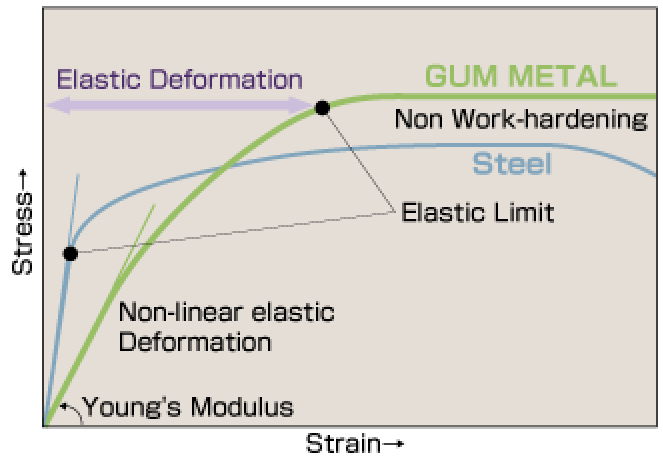
Irradiation & temperature effects on Super-Invar

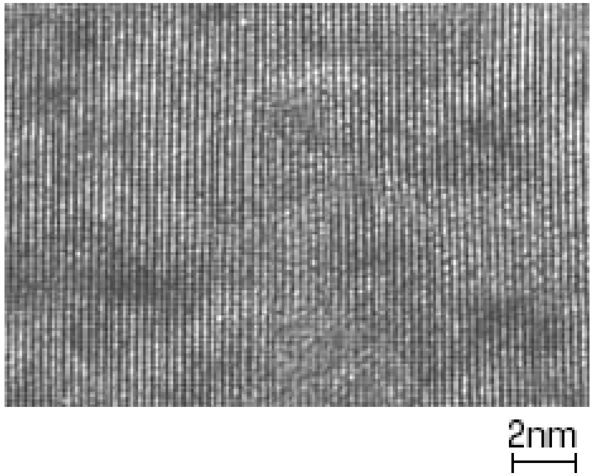


Studies of Gum Metal (Ti-12Ta-9Nb-3V-6Zr-O)

[Fig.1] Position of Young's Modulus and Strength of GUM MET



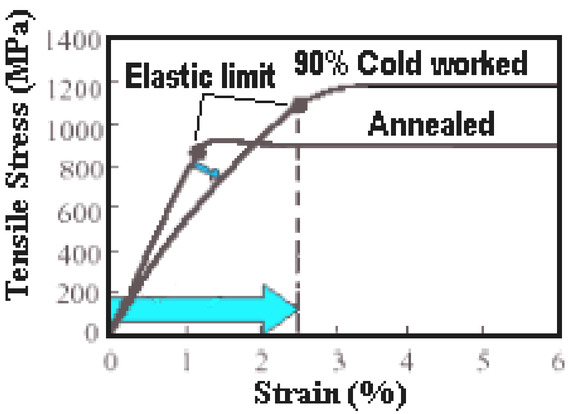


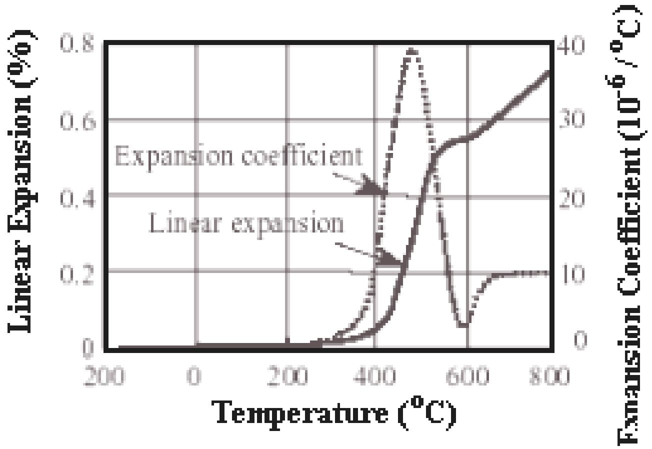


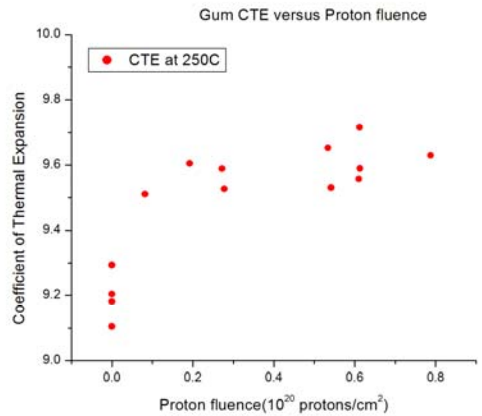
- **Super elasticity**
- **Super plasticity**
- **Invar property (near 0 linear expansion) over a wide temp range**
- **Elinvar property (constant elastic modulus over a wide temp range)**
- **Abnormality in thermal expansion "unrelated" to phase transformation**
- **It exhibits a dislocation-free plastic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

