PROPOSED

MATERIAL IRRADIATION STUDIES FOR LHC COLLIMATORS

Phase I & II

Nicholas Simos, BNL
N. Mokhov (FNAL)
A. Drees (BNL)

SCOPE

- Look into Phase I & II of the LHC Collimators and address the material choices, their chances of survival and the long-term meeting of the requirements

PHASE I

- How effective and resilient are carbon composite and graphite as baseline materials for Phase I ?

- Given that theoretical results are not able to answer these fundamental questions, what is the most prudent path in ensuring that both the constraints and the longevity of the chosen materials can be guaranteed ?

- Is there enough experience out there that can be used for assessment?
  - Neutron irradiation vs. High Energy Protons
  - Does graphite grade/type matter ?

- We propose to find out (ASAP)

SCOPE (continue)

PHASE II (Hybrid Secondary Collimators)

- Given that there is more time available to the team, search for most suitable materials should be easier

- Requirement for "excellent" mechanical tolerances – Can it be met with with materials like Cu, Be, etc.

- How about new "smart" materials such as Gum metal, AlBemet, Super-Invar?

- We propose to find out !

Phase I – Done Deal ????

Is it robust enough to get LHC to Phase II ?

ANSWER is Yes (if all assumptions are correct …)

What are the constraints?

Resistivity to be in check
Diffusivity/conductivity to be be in check
Deformations/warping to stay within tight limits (25 ❍m flatness)

What can spoil the soup?
Material damage, material damage, material damage ……
How drastically is impedance affected ?

WHY IS IT IMPORTANT THAT WE DO THESE TESTS?

Some physical properties of graphite materials (unirradiated)

	IG-110U	ETP-10	CX-2002U	GC-30	Boronized graphite
Density (g/cm^3)	1.76	1.75	1.65	1.45	1.88
Tensile strength (MPa)	25	35	30	42	–
Bending strength (MPa)	35	60	44	55	67
Modulus of elasticity (GPa)	10	11	12	22	12
Thermal conductivity (W(m K)) at $T = 20°C$	120	104	280	16	–
Coefficient of thermal expansion ($10^{-6}/K$), $T = 350–450°C$	4.5	3.8	2.6	2.2	–
Average grain size (μm)	20	40	–	–	–

[T. Maruyama, M. Harayama, Journal of Nuclear Materials 195(1992) 44-50]

Thermal conductivity and dimensional change of neutron-irradiated graphites IG-110U, ETP-10 and GC-30

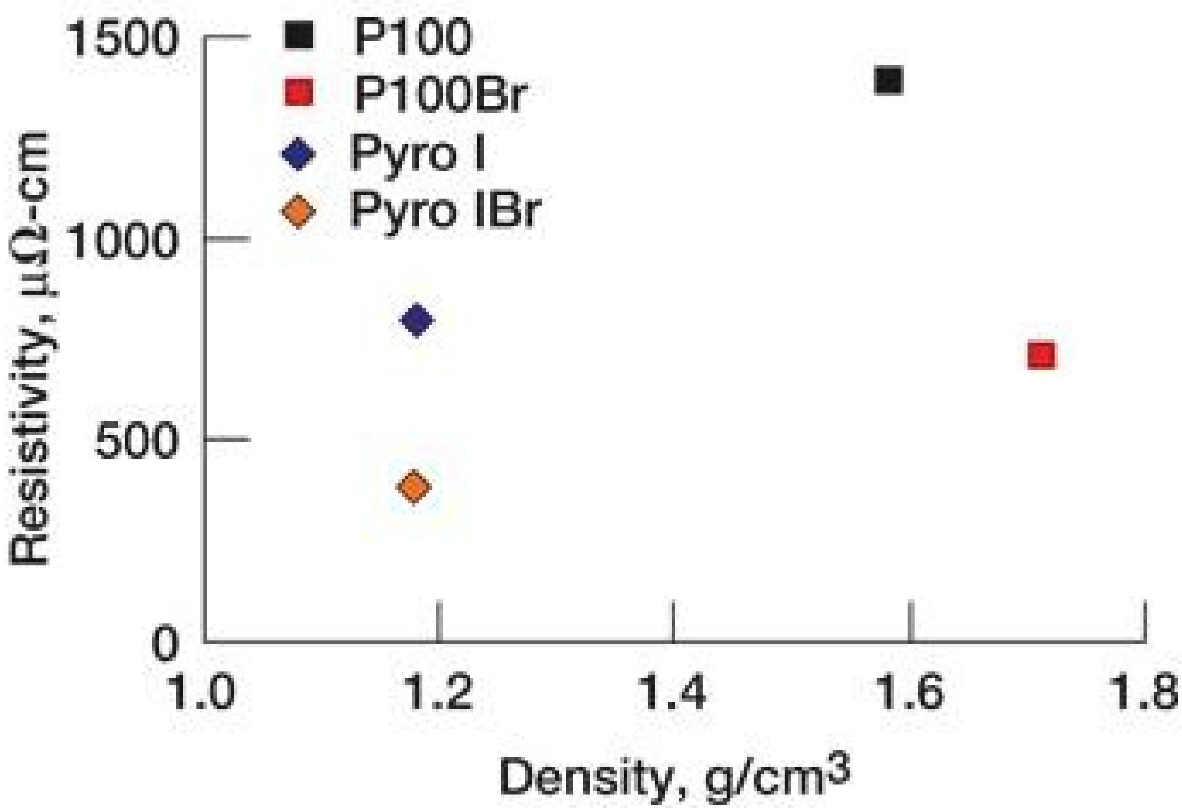
Irradiation	Thermal conductivity (W/(m K))			Dimensional change (%)		
	IG-110U	ETP-10	GC-30	IG-110U	ETP-10	GC-30
Unirradiated	119	101	16	–	–	–
0.02 dpa, 200°C	10.9	11.8	3.7	0.04	0.10	−0.14
0.25 dpa, 200°C	2.6	3.4	1.9	0.14	0.24	−0.68

WHY IS IT IMPORTANT THAT WE DO THESE TESTS?

Parameter	Unit	TCP	TCS
Azimuthal orientation		X, Y, S	various
Jaw material		C or C-C	C or C-C
Jaw length	cm	20	100
Jaw tapering	cm	2×10	2×10
Jaw dimensions	mm^2	65×25	65×25
Jaw coating		1 μm Cu	1 μm Cu
Jaw resistivity	$\mu\Omega$m	minimal	minimal
Surface roughness	μm	≤ 1	≤ 1.6
Surface flatness	μm	25	25
Heat load	kW	1.5	7
Max. operational temperature	$^\circ$C	50	50
Outbaking temperature	$^\circ$C	250	250
Maximum full gap	mm	60	60
Minimum full gap	mm	0.5	0.5
Knowledge of gap	μm	50	50
Jaw position control	μm	≤ 10	≤ 10
Control jaw-beam angle	μrad	≤ 15	≤ 15
Reproducibility of setting	μm	20	20
DOF movement (hor. collimator)		X, X', Y	X, X', Y
DOF movement (vert. collimator)		Y, Y', X	Y, Y', X
Positional installation accuracy	μm	100	100
Angular installation accuracy	μrad	150	150

