Irradiation Damage Studies for High Power Accelerators

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(with contribution from many colleagues)

Project-X Workshop Nov. 12-13, 2007

OVERVIEW

- **High Power Accelerator Targets**
  - **choices**
  - **identified challenges, solutions**
- **Background on relevant studies**
  - **Short term effects (shock)**
  - **Long term effects (irradiation damage to carbon-based materials and super alloys)**
- **Beam Windows**
- **Direction of R&D**

2+ MW Targets - Realistic ?

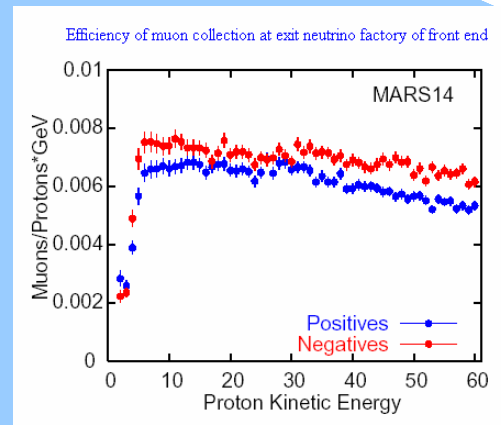
- An order of magnitude higher of operating drivers (excluding CW)
- Are sub-systems capable in providing/dealing with such power?
- While the target may represent a tiny portion of the overall infrastructure, its role in the functionality of the system is paramount
- Since no one-size-fits all works, the target choice must satisfy accelerator parameters that are set by physics
- Unfortunately, it is a two-way negotiation !!!!

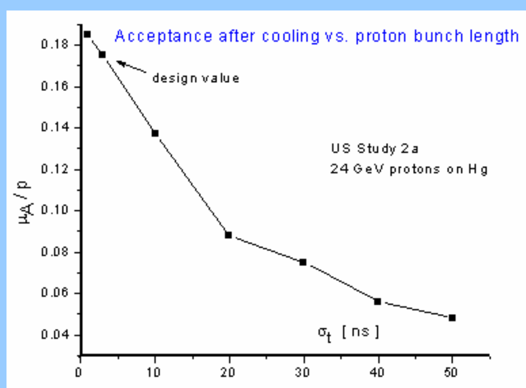
Establishing the Parameter Space

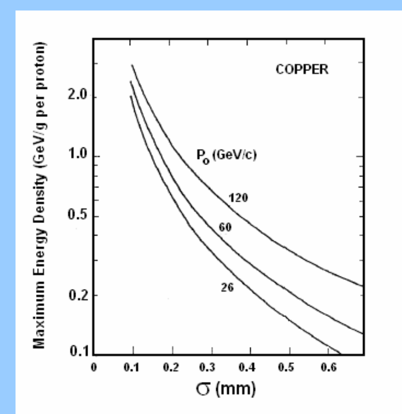
Protons per pulse required for 4 MW

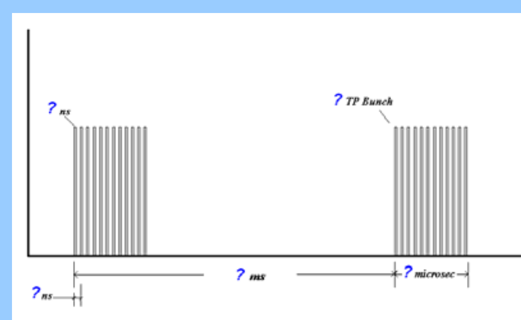
$$\overline{P}_{arc}(w) = E[eV] \times N \times e \times f_{rep}[Hz]$$

	10 Hz	25 Hz	50 Hz
10 GeV	250×10^{12}	100×10^{12}	50×10^{12}
20 GeV	125×10^{12}	50×10^{12}	25×10^{12}









Parameter Space

A happy medium between physics goals and engineering reality

Neutrino factory example

8.0 GeV < Energy < 20.0 GeV

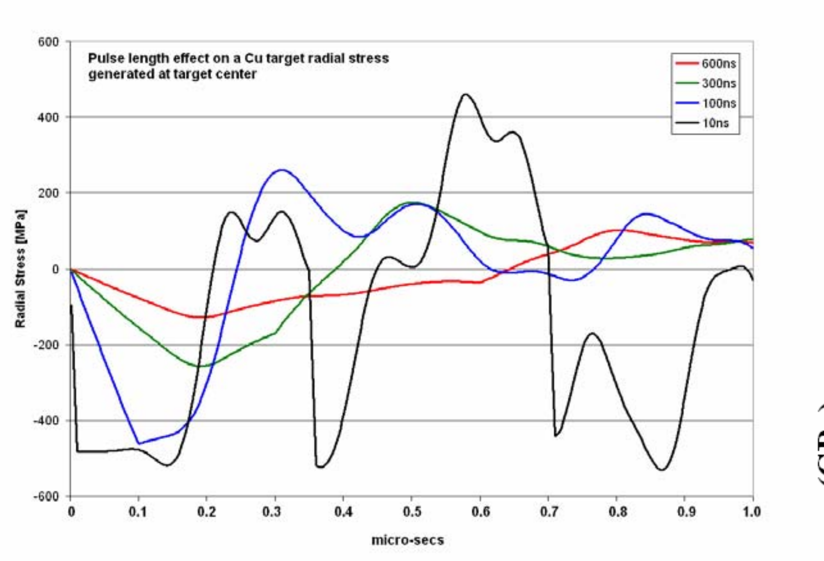
Rep Rate ~ 50(25) Hz

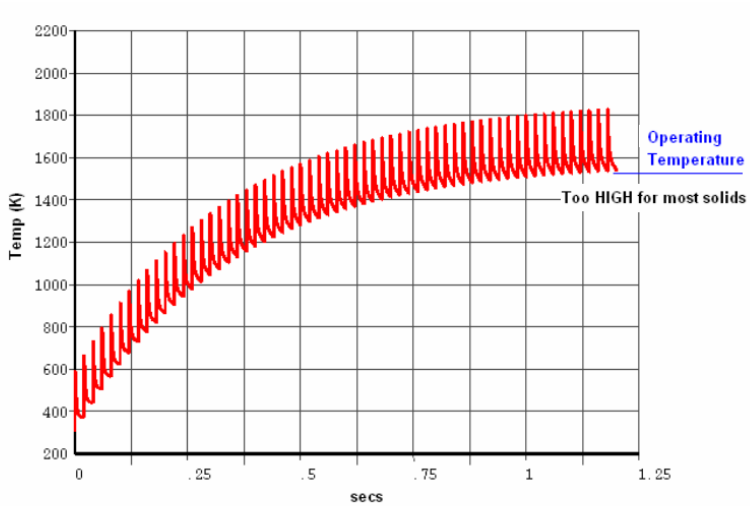
Intensity 50*10**(12) ppp, at 10(20) GeV

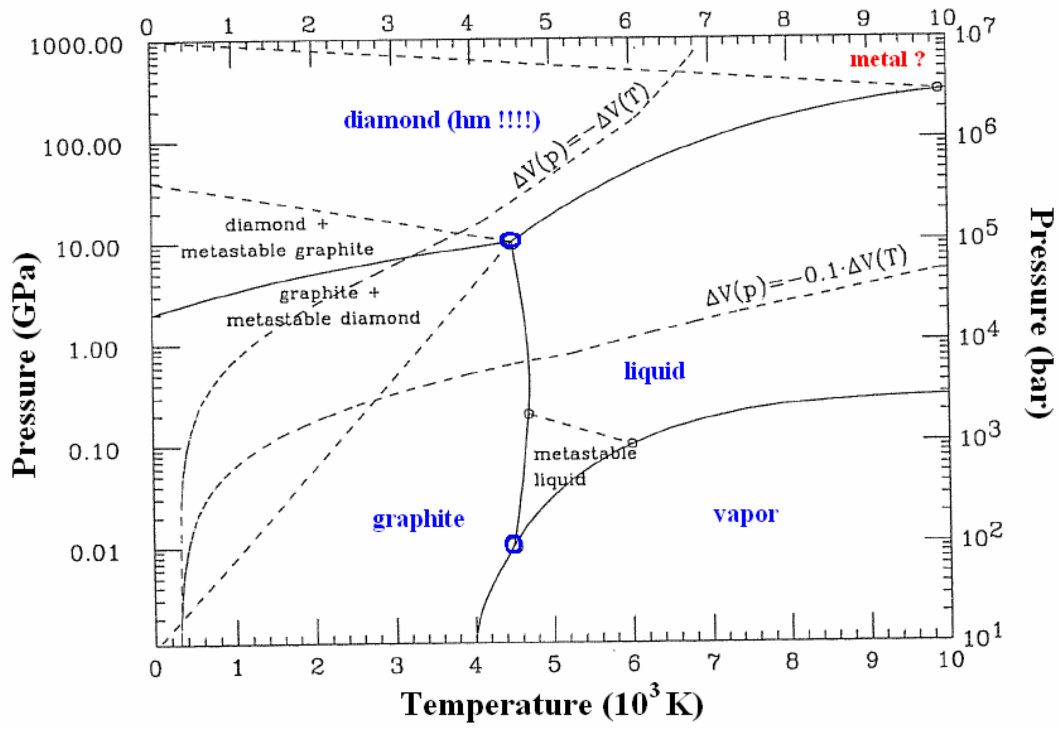
Bunch Length < 3 ns, for longitudinal acceptance

But while above parameter space may meet neutrino factory initiative needs it does not necessarily meet the needs of other experiments

Obstacles – Solid targets

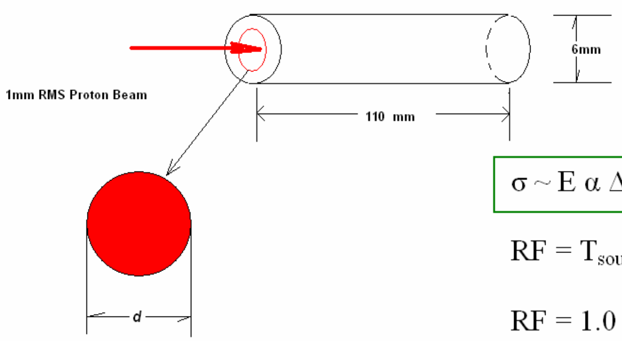






Pulse Structure Important?

24 GeV Protons on Copper Target



$$\sigma \sim E\,\alpha\,\Delta T/\,(1 - 2v) \cdot RF$$

$RF = T_{sound}/T_{pulse}$ (if $T_{sound} < T_{pulse}$)

$RF = 1.0$ (if $T_{sound} > T_{pulse}$)

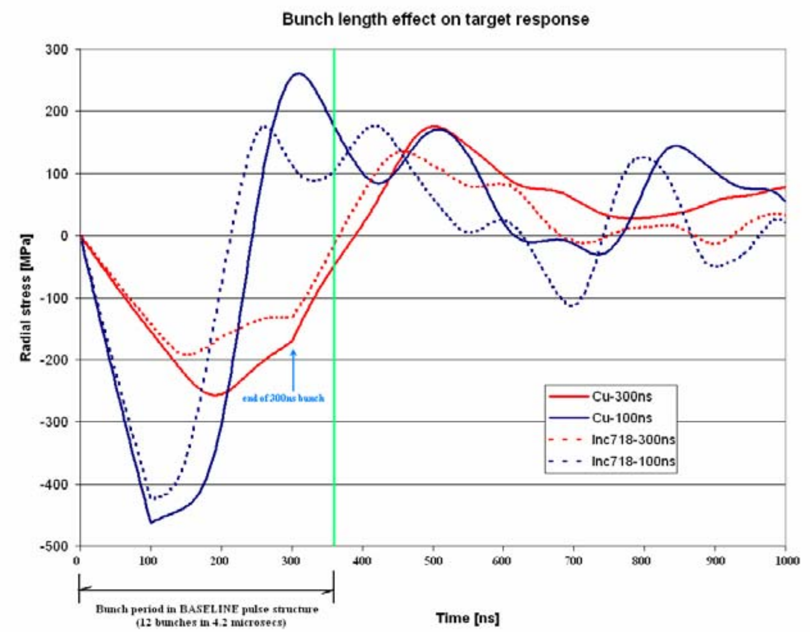
$T_{sound} = d/V_s$

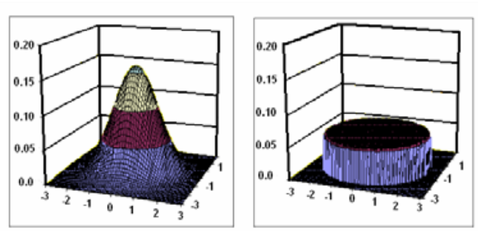
V_s = sound velocity in material

Parameters Affecting Shock Level in Solid Target

- Heat capacity (controlling temperature spike)
- Speed of sound in the material
- pulse length
- coeff. of thermal expansion
- Young's modulus

NOTE: If pulse is too short NO reduction in peak stress can be realized since heated zone does not have time to relax during deposition





Gaussian and equivalent uniform beam distribution for same number of particles

Target	25 GeV	16 GeV	8 GeV
	Energy Deposition (Joules/gram)		
Copper	376.6	351.4	234

Solid Targets – How far we think they can go?