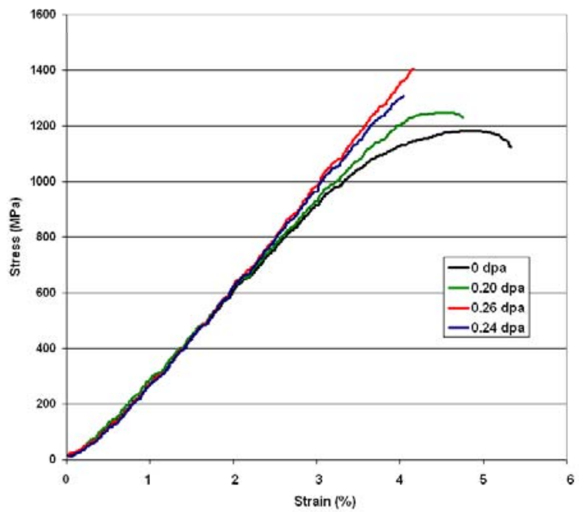
RESULT of cold-working !!!

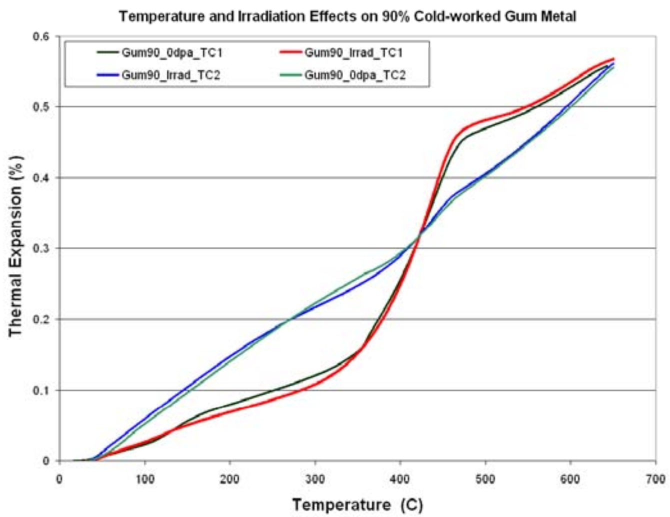
Effects of radiation and temperature on Gum metal



