High Power Target Material R&D

N. Simos, BNL

NFMCC Meeting, UCLA, CA

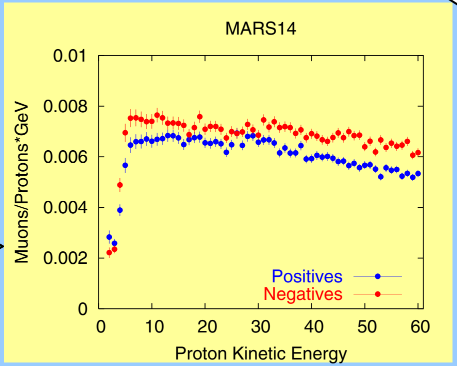
4 MW proton driver?

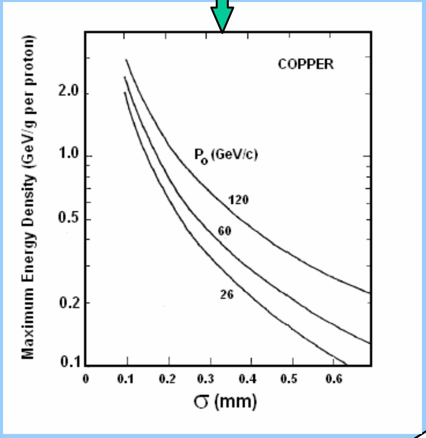
Operational Envelope & Inter-dependency of KEY parameters

Protons per pulse required for 4 MW

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

	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}





Desired bunch length as low as 2 ns !!!

Solid Targets – How far can they go?

1 MW ?	4 MW ?
Answer is **YES** for several materials **Irradiation damage is of primary concern** Material irradiation R&D pushing ever closer to anticipated atomic displacements while considering new alloys are needed	**Answer dependant on 2 key parameters:** 1 – rep rate 2 - beam size compliant with the physics sought A1: for rep-rate > 50 Hz + spot > 2mm RMS ➔ 4 MW possible (see note below) 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 4 MW might prove to be the challenge. CAN only be validated with experiments

R&D on irradiation damage

What does it mean for materials (microscopic & macroscopic terms) ?

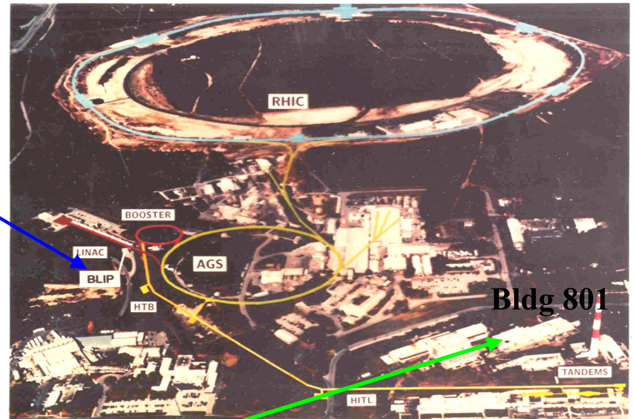
generation of voids/dislocations ➔ changes in physical and mechanical properties
trapping of gases, swelling ➔ density reduction

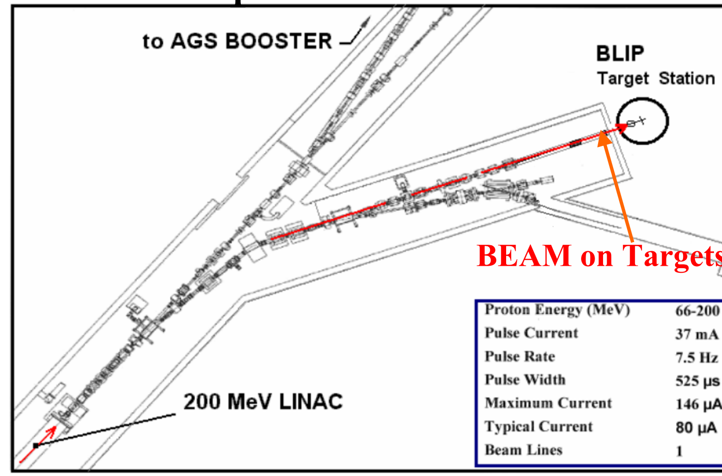
Effects of neutron irradiation from reactor experience

Question: does radiation type matter?

Experimental Process
Utilizing BNL Accelerator Complex

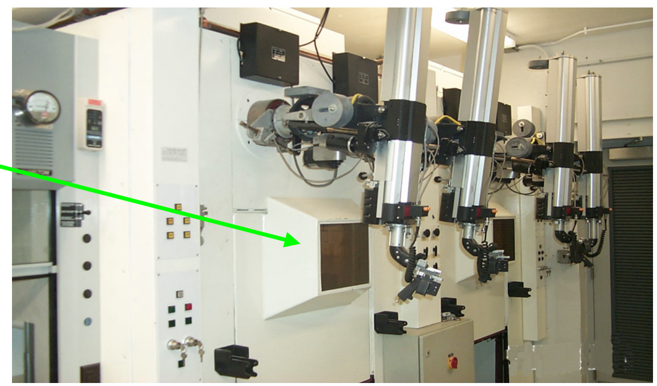
Irradiation takes place at BLIP using 200 MeV or 117 MeV protons at the end of Linac



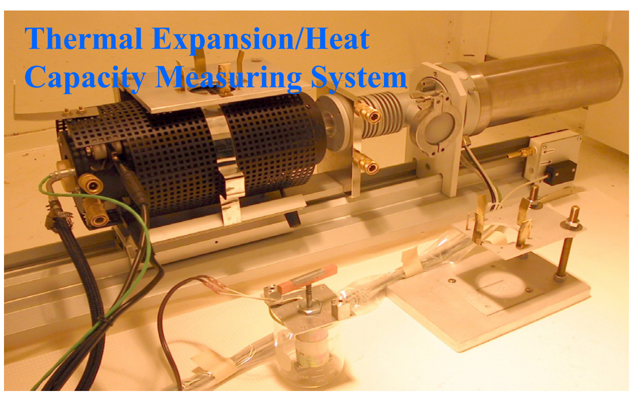


Proton Energy (MeV)	66-200
Pulse Current	37 mA
Pulse Rate	7.5 Hz
Pulse Width	525 μs
Maximum Current	146 μA
Typical Current	80 μA
Beam Lines	1

Post irradiation analysis at BNL Hot Labs



Thermal Expansion/Heat Capacity Measuring System



Remotely operated mechanical testing system

IRRADIATION STUDIES

PHASE I:

Super Invar and Inconel-718

PHASE II:

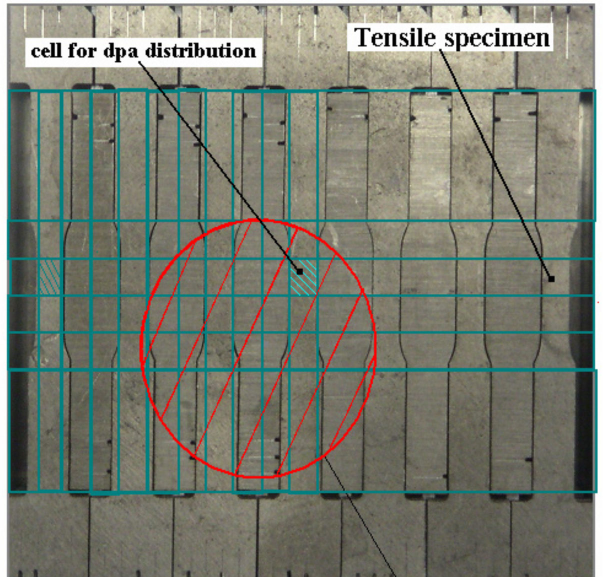
- 3D Carbon-Carbon Composite
- Toyota "Gum Metal"
- Graphite (IG-43)
- AlBeMet
- Beryllium
- Ti Alloy (6Al-4V)
- Vascomax
- Nickel-Plated Alum.

PHASE II-a:

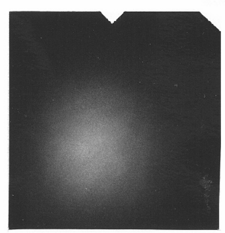
•2D Carbon-Carbon

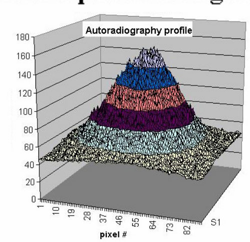
PHASE III:

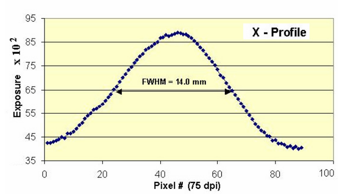
- 3D & 2D Carbon-Carbon
- 90% cold-worked "Gum Metal"
- Graphite (IG-43 & IG-430)
- AlBeMet
- Ti Alloy (6Al-4V)
- Copper & Glidcop
- W and Ta
- Vascomax
- Nickel-Plated Aluminum
- Super-Invar ➔ following annealing
- Graphite/titanium bonded target

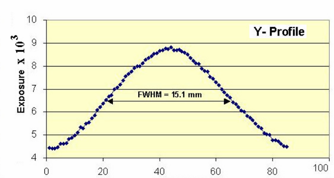


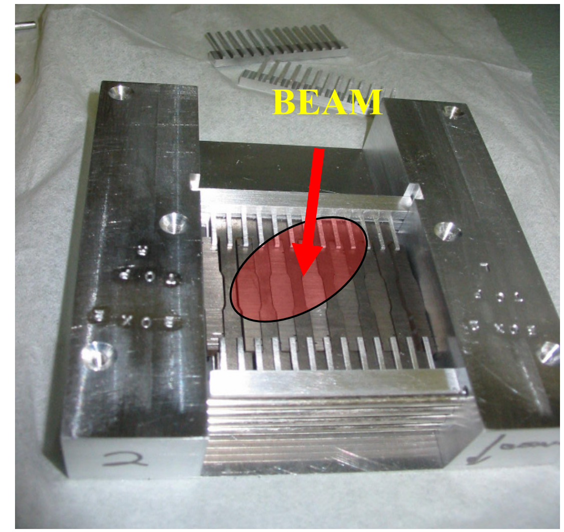
Beam footprint on targets (1σ)