1 MW ?	4 MW ?
Answer is **YES** for several materials	**Answer dependant on 2 key parameters:** 1 – rep rate 2 - beam size compliant with the physics sought
Irradiation damage is of primary concern	A1: for rep-rate > 50 Hz + spot > 2mm RMS ➔ 4 MW possible (see note below)
Material irradiation R&D pushing ever closer to anticipated atomic displacements while considering new alloys **is needed**	A2: for rep-rate < 50 Hz + spot < 2mm RMS ➔ Not feasible (ONLY moving targets)
	NOTE: While thermo-mechanical shock may be manageable, removing heat from target at 2+ MW might prove to be the challenge. **CAN only be validated with experiments**

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)

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

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

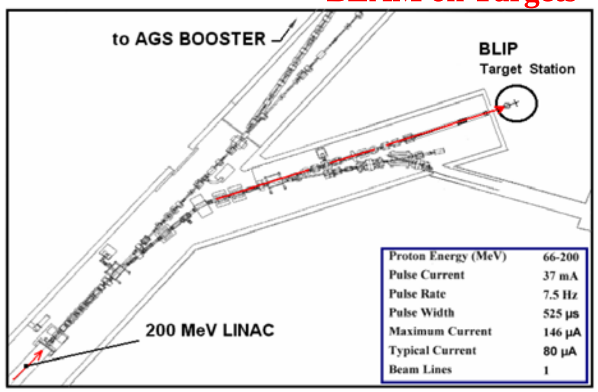
Explore the effects of proton/neutron flux on these materials with interesting macroscopic properties ➔

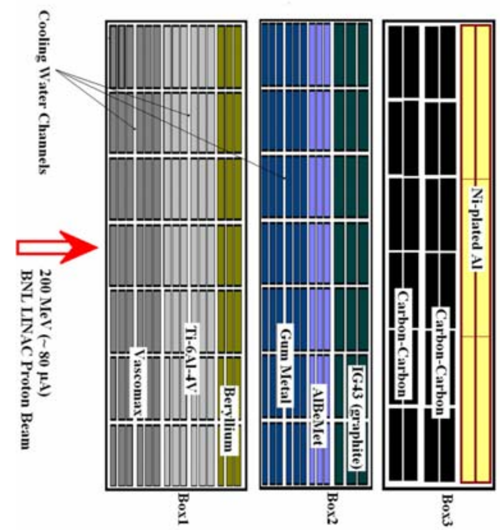
- super-alloys
- carbon composites
- graphite

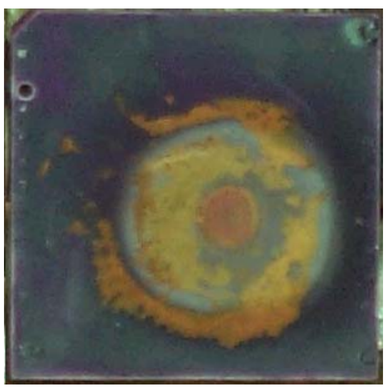
Radiation Damage R&D

Irradiation at BLIP
(200 MeV or 117 MeV
protons at the end of Linac)

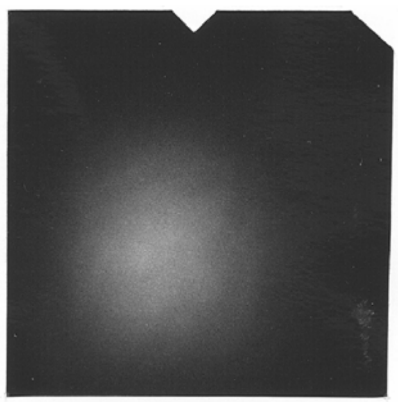
BEAM on Targets



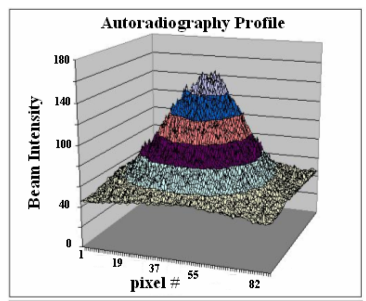


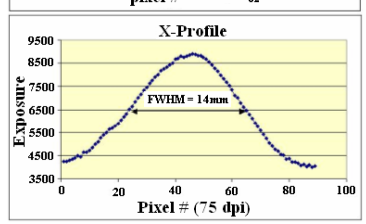


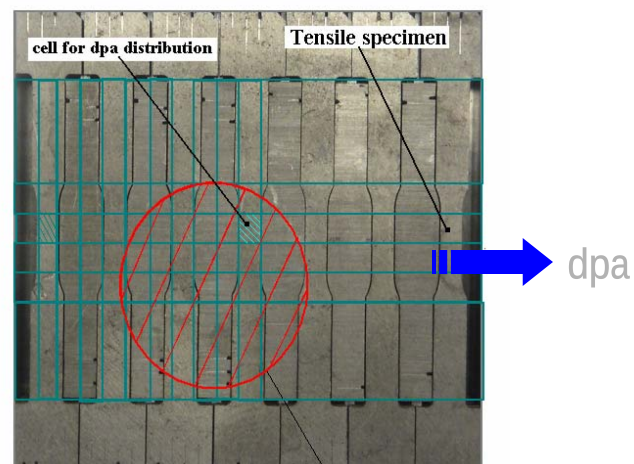
Irradiation temperature during exposure (TSP)



Nickel foil for proton beam profile



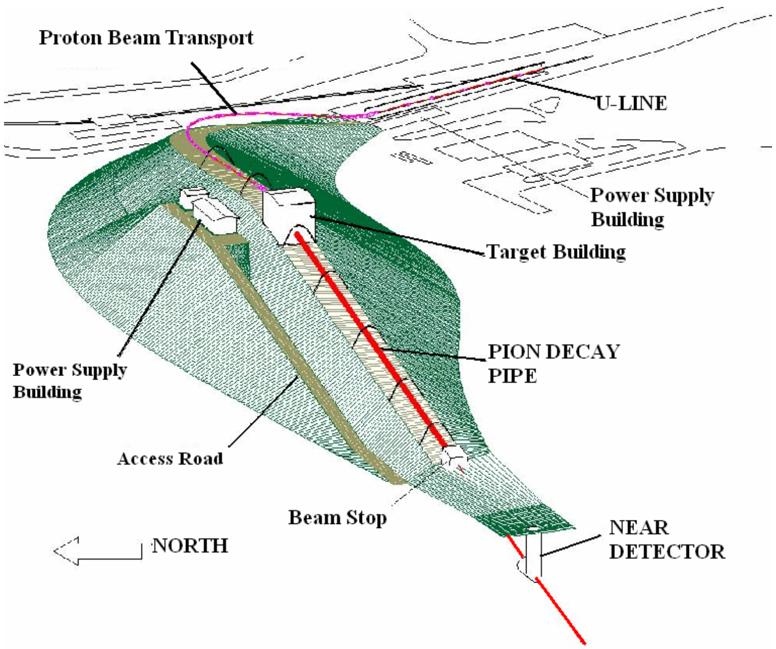


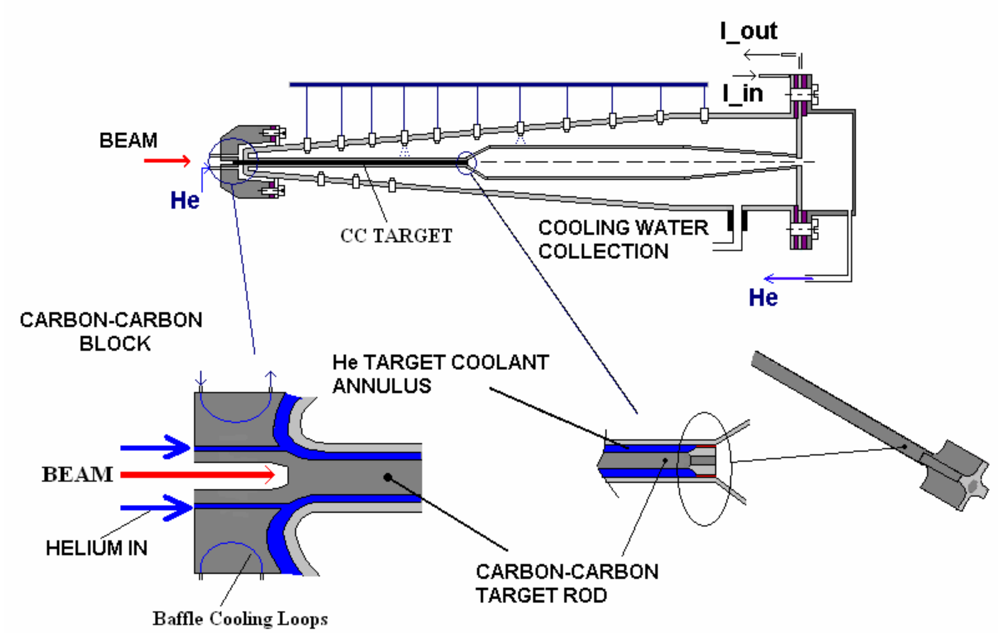


Beam footprint on targets (1σ)

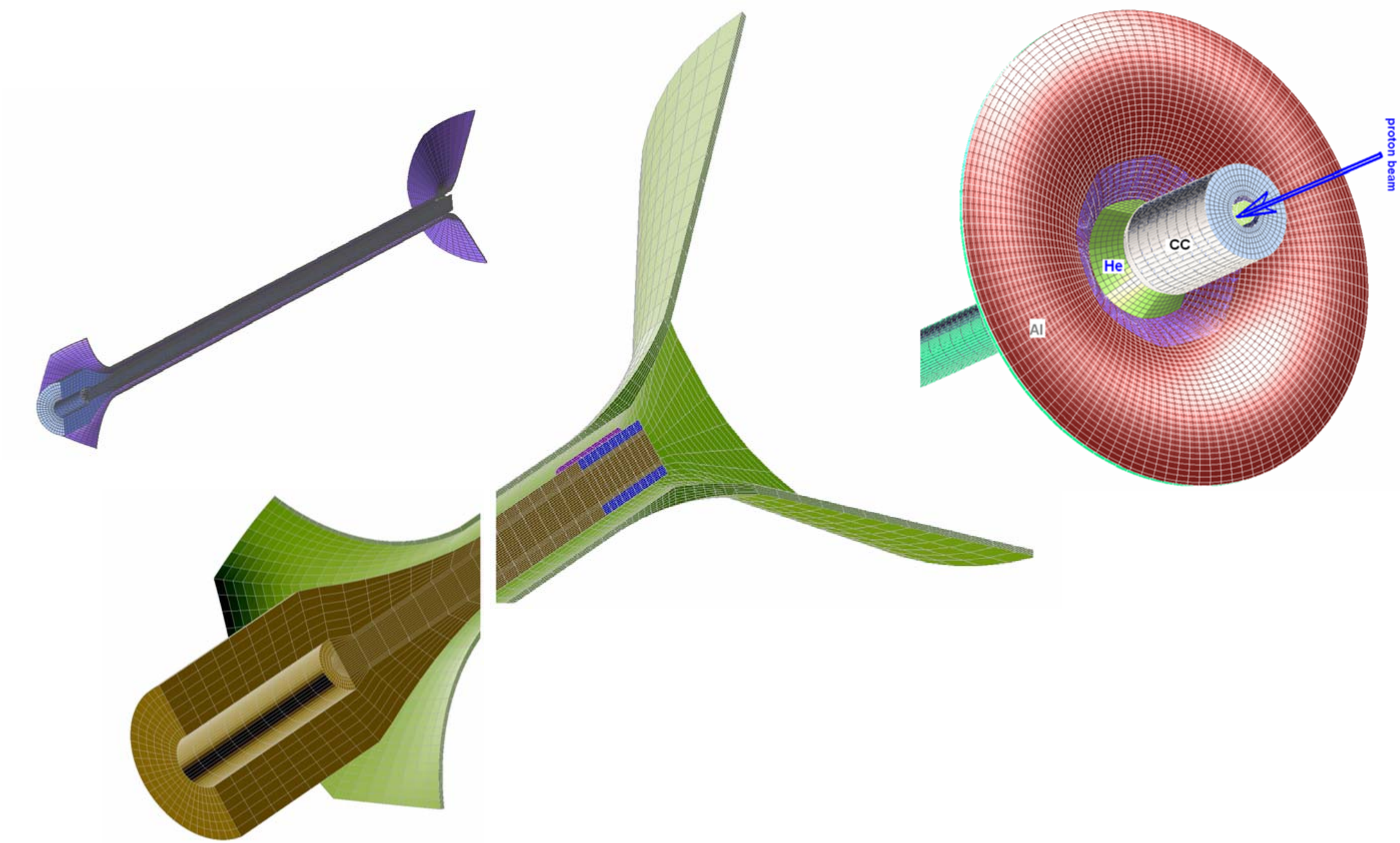
Focusing on carbon-composites & graphite