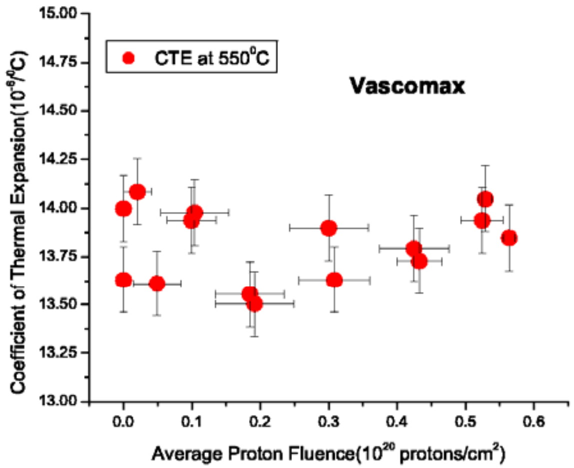


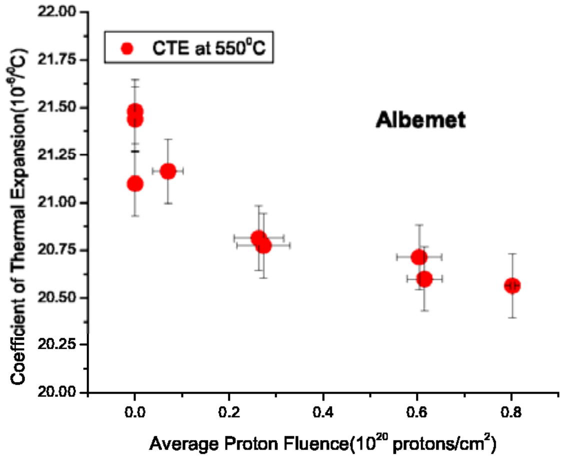


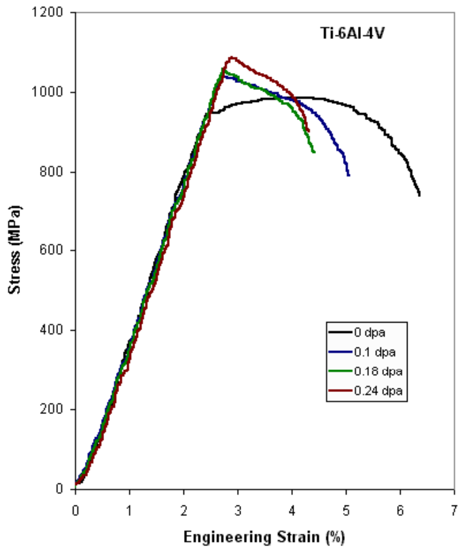


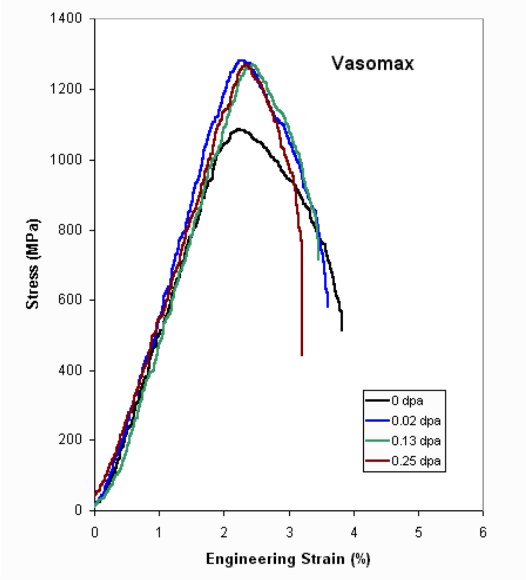


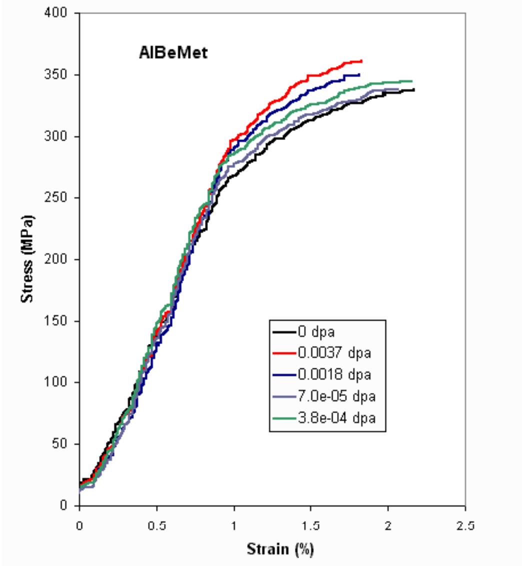
Radiation Damage Studies – Other Candidates