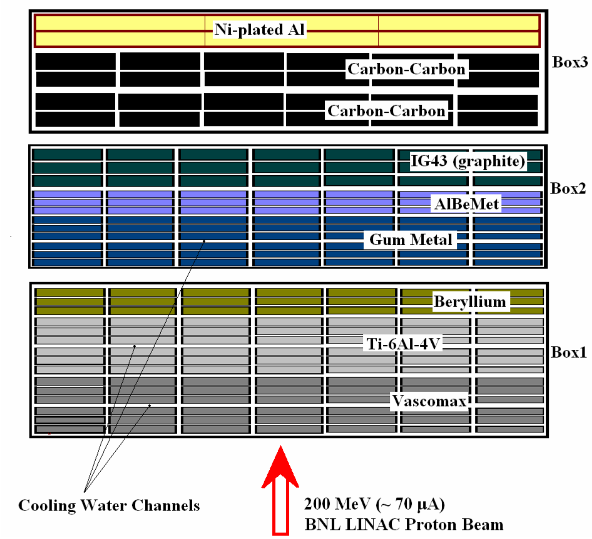




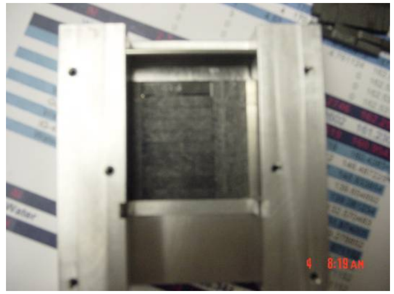
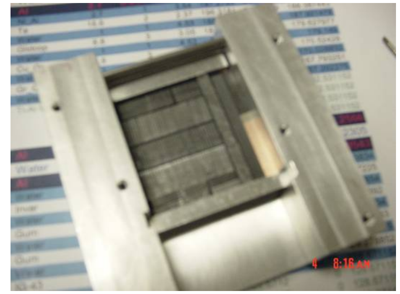
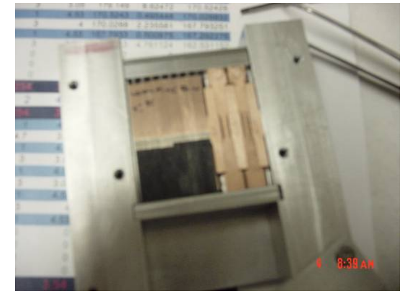
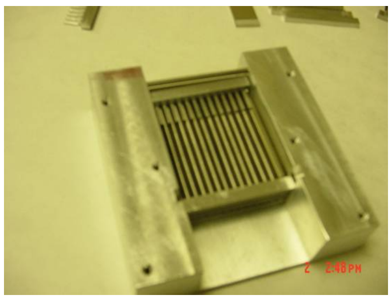
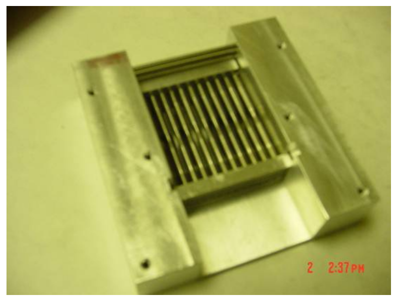
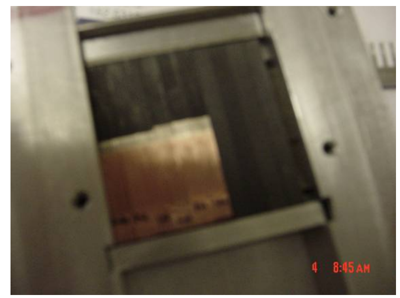
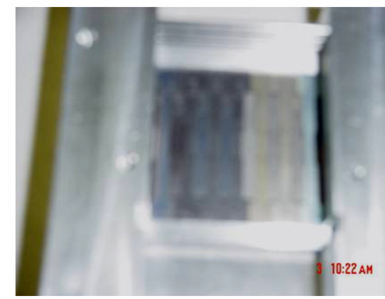
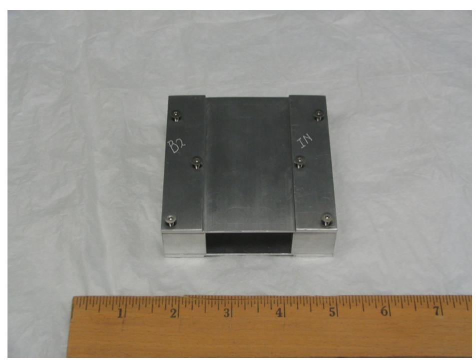




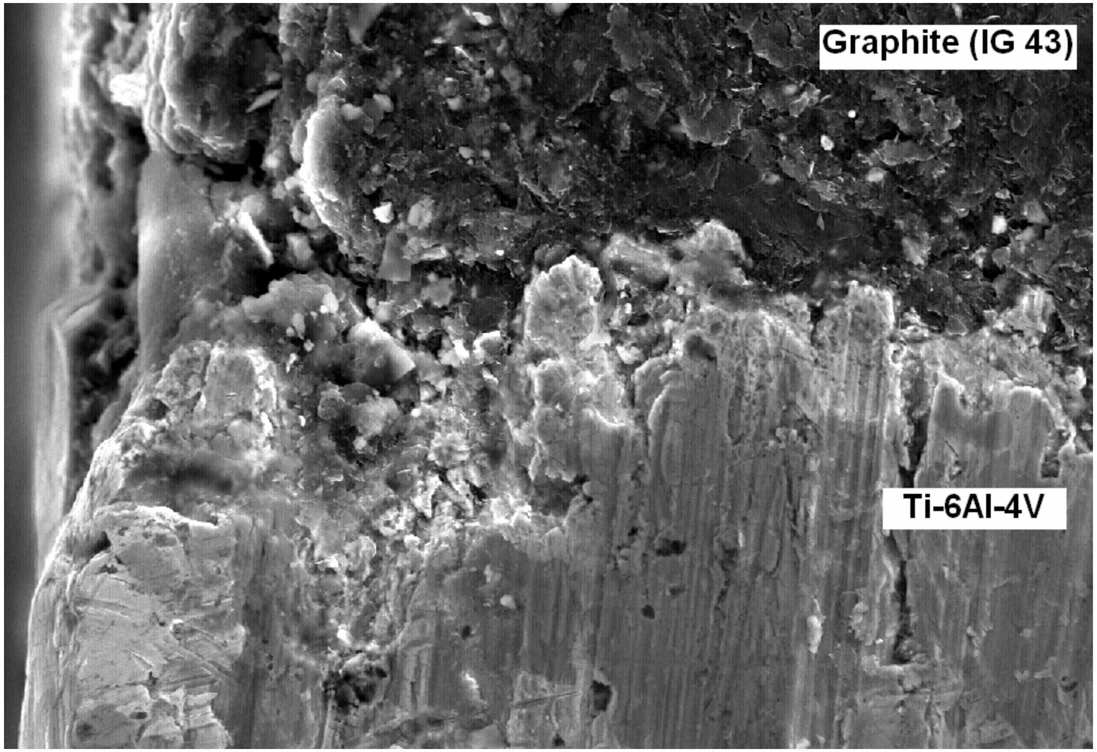




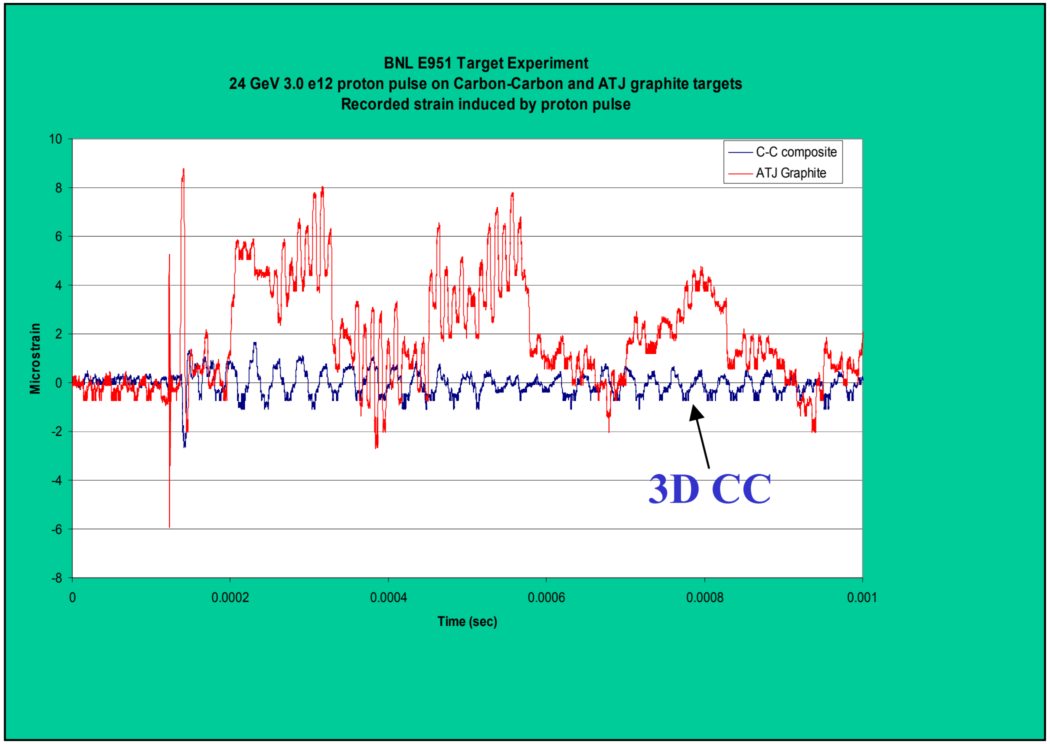
PHASE III - Preparations

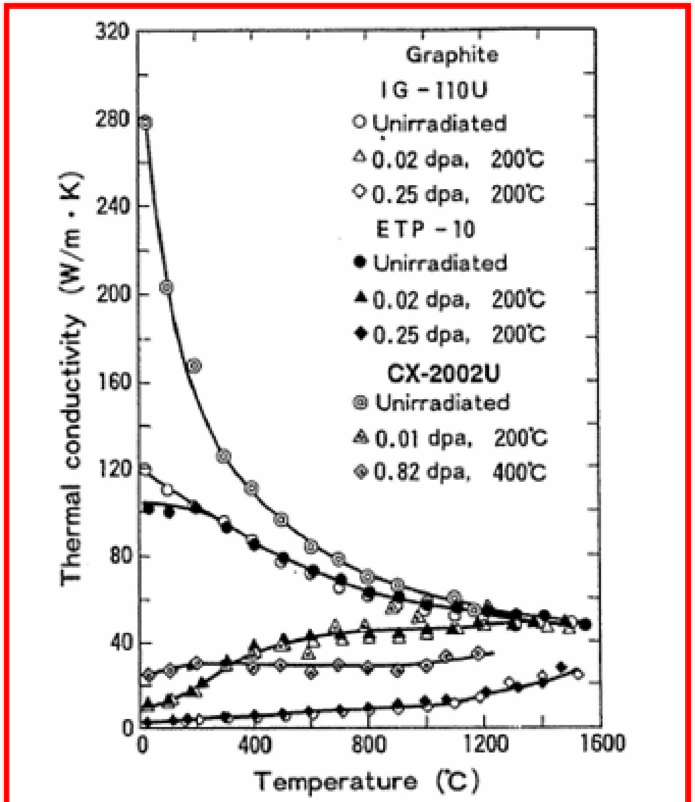










Specially bonded graphite/titanium target exposed to proton irradiation



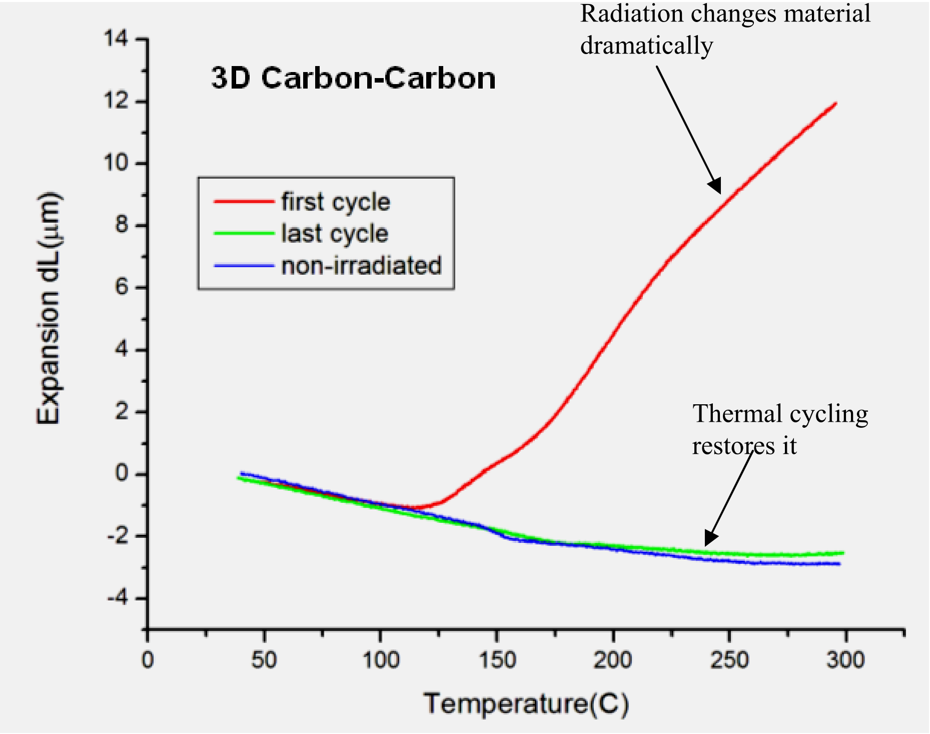
Graphite vs. Carbon-Carbon



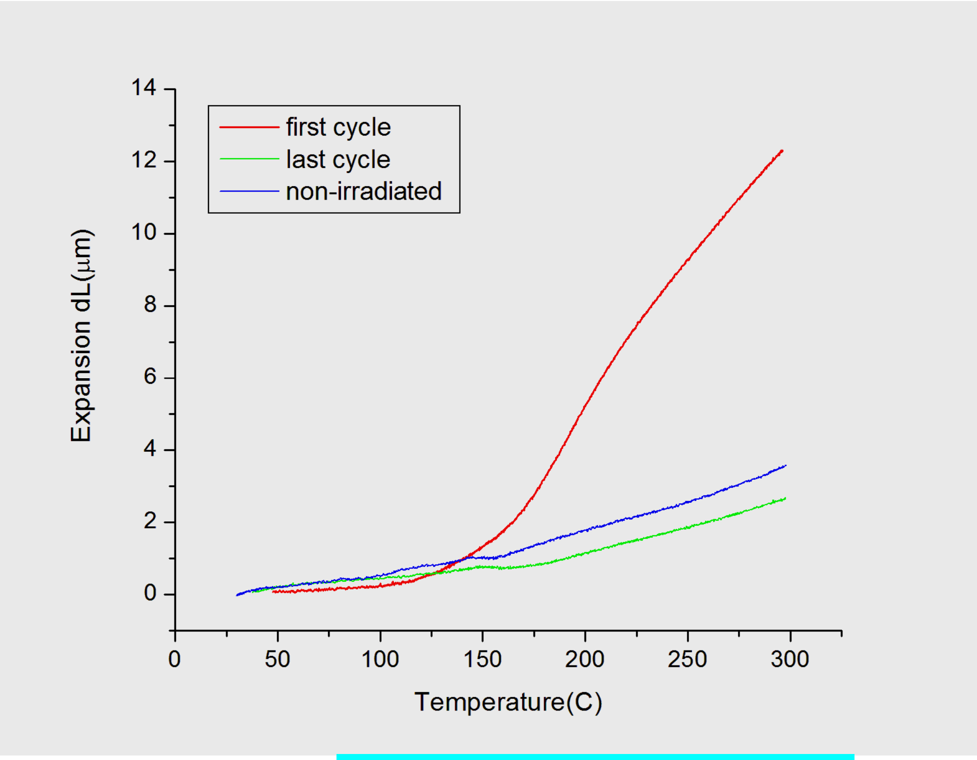


Thermal conductivity of neutron-irradiated graphites.