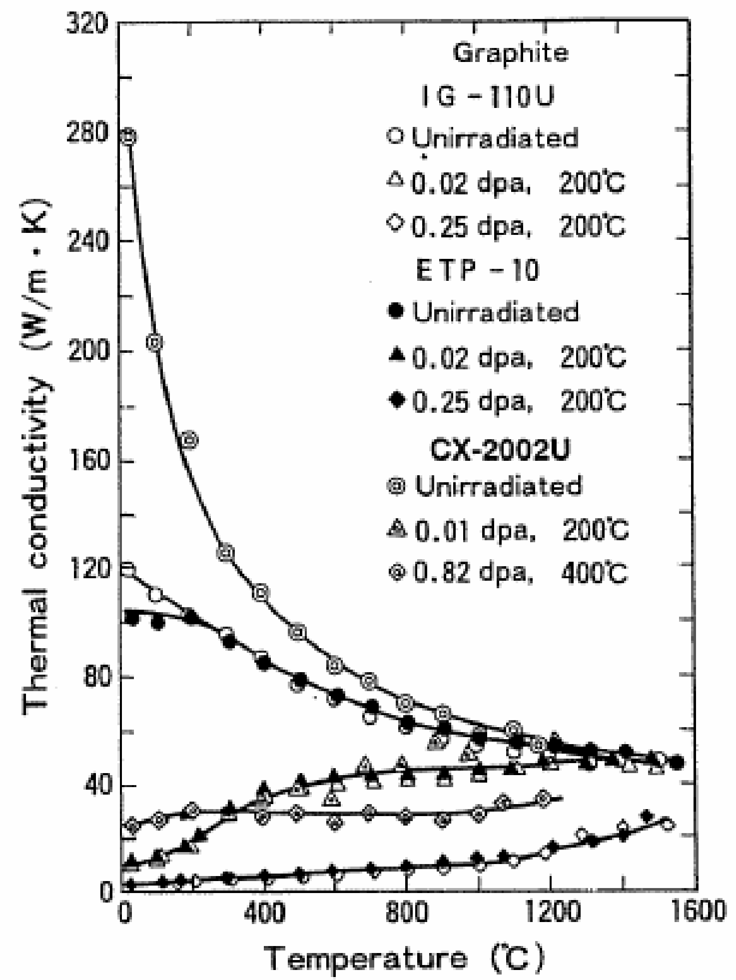
- Phase 2 will reduce the collimator induced impedance (metallic).
- Phase 2 will use a good vacuum material.
- Phase 2 will provide better absorption and lower inefficiency (higher Z and long or double components)!
- Phase 2 will achieve flatness tolerances (25 μm).
- Phase 2 will be less robust but only be used in stable conditions and will provide maximum in-situ spare surface (rotating collimator).

Graphite Grade Choices & Resistivity



WHY IS IT IMPORTANT THAT WE DO THESE TESTS?

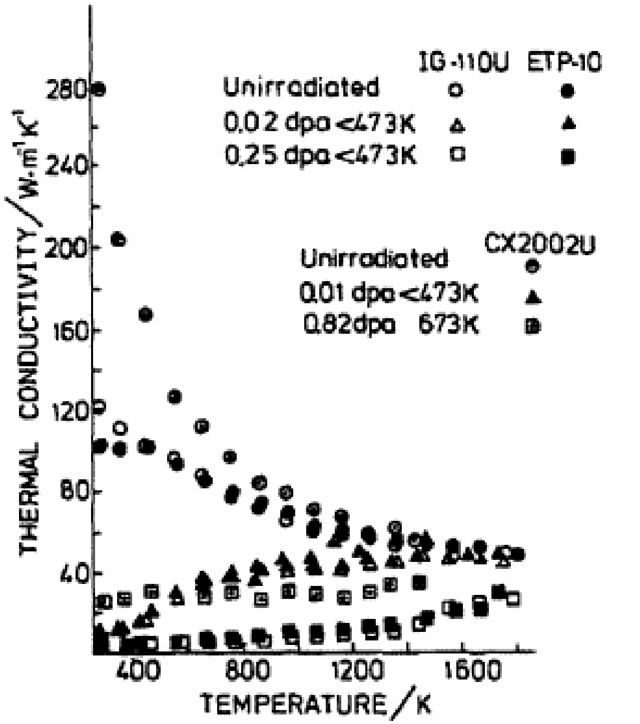
Note the variation with
Different graphites



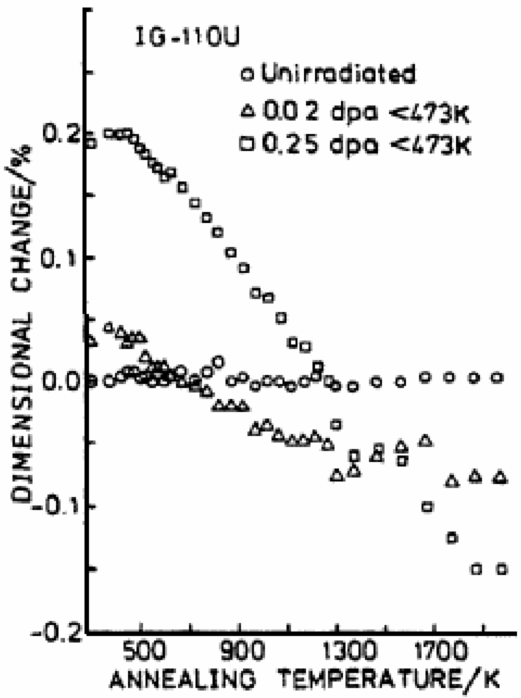
Thermal conductivity of neutron-irradiated graphites.

[T. Maruyama, M. Harayama, Journal of Nuclear Materials 195(1992) 44-50]

WHY IS IT IMPORTANT THAT WE DO THESE TESTS?



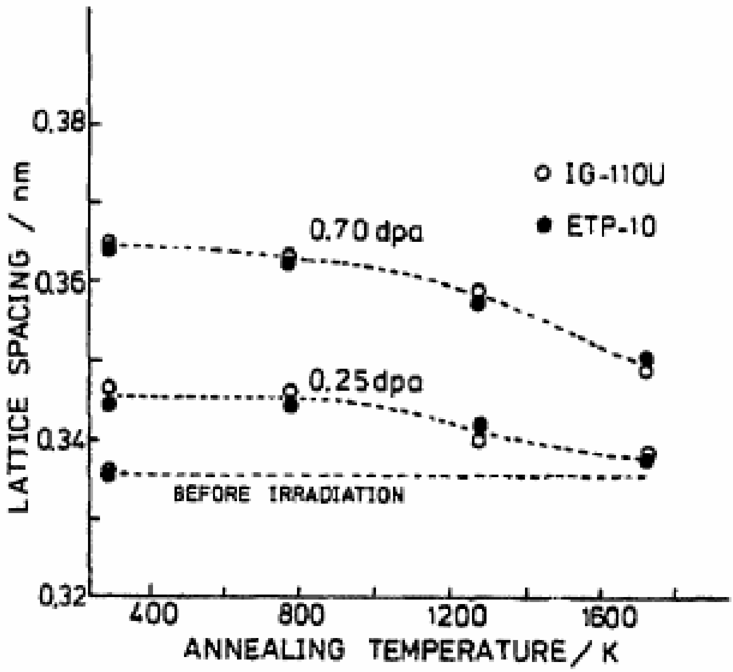
Change in thermal conductivity of neutron-irradiated graphite.



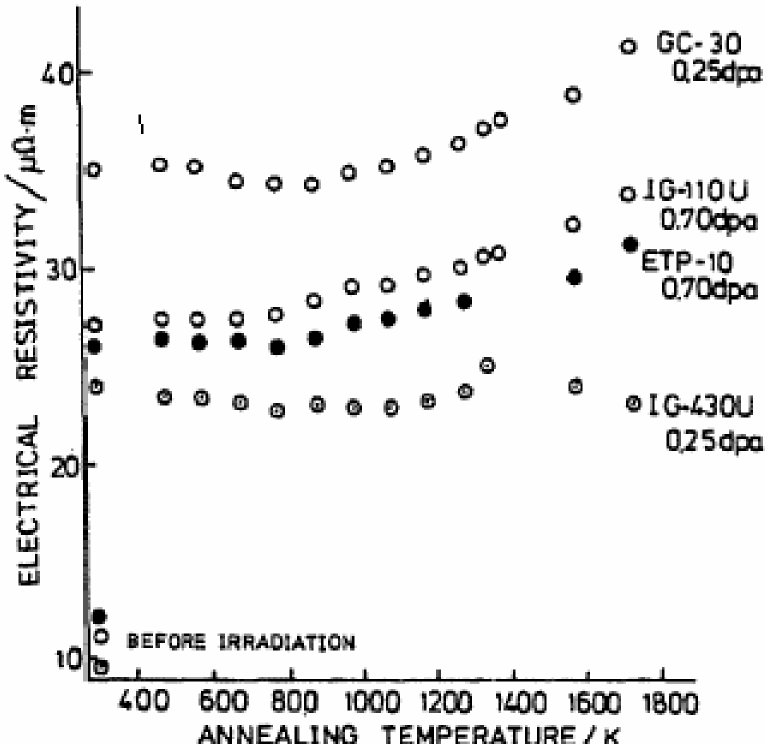
Variation in dimensional change of neutron-irradiated graphite.