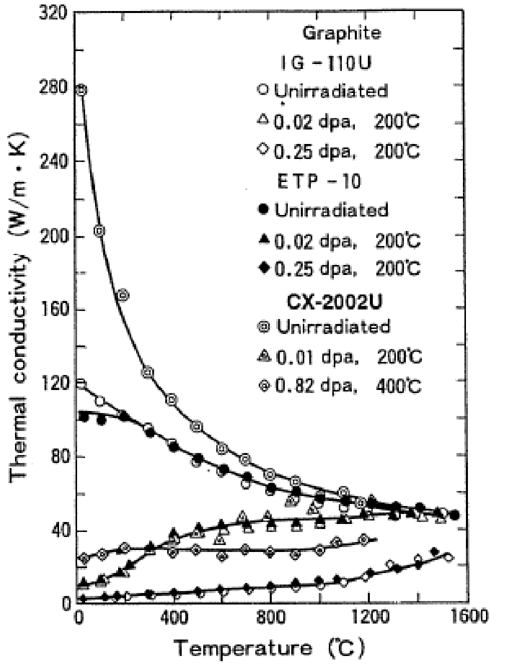






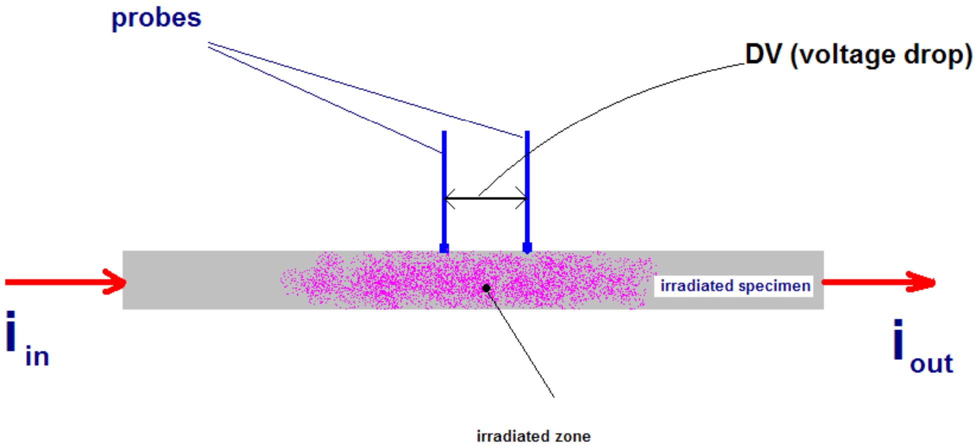


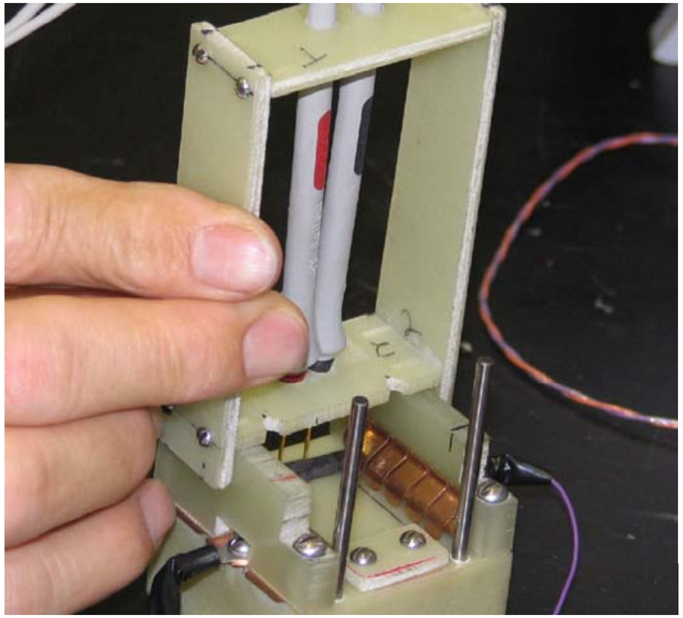
Radiation Effects on Conductivity

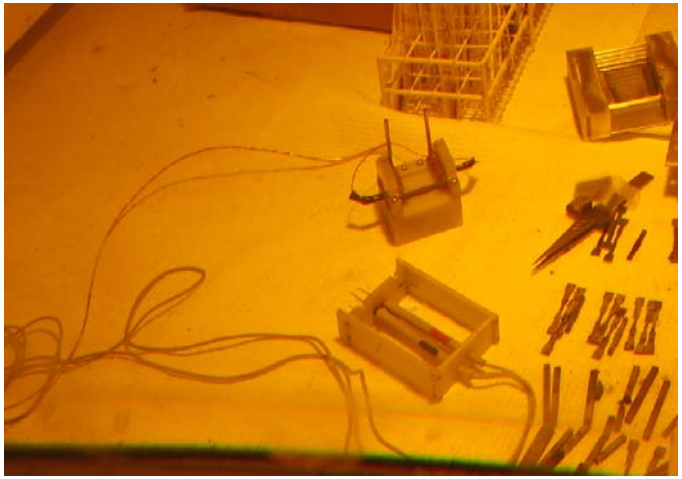


Thermal conductivity of neutron-irradiated graphites.

Electrical resistivity → Thermal conductivity







Some VERY preliminary results

Glidcop in both axial and transverse directions (~ 1 dpa) sees 40% reduction

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

Neutron Irradiation Phase

Irradiation Exposure COMPLETED in June 2007

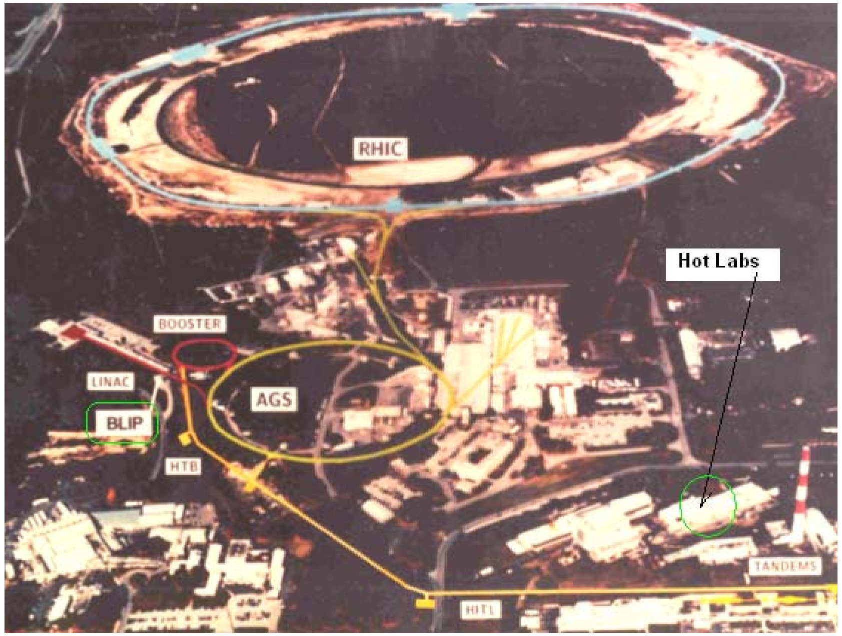
Materials include:

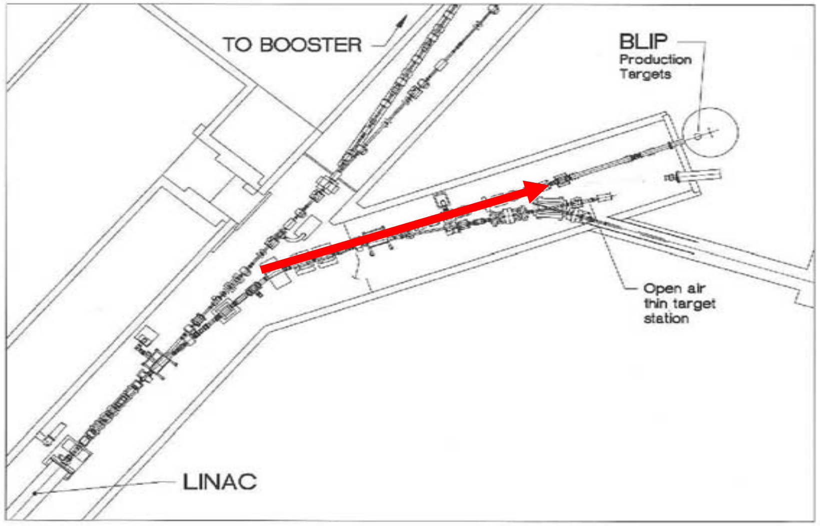
- Copper/Glidcop
- Isotropic graphite (IG-430)
- Super-Invar/Gum metal/Ti-6Al-4V

Materials are in a “cool-down” phase

MARS analyses performed

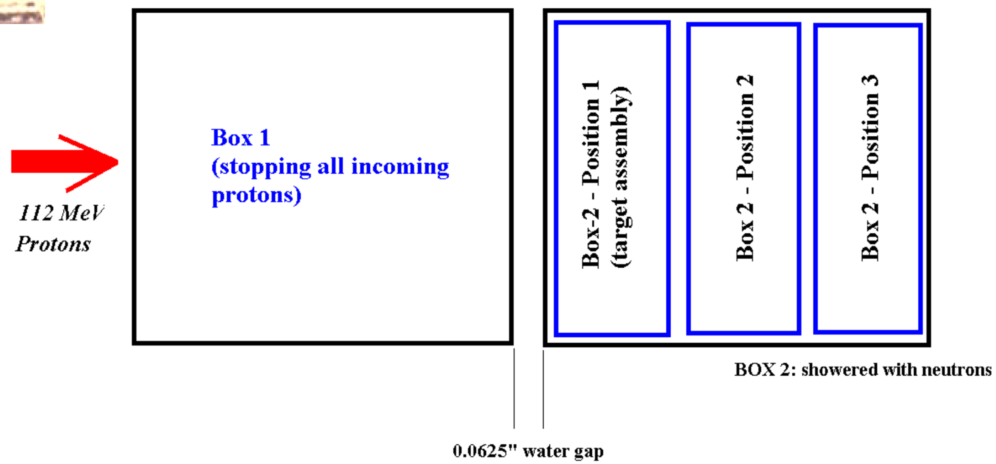
Irradiation Studies using the BNL Accelerator Complex