Neutrino Superbeam Studies

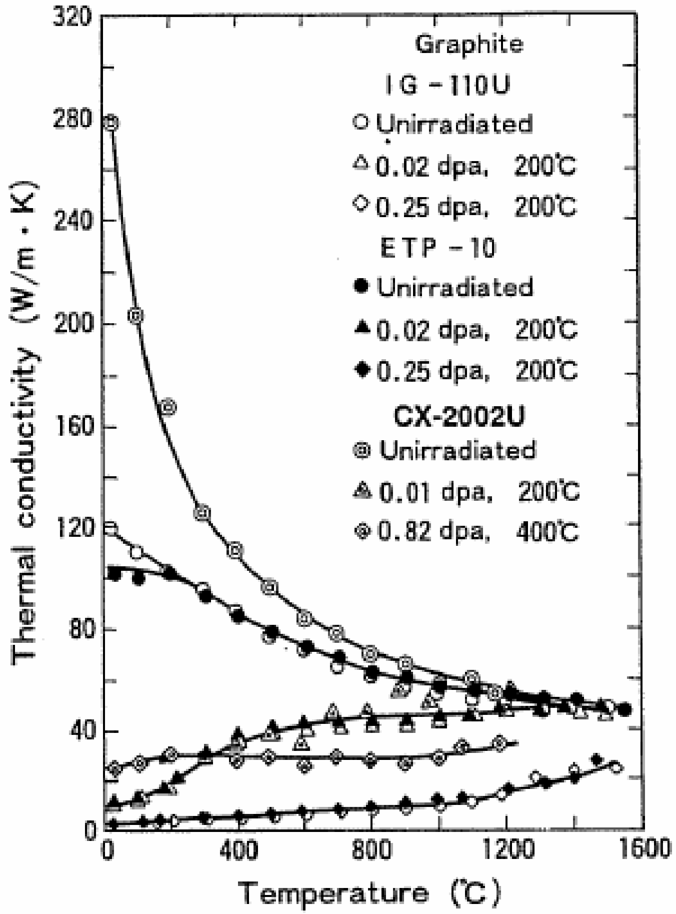




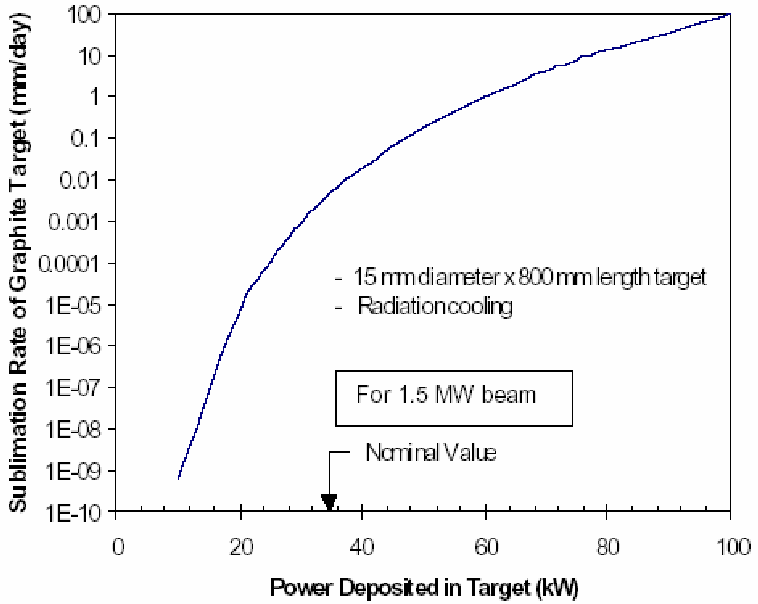
Superbeam Target Concept



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

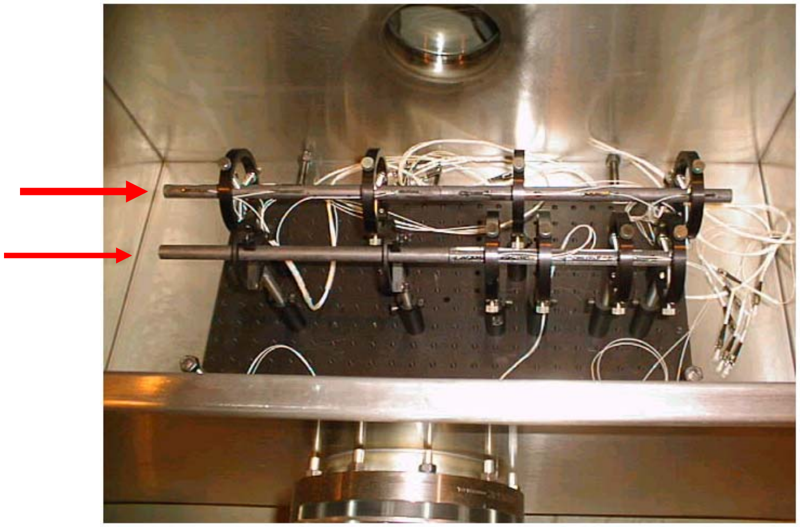


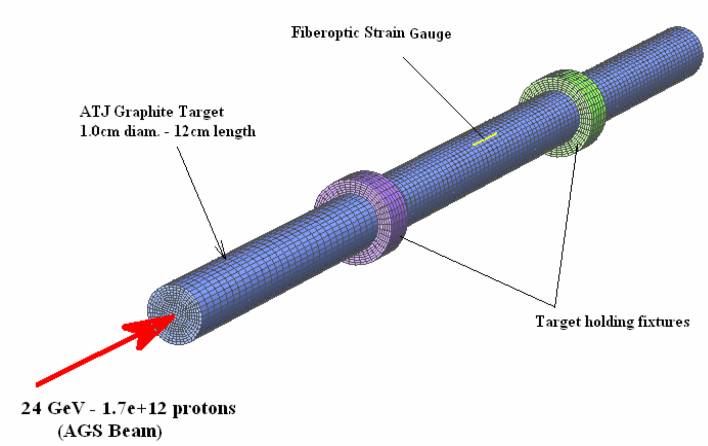
Thermal conductivity of neutron-irradiated graphites.



A graphite target may "dissapear" due to sublimation (in vacuum) in a single day at the 4 MW level

Beam Studies: Graphite & CC Composite at the AGS

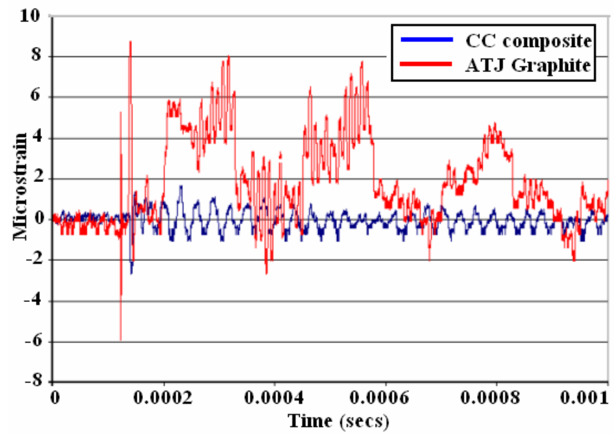




<ins>**The love affair with carbon composites**</ins>

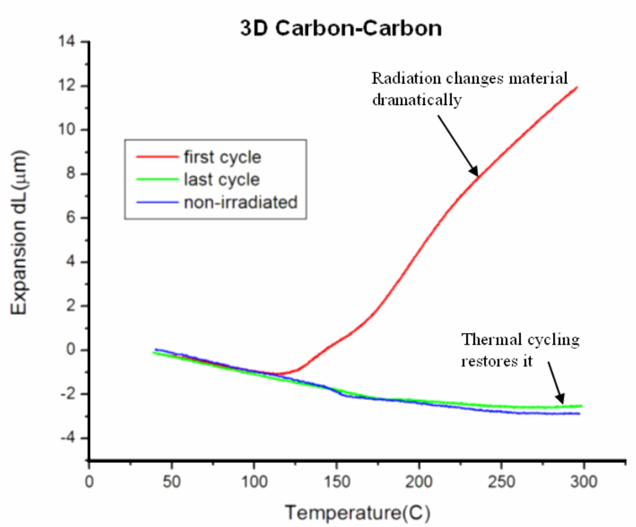
Irradiation has a profound effect on thermal conductivity/diffusivity

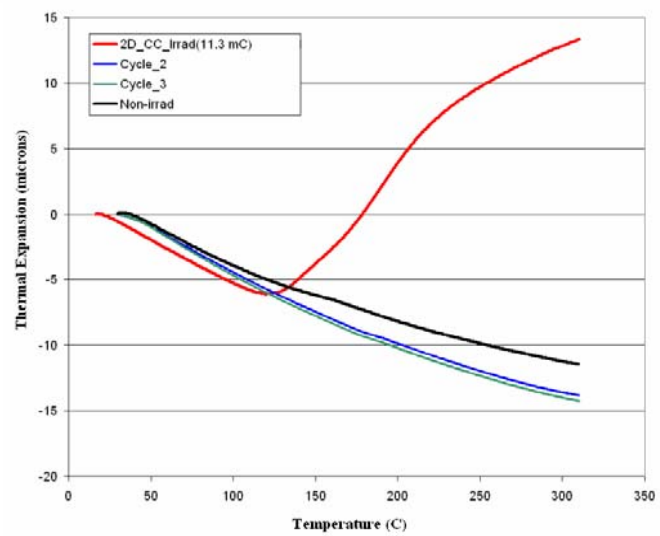
CC composite at least allows for fiber customization and thus significant improvement of conductivity.