[T. Maruyama, M. Harayama, Journal of Nuclear Materials 195(1992) 44-50]

WHY IS IT IMPORTANT THAT WE DO THESE TESTS?



Change in lattice spacing of basal planes of neutron-irradiated graphite by isochronal annealing.

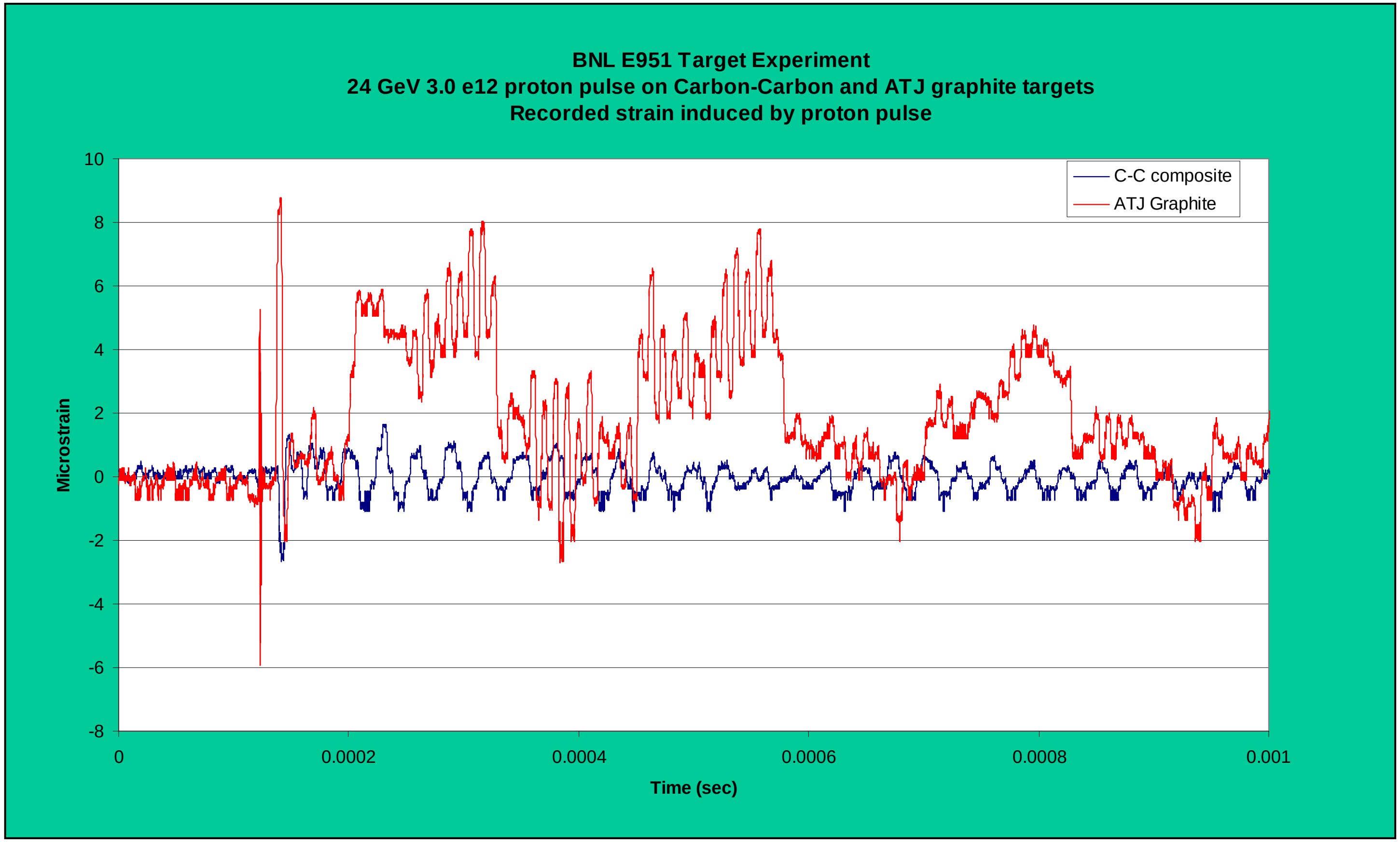


Change in electrical resistivity of neutron-irradiated graphite by isochronal annealing.

[T. Maruyama, M. Harayama, Journal of Nuclear Materials 195(1992) 44-50]

Graphite vs. Carbon-Carbon Composite

Results from the Muon Collaboration Experiment BNL E951



CC is clearly less responding to shock. It is also stronger (normal planes) than graphite but much weaker in off-normal planes.

Do things hold true after irradiation?

PHASE I & II COLLIMATOR MATERIAL STUDY

Carbon-Carbon Composite

GRAPHITE (what grade ?)

Alternatives ?
Beryllium
AlBeMet

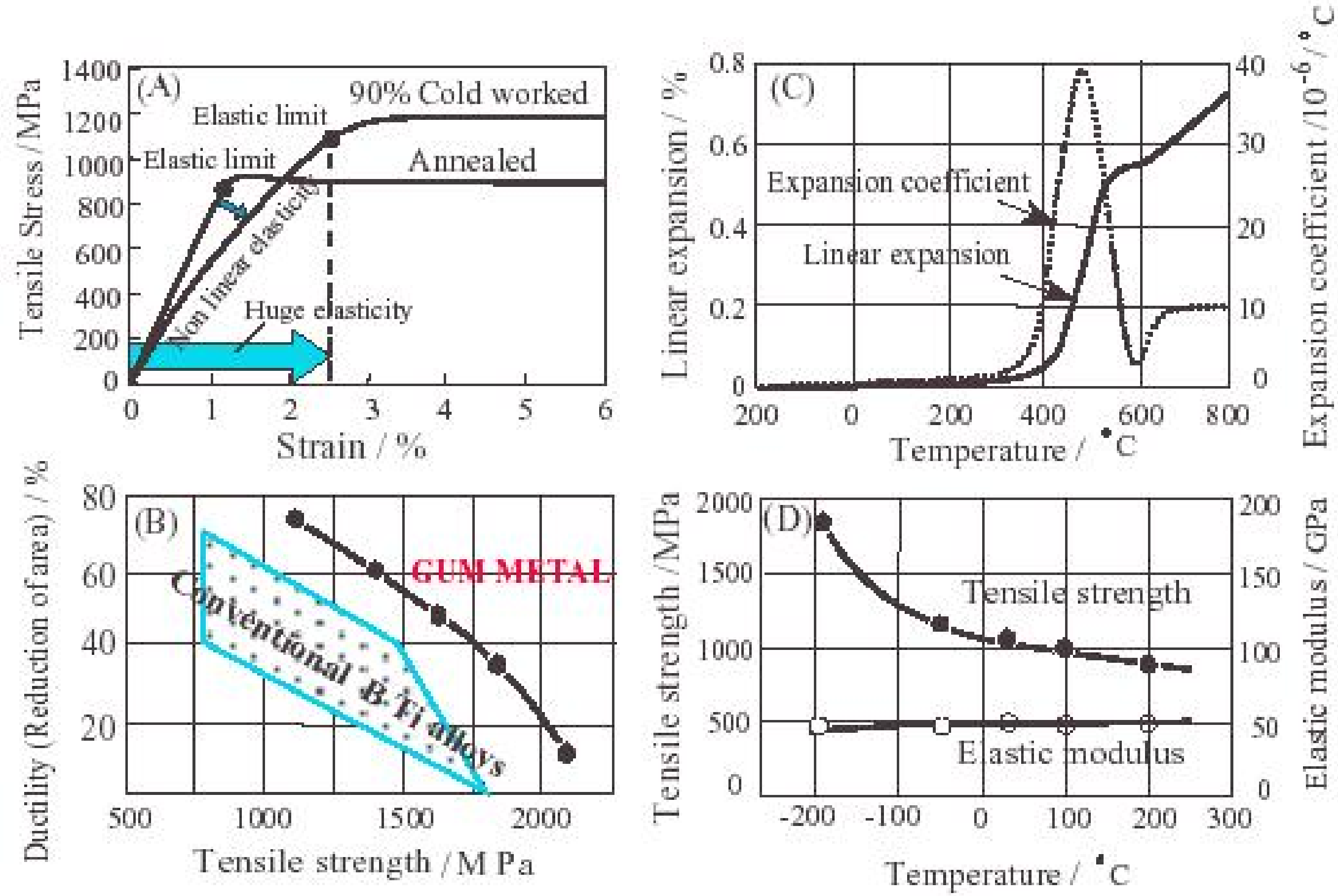
Cu (Baseline-Hybrid Collimator) – irradiation-induced unknowns

Super-Invar → REVISITED !!!!

