MATERIAL IRRADIATION STUDIES FOR HIGH-INTENSITY PROTON BEAM TARGETS

Current & Future Activities

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contribution from

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- **K. McDonald, Princeton , J. Sheppard, SLAC**
- **K. Yoshimura and Y. Hayato, KEK**
- **N. Mokhov & P. Hurh (FNAL)**

2-4 MW ????

What do we need to get us there:

- low elasticity modulus (remember ♦ ~ *E* ♋ 👎*T)*
- low thermal expansion
- high heat capacity
- good diffusivity to move heat away from hot spots
- high strength
- resilience to shock/fracture strength
- resilience to irradiation damage
- **Other than that, we are not asking for much!!!!**

And another thing: 4 MW on what spot size?

Is there hope?

Several "smart" materials or new composites may be able to meet some of the desired requirements:

- **new graphite grades**
- **customized carbon-carbon composites**
- **Super-alloys (gum metal, albemet, super-invar, etc.)**

While calculations based on non-irradiated material properties may show that it is possible to achieve 2 or even 4 MW, irradiation effects may completely change the outlook of a material candidate

ONLY way is to test the material to conditions similar to those expected during its life time as target

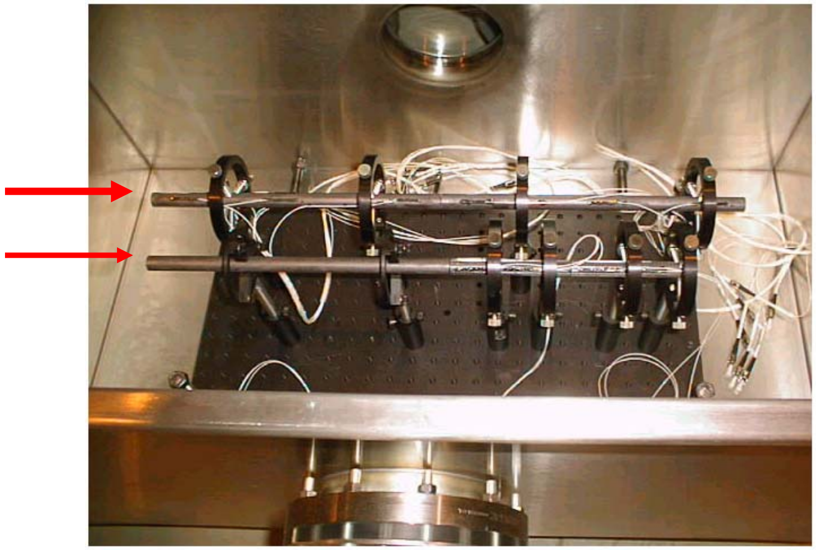
What are we after?

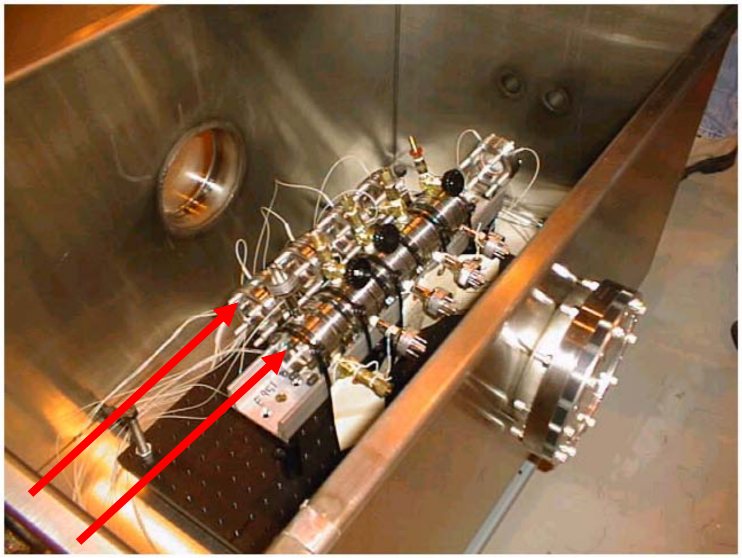
- High Intensity/High Power Targets
- Low Z or high Z
- Alloys, composites, “smart” materials
- Assessment of irradiation damage of these non-traditional materials
- Driving target scenarios to their limit through simulations – Use experimental data to back-feed the simulations.

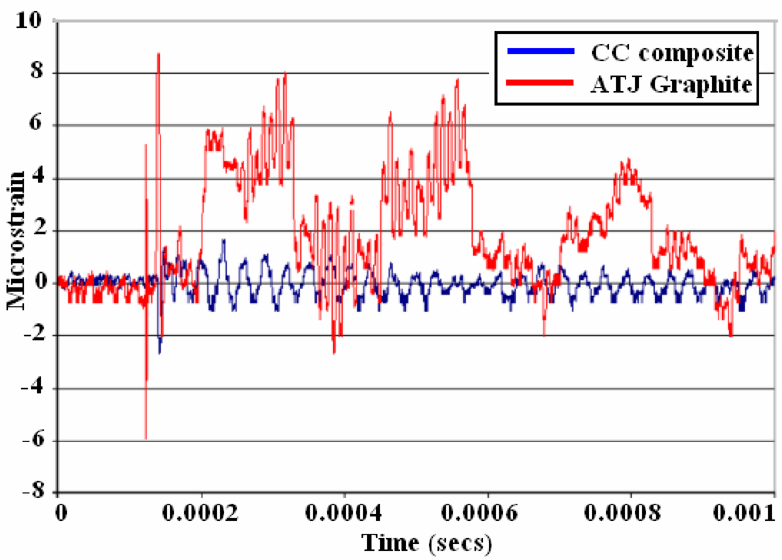
Target Studies

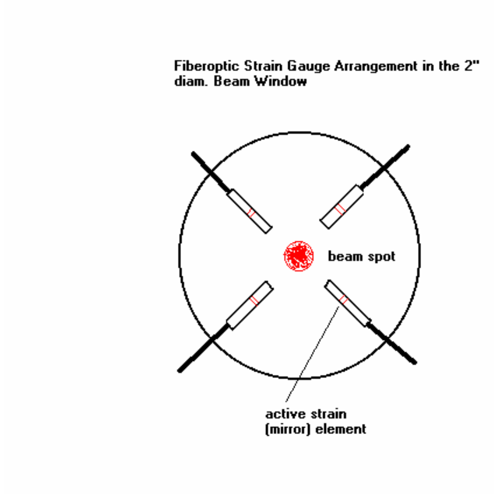
- Beam on targets (E951)
- Material irradiation
- New activities
  - more irradiation studies/beam on targets (p-bar at FNAL)
  - Laser-based shock studies
- Simulations and benchmarking
  - ANSYS & LS-DYNA