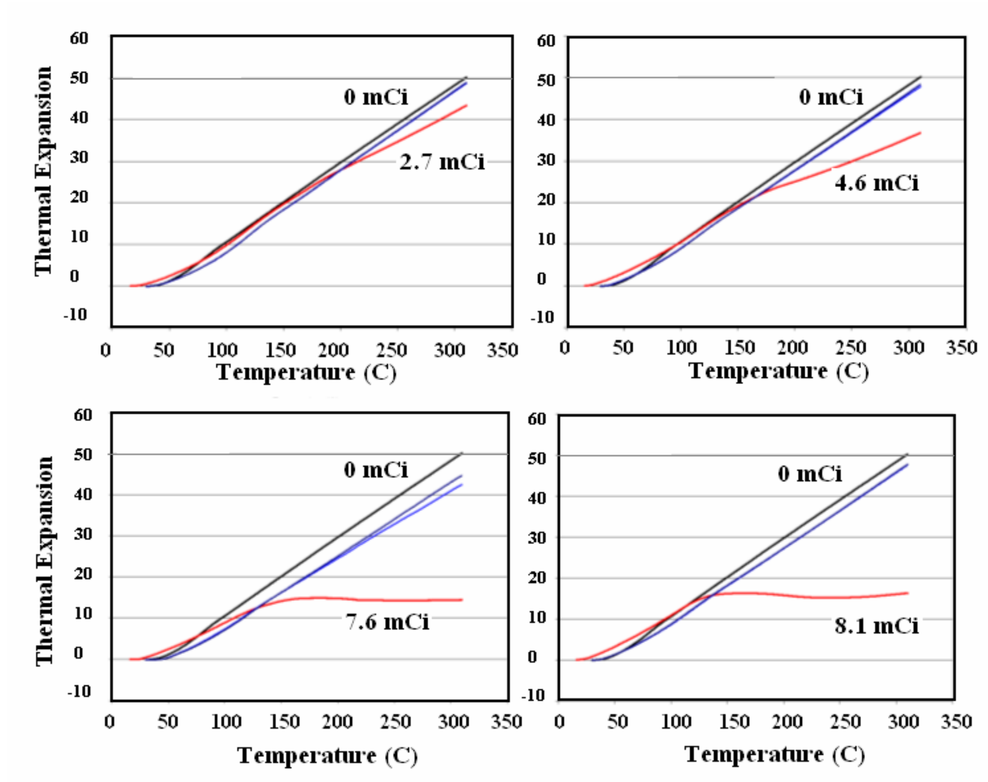


Yet to know for sure how carbon composites respond to radiation

Irradiation effects and “annealing” of carbon composites

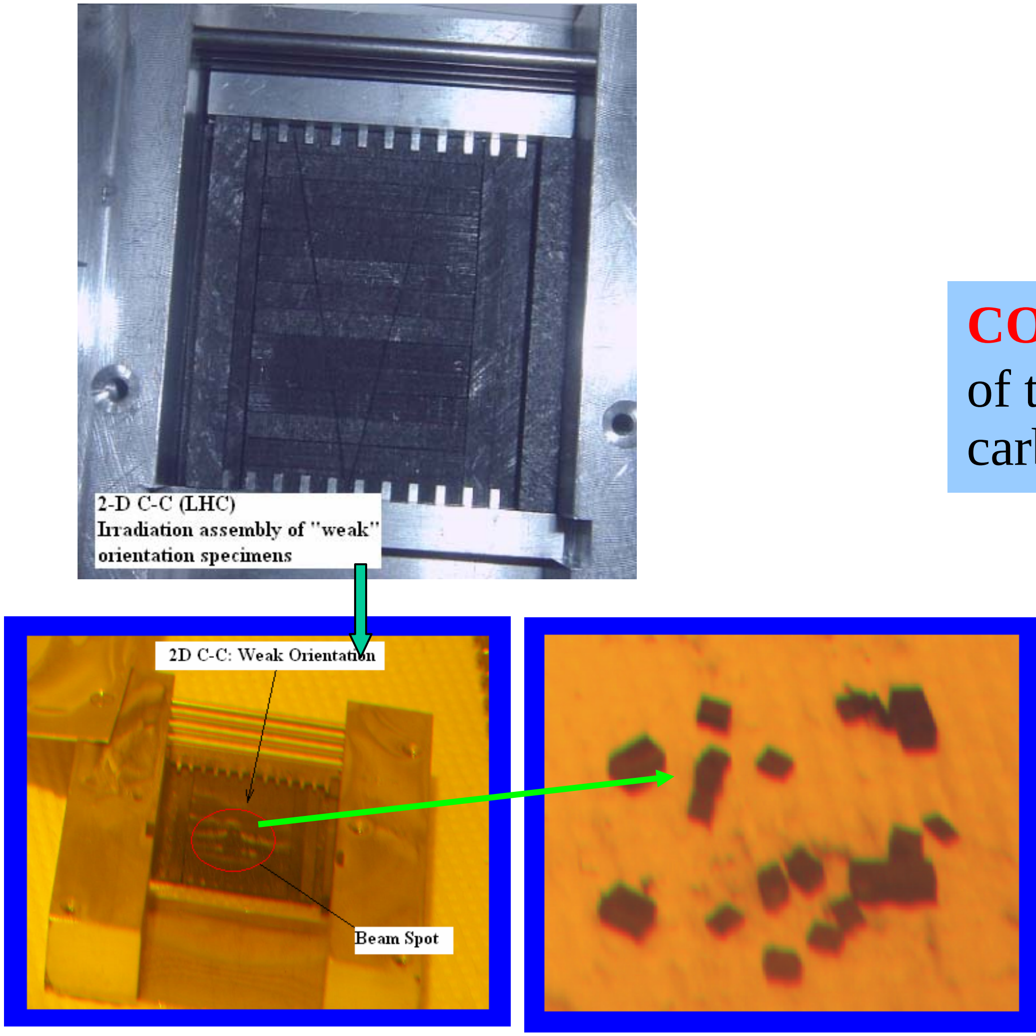






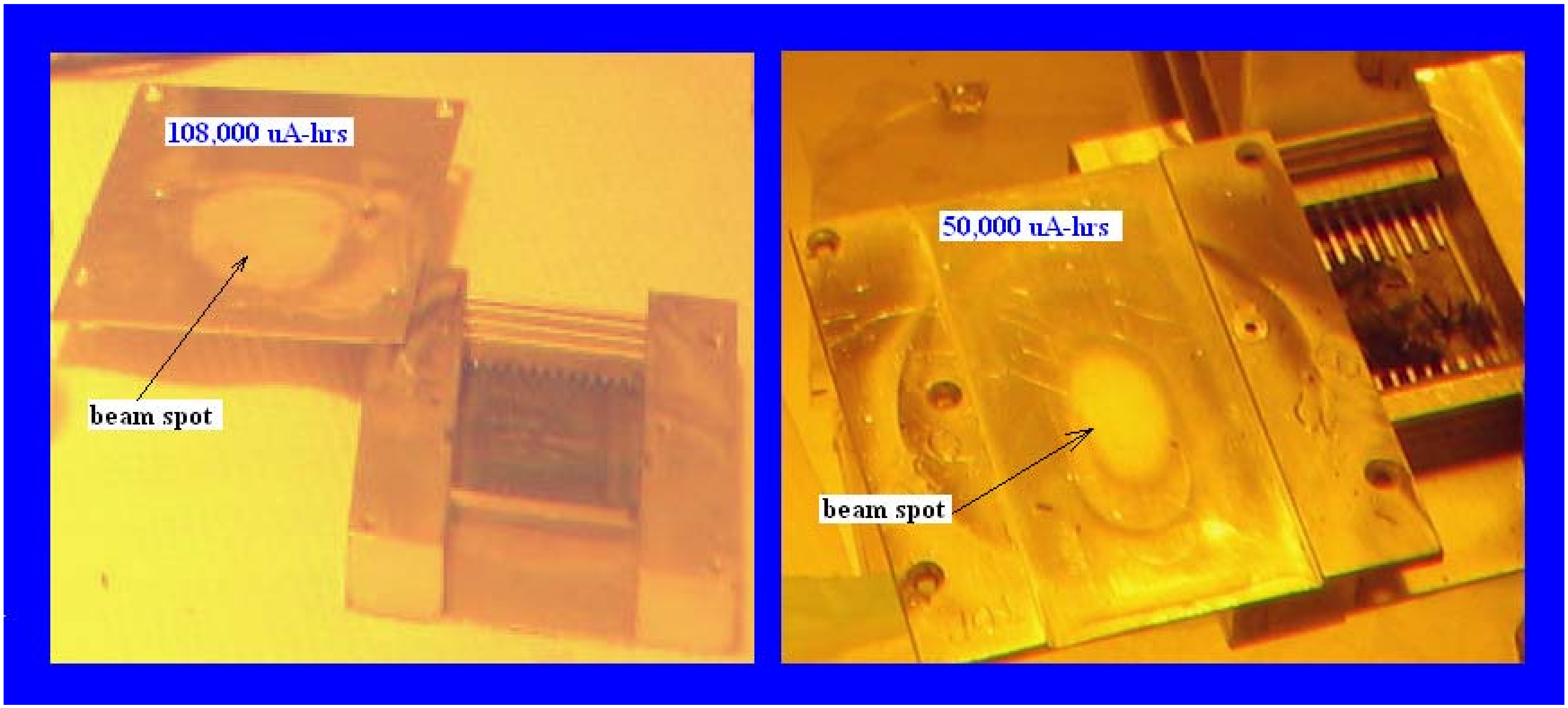
Signs of trouble !!

“weak” reinforcing fiber orientation

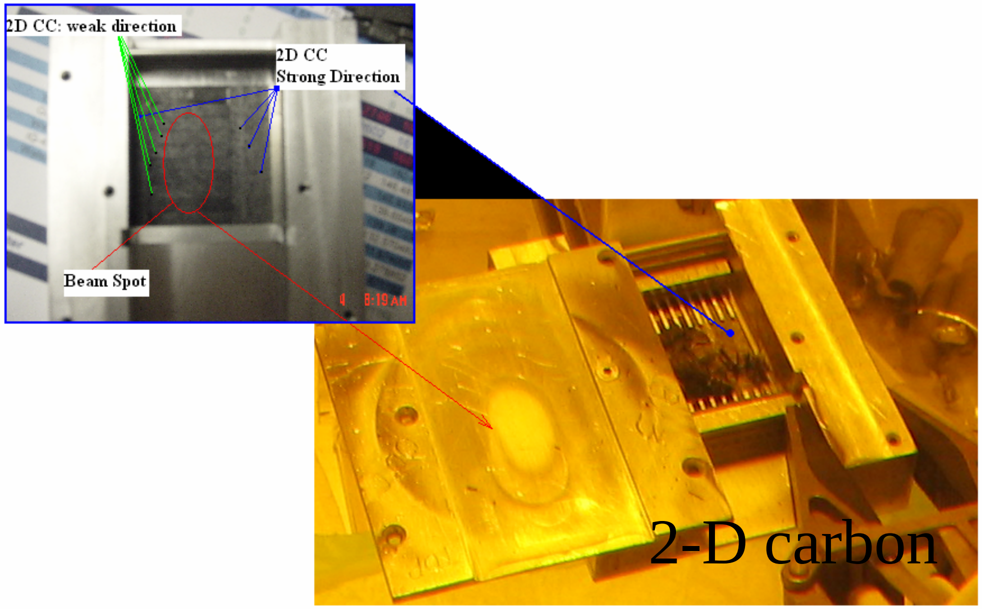


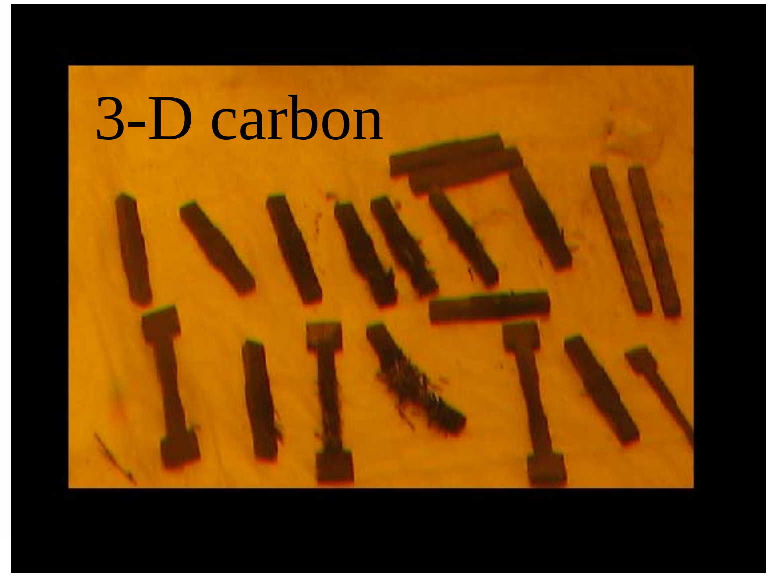
CONCERN: is damage characteristic of the 2-D structure or inherent to all carbon composites?

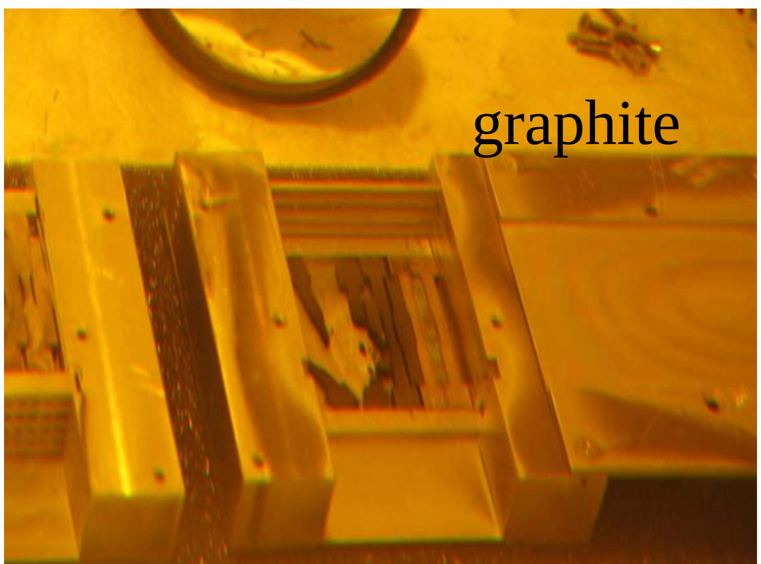
Follow-up Irradiation Phase for 2-D; 3-D Carbon composites and Graphite



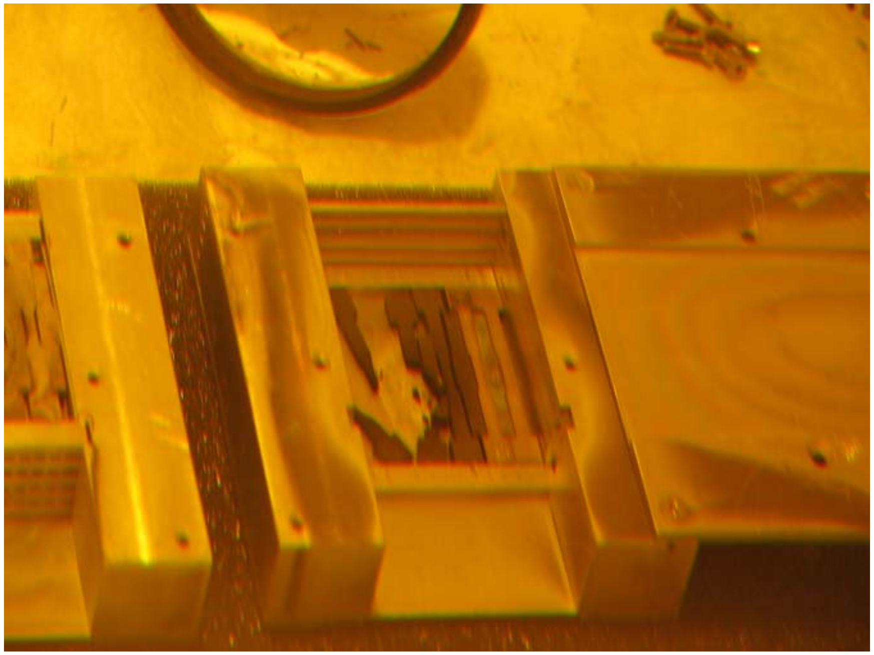
Condition of most heavily bombarded specimens after irradiation (fluence ~10^21 p/cm2)