Toyota "Gum Metal" → interesting material

Inconel-718 → until further notice

WHY Gum Metal (Toyota Ti alloy)

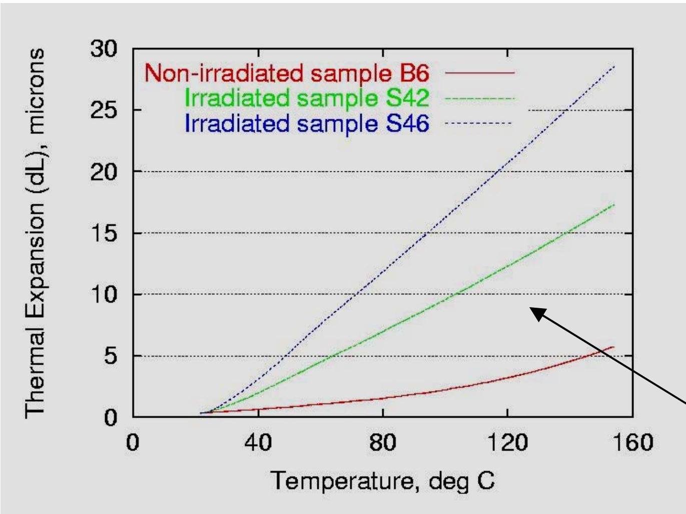


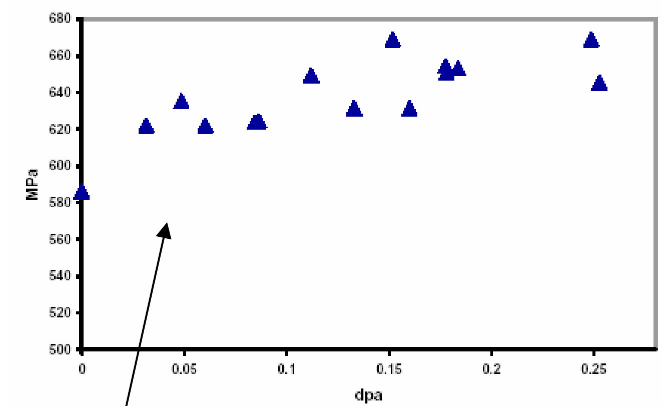
WHY AlBeMet ?

AlBeMet® Property Comparison

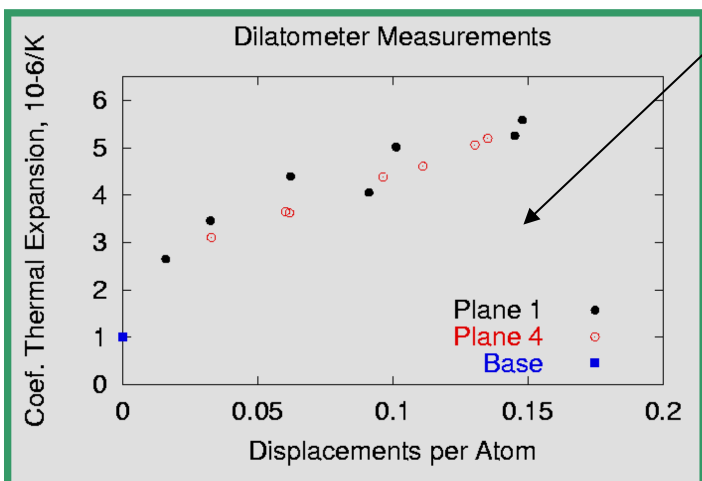
Property	Beryllium S200F/AMS7906	AlBeMet AM16H/AMS7911	E-Material E-60	Magnesium AZ80A T6	Aluminum 6061 T6	Stainless Steel 304	Copper H04	Titanium Grade 4
Density lbs/cuin (g/cc)	0.067 (1.85)	0.076 (2.10)	0.091 (2.51)	0.065 (1.80)	0.098 (2.70)	0.29 (8.0)	0.32 (8.9)	0.163 (4.5)
Modulus MSI (Gpa)	44 (303)	28 (193)	48 (331)	6.5 (45)	10 (69)	30 (205)	16.7 (115)	15.2 (105)
UTS KSI (Gpa)	47 (324)	38 (262)	39.3 (273)	49 (340)	45 (310)	75 (515)	45 (310)	95.7 (660)
YS KSI (Gpa)	35 (241)	28 (193)	N/A	36 (250)	40 (275)	30 (205)	40 (275)	85.6 (590)
Elongation %	2	2	< .05	5	12	40	20	20
Fatigue Strength KSI (Gpa)	37.9 (261)	14 (97)	N/A	14.5 (100)	14 (95)	N/A	N/A	N/A
Thermal Conductivity btu/hr/ft/F (W/m-K)	125 (216)	121 (210)	121 (210)	44 (76)	104 (180)	9.4 (16)	226 (391)	9.75 (16.9)
Heat Capacity btu/lb-F (J/g-C)	.46 (1.95)	.373 (1.56)	.310 (1.26)	.251 (1.05)	.214 (.896)	.12 (.5)	.092 (.385)	.129 (.54)
CTE ppm/F (ppm/C)	6.3 (11.3)	7.7 (13.9)	3.4 (6.1)	14.4 (26)	13 (24)	9.6 (17.3)	9.4 (17)	4.8 (8.6)
Electrical Resistivity ohm-cm	4.2 E-06	3.5 E-06	N/A	14.5 E-06	4 E-06	72 E-06	1.71 E-06	60 E-06

BNL Material R&D Study (super Invar/Inconel-718)