24 GeV AGS Protons on Targets: Graphite & CC Composite Targets
Beam Windows (thick, target-like and thin)

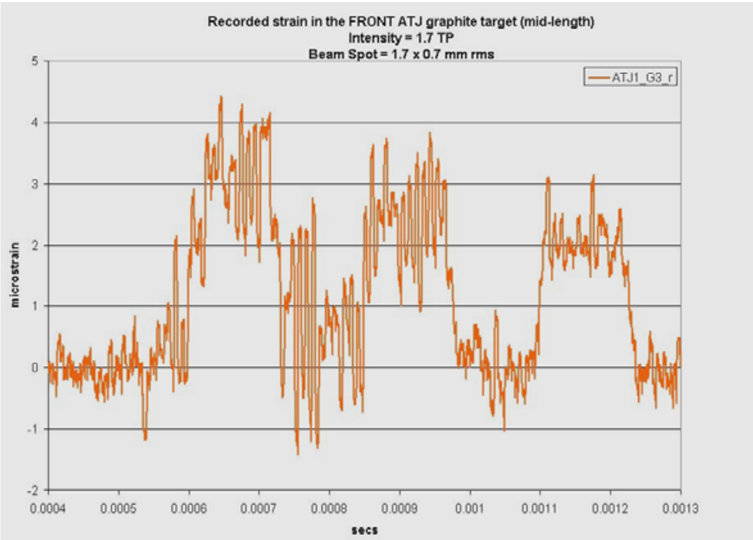


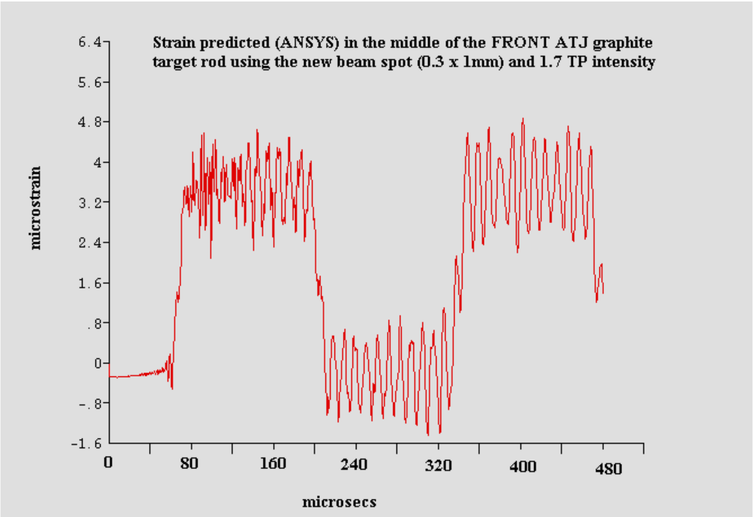


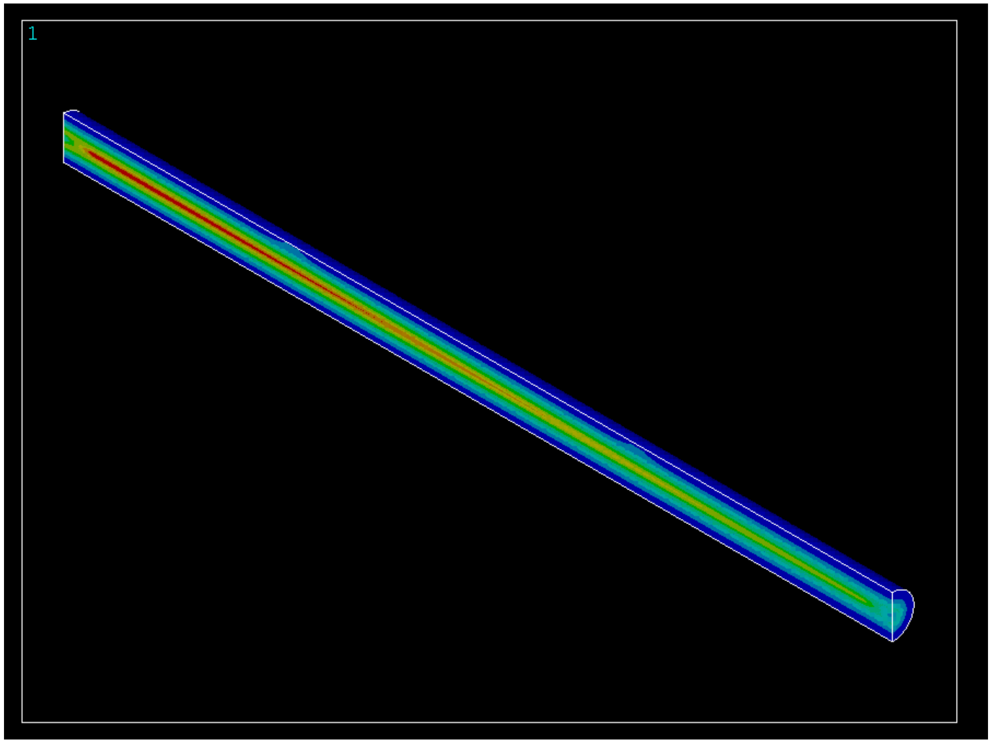




Experimental vs. simulation (ANSYS) prediction of graphite target response

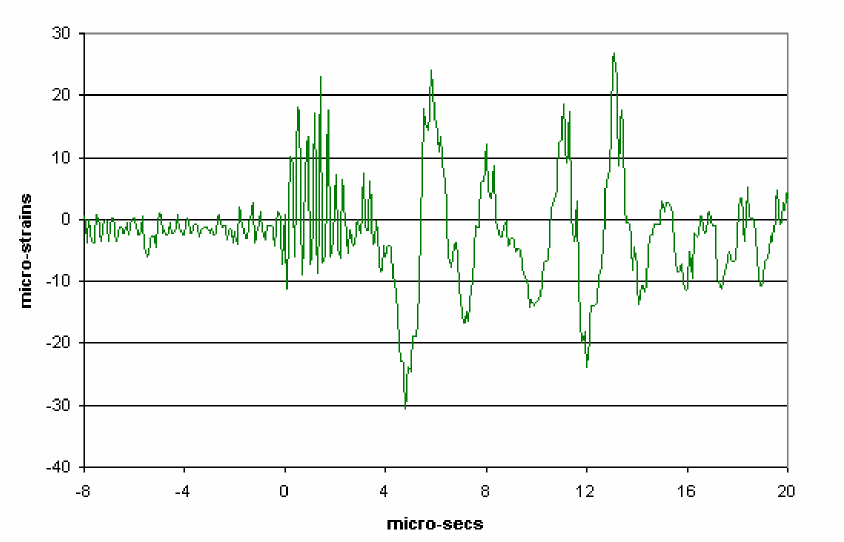


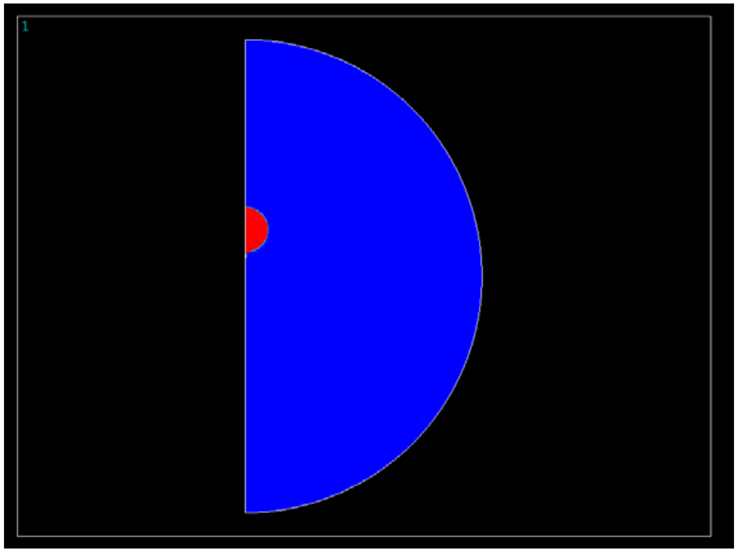


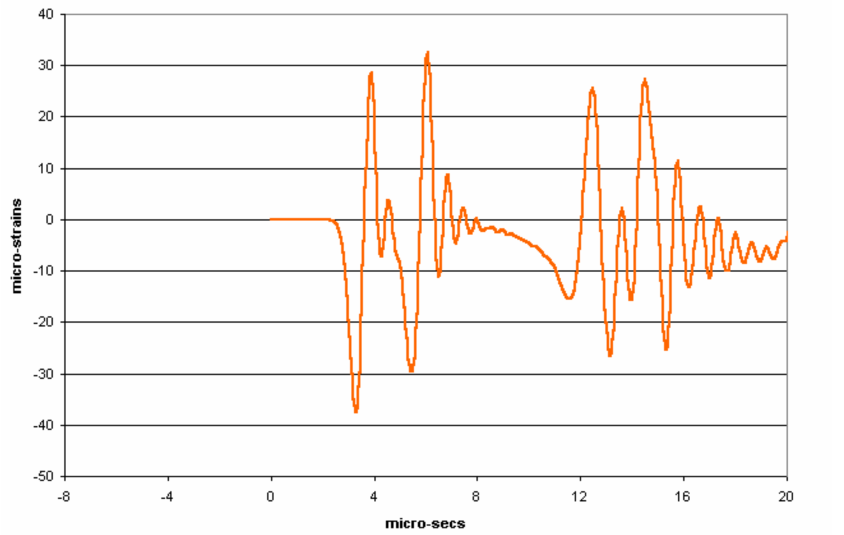


Beam Window Experiment (E951)

Experimental Strain Data vs. Simulation







IRRADIATION STUDIES

PHASE I:

- Super Invar
- Inconel-718

PHASE II:

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

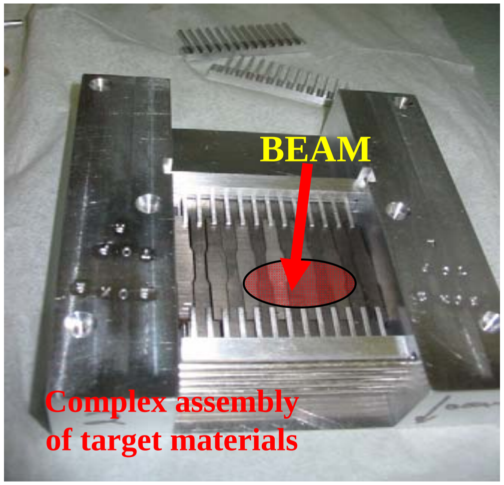
BEAM PARAMETERS

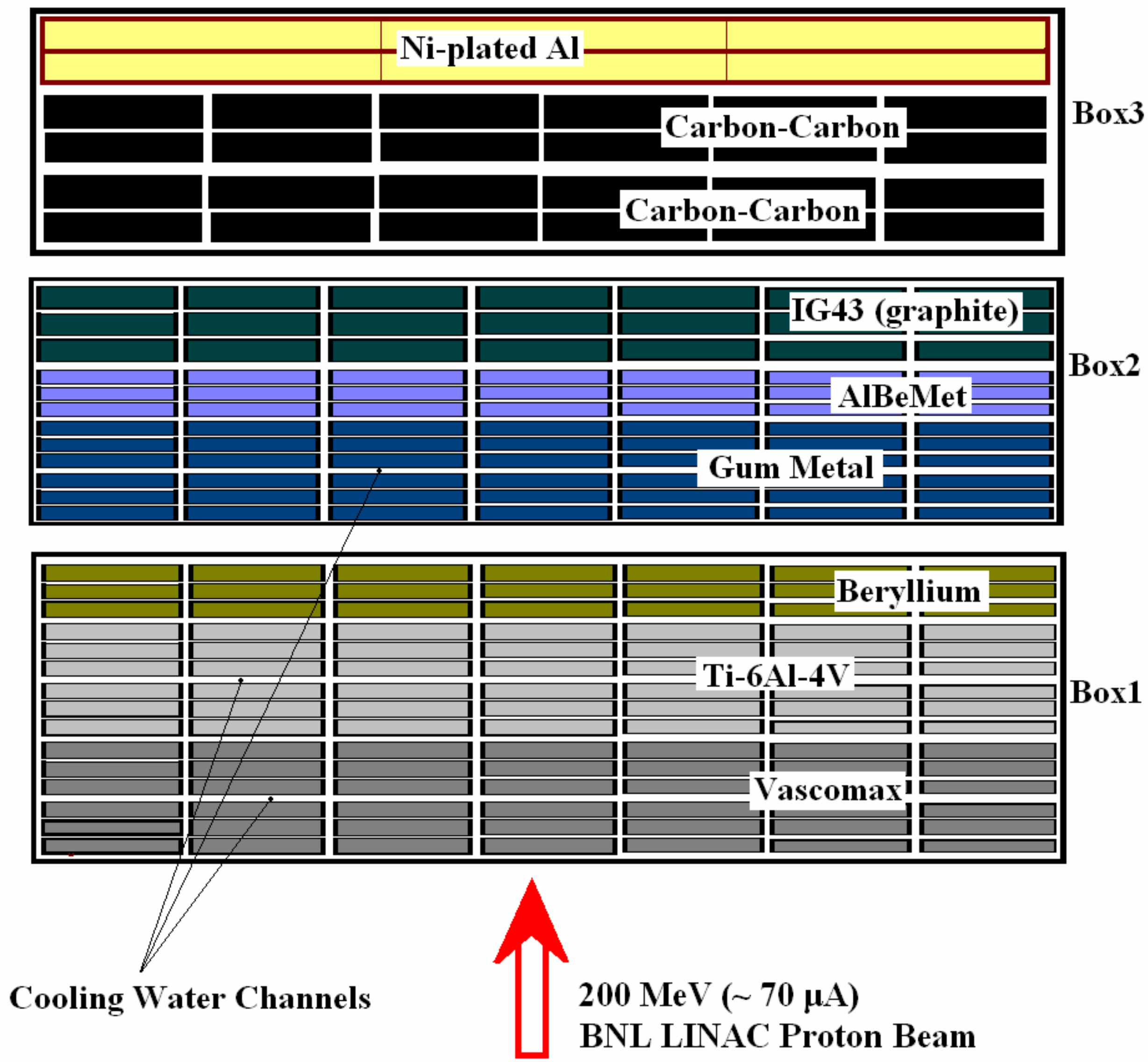
200/117 MeV protons; ~ 70 μA

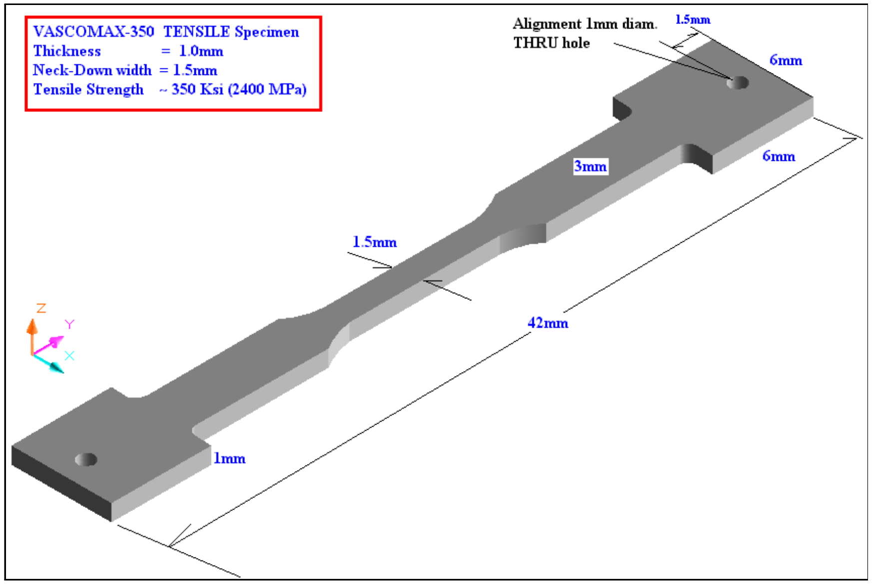
Spot size FWHM ~ 14 mm

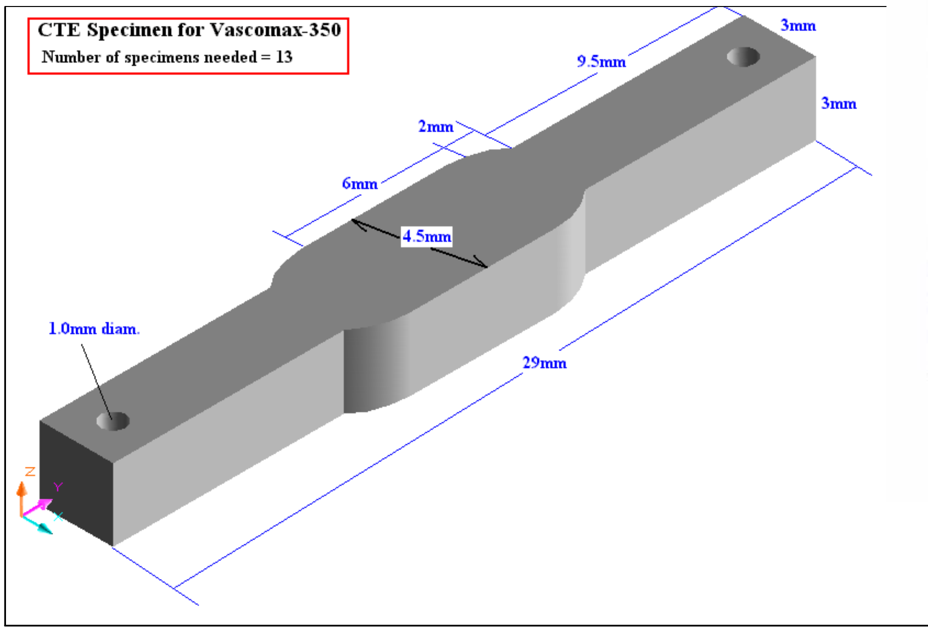
PHASE II-a:

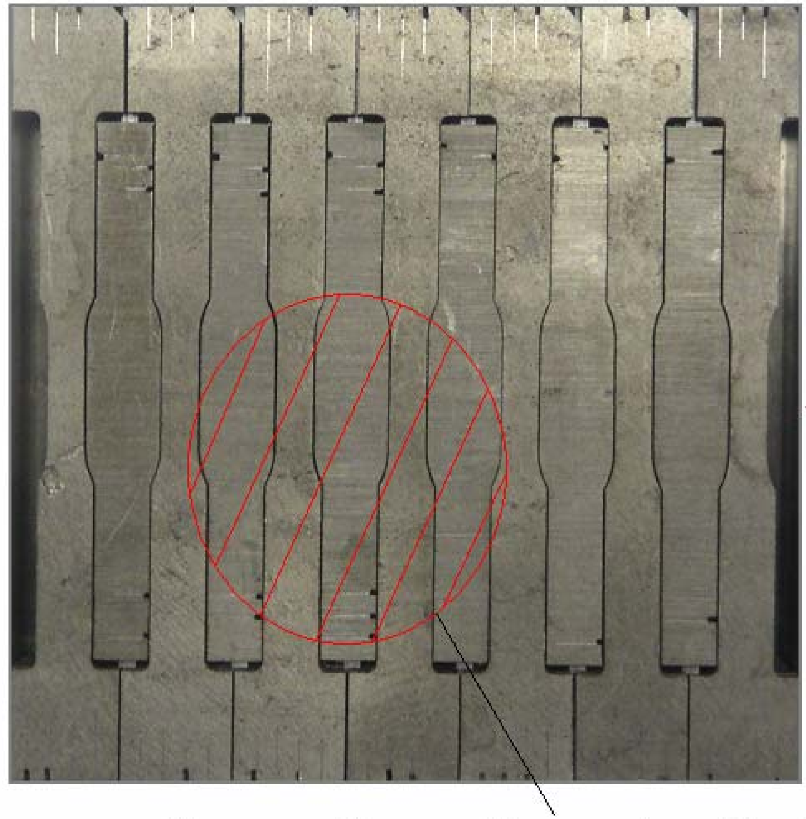
- 2D Carbon-Carbon Composite




Ni-plated Al
Carbon-Carbon
Carbon-Carbon
Box3
IG43 (graphite)
AlBeMet
Gum Metal
Box2
Beryllium
Ti-6Al-4V
Vascomax
Box1
Cooling Water Channels
200 MeV (~ 70 µA)
BNL LINAC Proton Beam

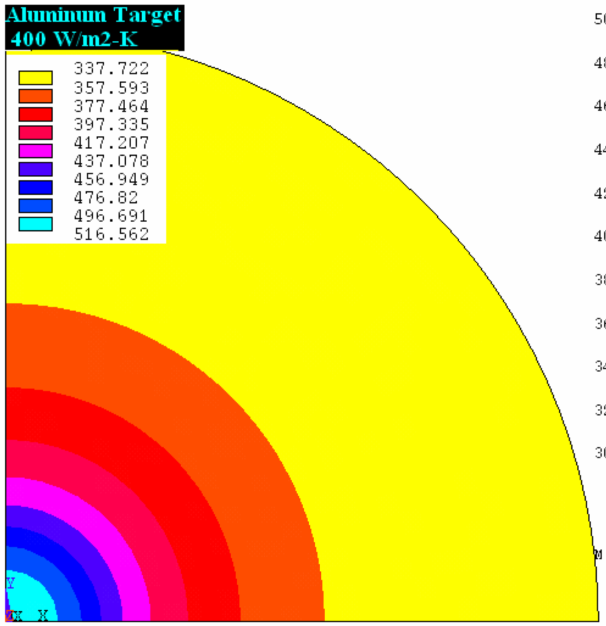


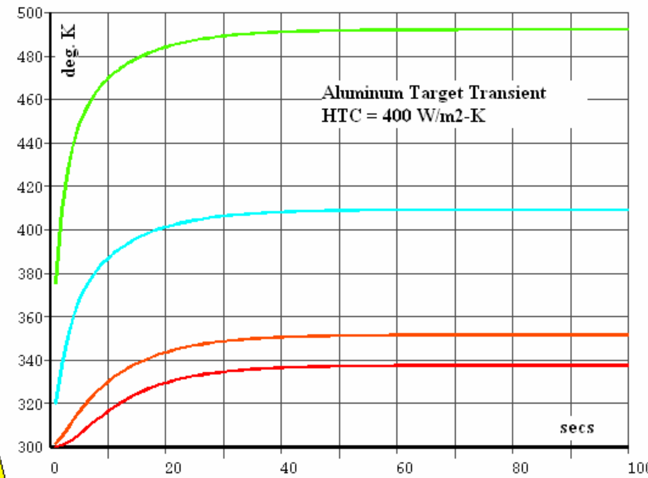


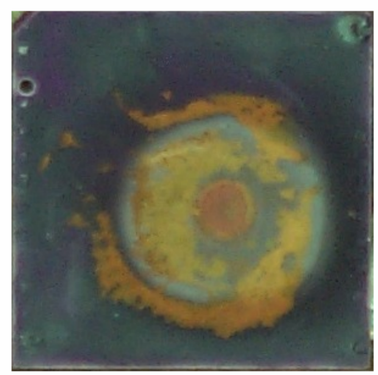


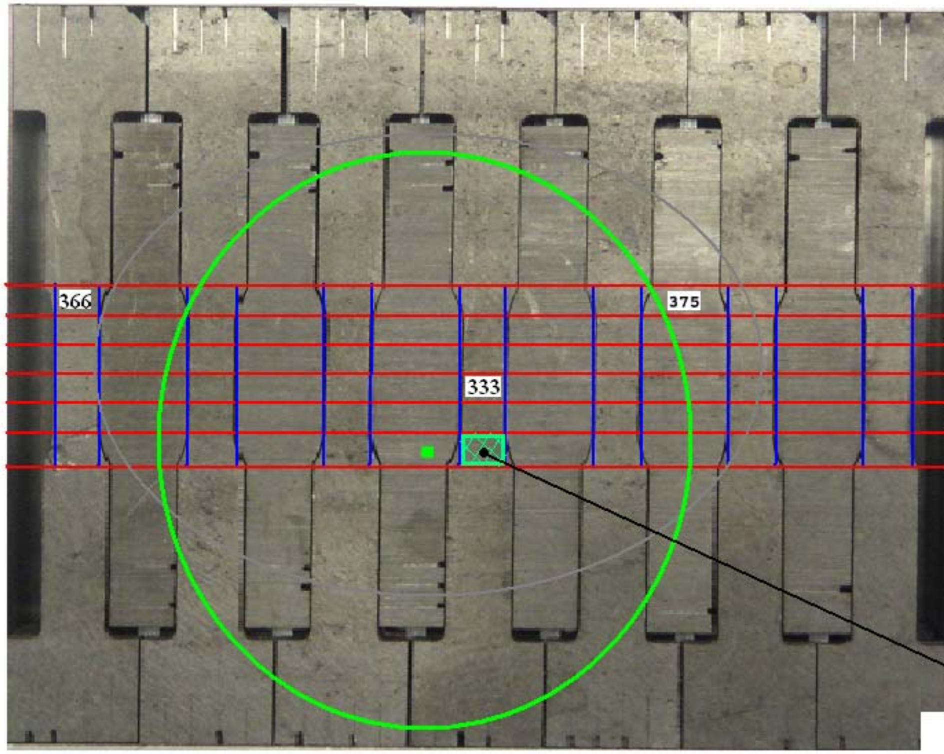
Proton Beam Footprint (1σ)

Irradiation Temperature Assessment Using Thermal Sensitive Paint (TSP)









Results of autoradiographic beam profile measurements for the 2004 BLIP irradiation, using the "downstream" nickel foil.