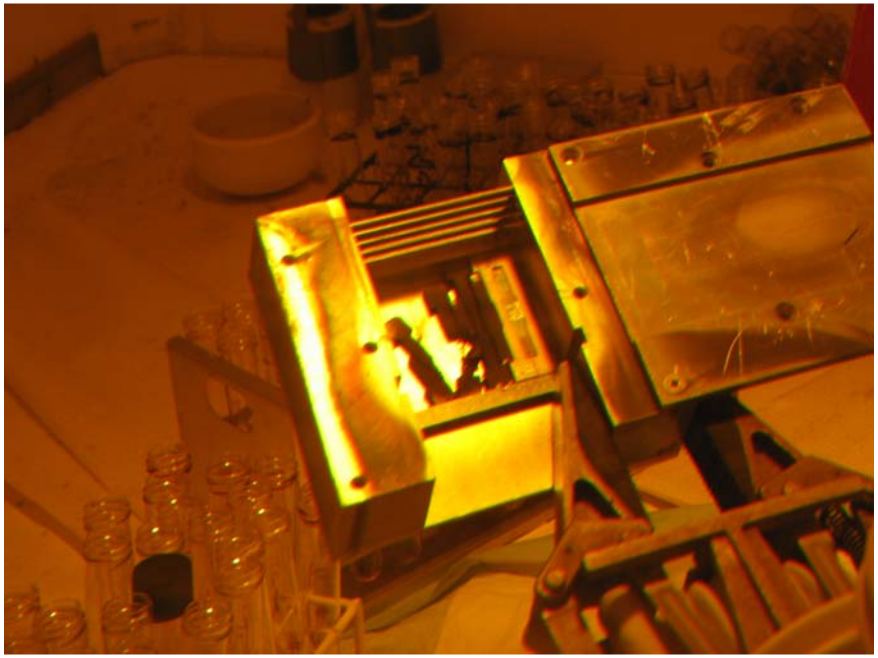






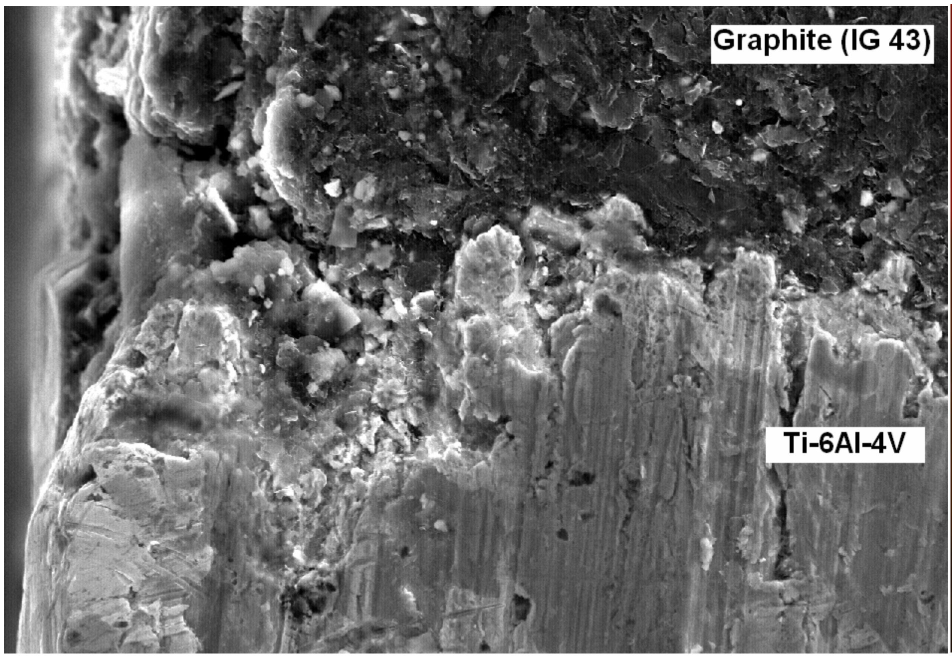
Damage in Graphite

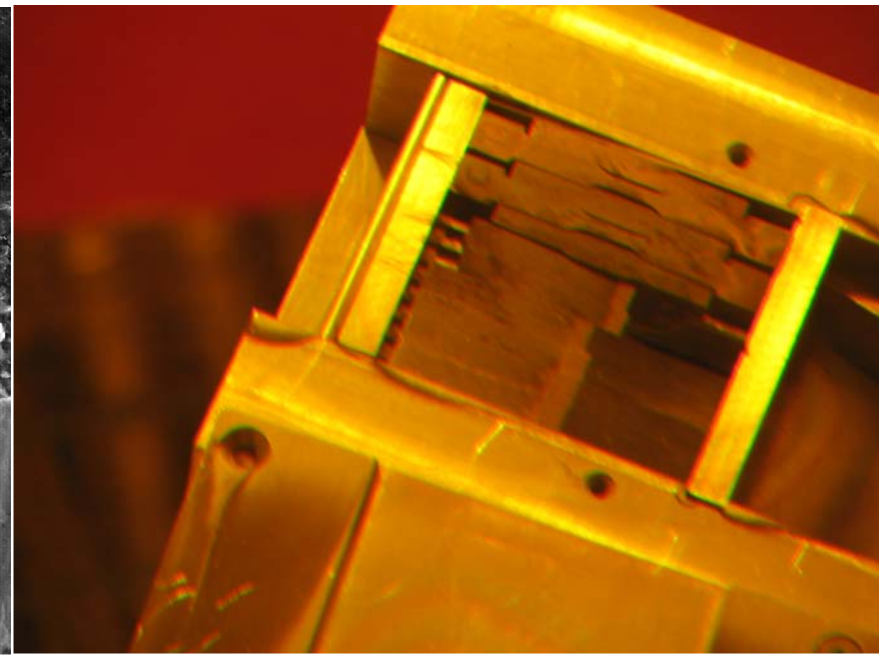




Graphite – Irradiation Effects on Bonding

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)

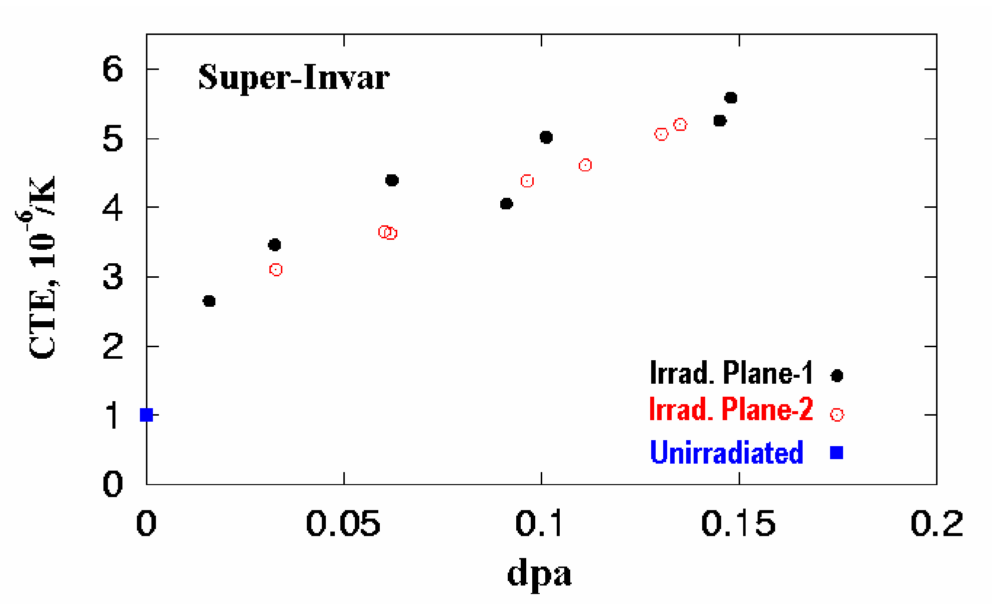




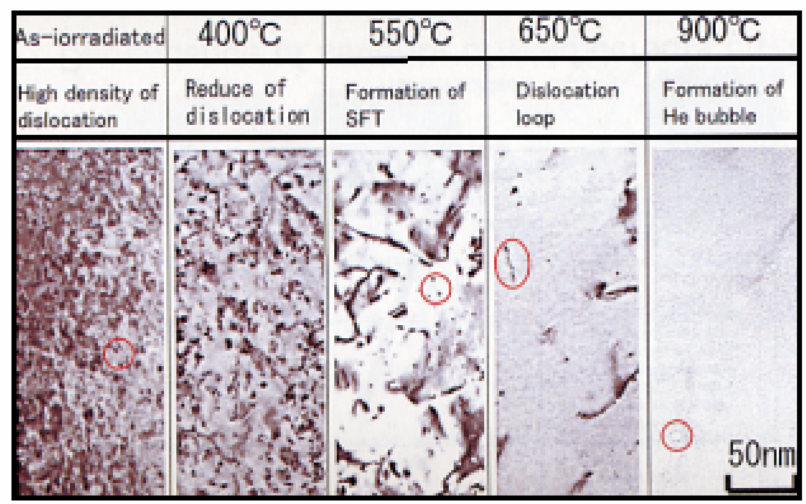
Irradiation studies on super-Invar

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

Effect of modest irradiation



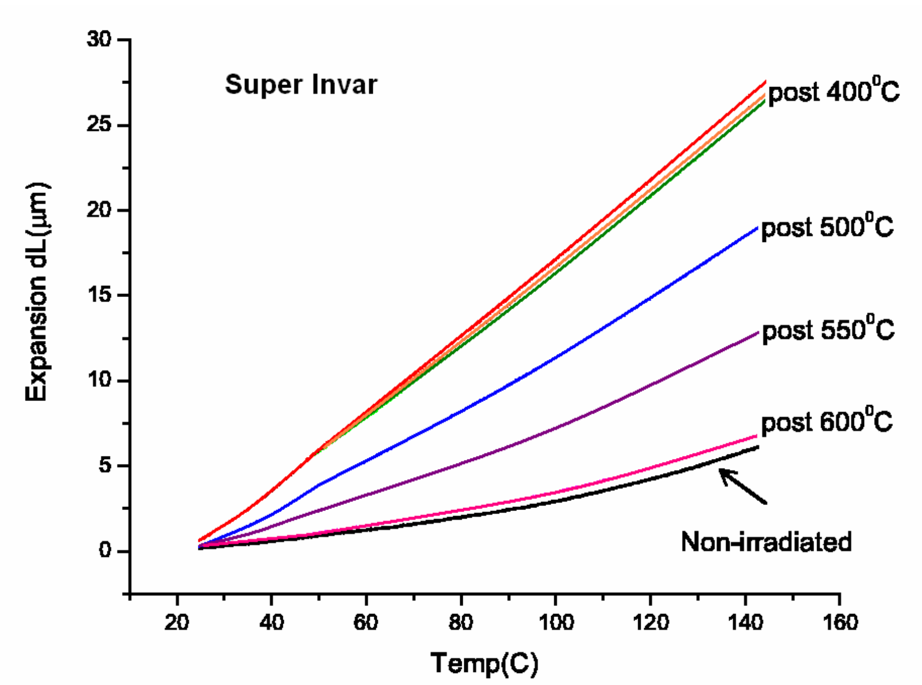
Annealing or defect mobility at elevated temperature



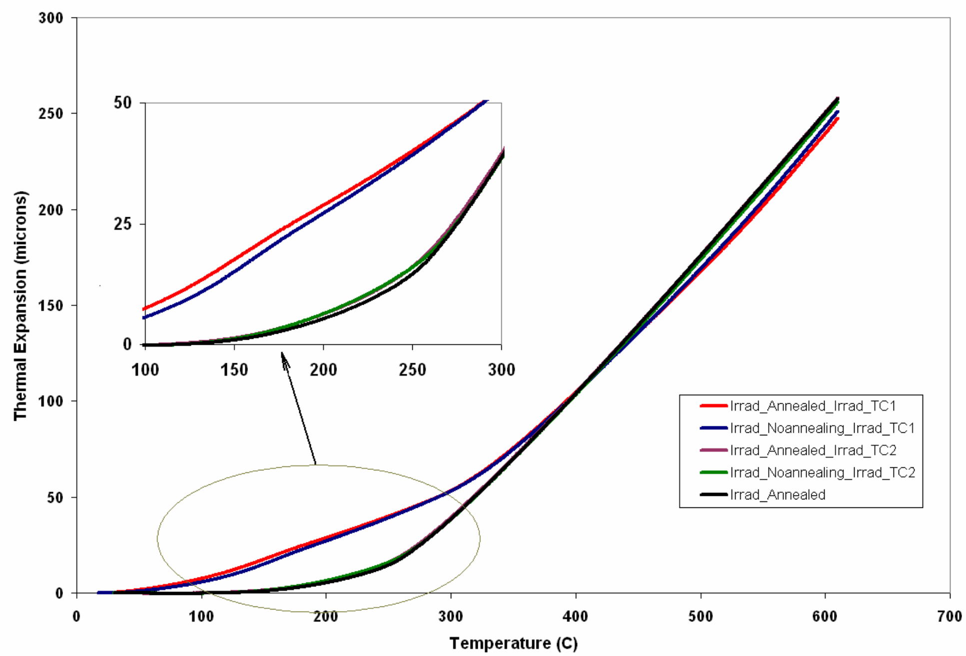
Y. Ishiyam et. al., J. Nucl. Mtrl. 239 (1996) 90-94