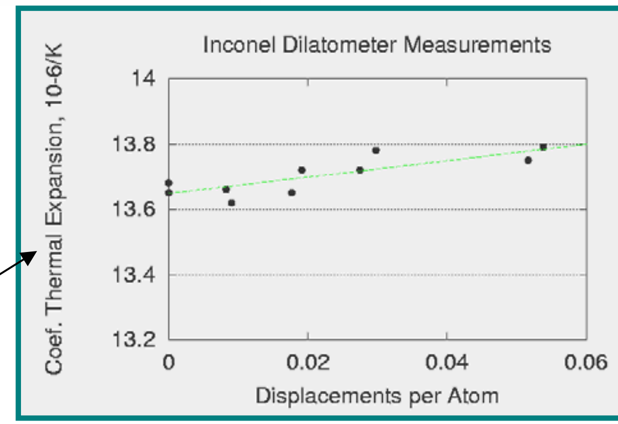


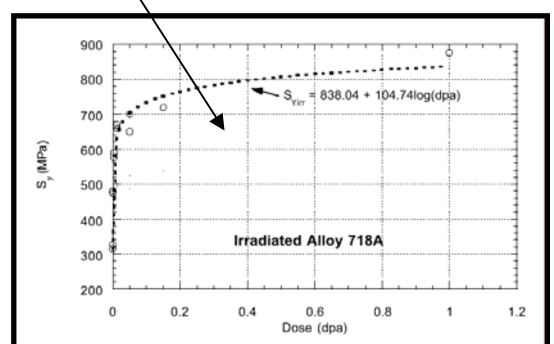


Invar



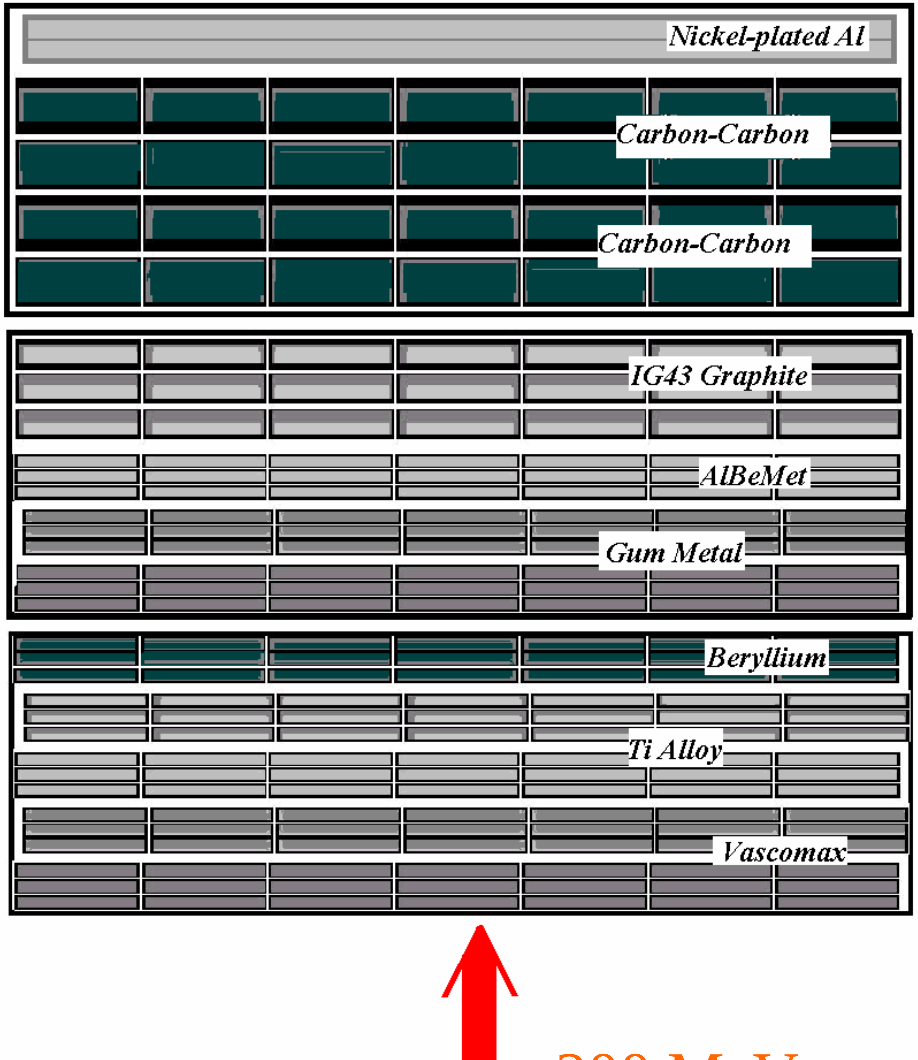
Inconel



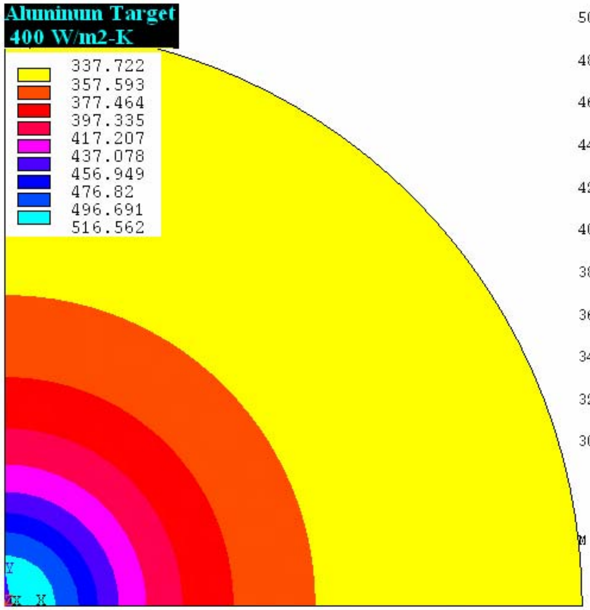


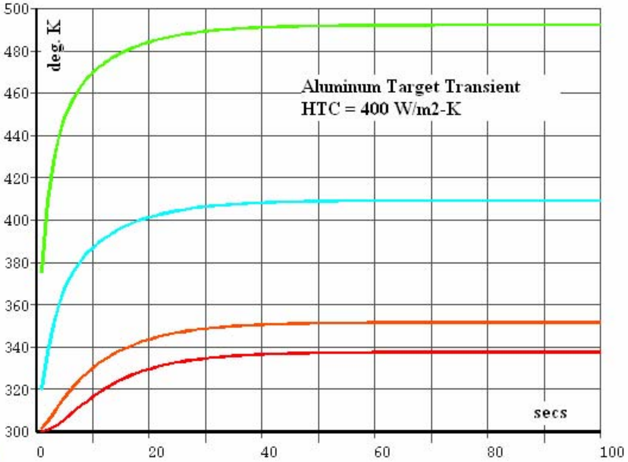
Effect of irradiation in HFIR on the room-temperature yield strength of Alloy 718A

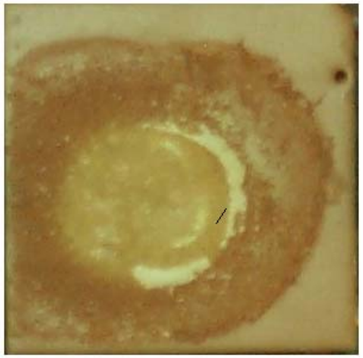
Current BNL Material R&D Study

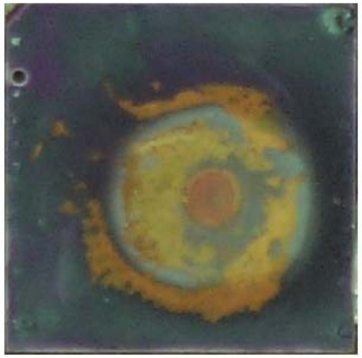


200 MeV protons (~70 μA)


Aluminum Target
400 W/m2-K
337.722
357.593
377.464
397.335
417.207
437.078
456.949
476.82
496.691
516.562

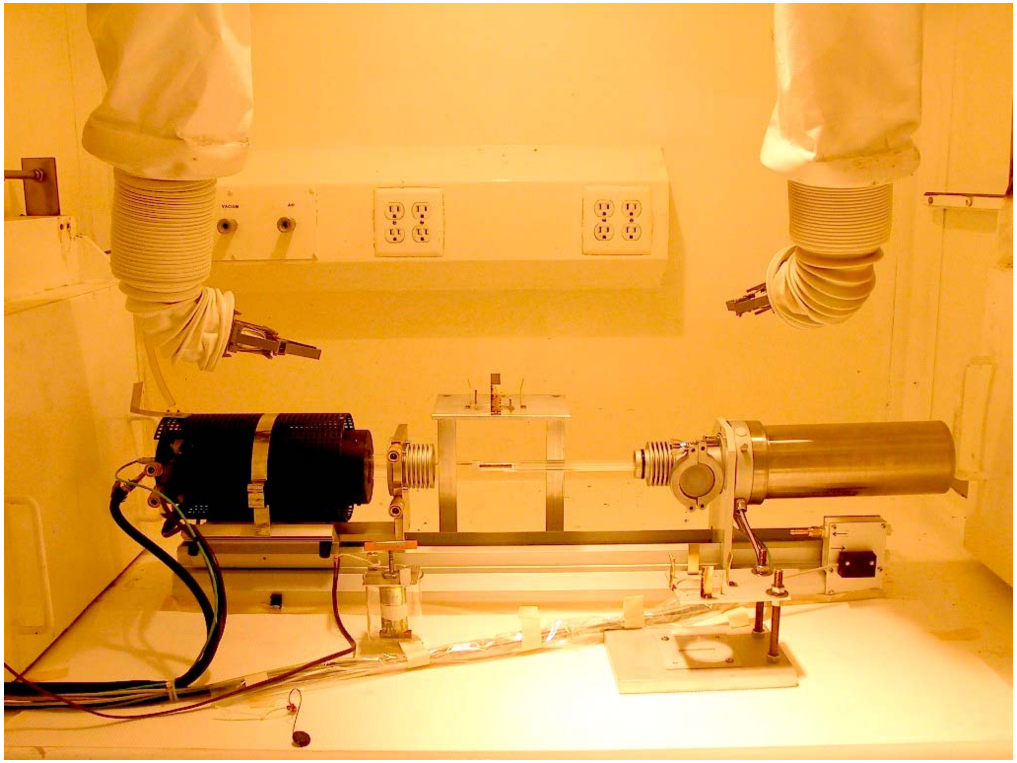

deg. K
Aluminum Target Transient
HTC = 400 W/m2-K
secs
500
480
460
440
420
400
380
360
340
320
300
0
20
40
60
80
100