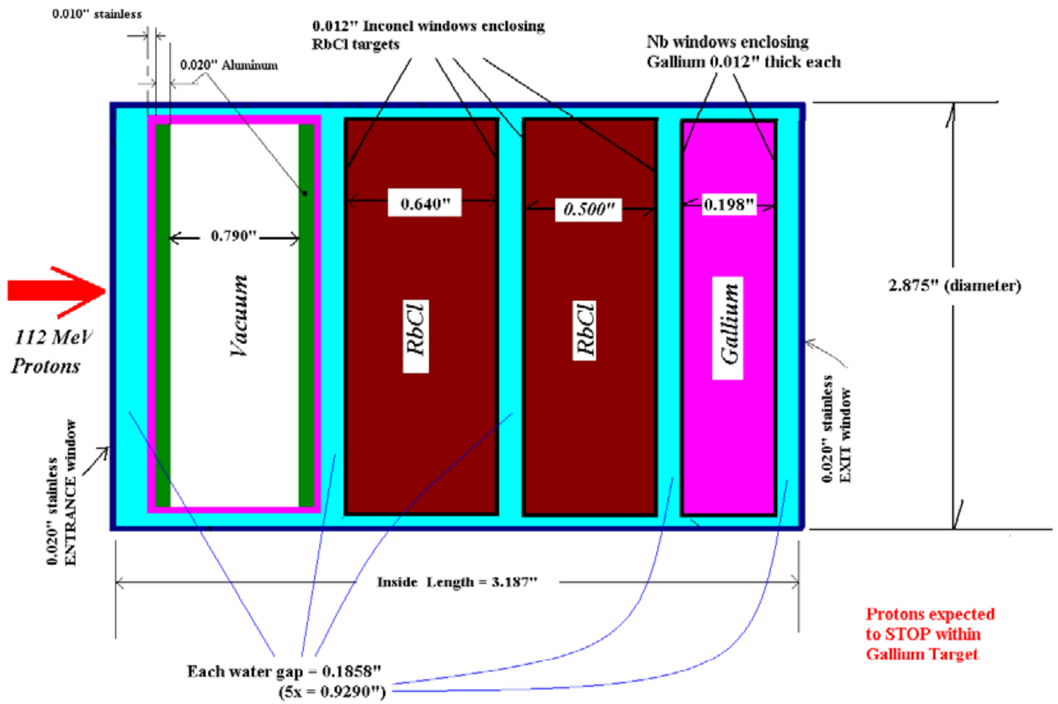


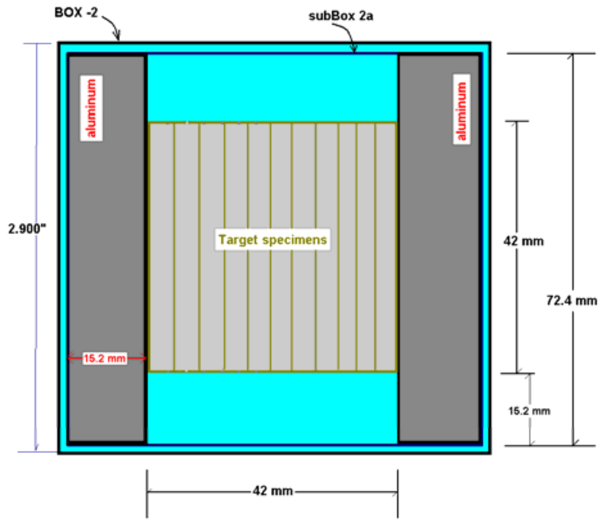
Schematic of BLIP Beam Line

Target Lay-out



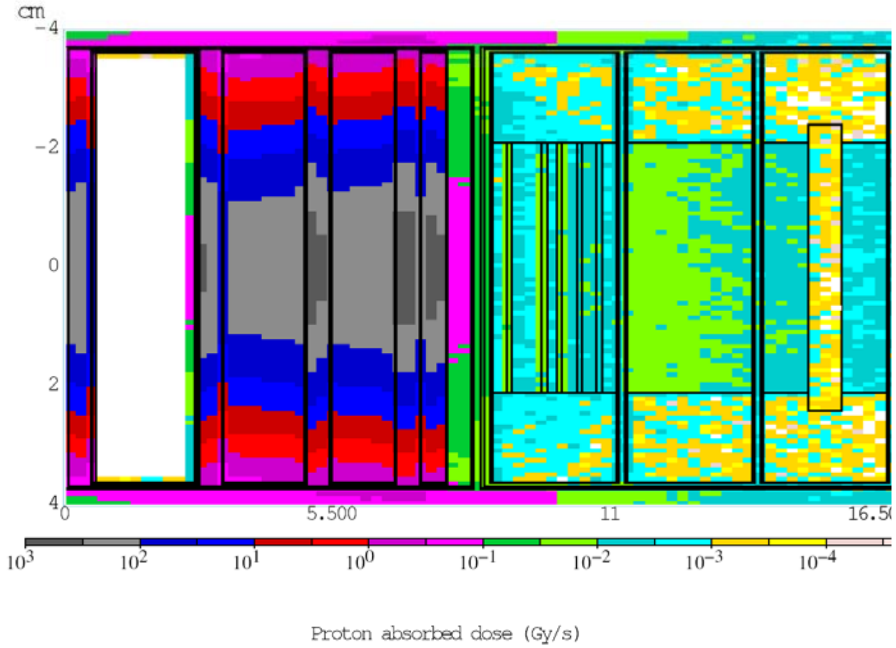
Neutron Irradiation Studies using the BNL Accelerator Complex