“annealing” of super-Invar

Following 1st irradiation

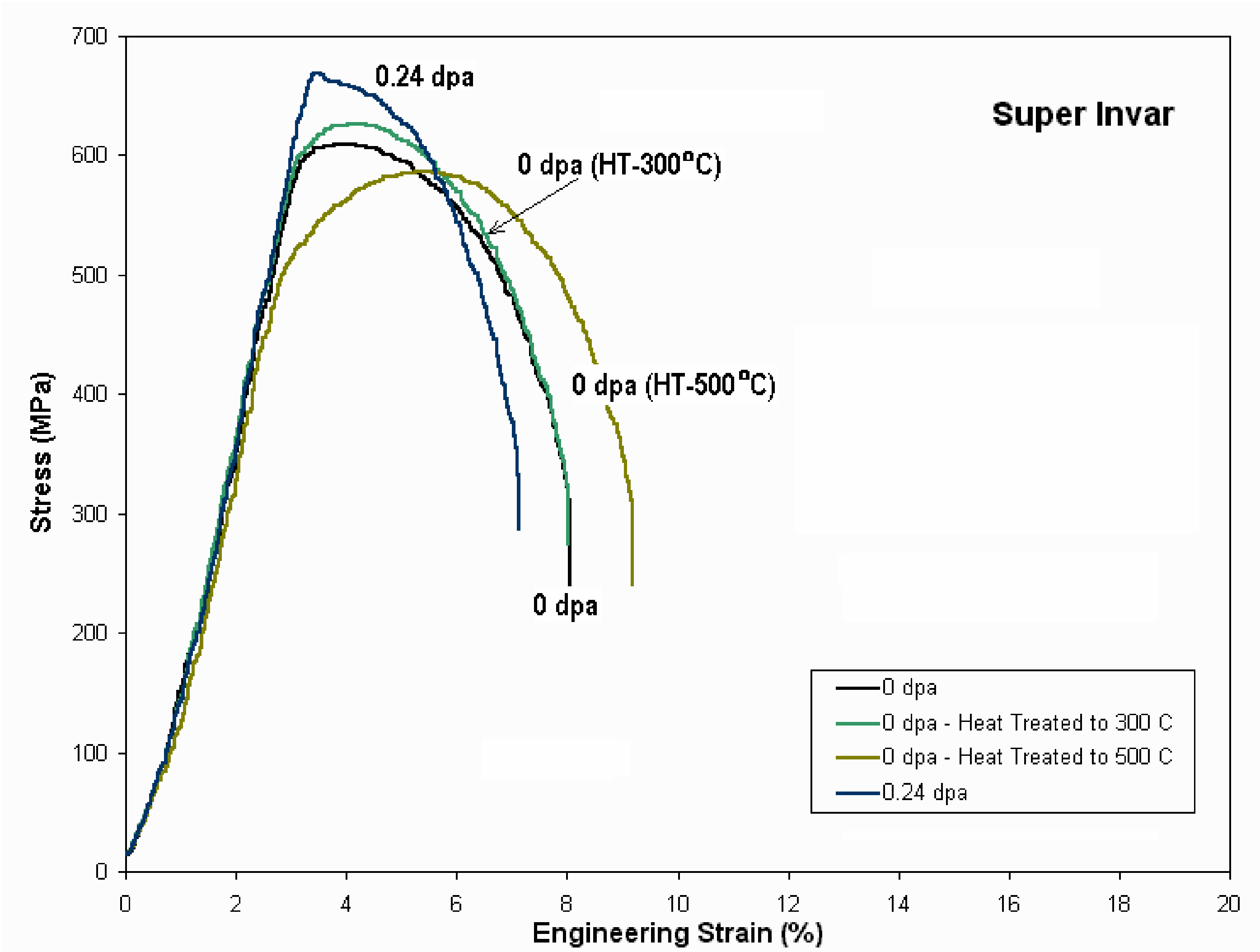


Following annealing and 2nd irradiation

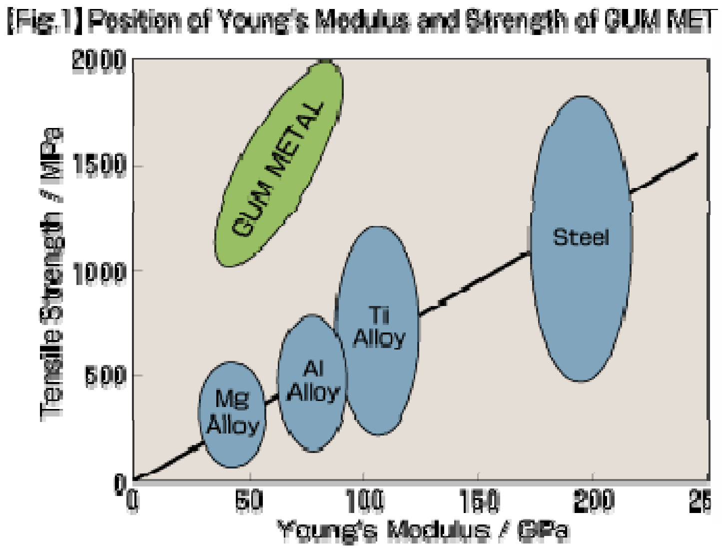


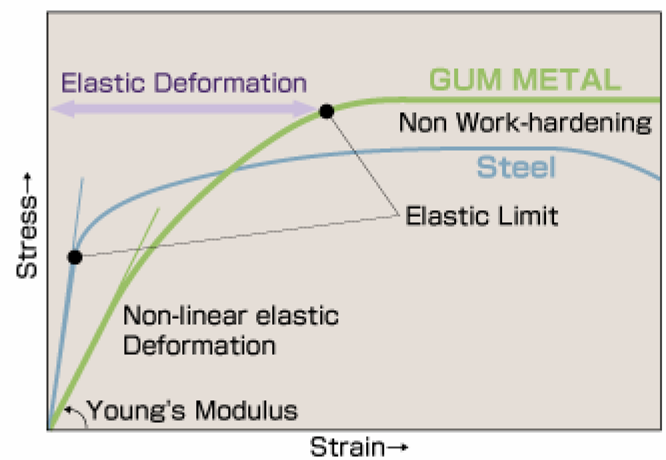
ONGOING 3rd irradiation phase: neutron exposure

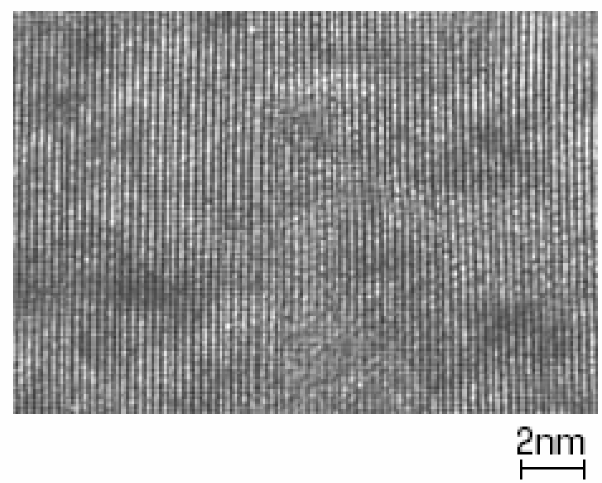
super-Invar stress-strain



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



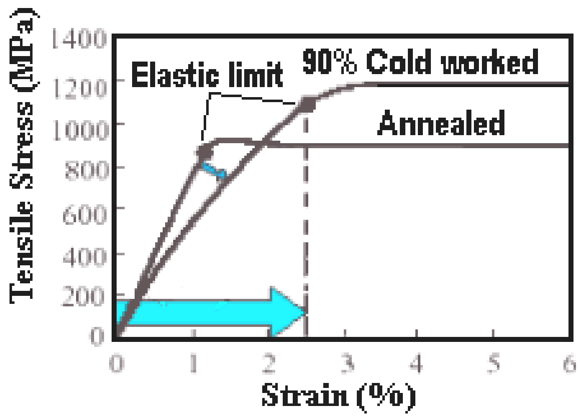


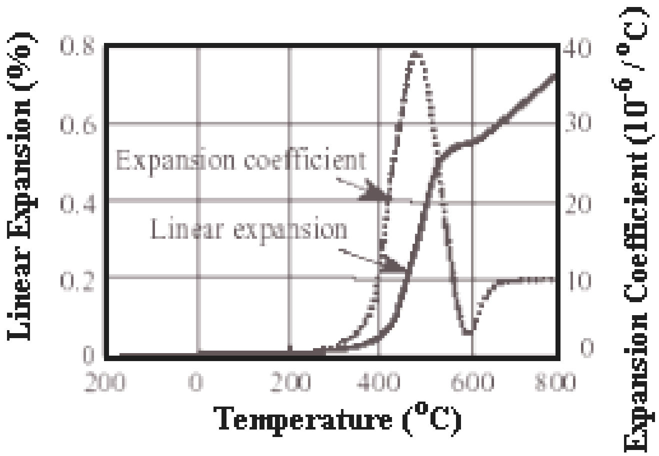


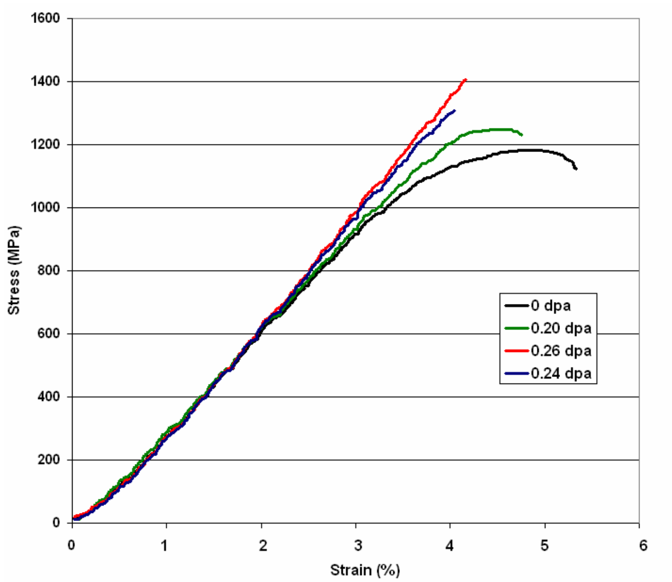
- **Super elasticity**
- **Super plasticity**
- **Invar property (near 0 linear expansion) over a wide temp range**
- **Elinvar property (constant elastic modulus over a wide temp range)**
- **Abnormality in thermal expansion “unrelated” to phase transformation**
- **It exhibits a dislocation-free plastic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

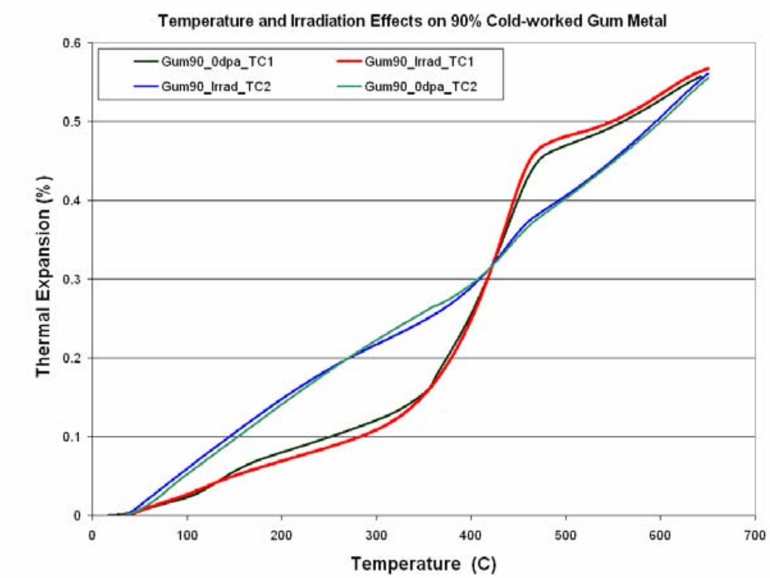
RESULT of cold-working !!!