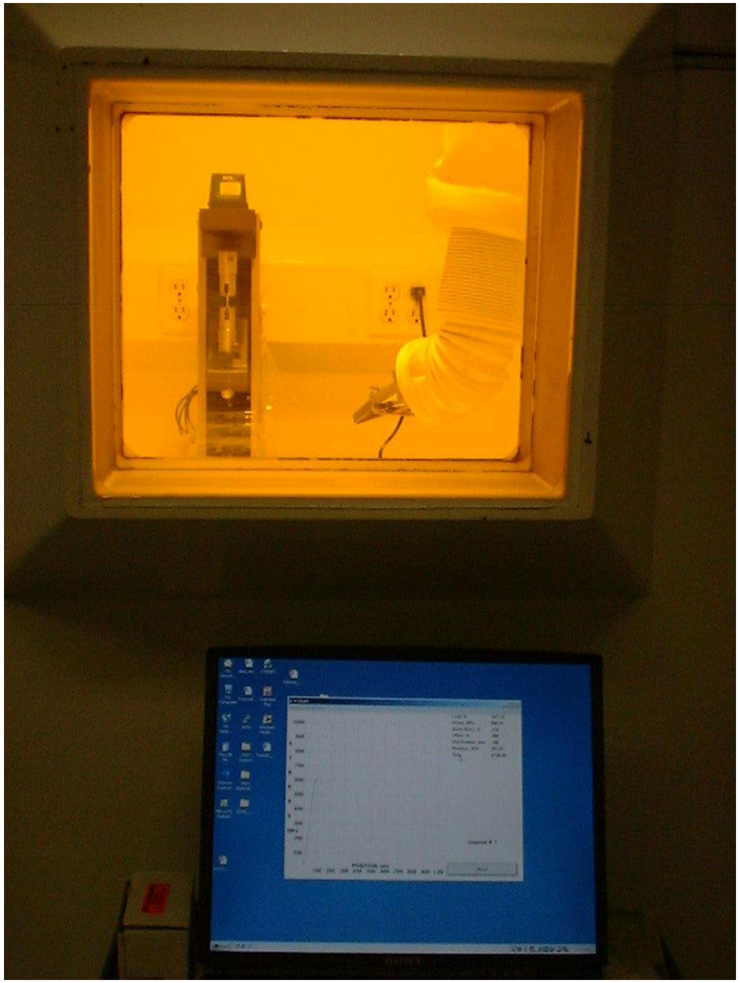


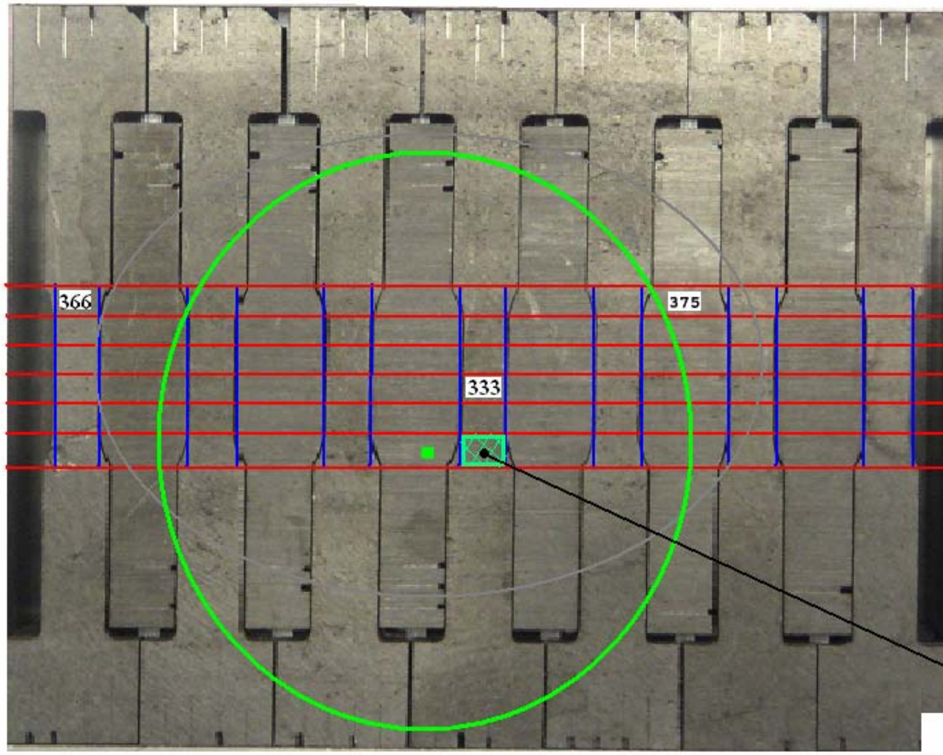


ON-GOING Post-Irradiation Study at BNL Hot Cell

Dilatometer – Mechanical Tester







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

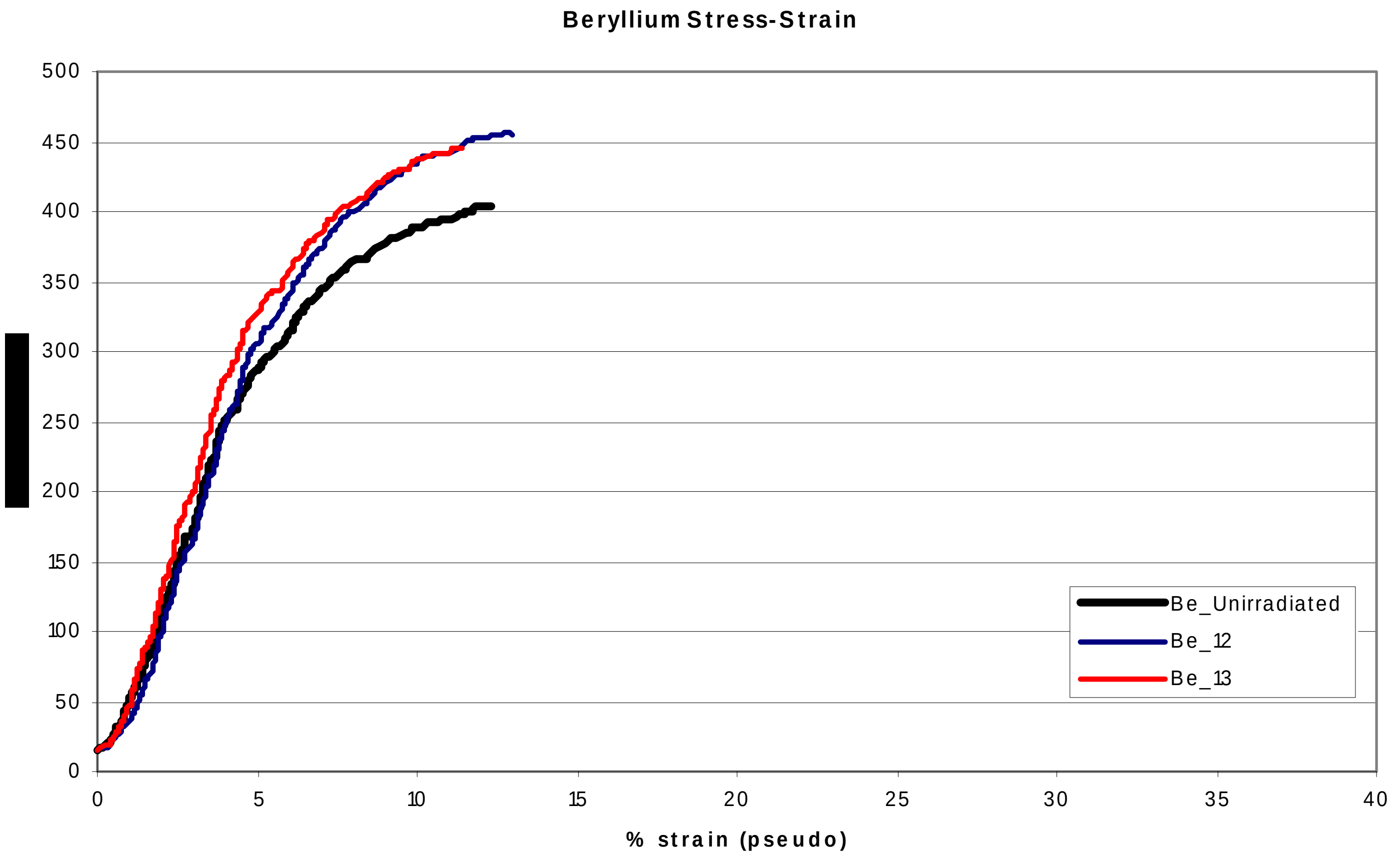
VASCOMAX SAMPLE dpa estimates

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