3D CC Annealing Behavior !!



90-degree fiber orientation



45-degree plane ("weak" orientation)

Good news were associated with modest beam exposure (~ 25,000 uA-hrs). More needed to be done to validate that carbon composites can replace graphite.

Embarked into a 2-phase new study

Phase 1 ➔ Assess the 2D carbon-carbon under heavy irradiation

Phase 2 ➔ Expose 2D & 3D carbon-carbon composites under identical experimental conditions

Phase-1: 2D Carbon Composite

PEAK integrated flux achieved **~ 7 x 10^21 protons/cm^2**

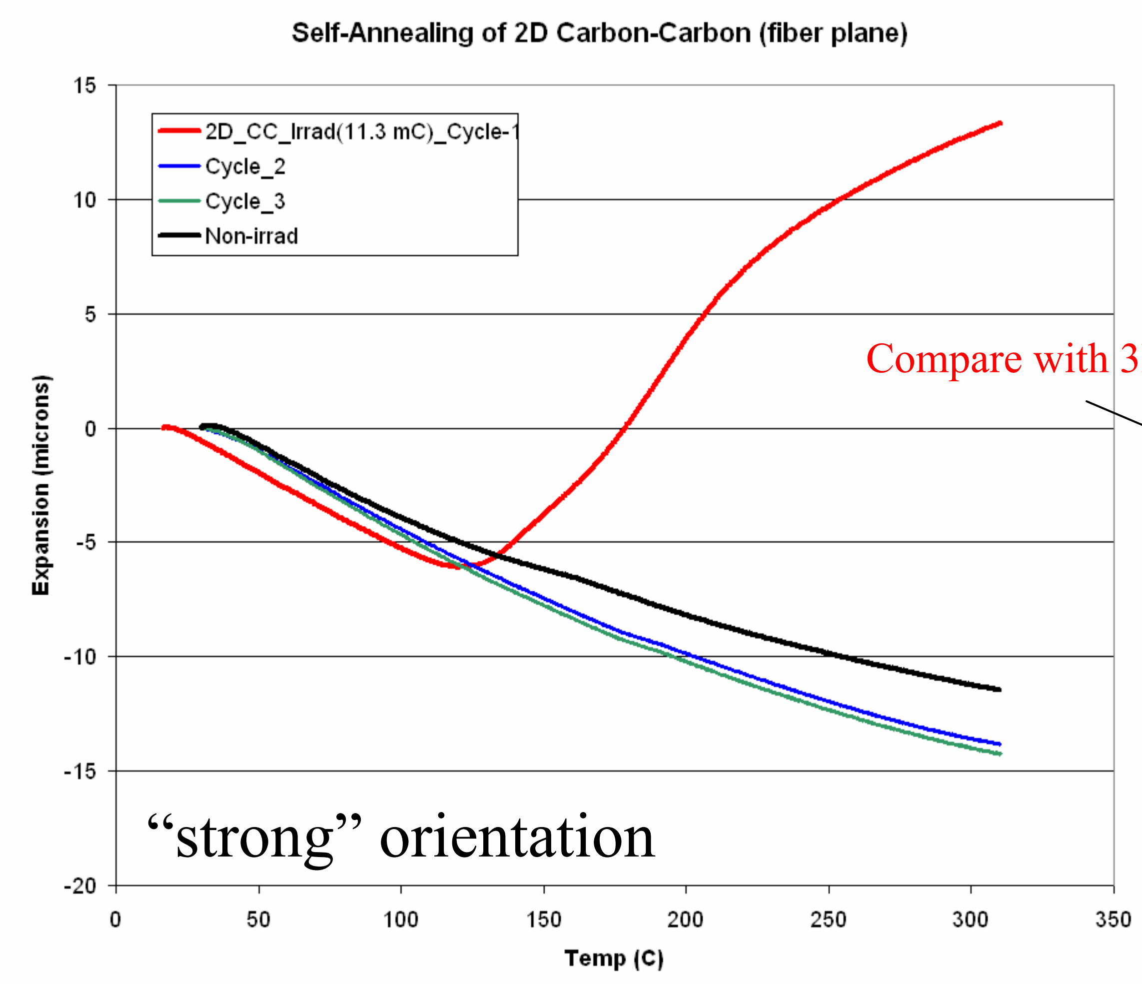
Integrated beam current ~ 108,000 uA-hrs

Post-irradiation analysis of the exposed 2-D carbon composite revealed both good and bad news:

GOOD NEWS: the composite exhibits self-healing behavior (as in the case of the 3-D counterpart)

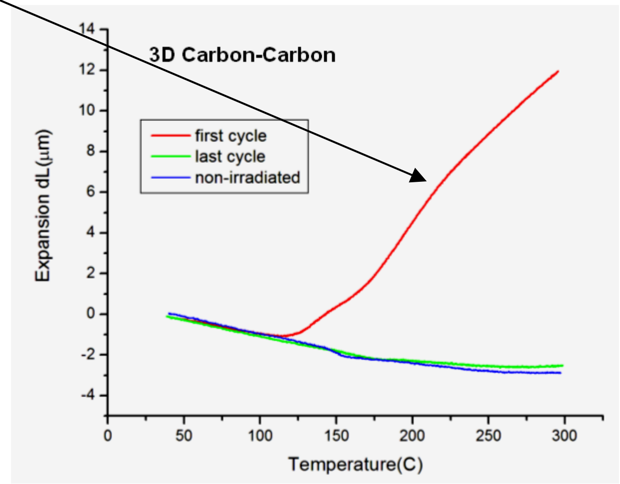
BAD NEWS: Serious structural degradation is observed as a result of high fluences
Damage more pronounced along the "weak" orientation

Good News: 2D carbon composite exhibits self-healing through thermal annealing

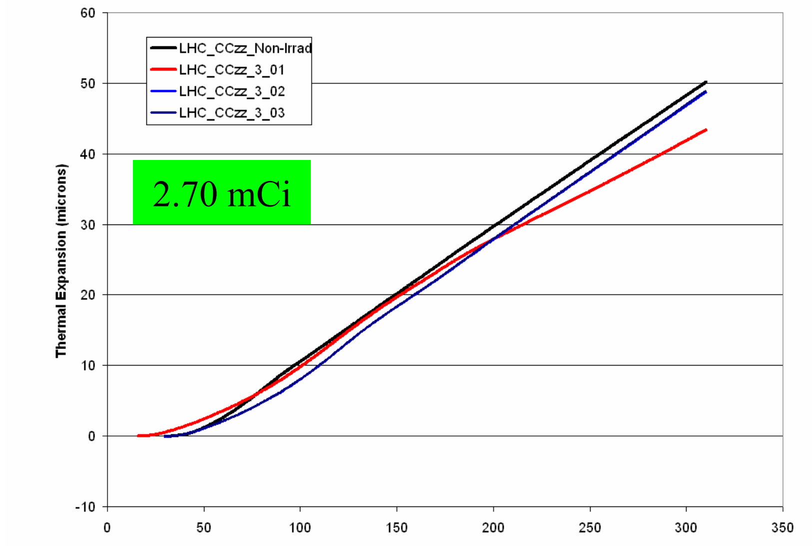


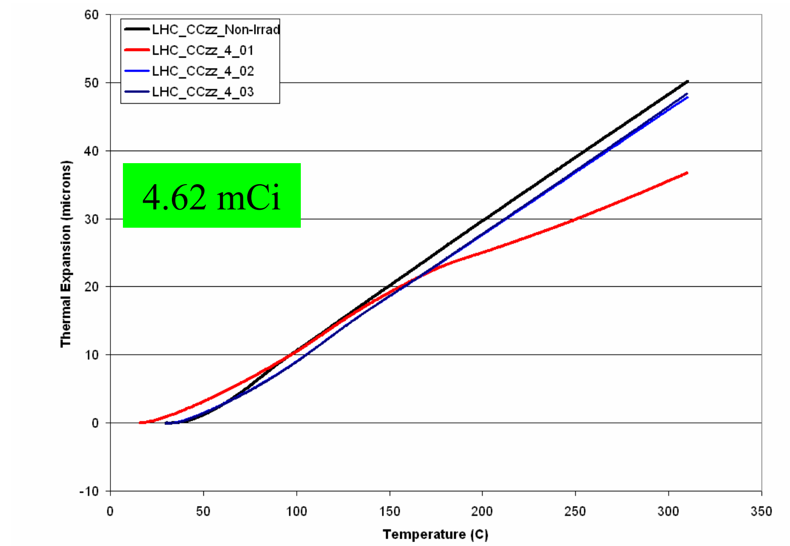
“strong” orientation

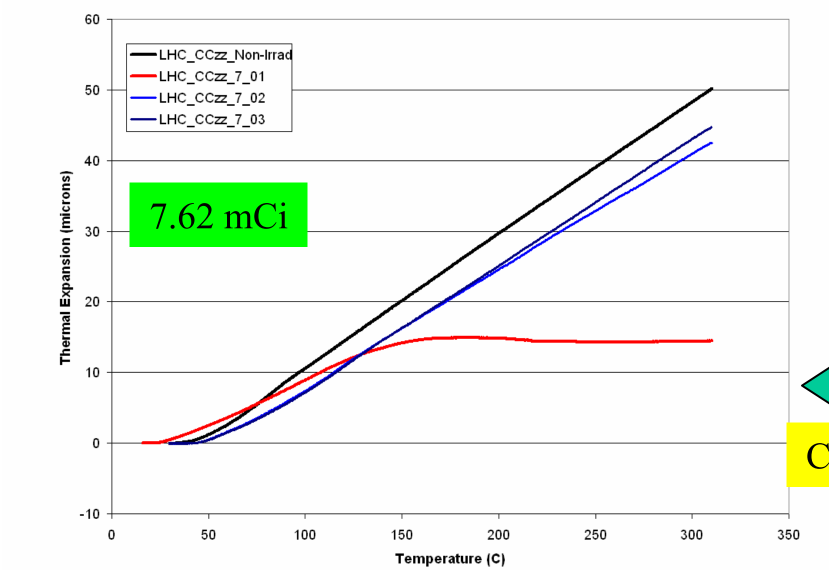
Compare with 3D counterpart



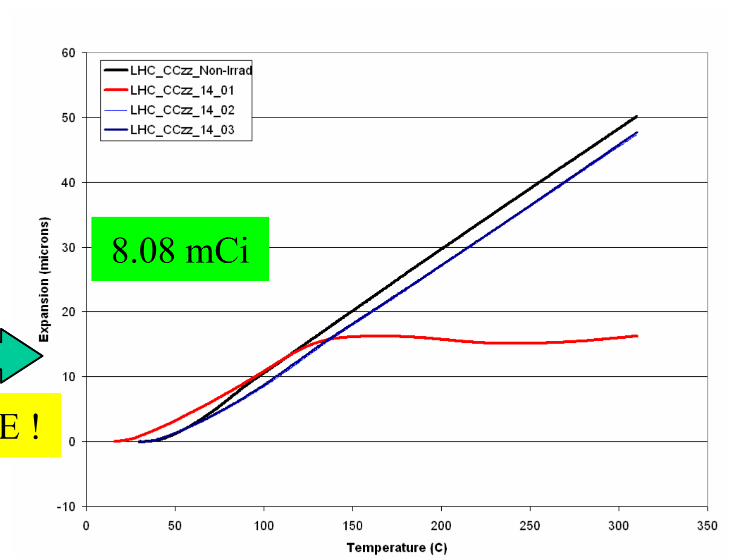
How well is our nanometer-level analysis controlled/stabilized?