Horizontal position looking at the surface where the beam enters the foil	Vertical position	Horizontal rms width (σ)	Vertical rms width (σ)
2.9 ± 0.5 mm left of center	4.5 ± 0.5 mm below center	8.1 ± 0.3 mm	8.4 ± 0.3 mm

Irradiation Damage Analysis (dpa) showed that this cell associated with the tensile specimenn experiences most damage

266	267	268	269	270	271	272	273	274	275	276	277	278
253	254	255	256	257	258	259	260	261	262	263	264	265
240	241	242	243	244	245	246	247	248	249	250	251	252
227	228	229	230	231	232	233	234	235	236	237	238	239
214	215	216	217	218	219	220	221	222	223	224	225	226
201	202	203	204	205	206	207	208	209	210	211	212	213

166	167	168	169	170	171	172	173	174	175	176	177	178
153	154	155	156	157	158	159	160	161	162	163	164	165
140	141	142	143	144	145	146	147	148	149	150	151	152
127	128	129	130	131	132	133	134	135	136	137	138	139
114	115	116	117	118	119	120	121	122	123	124	125	126
101	102	103	104	105	106	107	108	109	110	111	112	113

Tensile Vsc#s 1;8;15

CTE Vsc# 5

Tensile Vsc #s 4;11;18

VASCOMAX SAMPLE ACTIVATION

CTEs: 7.52 mCi - 151.2 mCi
Tensile: 5.59 mCi - 42.6 mCi

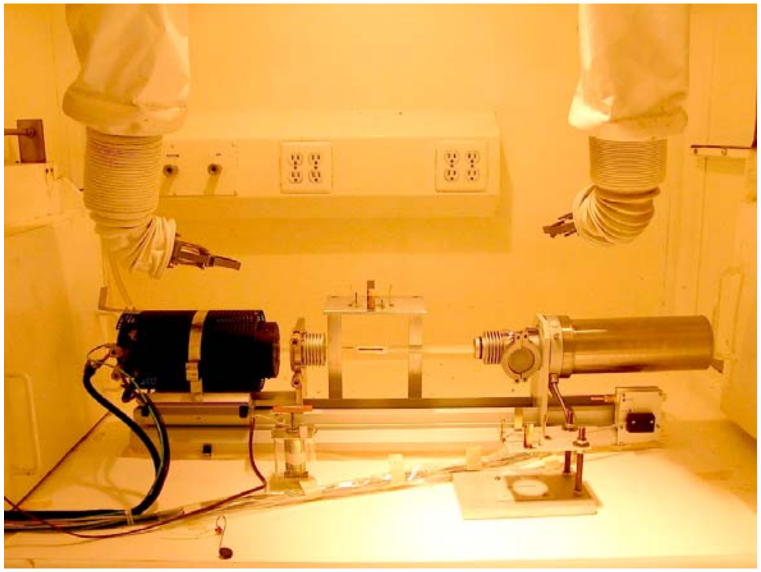
VASCOMAX SAMPLE dpa estimates

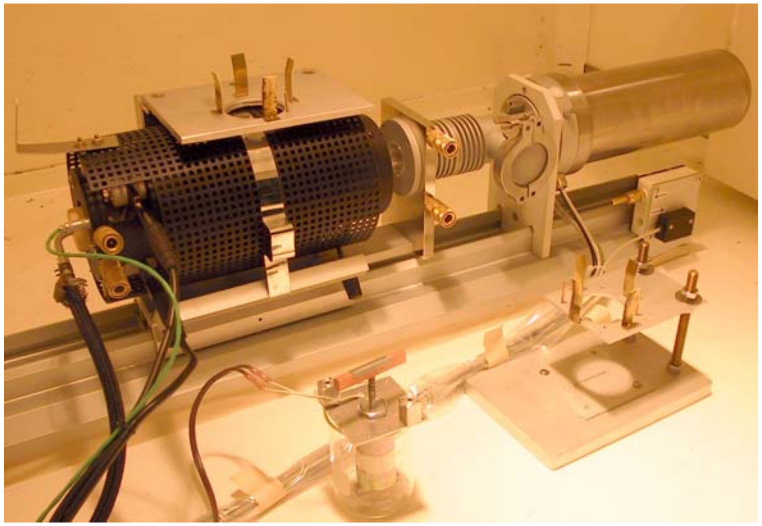
Cell 133:
from neutrons : 0.011336 dpa
from protons: 0.222335 dpa

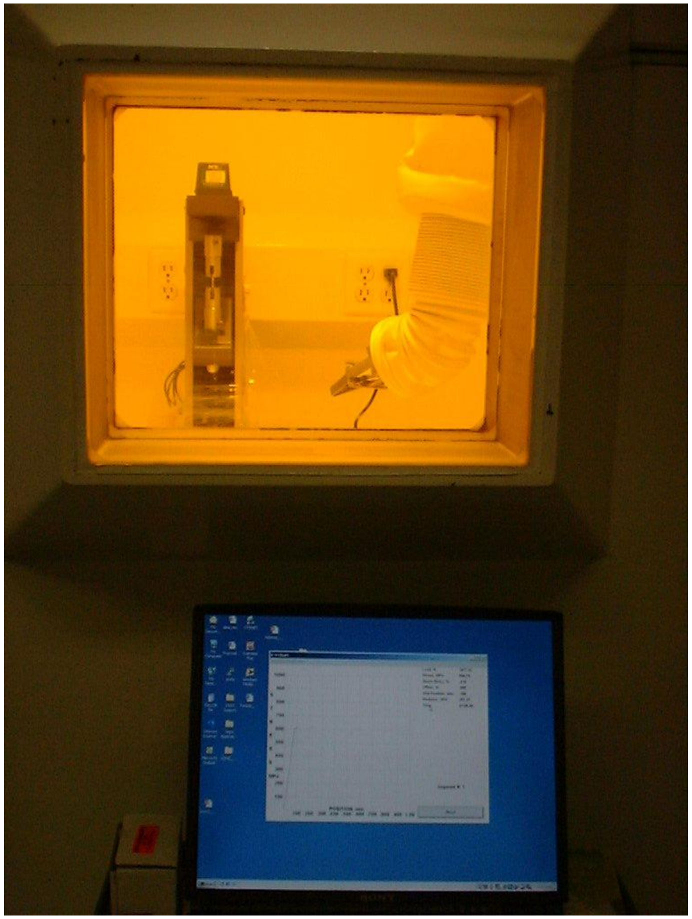
Cell 233:
from neutrons: 0.013827 dpa
from protons: 0.2214 dpa

Cell 220:
from neutrons: 0.0157 dpa
from protons: 0.24377 dpa

Dilatometer and Tensile Testing Arrangement at BNL Hot Cell Facility Used in Post-Irradiation Study





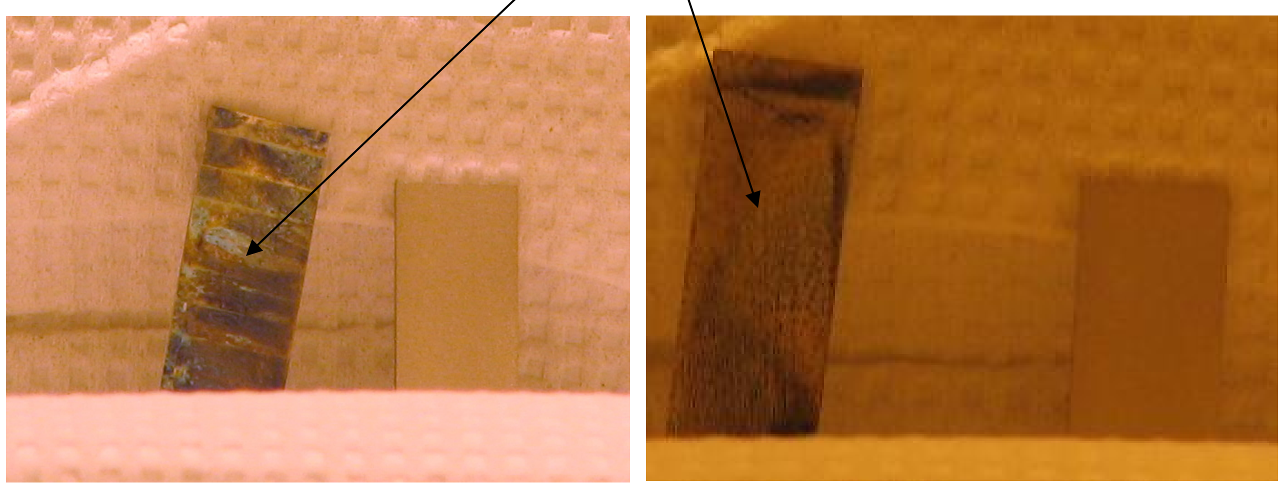


WHY DO WE WANT TO DO THESE TESTS?

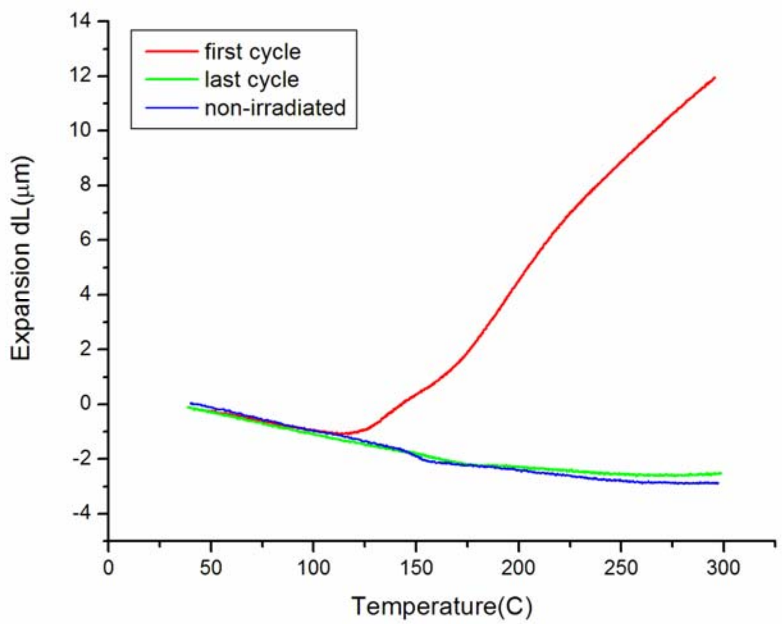
Non-irradiated HORN material

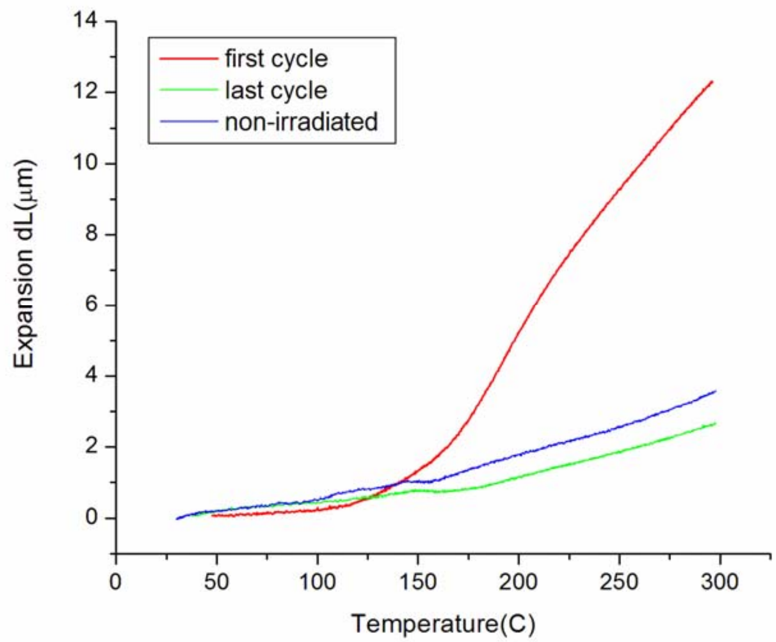
Is nickel-plating the way to prolong life of HORN? Jury is still out BUT preliminary assessment not favorable