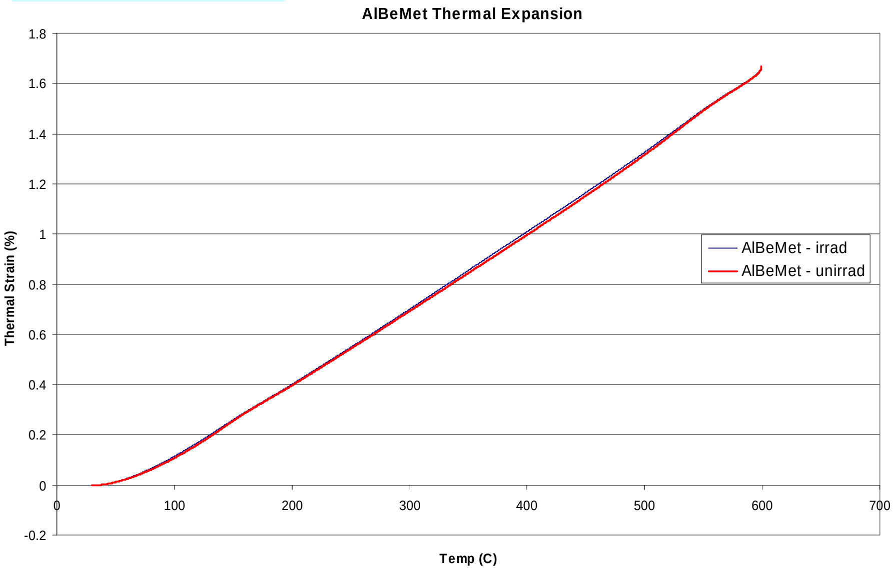
Cell 233:
from neutrons: 0.013827 dpa
from protons: 0.2214 dpa

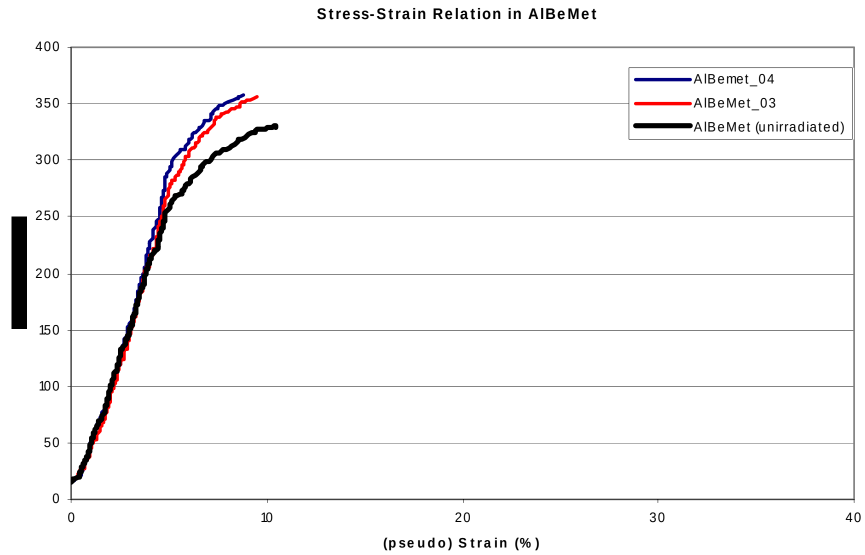
Cell 220:
from neutrons: 0.0157 dpa
from protons: 0.24377 dpa

Beryllium Preliminary Post-Irradiation Results

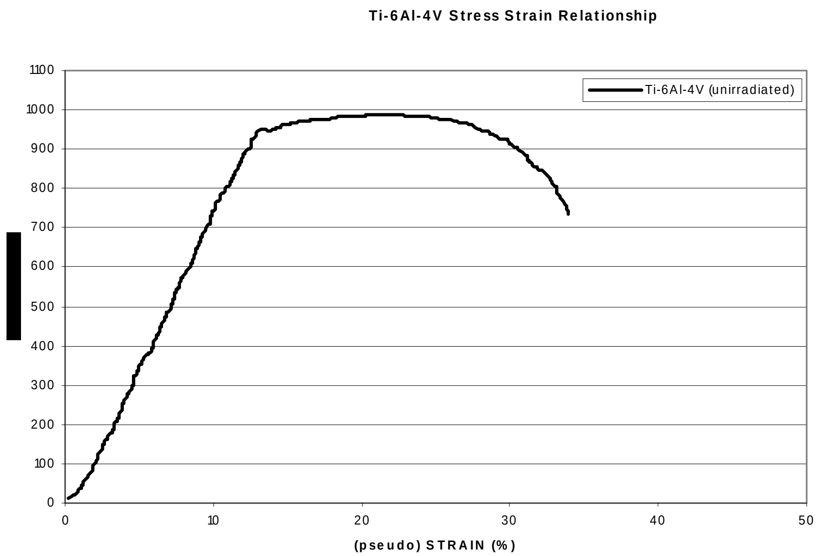


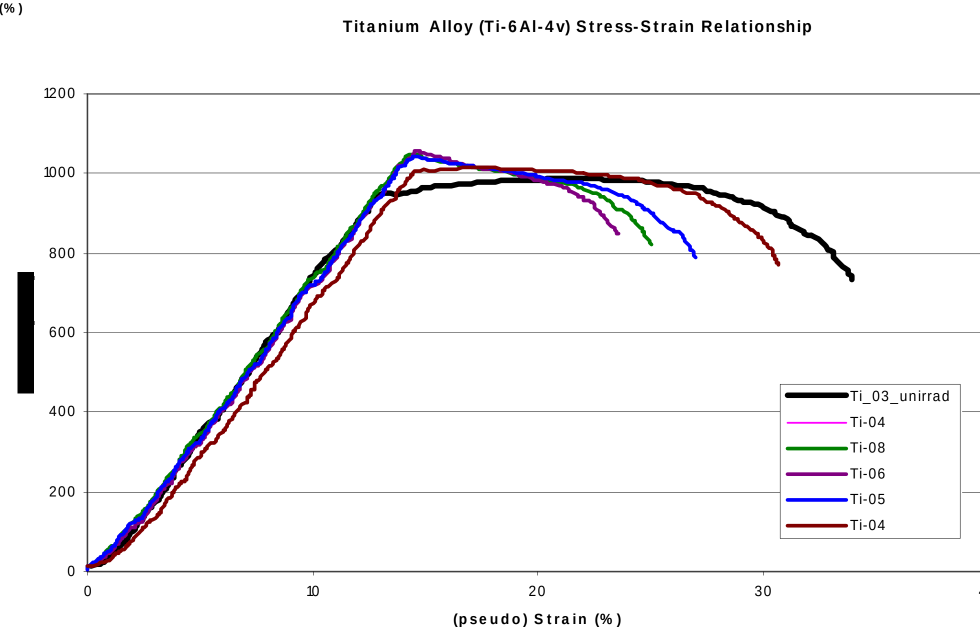
AlBeMet Preliminary Post-Irradiation Results