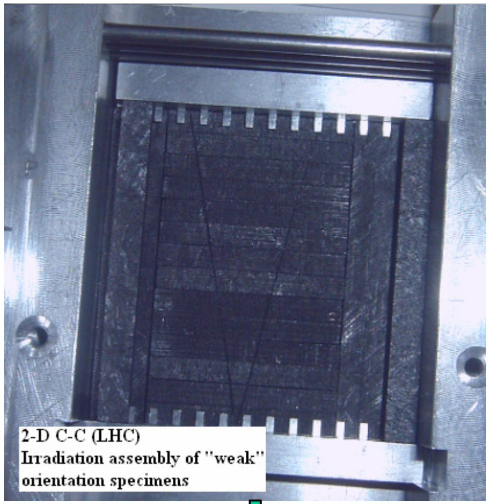


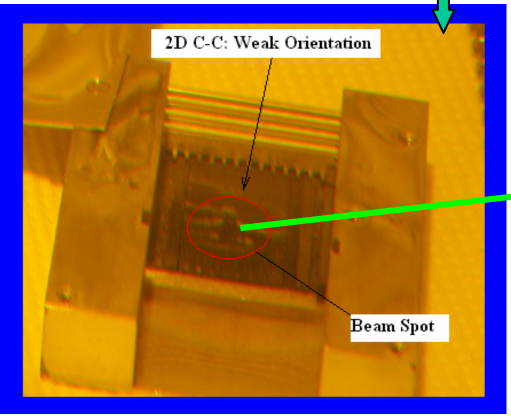
COMPARE !

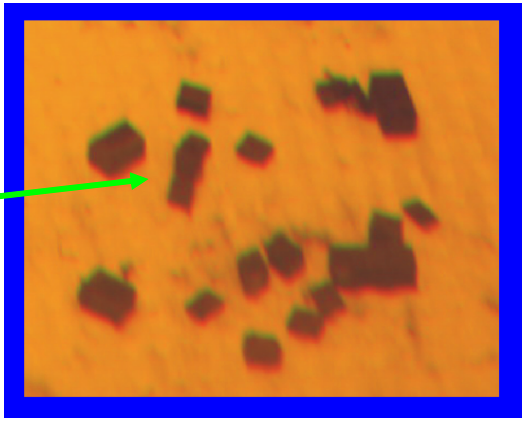


Bad News: Structural degradation

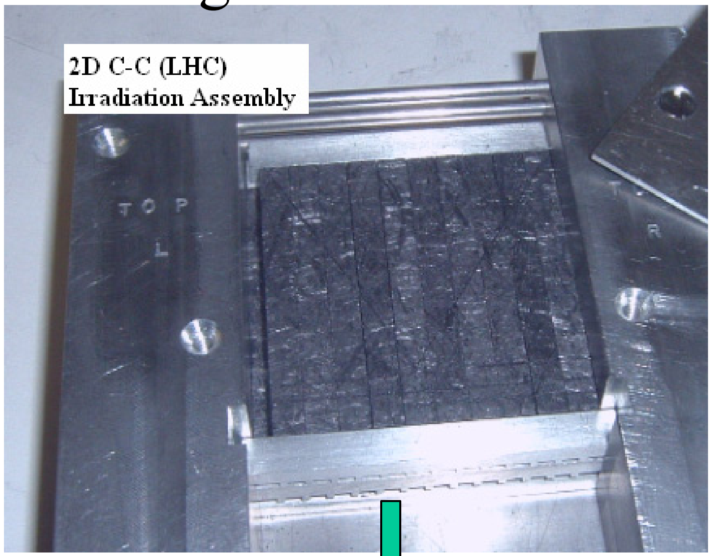
"weak" orientation

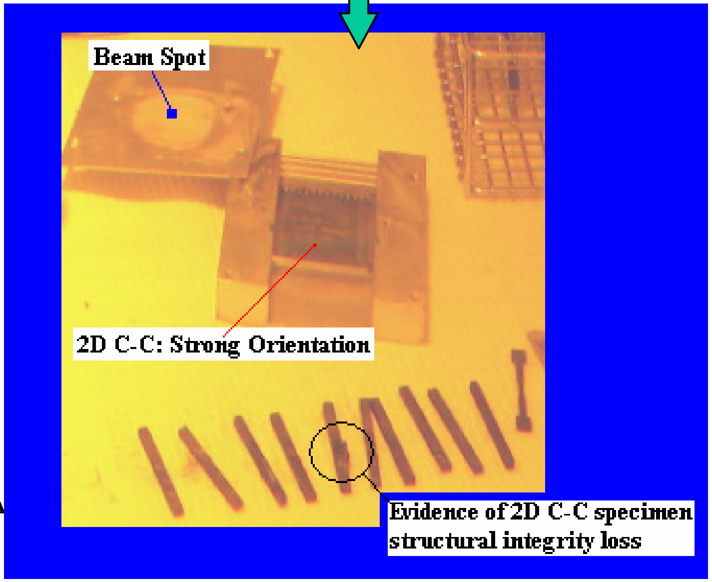






"strong" orientation





“Unexpected” 2-D CC damage left us scratching our heads

Is it just the 2D carbon composite that is susceptible to high fluences
OR
This holds true will ALL carbon composites (2D & 3D) ?

The mixed-bag of news prompted us to go through another exposure where 2D and 3D carbon composites are irradiated under identical conditions

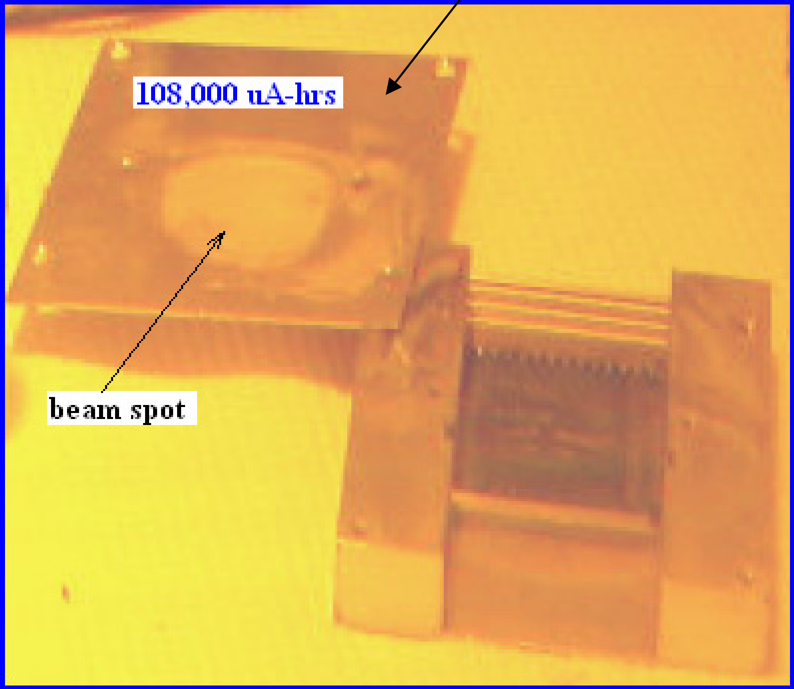
↓

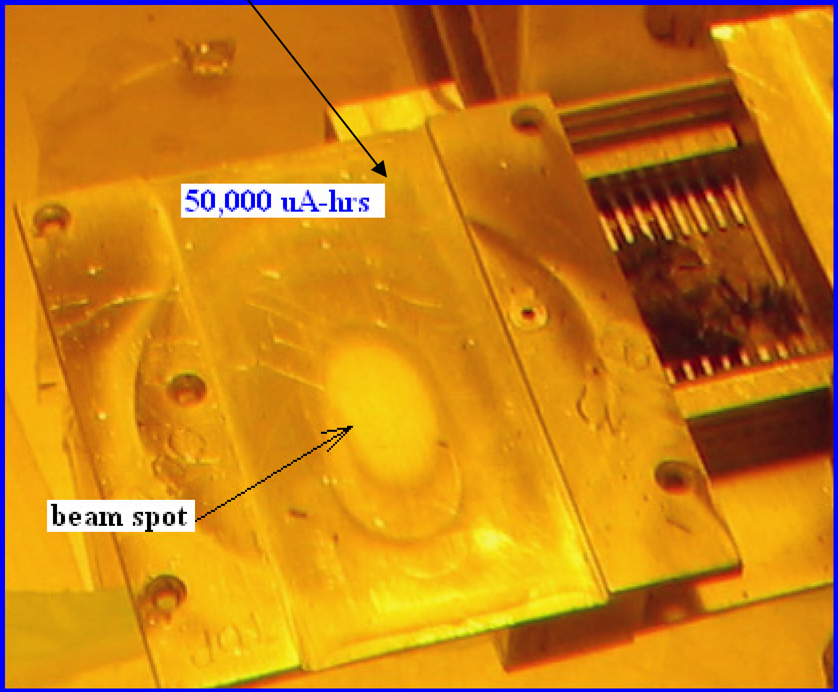
Irradiation of the two carbon composites along with two graphite grades (IG-43 and IG-430) was performed in Spring 2006. Integrated current reached ~ 50,000 uA-hrs (but likely under tighter beam spot!!)