Ni-plated material AFTER irradiation



CC composite “annealing” behavior





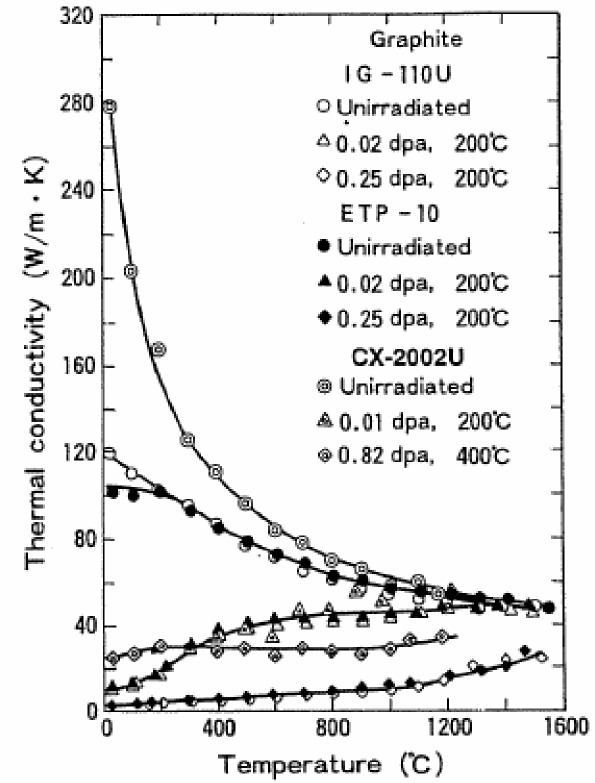
WHY Carbon-Carbon and not graphite?

IRRADIATION EFFECTS ON GRAPHITE

Irradiation has a profound effect on thermal conductivity/diffusivity

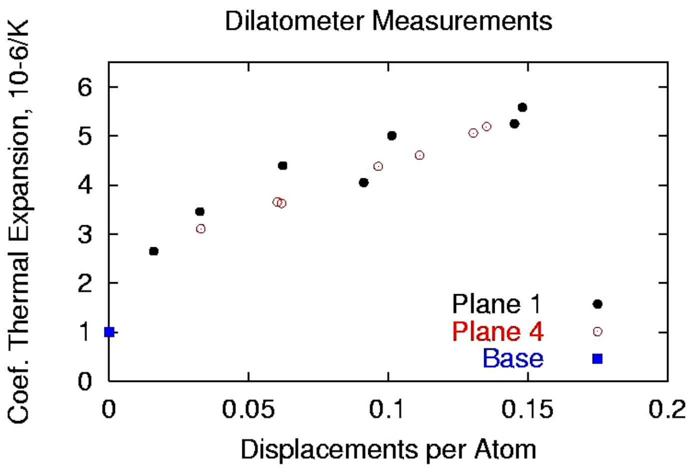
CC composite at least allows for fiber customization and thus significant improvement of conductivity.

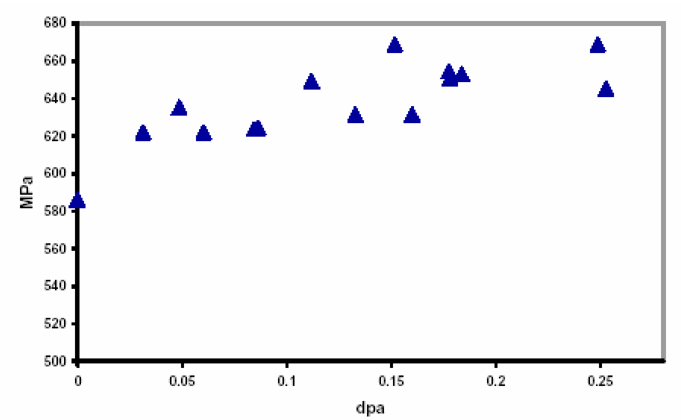
NOTE that assessment of irradiation effects on conductivity of CC composite yet to be completed

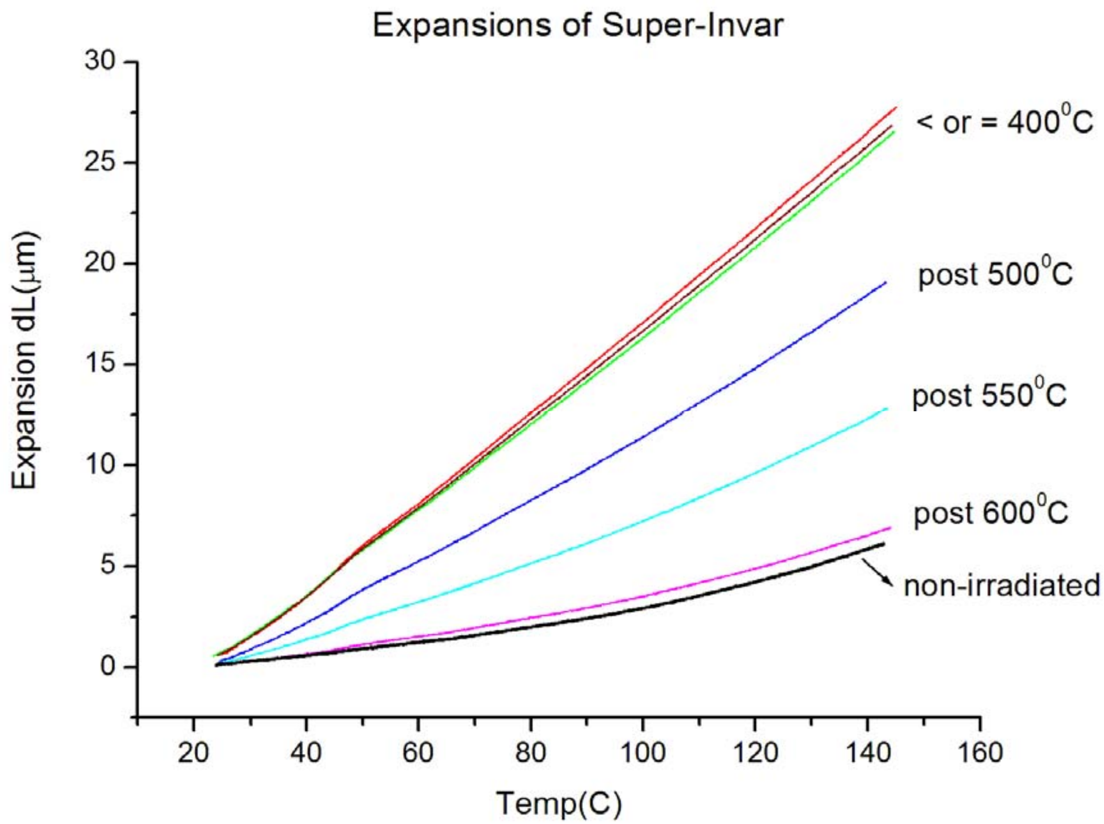


Thermal conductivity of neutron-irradiated graphites.

Super Invar: Serious candidate?