Effects of radiation and temperature on Gum metal

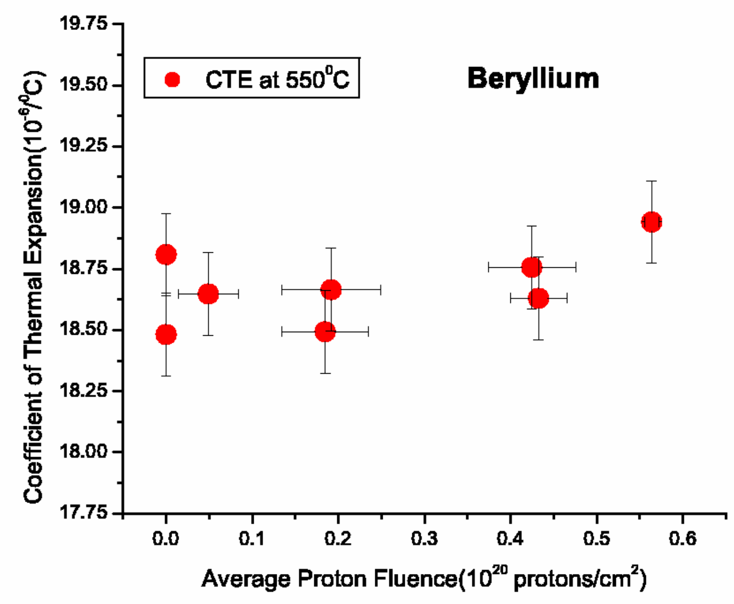


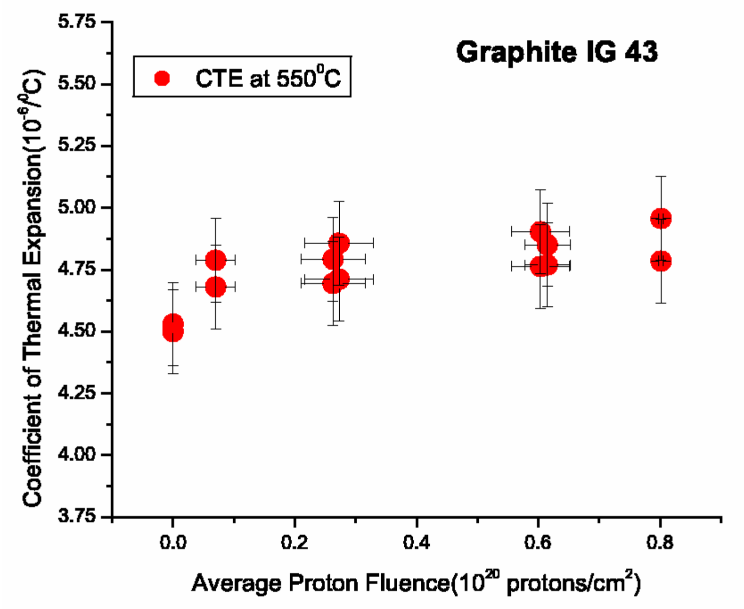




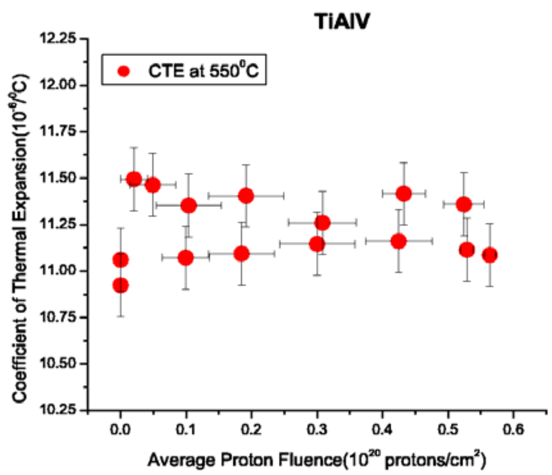


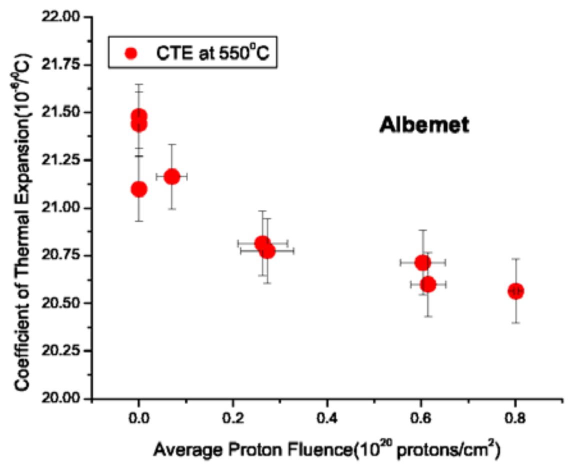
Radiation Damage Studies – Promising Materials

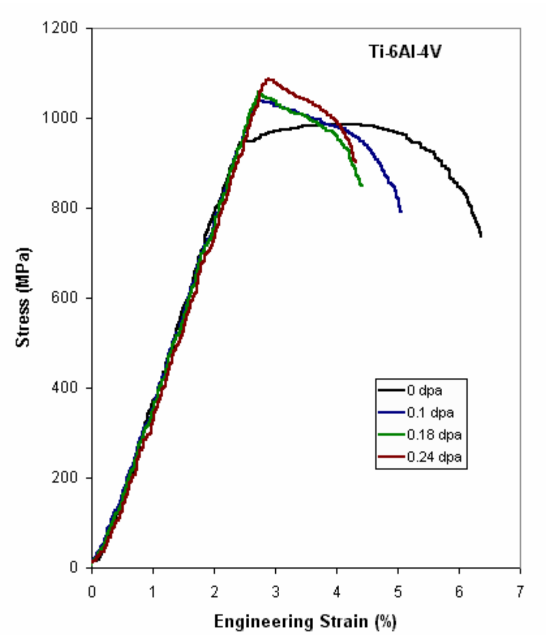


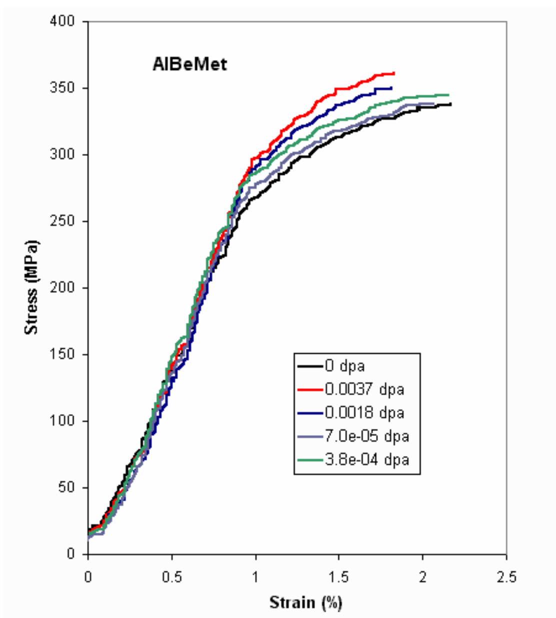


Radiation Damage Studies – Promising Materials

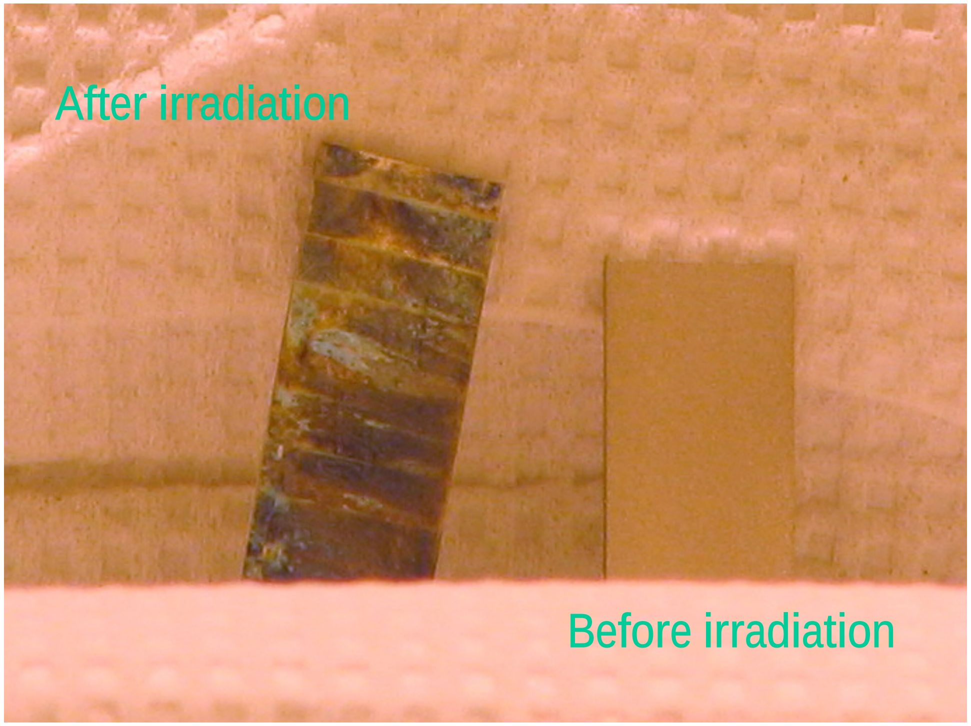






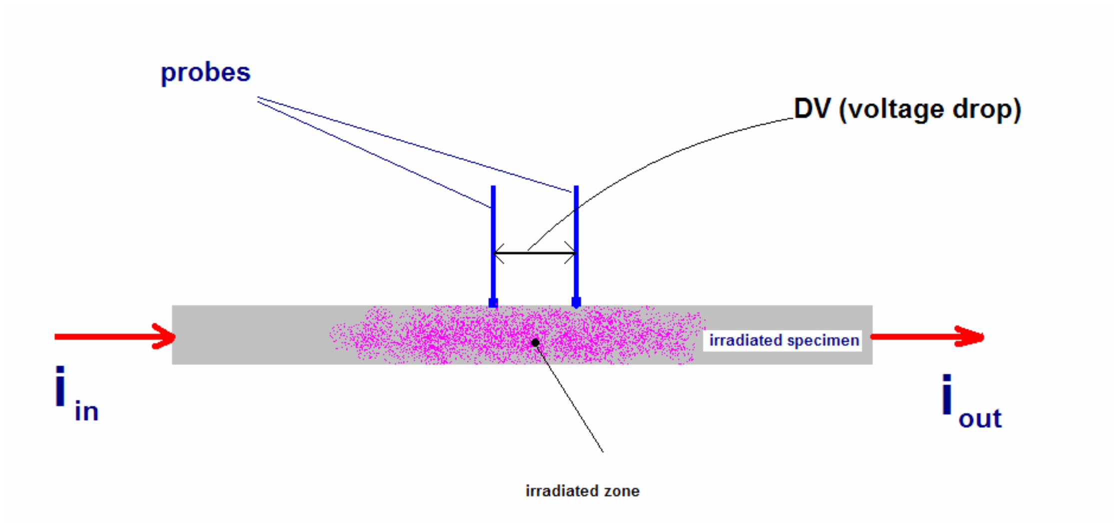


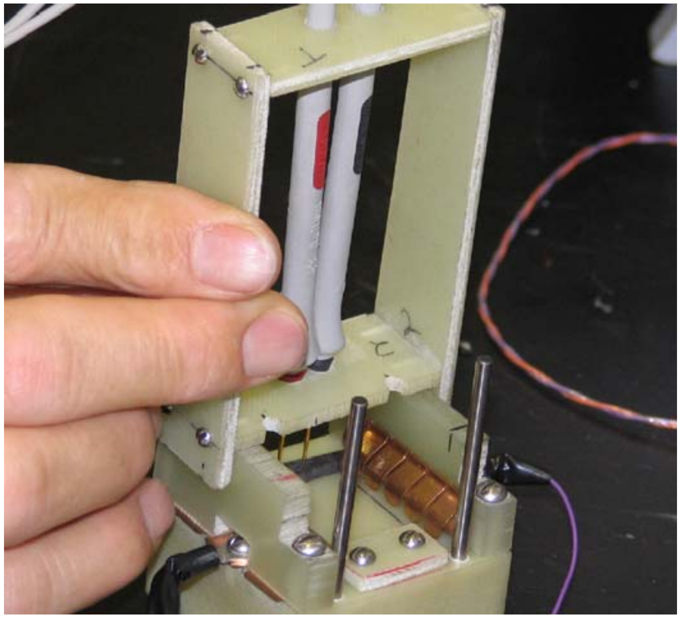
Irradiation effect on magnetic horn
(Ni-plated aluminum)

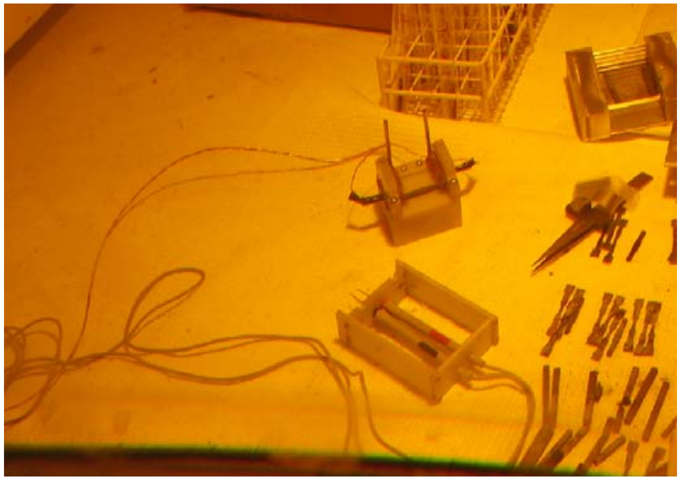


A low-Z material such as AlBemet (need low-Z but with good strength to not impede the flight of pions produced in the target) that has exhibited (thus far) excellent resistance to corrosion while maintaining strength and ductility under irradiation could be the magnetic horn material

Electrical resistivity/thermal conductivity







Some preliminary results

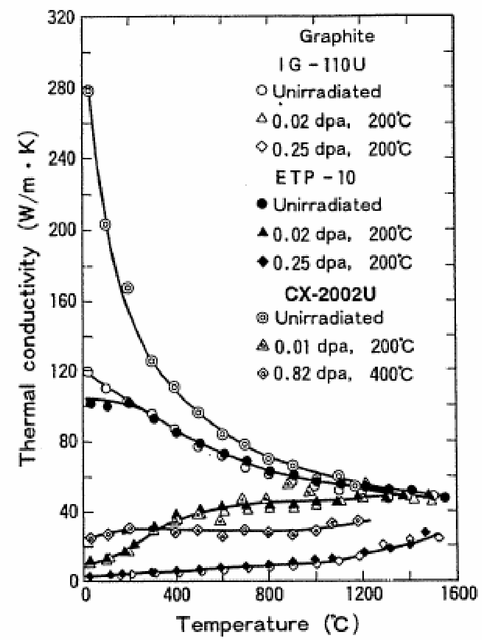
3-D CC (~ 0.2 dpa) conductivity reduces by a factor of 3.2

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

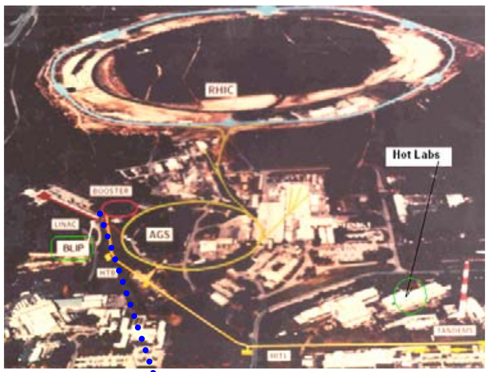
Ti-6Al-4V (~ 1dpa) ➔ ~ 10% reduction

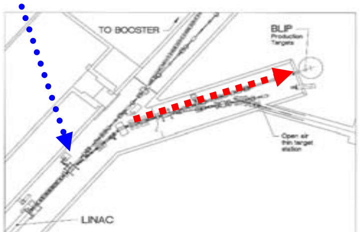
Glidcop ➔ ~ 40% reduction



Thermal conductivity of neutron-irradiated graphites.