PRELIMINARY assessment of exposures

2005 Irradiation

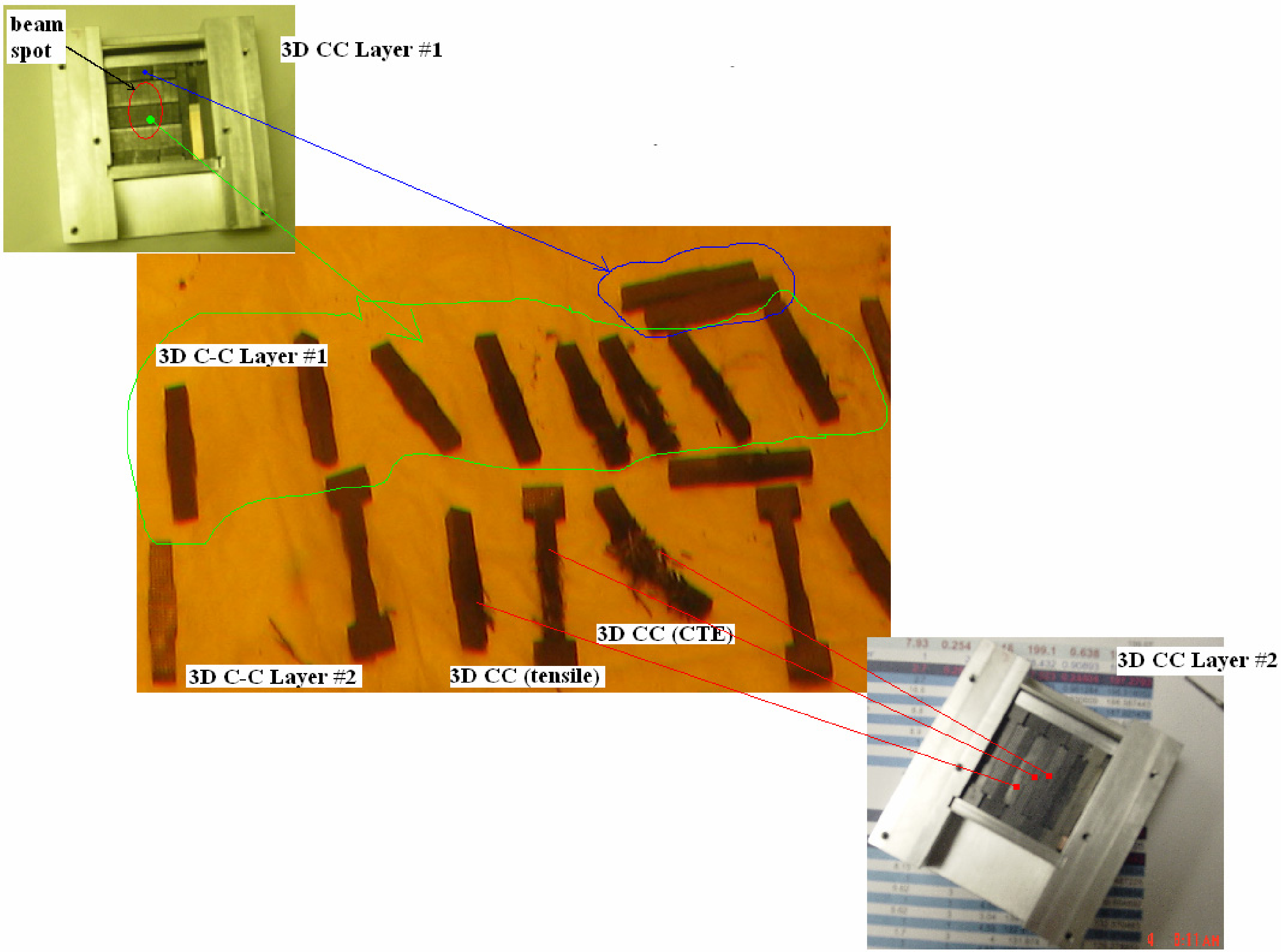
2006 Irradiation





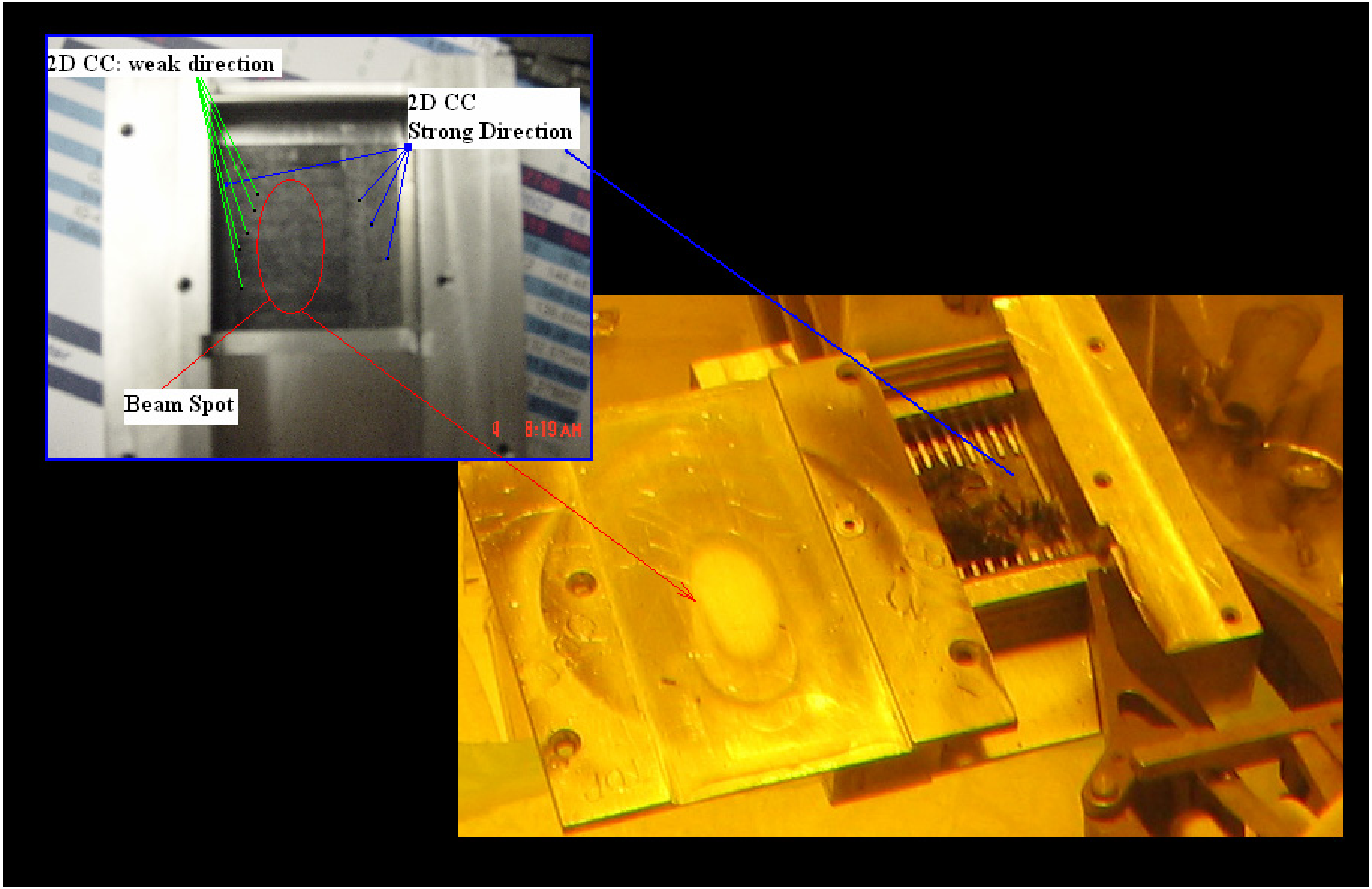
Nickel foils of the 2006 irradiation are currently being analyzed (radiography) to establish shape of proton beam

Damage in 3-D carbon composite. Note the complete disintegration of irradiated specimens situated within the 1-sigma of the beam



Damage even worse in 2-D carbon composite.

Severe disintegration especially of "weak-orientation" falling within 1-sigma of the beam



BACK TO THE DRAWING BOARD

Take another look at super-Invar

Look into other super-alloys (gum metal, titanium alloys, etc.)

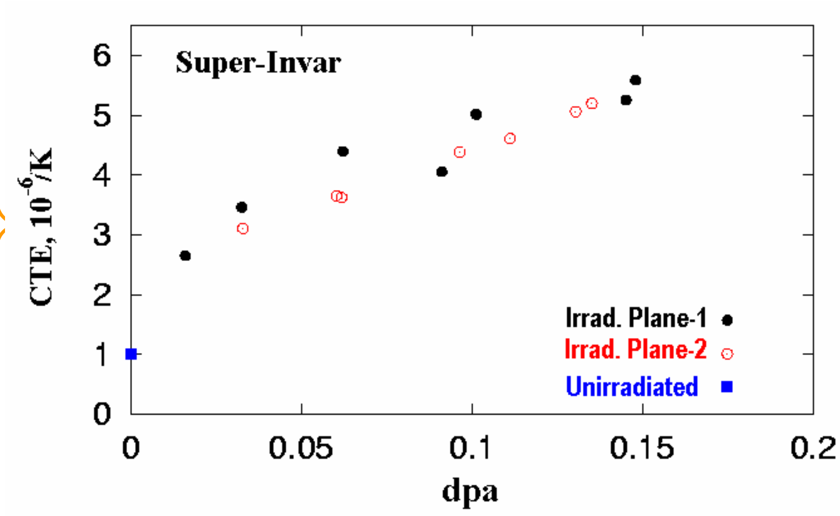
Explore new graphite grades

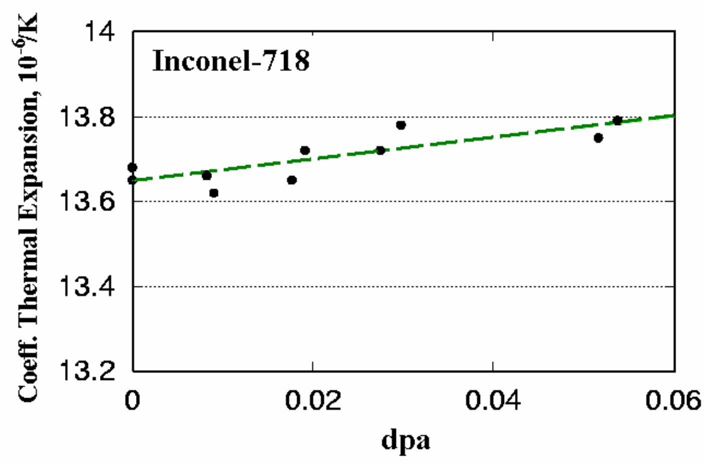
Further evaluate AlBeMet

Re-assess high-Z range (Ta, W)

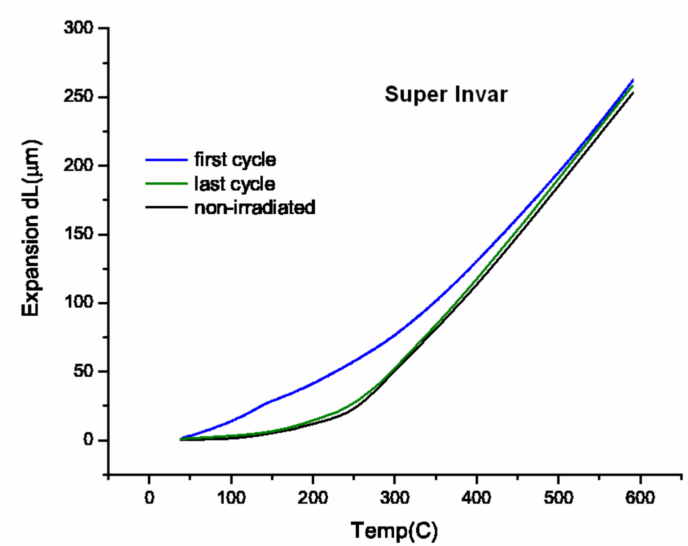
Re-evaluation of super Invar

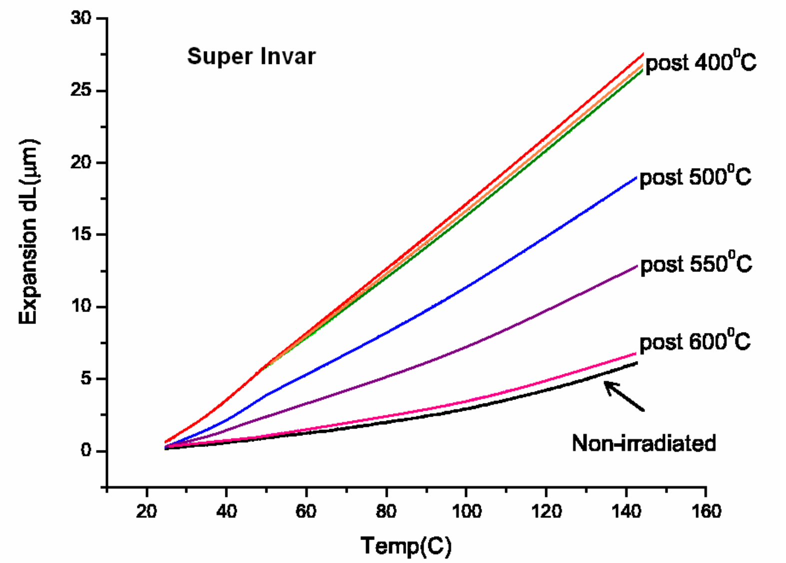
Modest level of irradiation takes away the low thermal expansion exhibited by the un-irradiated super Invar



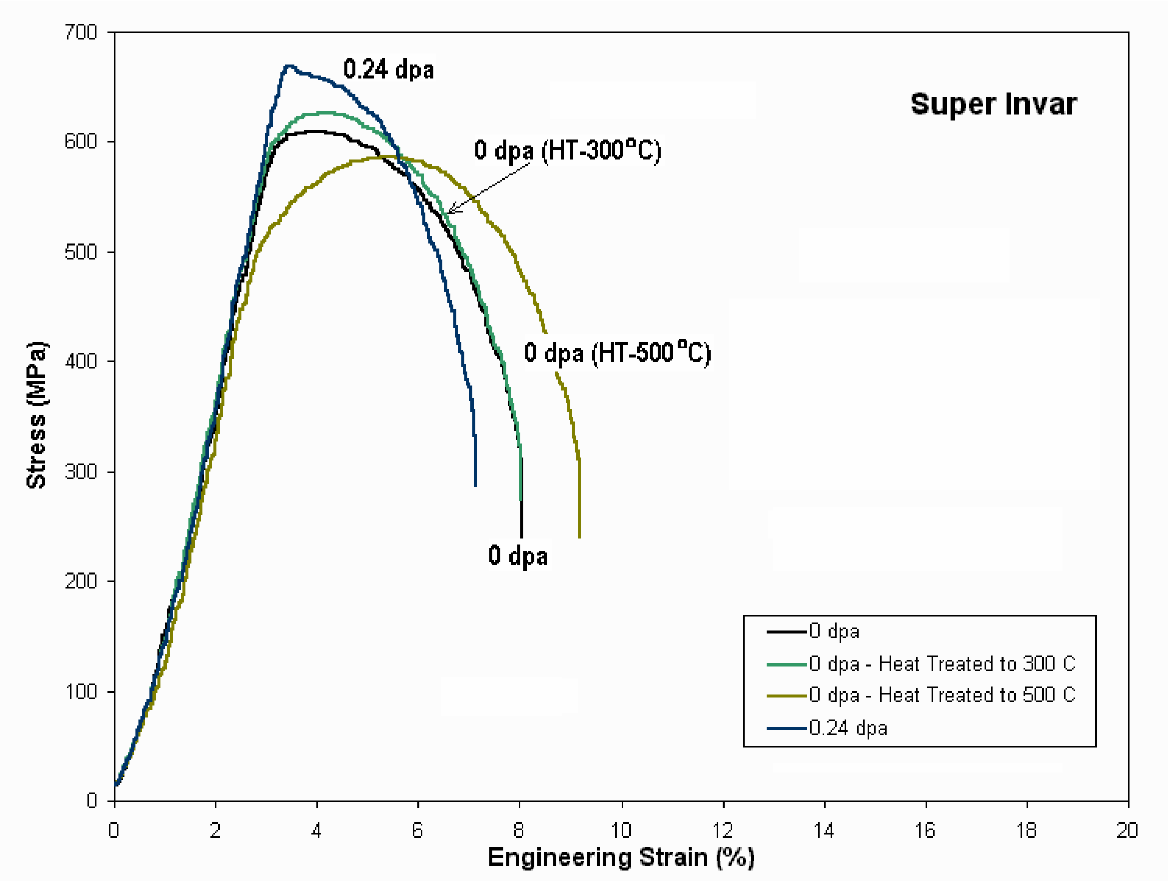


Thermal cycling with temp. threshold identified experimentally as $T_{threshold}$ > 600 C restores material !!