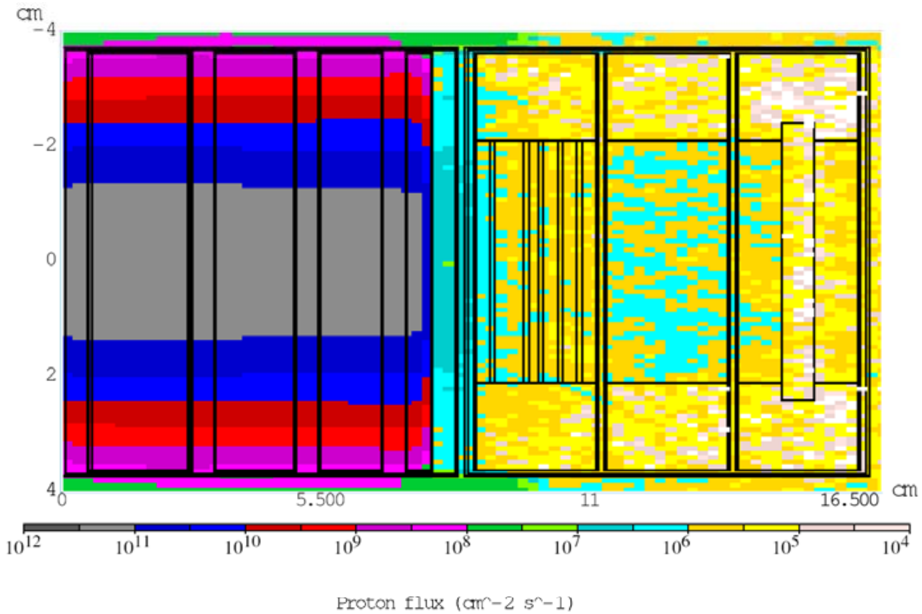




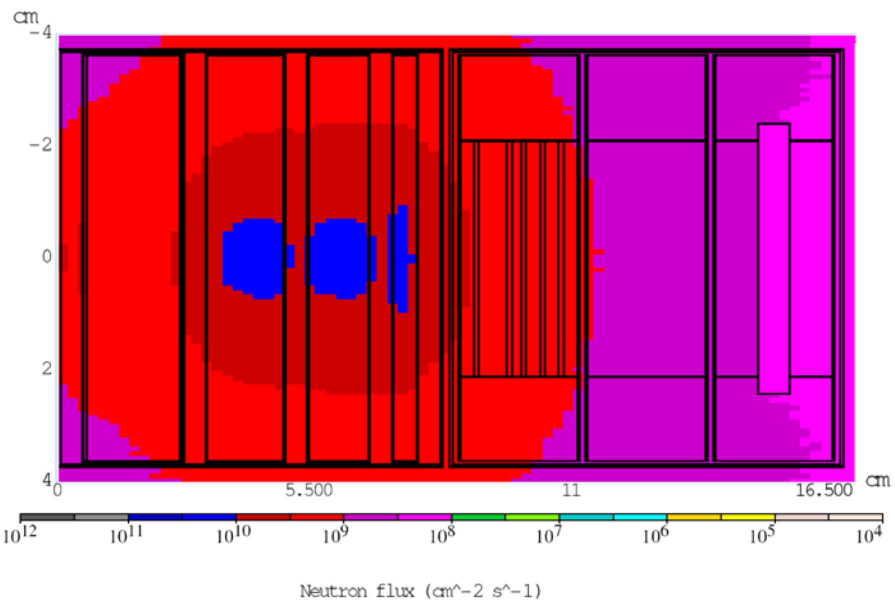
BOX 1: contains isotope production targets which are expected to stop all protons and generate a neutron flux downstream

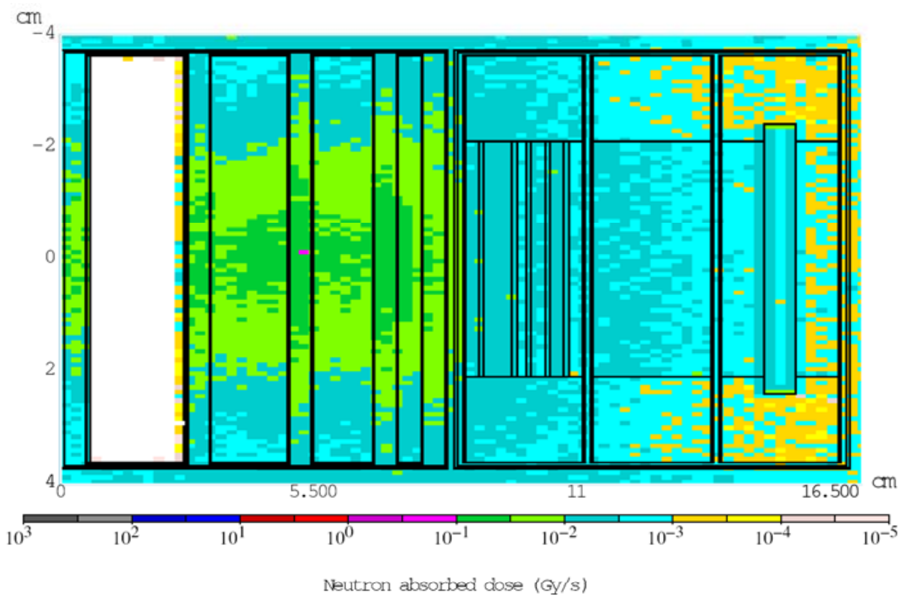
Neutron Irradiation Studies using the BNL Accelerator Complex
PROTON Flux & Dose