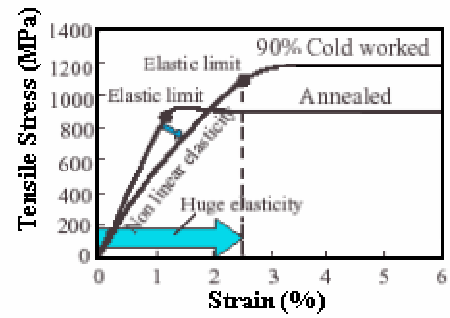


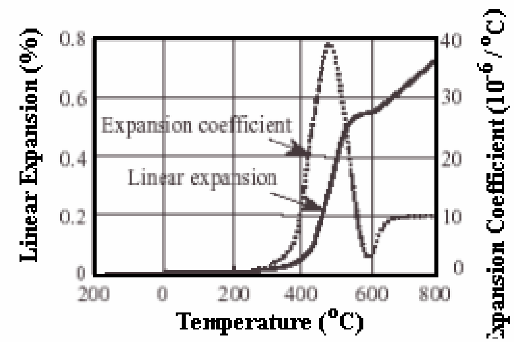


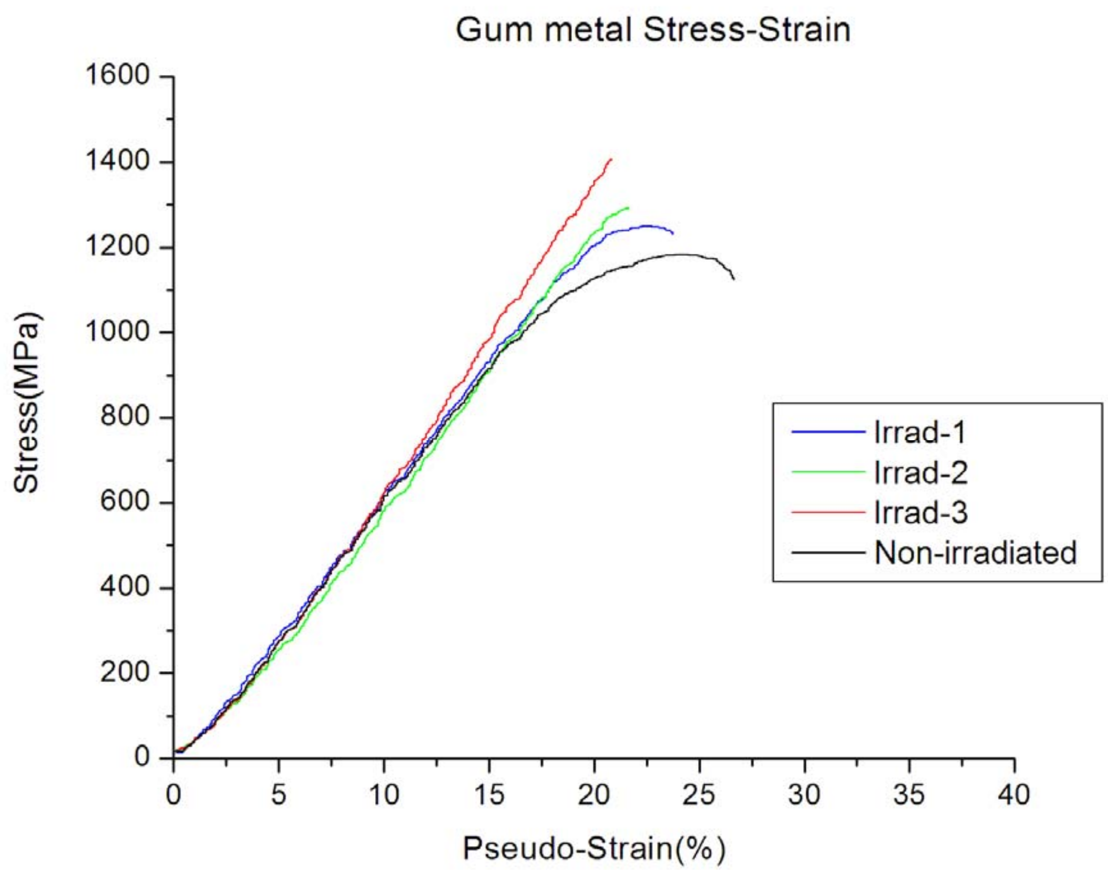


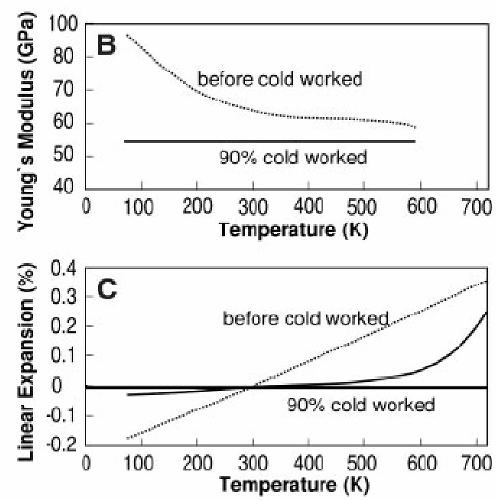
GUM Metal

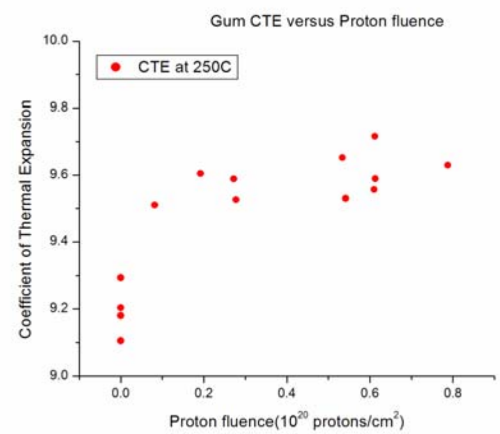
90% cold-worked may be of interest (if it holds these properties after irradiation)



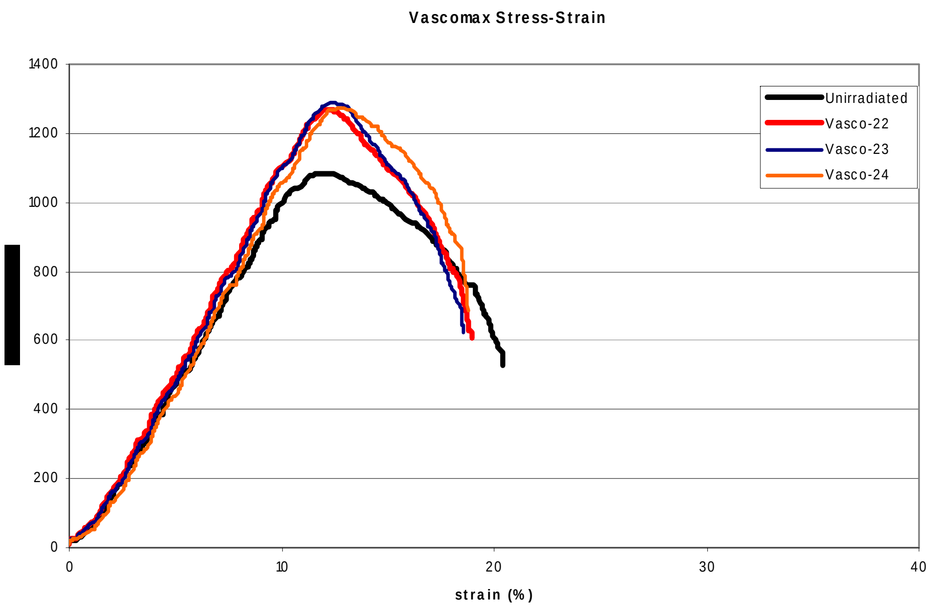




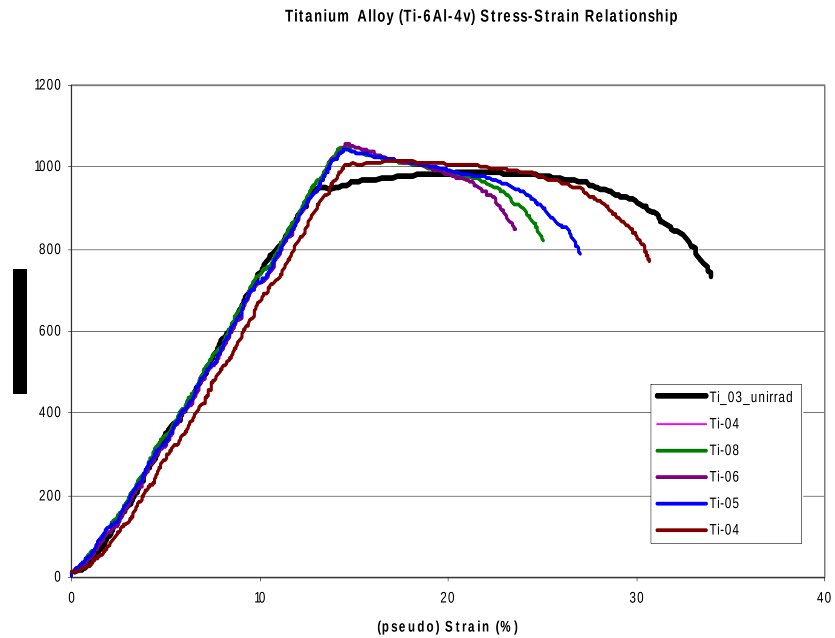


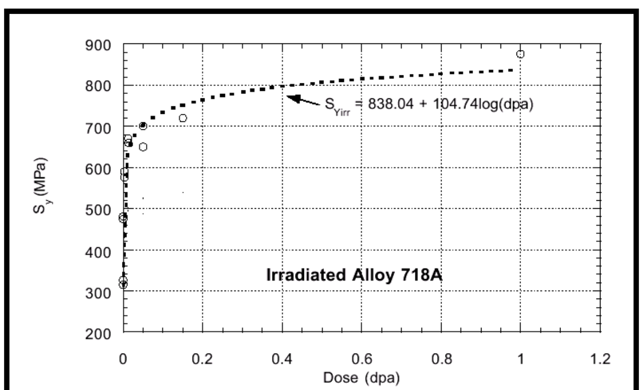


Vascomax

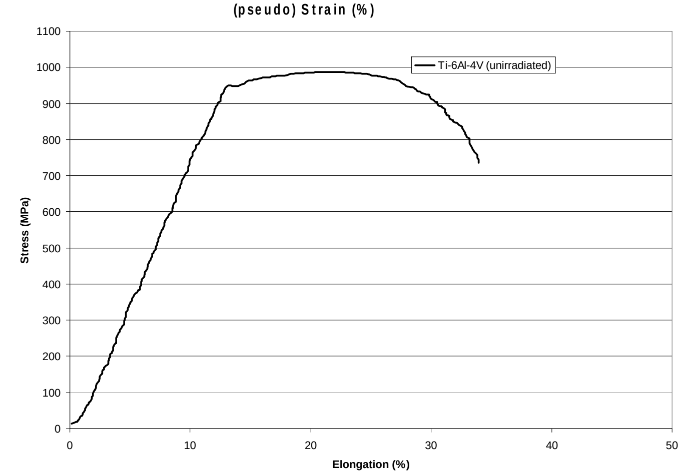


Ti alloy (6Al-4V)

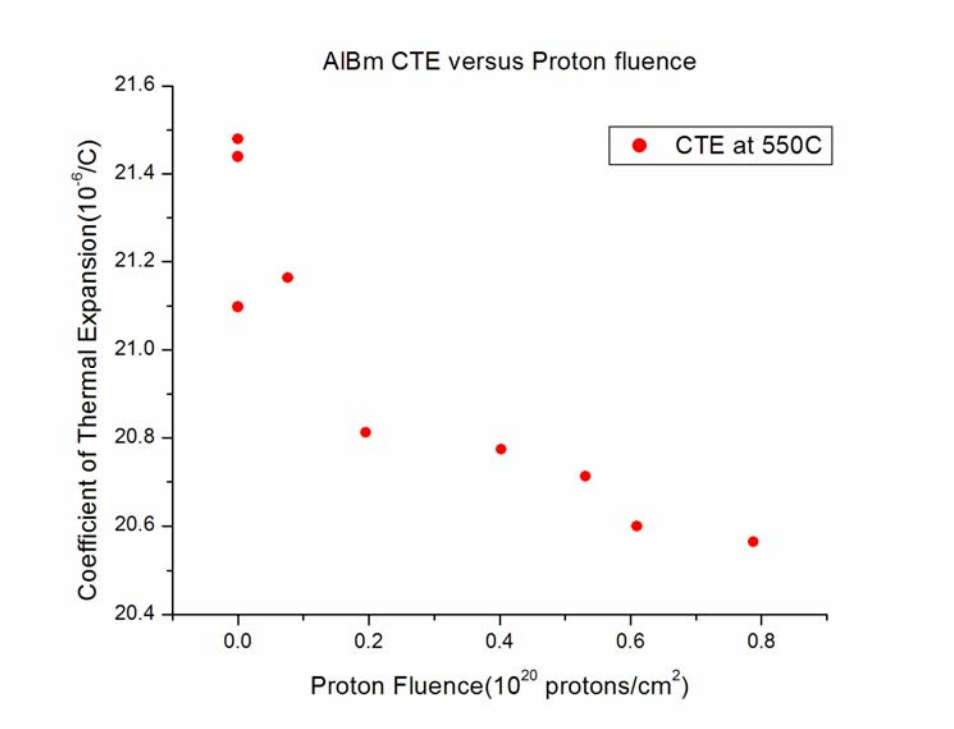


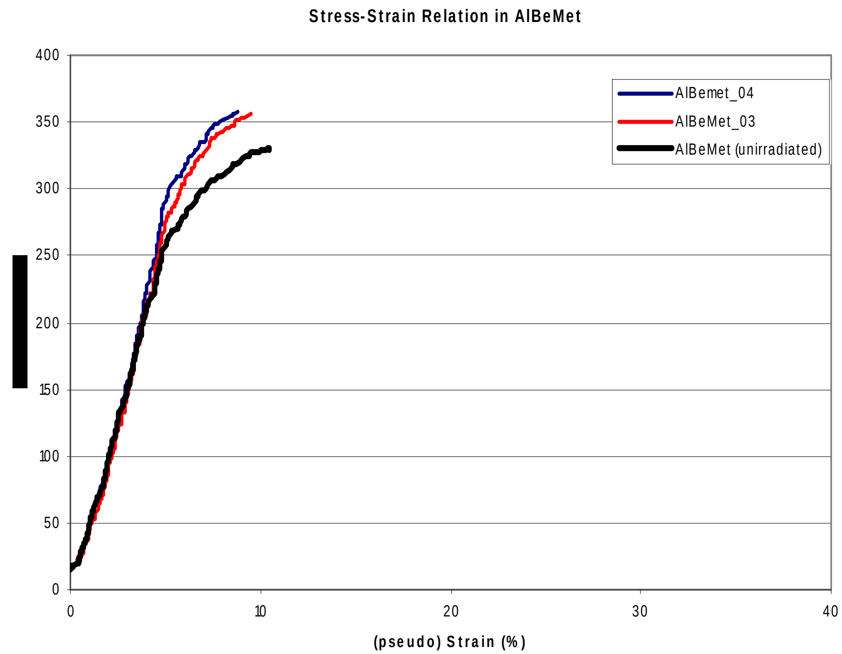


Effect of irradiation in HFIR on the room-temperature yield strength of Alloy 718A