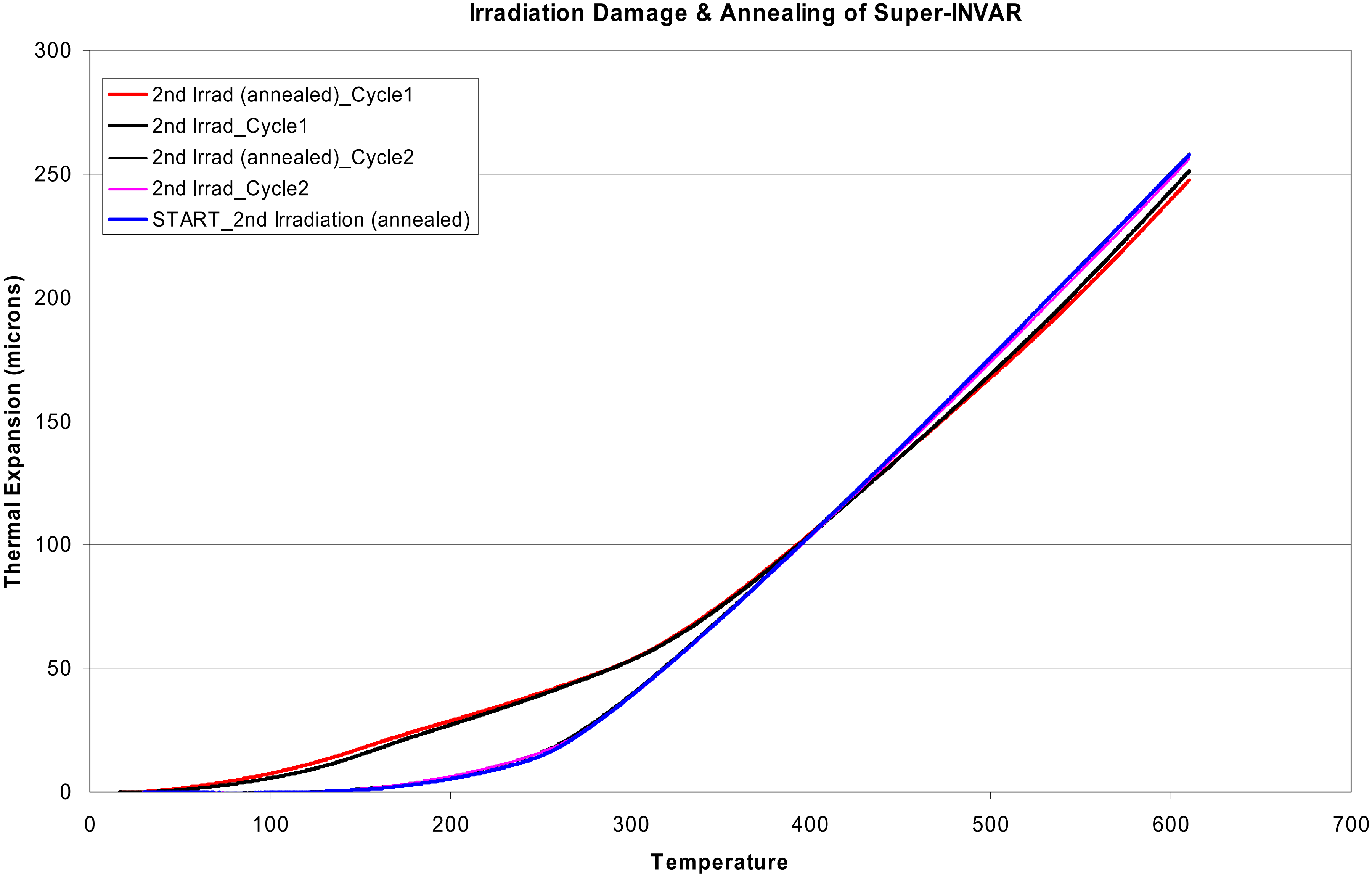


Re-evaluation of super Invar

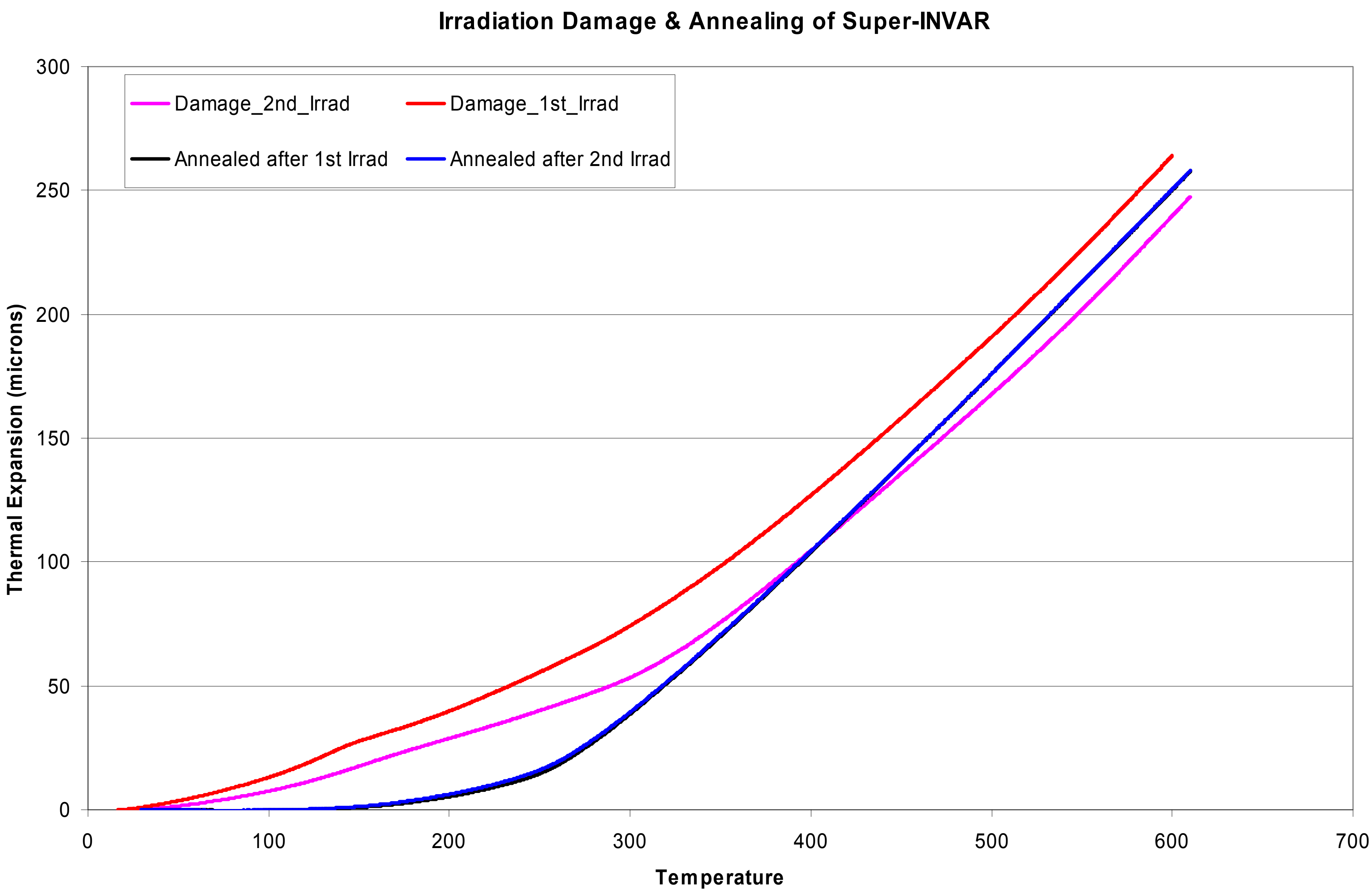


Remote RE-ASSEMBLY in Hot Cell
Half of layer undergone annealing (>600 C)

Back in the "OVEN" !!!



Irradiation Damage & Annealing of Super-INVAR
2nd Irrad (annealed)_Cycle1
2nd Irrad_Cycle1
2nd Irrad (annealed)_Cycle2
2nd Irrad_Cycle2
START_2nd Irradiation (annealed)
Thermal Expansion (microns)
300
250
200
150
100
50
0
0
100
200
300
400
500
600
700
Temperature



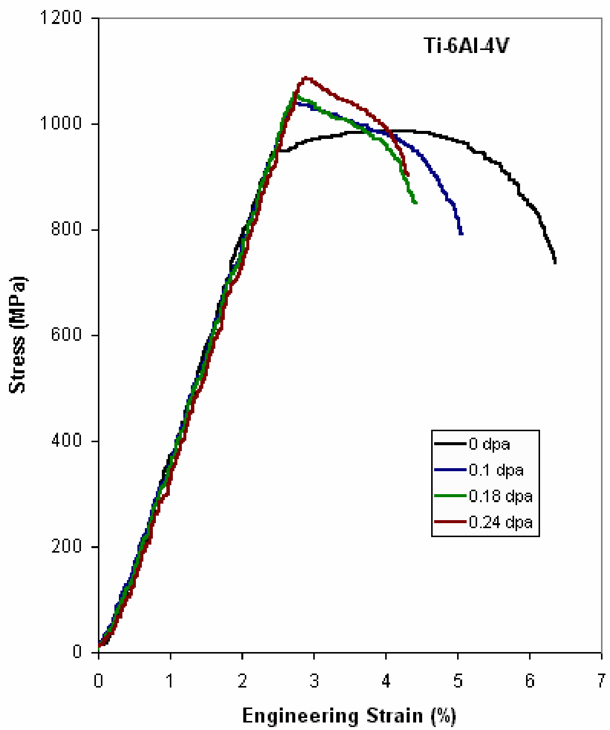
Irradiation Damage & Annealing of Super-INVAR
Damage_2nd_Irrad
Damage_1st_Irrad
Annealed after 1st Irrad
Annealed after 2nd Irrad
Thermal Expansion (microns)
Temperature
0
50
100
150
200
250
300
0
100
200
300
400
500
600
700

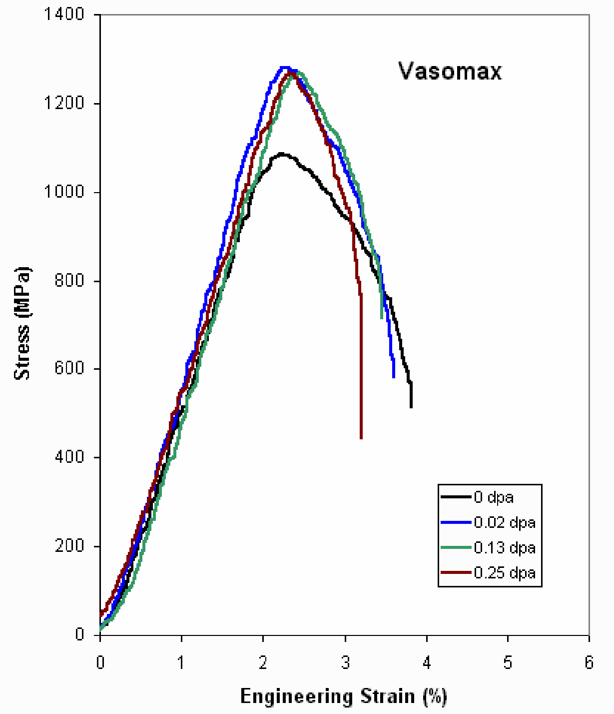
Questions to be answered regarding annealing

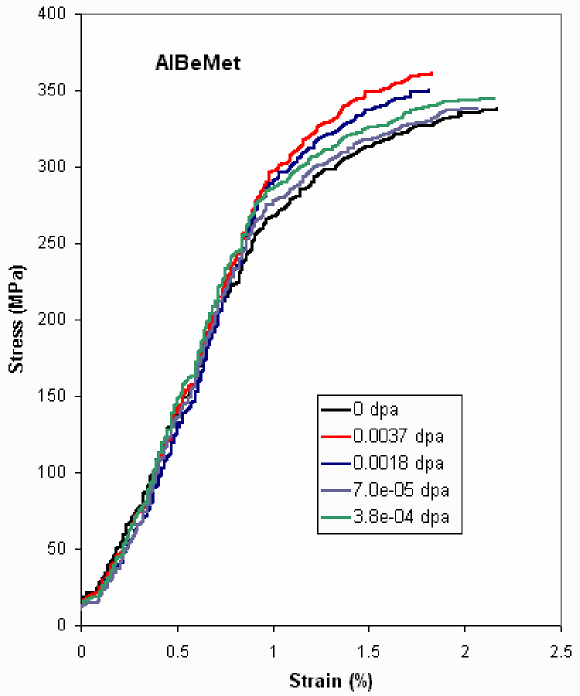
- How is irradiation damage influenced by high temperatures during irradiation and if yes where is the threshold?
  - A difficult but not impossible task – achieve same exposure at different irradiation temperatures
  - Identifying the temperature threshold will allow for life extension of the material in the irradiation environment

- Do materials exhibit similar damage following annealing and re-irradiation ?
  - Studies from neutron exposure indicate that the number of voids, while decrease in size, increase in number during re-irradiation
  - To address that, irradiated and then annealed super-Invar has been exposed to irradiation

Radiation effect on ductility & strength – How important is ductility?