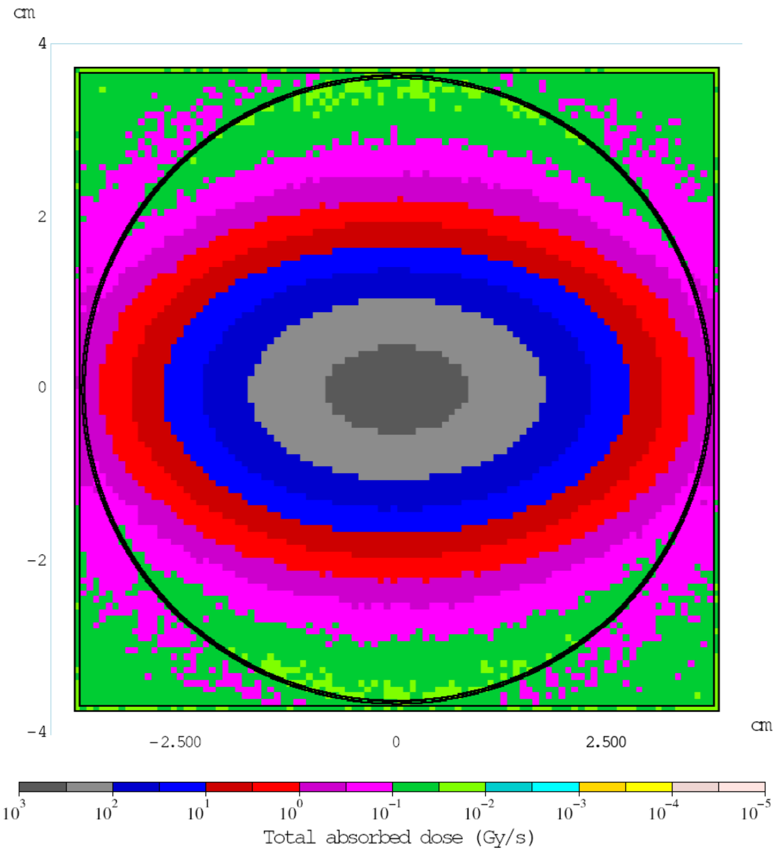


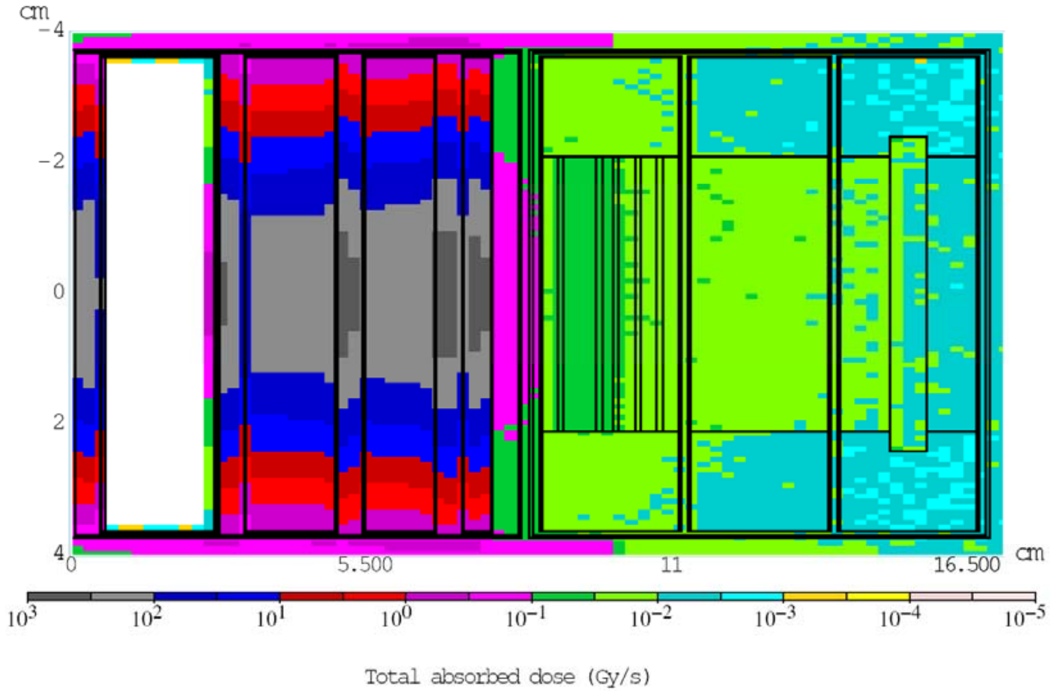
Irradiation Studies using the BNL Accelerator Complex
NEUTRON Flux & Dose





Irradiation Studies using the BNL Accelerator Complex
TOTAL Absorbed Dose





Irradiation damage assessment – to date

- While carbon composites (including the 2-D carbon used in Phase I) exhibit stability in their thermal expansion coefficient in the temperature range they are expected to operate normally, they experience a dramatic change in their CTE with increased radiation. However they are able to fully reverse the "damage" with thermal annealing

- Carbon composites also showed that with increased proton fluence (> 0.2 10^21 p/cm2) they experience serious structural degradation. This finding was confirmed for the family of such composites and not only for the 2-D composite used in the lHC.

- It was also experimentally shown that under similar conditions, graphite also suffers structurally the same way as the carbon composites

- Proton radiation was shown to not effect the thermal expansion of Copper and Glidcop that are considered for Phase II

- Encouraging results were obtained for super-Invar, Ti-6Al-4V alloy and AlBeMet

SUMMARY

- **Information to-date is available from low power accelerators and mostly from reactor (neutron irradiation) experience. Extrapolation is not allowed!**
- **Advancements in material technology (alloys, smart materials, composites) provide hope BUT must be accompanied by R&D for irradiation damage**
- **Need to continue experimental activities that will address, in a systematic manner, radiation effects on new materials for levels that are beyond the nominal power (already discussions for upgrading the machine)**