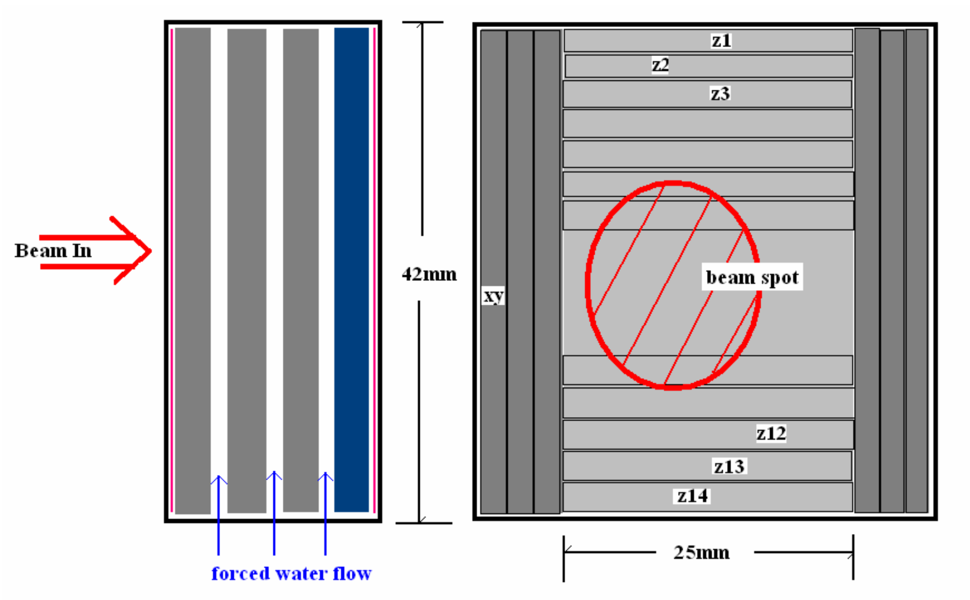


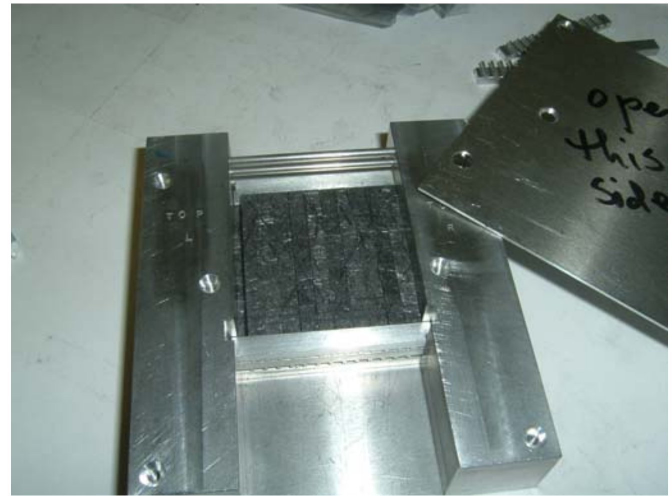
AlBeMet

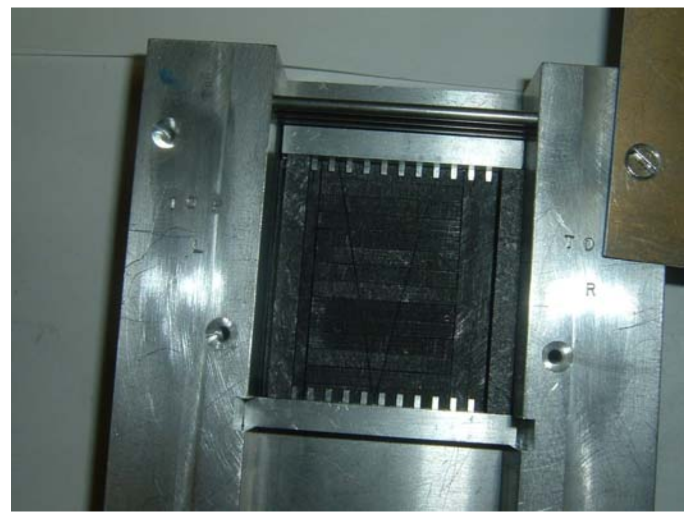

AlBm CTE versus Proton fluence
Coefficient of Thermal Expansion(10^{-6}/C)
21.6
21.4
21.2
21.0
20.8
20.6
20.4
CTE at 550C
0.0
0.2
0.4
0.6
0.8
Proton Fluence(10^{20} protons/cm^2)


Stress-Strain Relation in AlBeMet
[redacted]
400
350
300
250
200
150
100
50
0
AlBemet_04
AlBeMet_03
AlBeMet (unirradiated)
0
10
20
30
40
(pseudo) Strain (%)

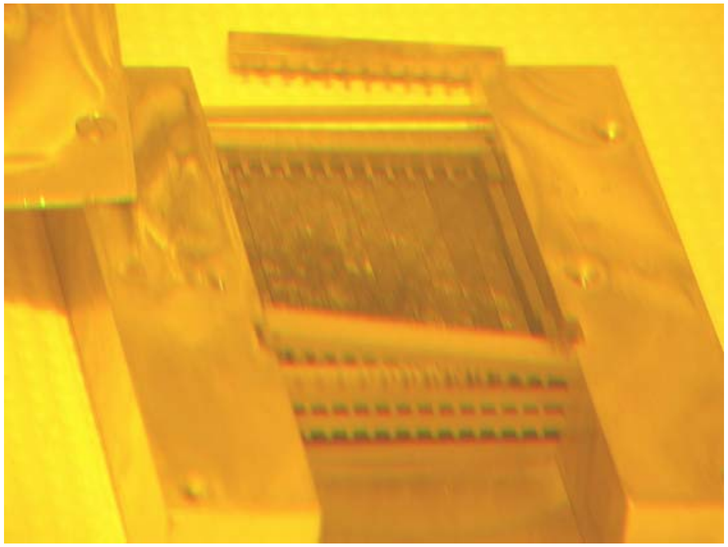
2D carbon-carbon Irradiation at BNL BLIP Facility

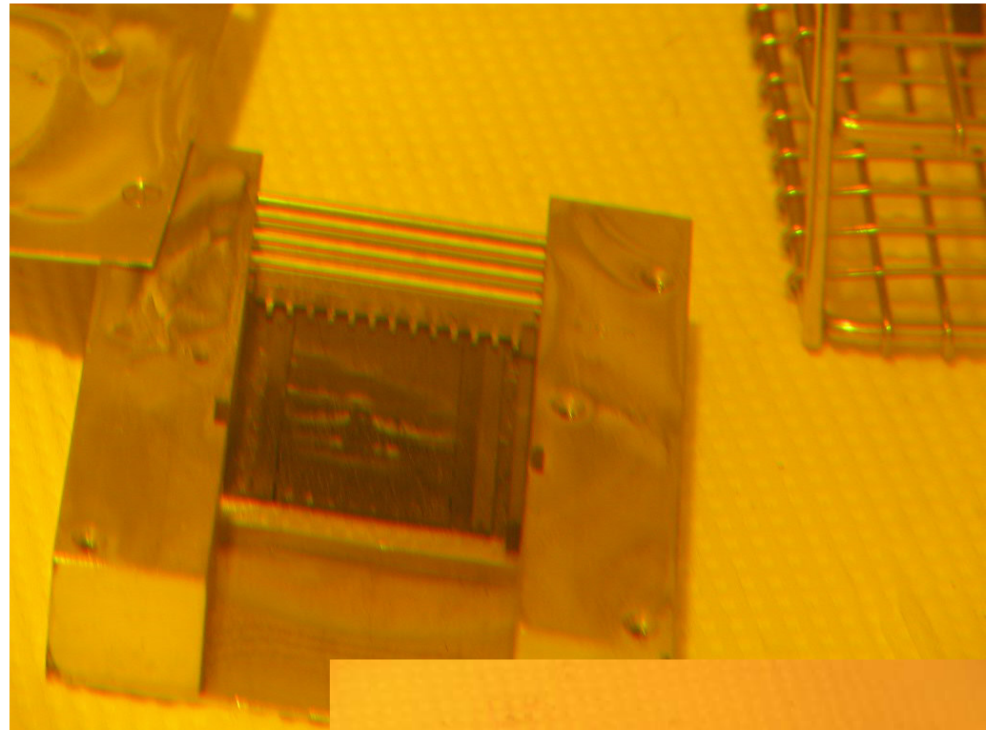


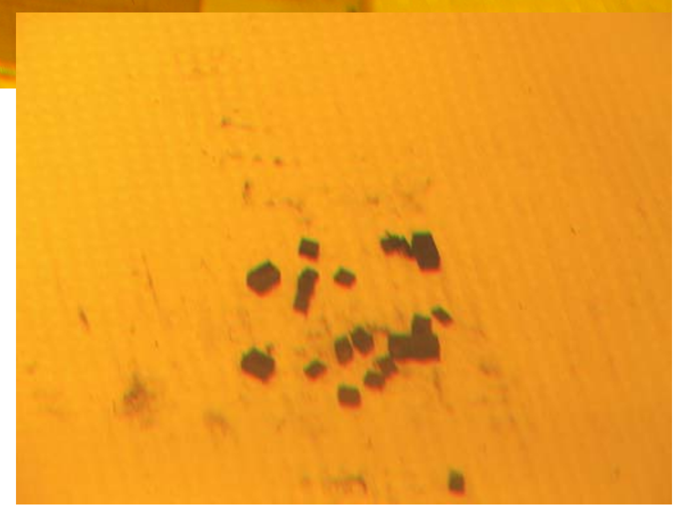




Preliminary 2D carbon-carbon post-irradiation







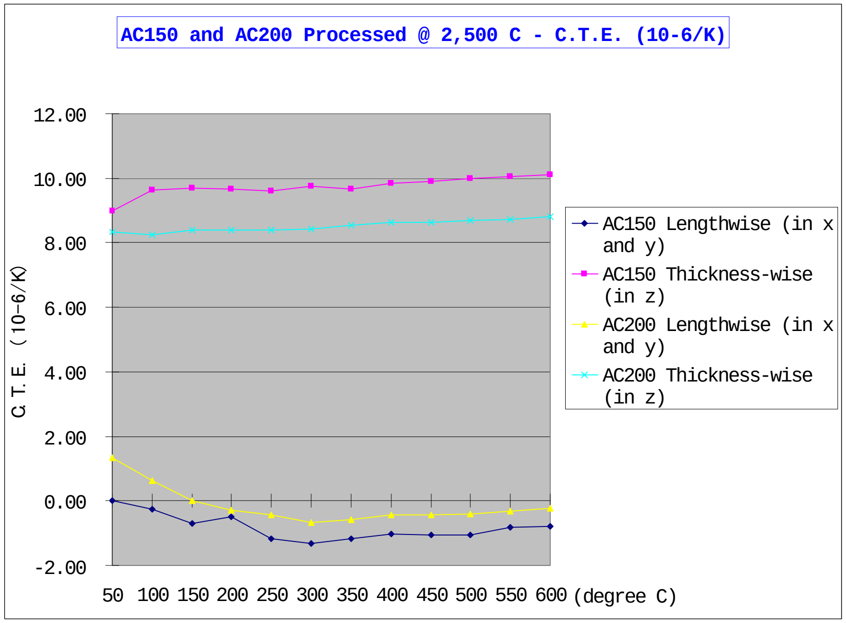
BLIP Proton Beam Exposure Records of LHC Collimator Carbon-Carbon Specimens