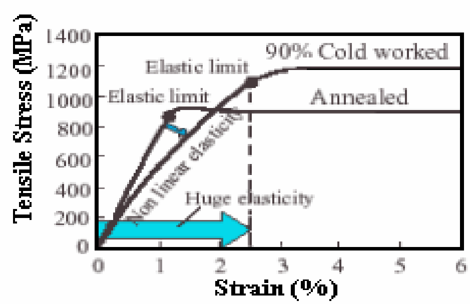


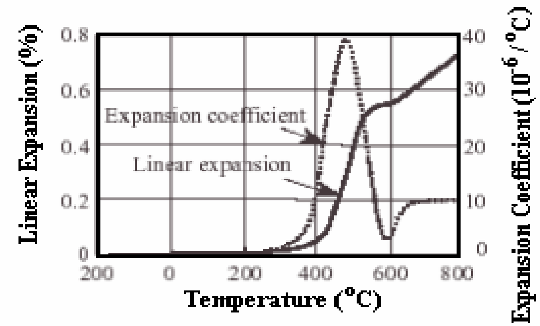


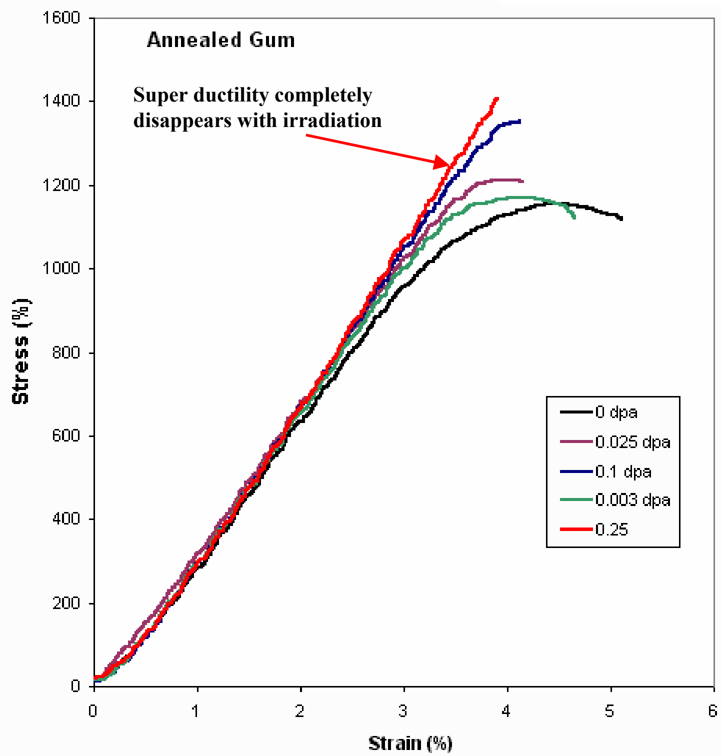


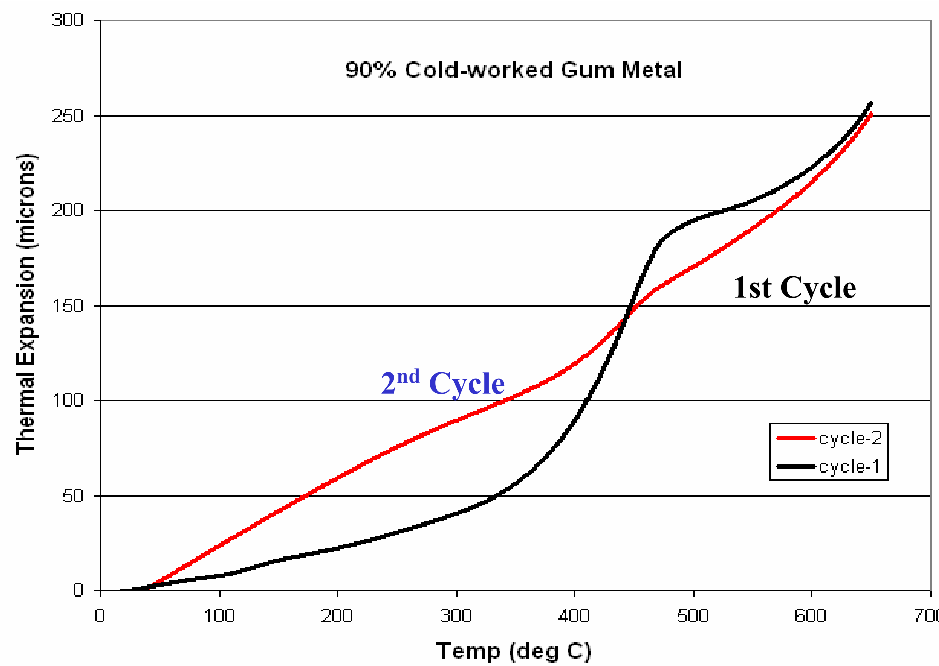
The high expectations of gum metal

Enhancement of properties are attributed to the “dislocation-free” plastic deformation mechanism

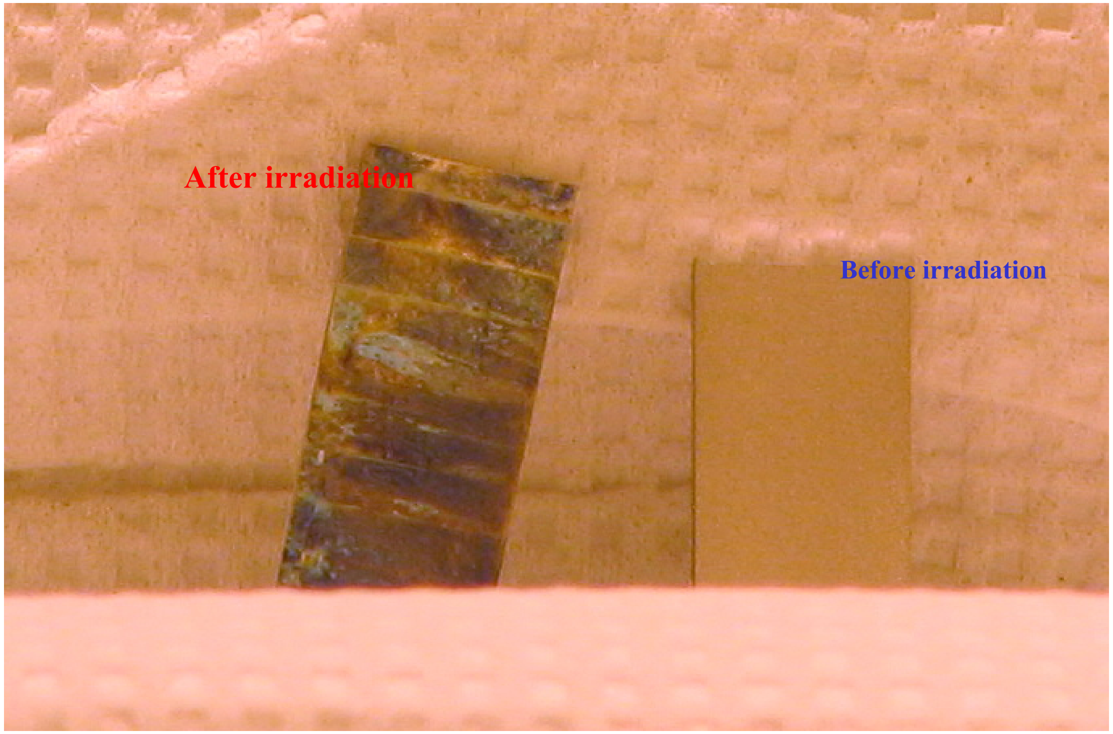


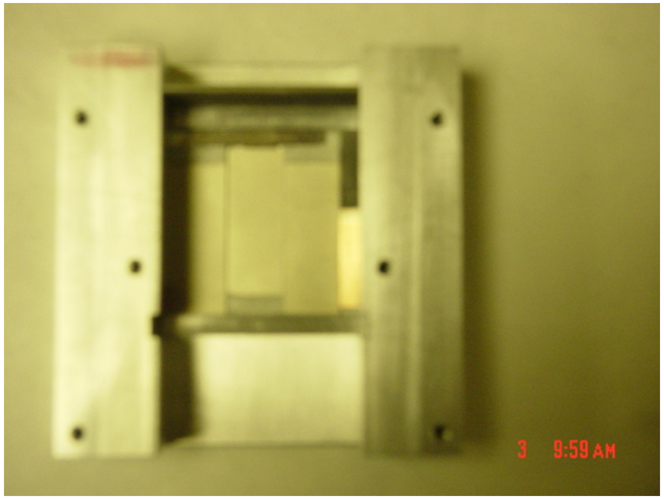






Serious degradation of magnetic horn material
(nickel-plated aluminum) used in the NuMI experiment at FNAL!
Retested during Phase III with double the exposure and waiting examination





SUMMARY

The value of performing R&D prior to moving too far ahead based on "expectations" has been clearly demonstrated

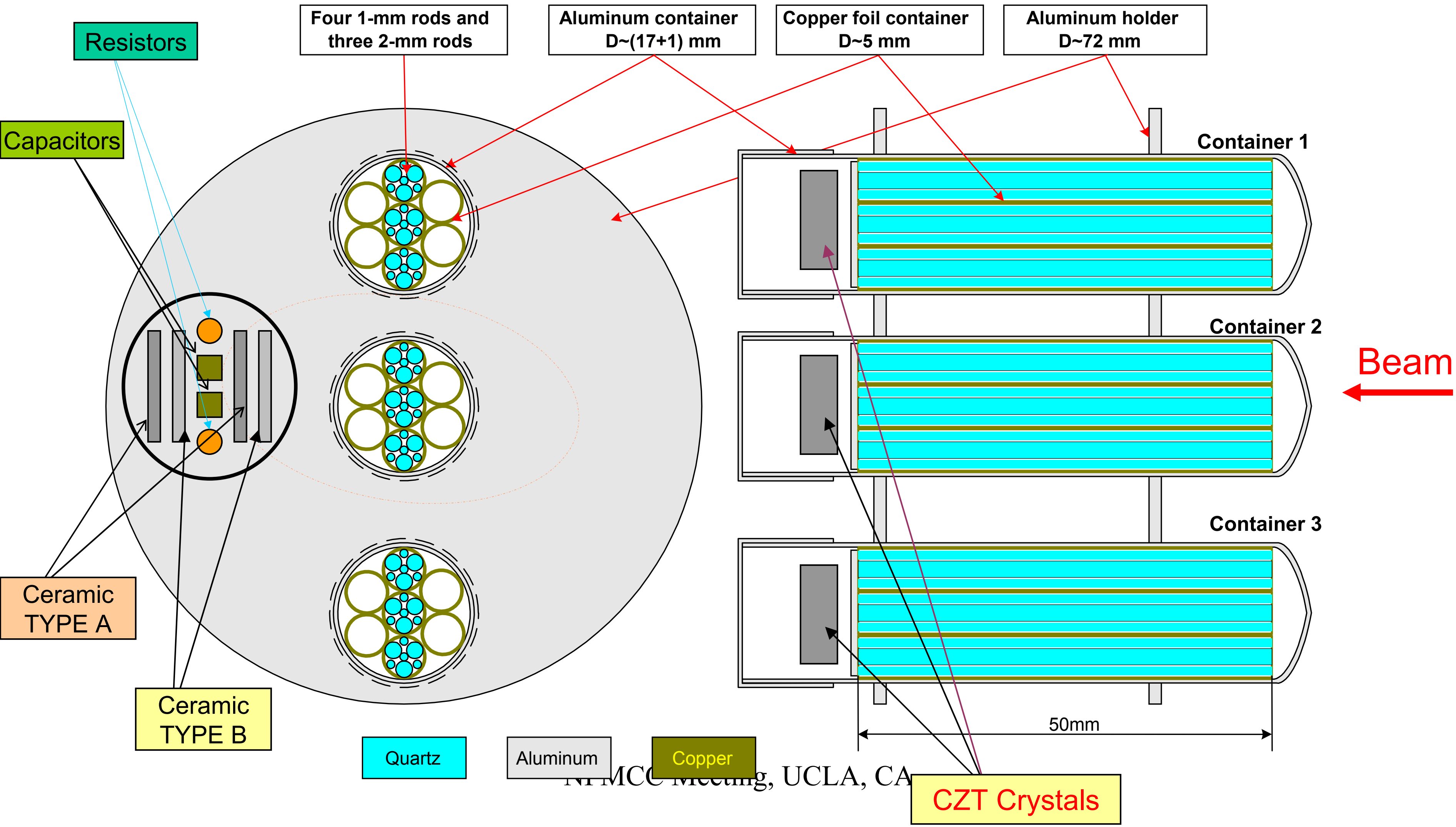
Further experimental scrutiny of 2D or 3D carbon composites for irradiation damage effects is not recommended. These composites clearly CANNOT tolerate the high fluences required by high-power beam targets. These results should prompt a change of course in the search for materials for the multi-MW beam targets.