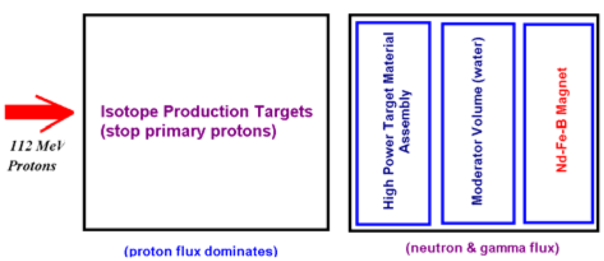
Neutron-Gamma and Electron Irradiation
R&D Using the BNL 112 MeV Linac



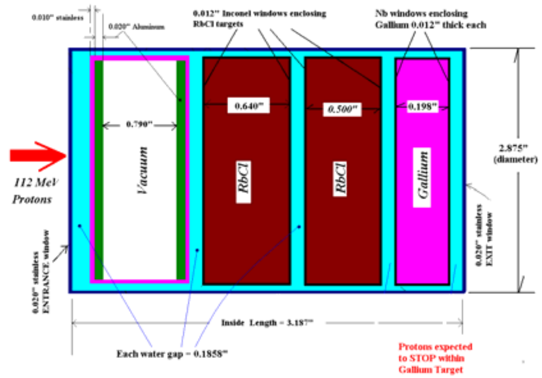


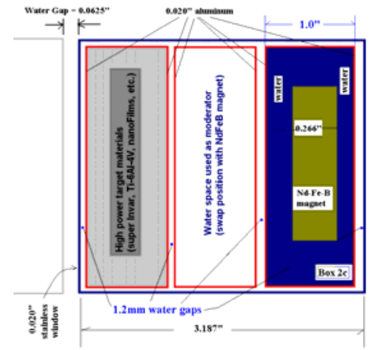
Schematic of BLIP Beam Line

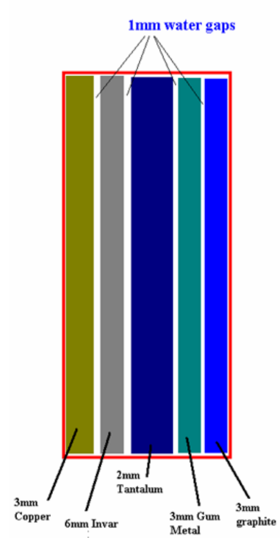
Target Lay-out

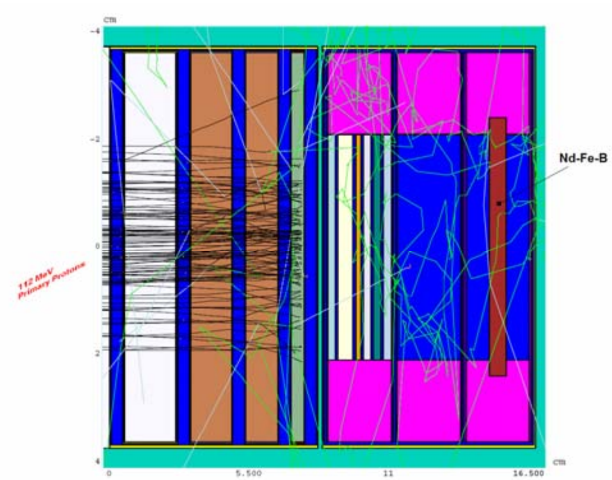


Target Assembly Details









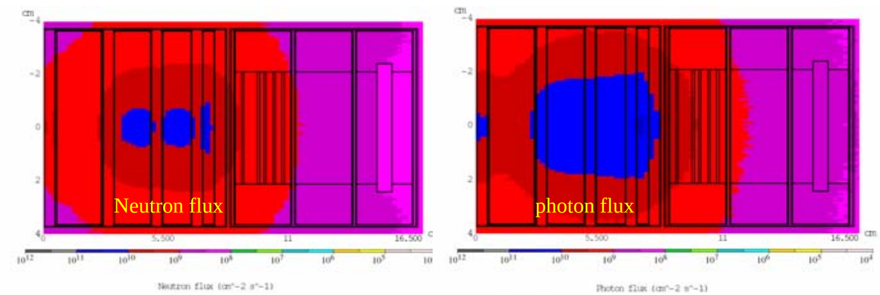
Representation of Entire Test Set-up by MARS model

Primary and secondary particle tracks

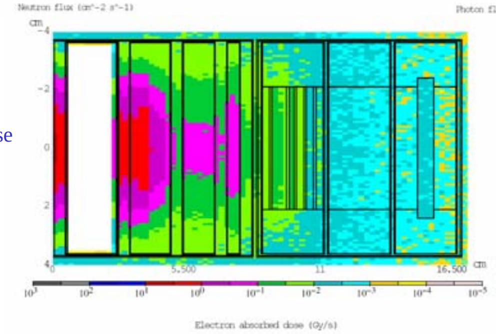
Project-X Workshop Nov. 12-13, 2007

Absorbed Dose, Flux and Spectra

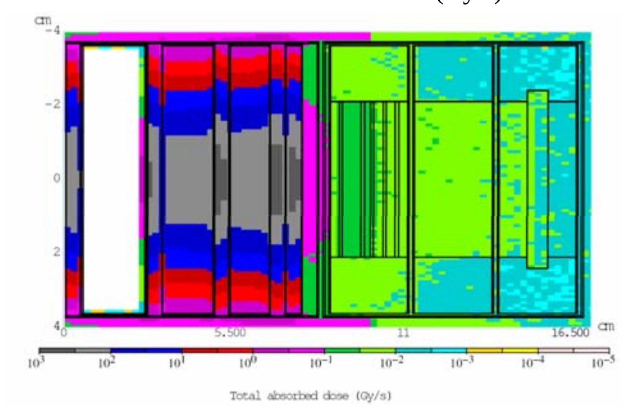
Neutron, gamma and electron fluxes estimates - irradiation damage experiment
Results shown are normalized to 1.0e+12 protons/sec



electron dose (Gy/s)



Total Absorbed Dose (Gy/s)



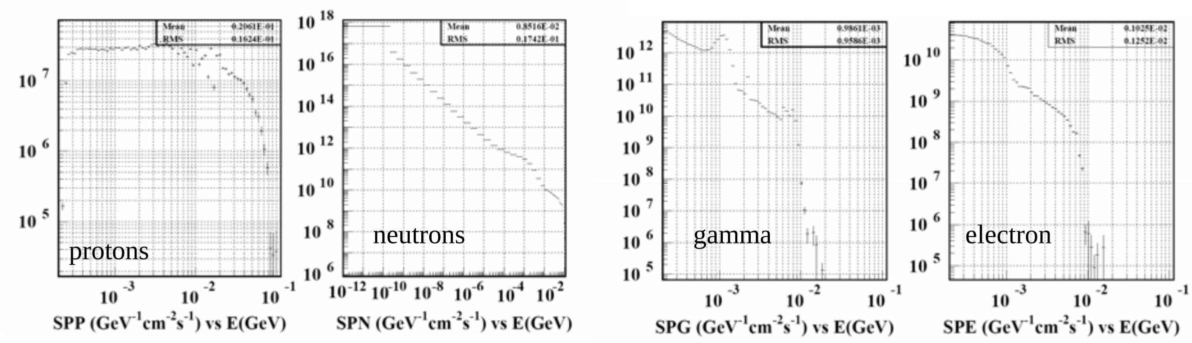
NdFeB Magnet Exposure Summary

Beam and doses received summarized below:

Magnet 1: 78,000 uA-hrs (1.8 Grad)
Magnet 2: 45,000 uA-hrs (1.0 Grad)
Magnet 3: 50,000 uA-hrs (1.2 Grad)
Magnet 4: 11,000 uA-hrs (240 Mrad)
Magnet 5: 2,300 uA-hrs (50 Mrad)

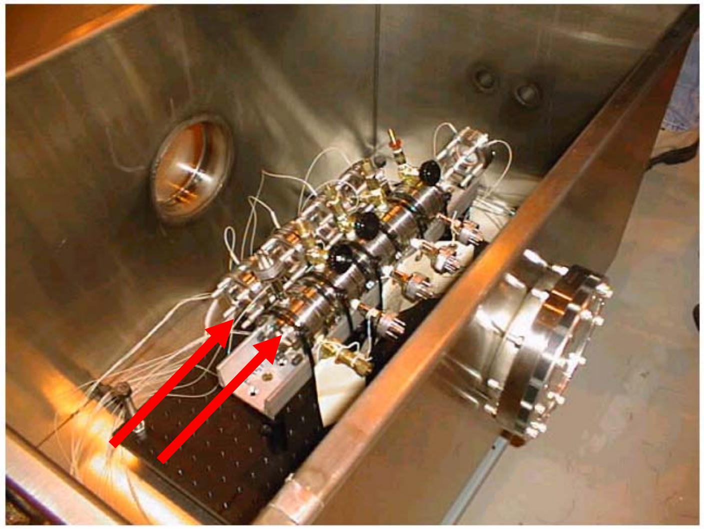
Estimated Energy Spectra (Ti-6Al-4V)

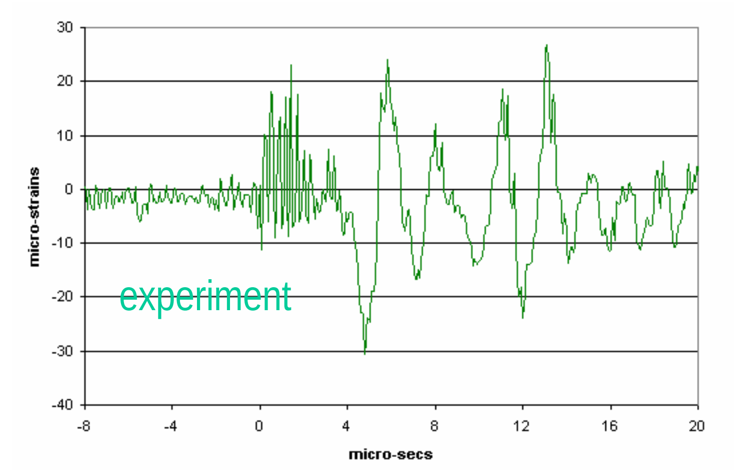
(to be revised using higher statistics in MARS code)

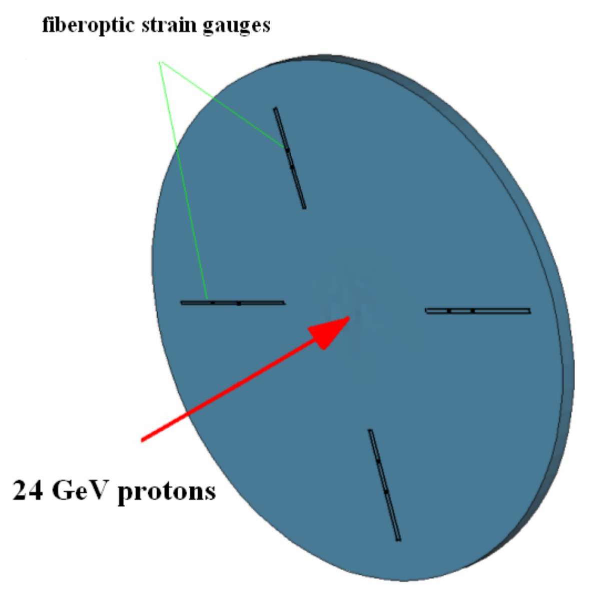


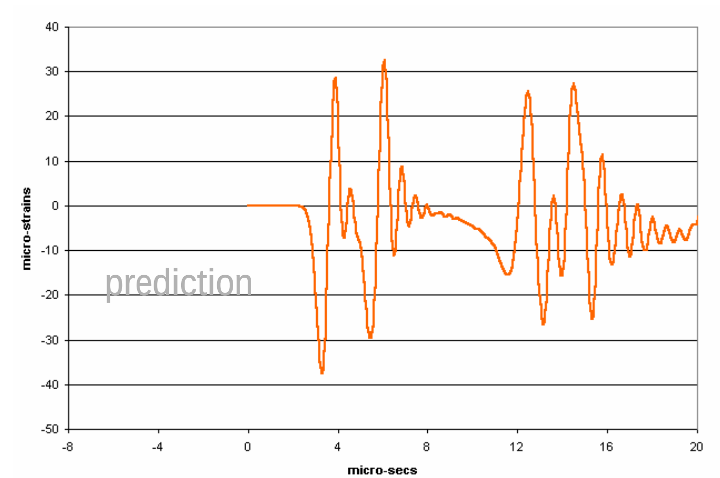
Beam-induced shock on thin windows

1. Havar
2. Inconel-718
3. Ti-6Al-4V
4. Aluminium









SUMMARY

- **Information to-date is available from low power accelerators and mostly from reactor (neutron irradiation) experience. Extrapolation is RISKY**
- **Where should R&D be directed to meet Project-X performance requirements?**
  - **Establishing relationship between neutron and proton damage will render useful the library of data from the neutron community**
  - **Zoom into the response of materials such as graphite (which already has a long relationship with the reactor-neutron community)**
  - **Follow advancements in material technology (alloys, smart materials, composites) provide hope BUT must be accompanied by R&D for irradiation damage**