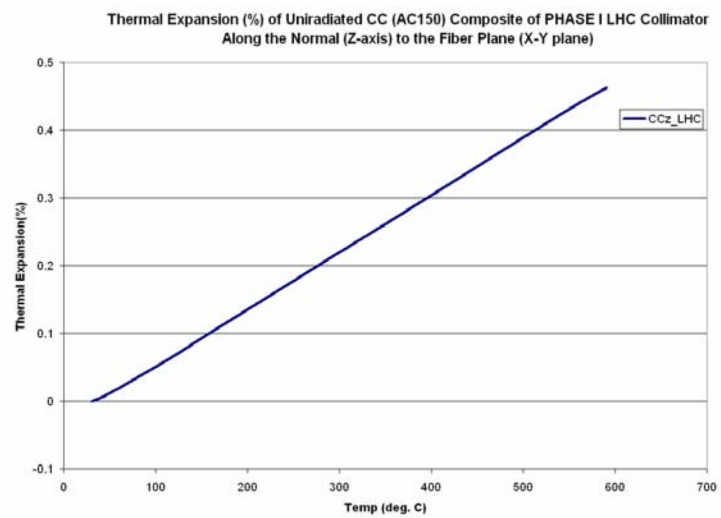
Date	Time	uAmpHrs received	Beam On Target Hours	Comments
4/28/2005	14:13	993.56	9.80	SOB 4/28/05 14:13 in Ch 1 Intg=89200.64 E=117.85 MeV
4/29/2005		2281.01	23.00	
4/30/2005		2345.24	23.00	
5/1/2005		2428.53	24.00	
5/2/2005		2404.11	24.00	
5/3/2005		2383.66	24.00	
5/4/2005		2404.80	24.00	
5/5/2005		2446.74	24.00	
5/6/2005		2481.99	24.00	
5/7/2005		2407.71	23.00	
5/8/2005		2499.22	24.00	
5/9/2005		2391.06	23.50	
. . .	. . .	. . .	. . .	. . .
6/10/2005		2000.00	23.50	Integrator failure - estimated numbers
6/11/2005		2000.00	23.00	Integrator failure - estimated numbers
6/12/2005		2000.00	23.50	Integrator failure - estimated numbers
6/13/2005		2000.00	22.00	Integrator failure - estimated numbers
6/14/2005		1941.61	22.50	Ran at 200MeV from 09:30 to 16:30hrs
6/15/2005		1899.18	22.50	
6/16/2005		1187.46	16.50	
6/17/2005		536.13	10.00	
6/18/2005		657.79	10.66	Ran 200MeV from 08:55 to 17:15hrs
6/19/2005		1885.68	24.00	
6/20/2005	22:00	1158.45	21.00	Ran 200MeV from 08:50 to 17:07hrs EOB 22:00
Sums		108085.39	1177.40	

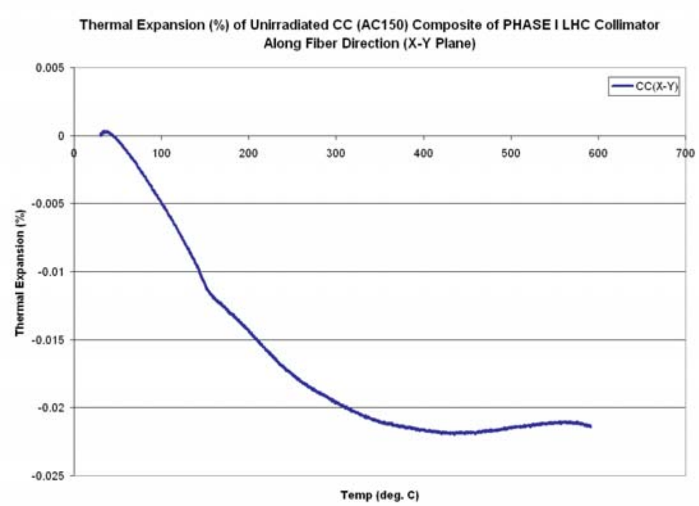
2D carbon-carbon post-irradiation

Company provided data on the 2D CC Material irradiated

NOTE: Results shown are in terms of Coefficient of Thermal Expansion



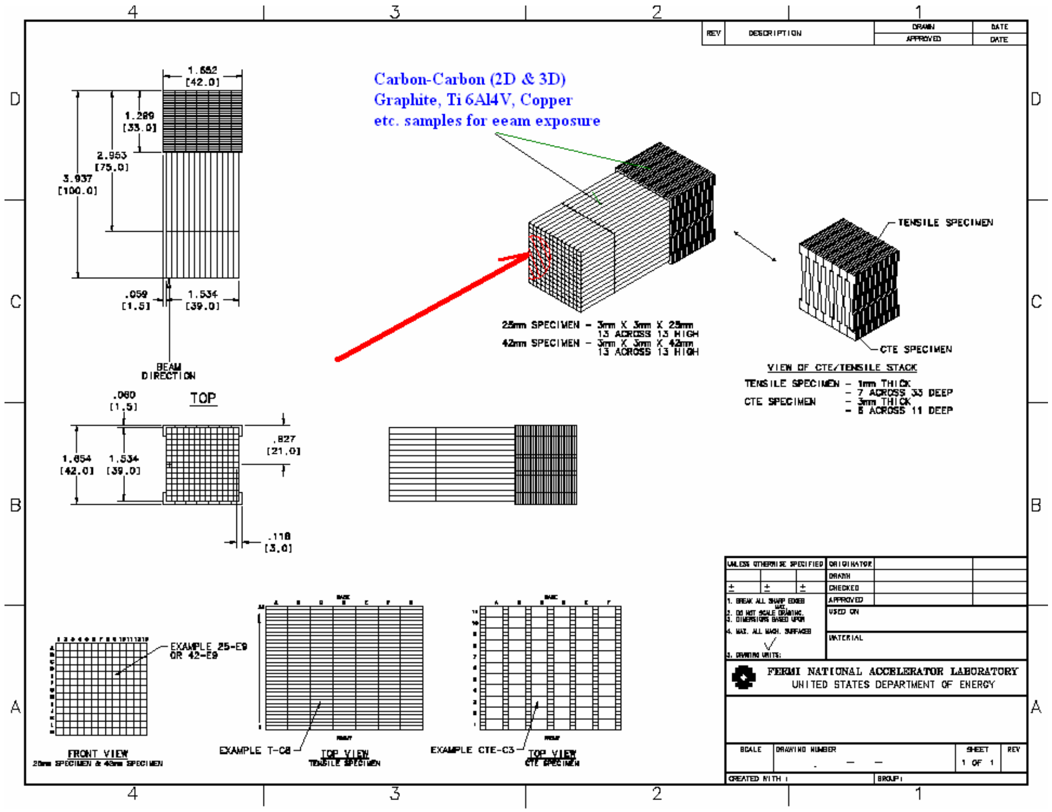




Post Irradiation Activities

- CTE measurements on 2-D carbon composite
- Testing of graphite and Carbon-Carbon to cycles up to 1100 C
  - in vacuum
  - with forced helium
- Thermal diffusivity and electrical resistivity measurements of the irradiated material matrix
- Closer examination of the Ni-plated aluminum for de-lamination, resistivity changes
- Damage assessment for defect generation/growth on specimens using ultrasonic techniques (more of an issue in graphite & CC)
- **Studies suggest that loss of strength is the direct result of irradiation-induced loss of "cold-work". Relate that to the performance of gum metal**

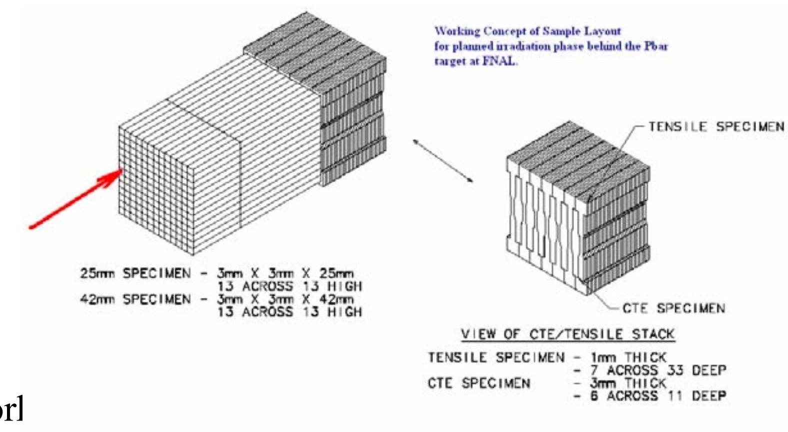
Future Target Studies at Pbar Facility (FNAL)



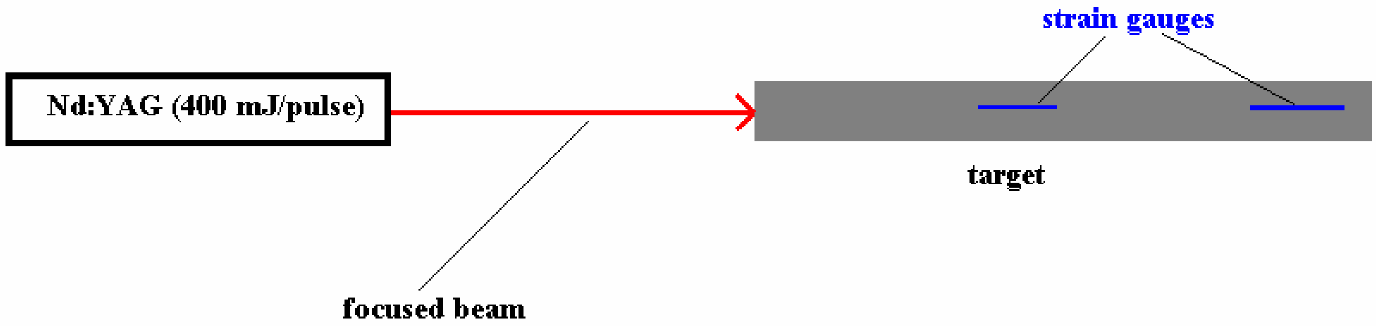
What we hope to get out of it ?

-Shock induced failure

- Information regarding damage at different doses and at different different ratios of protons to neutrons



Generation of stress waves/shock by transient surface heating



ASSESS target degradation through
micro-fracturing using ultrasound