FOCUS needs to be shifted toward:

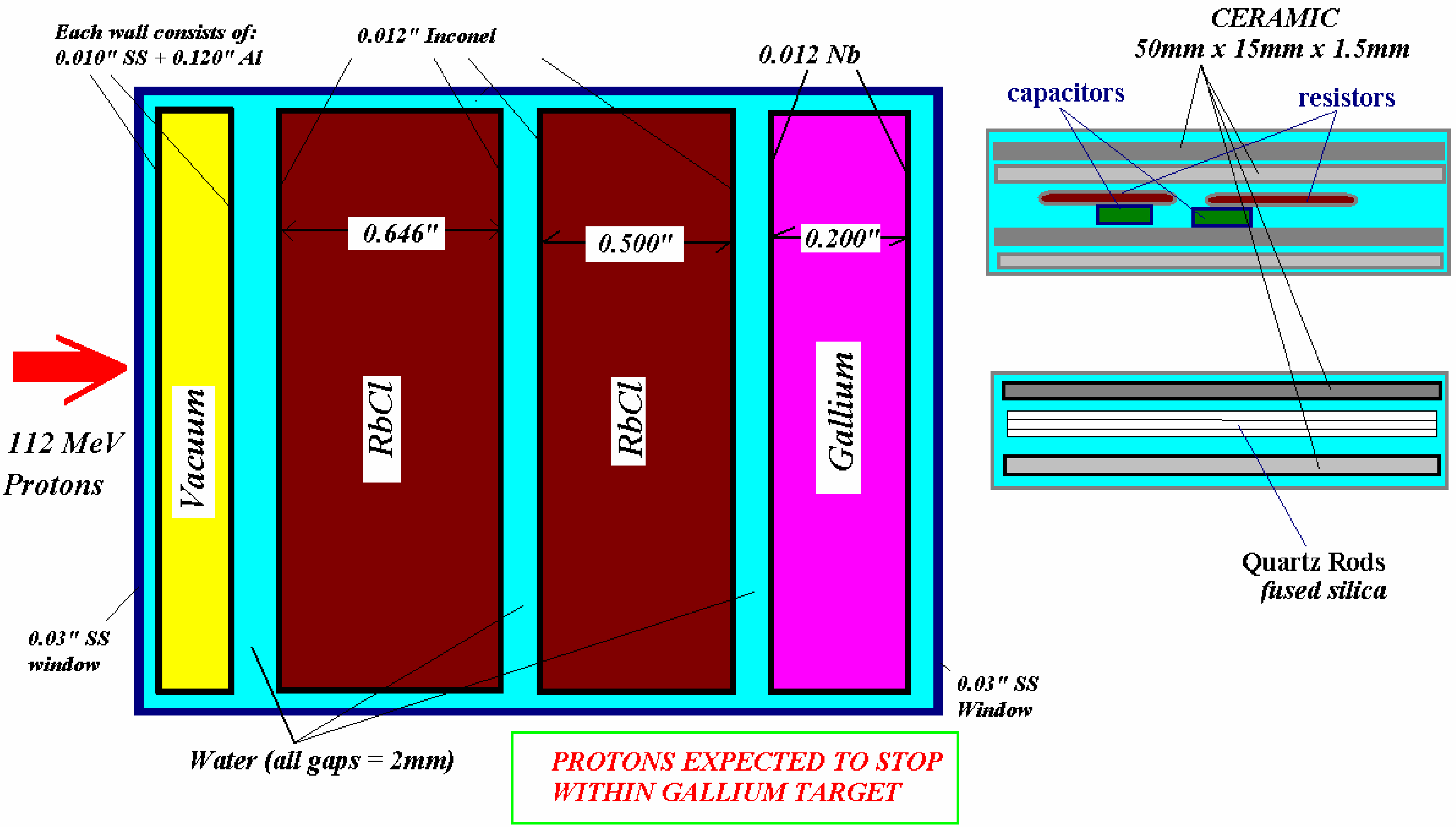
- Low-Z: new graphite grades such as isotropic graphite IG-430 and AlBeMet
- Mid-Z: Titanium alloys, Vascomax, super-Invar
- High-Z: New alloys of Ta and W

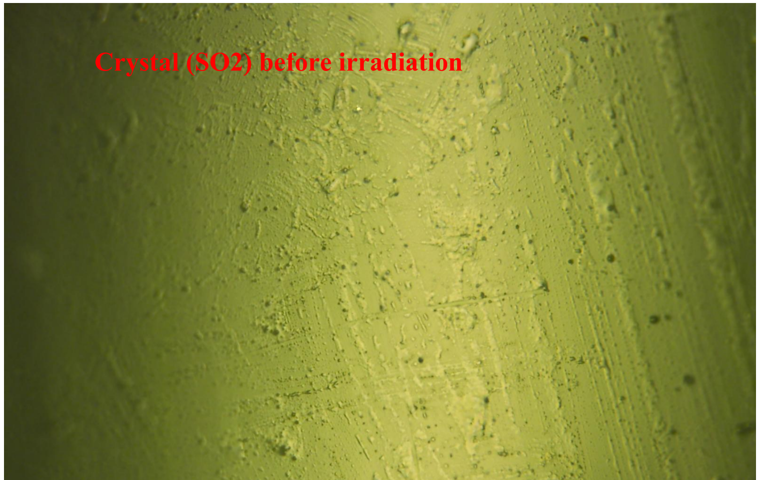
Some interesting irradiation damage findings !!!

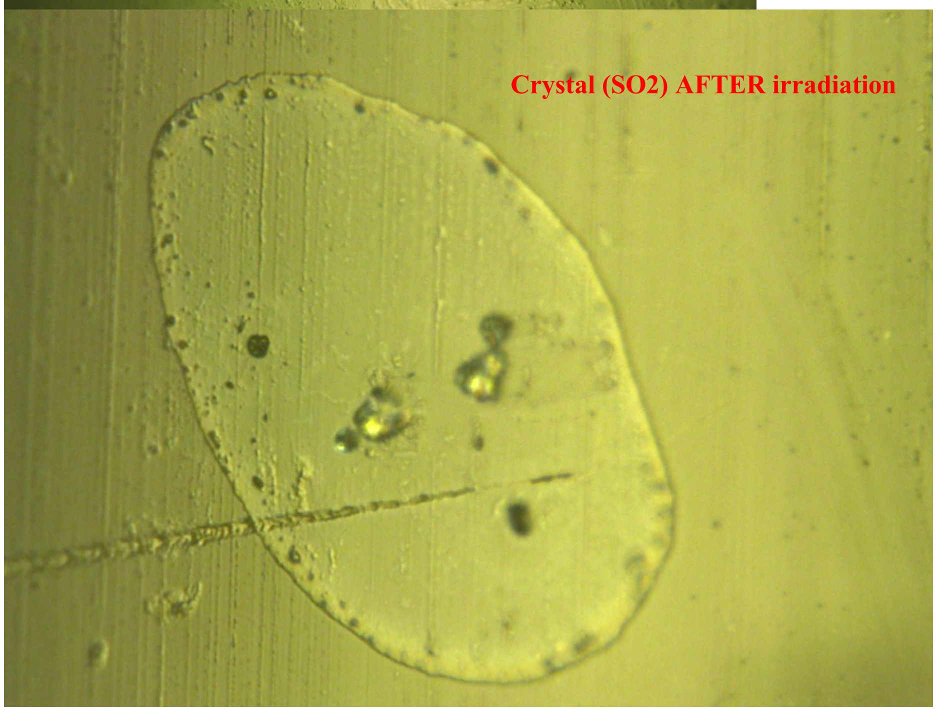
Ceramics/Resistors/Capacitors integrated with quartz rods and CZT crystals

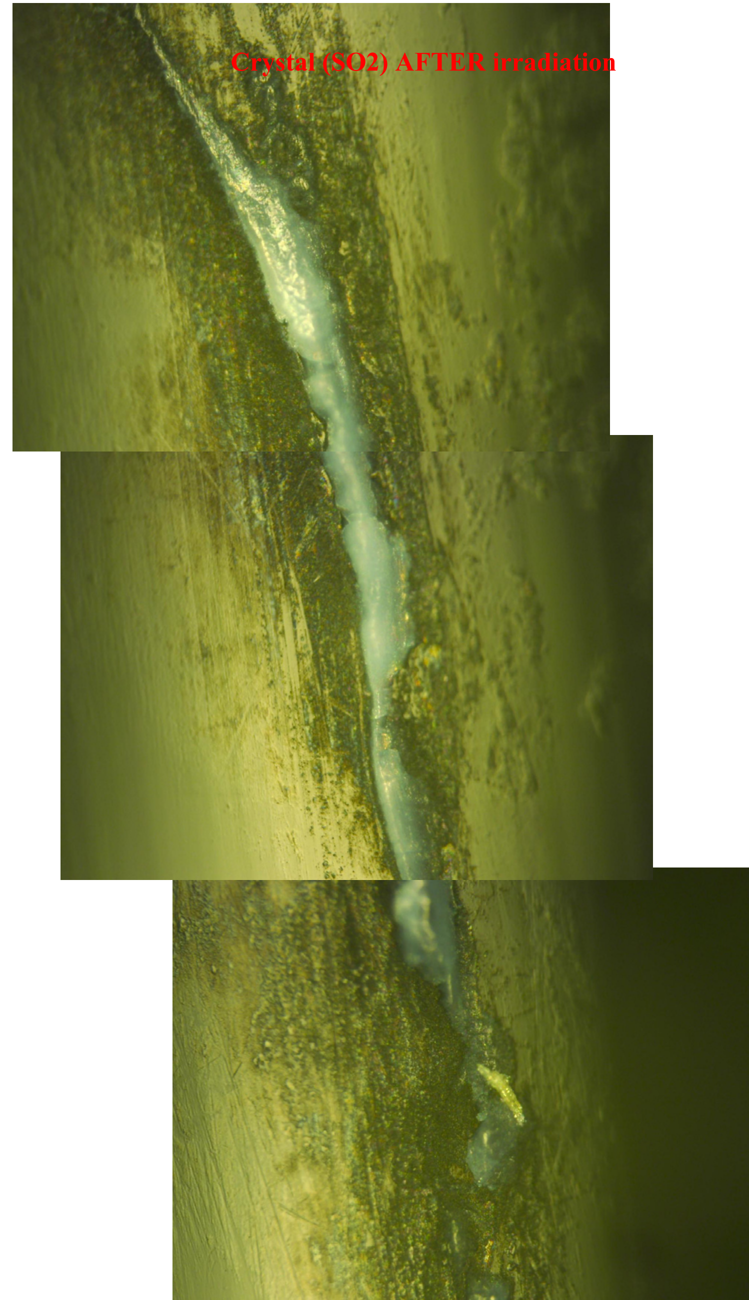


Neutron Exposure




Crystal (SO2) before irradiation


Crystal (SO2) AFTER irradiation


Crystal (SO2) AFTER irradiation