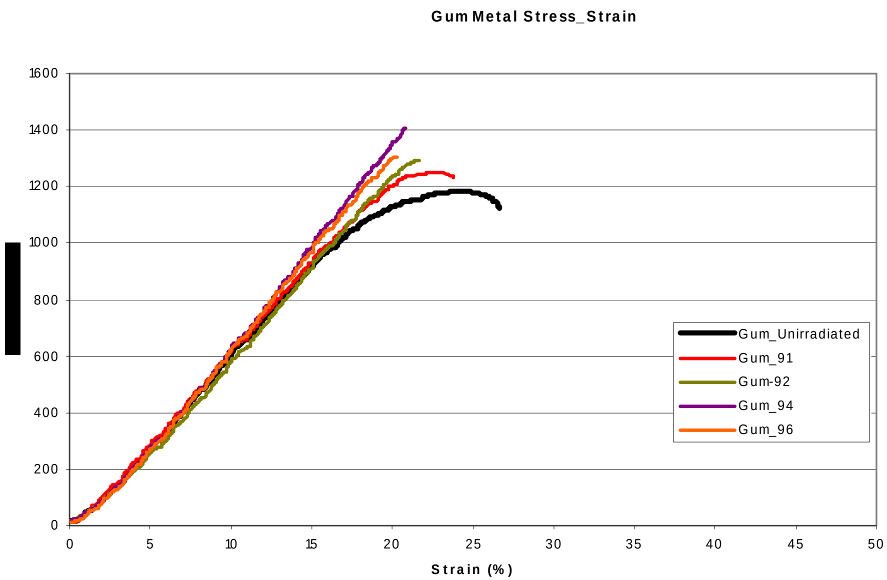


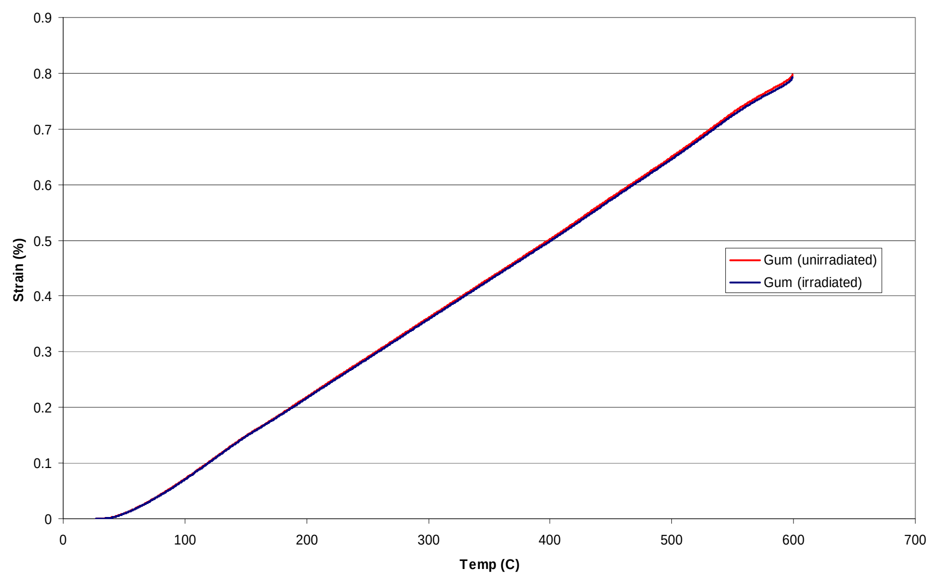
Ti6Al4V Alloy: Preliminary Post-Irradiation Results



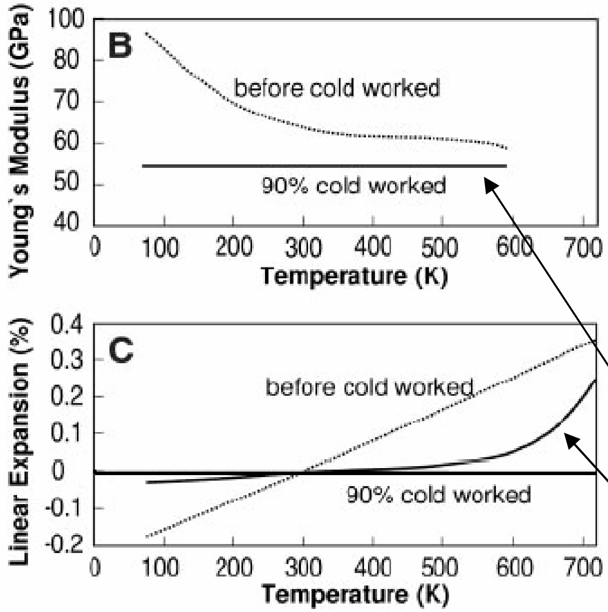


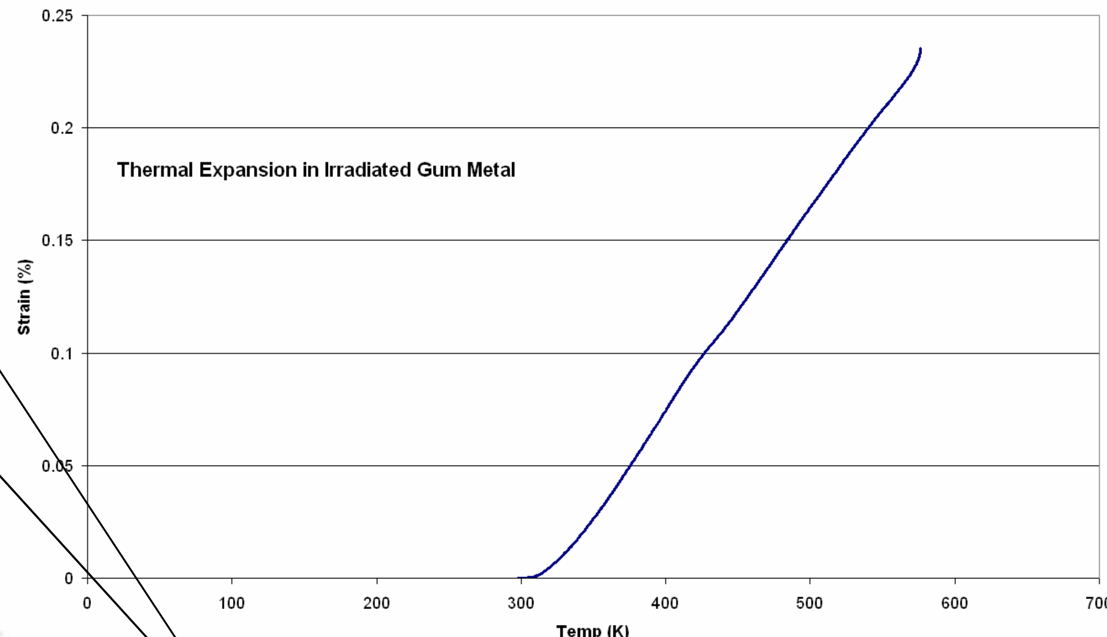
Gum Metal Preliminary Post-Irradiation Results

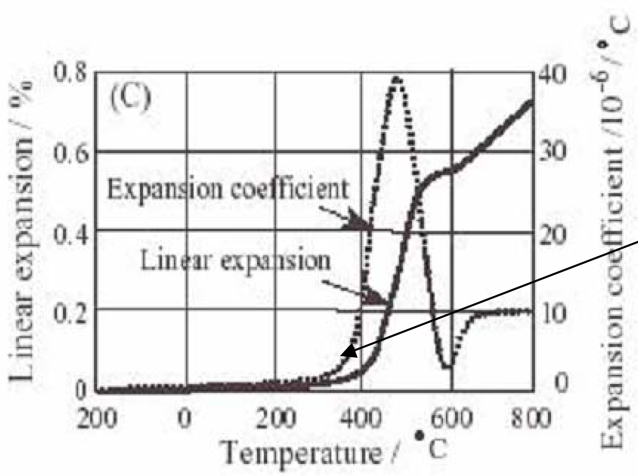




Effects of Irradiation on Gum Thermal Expansion

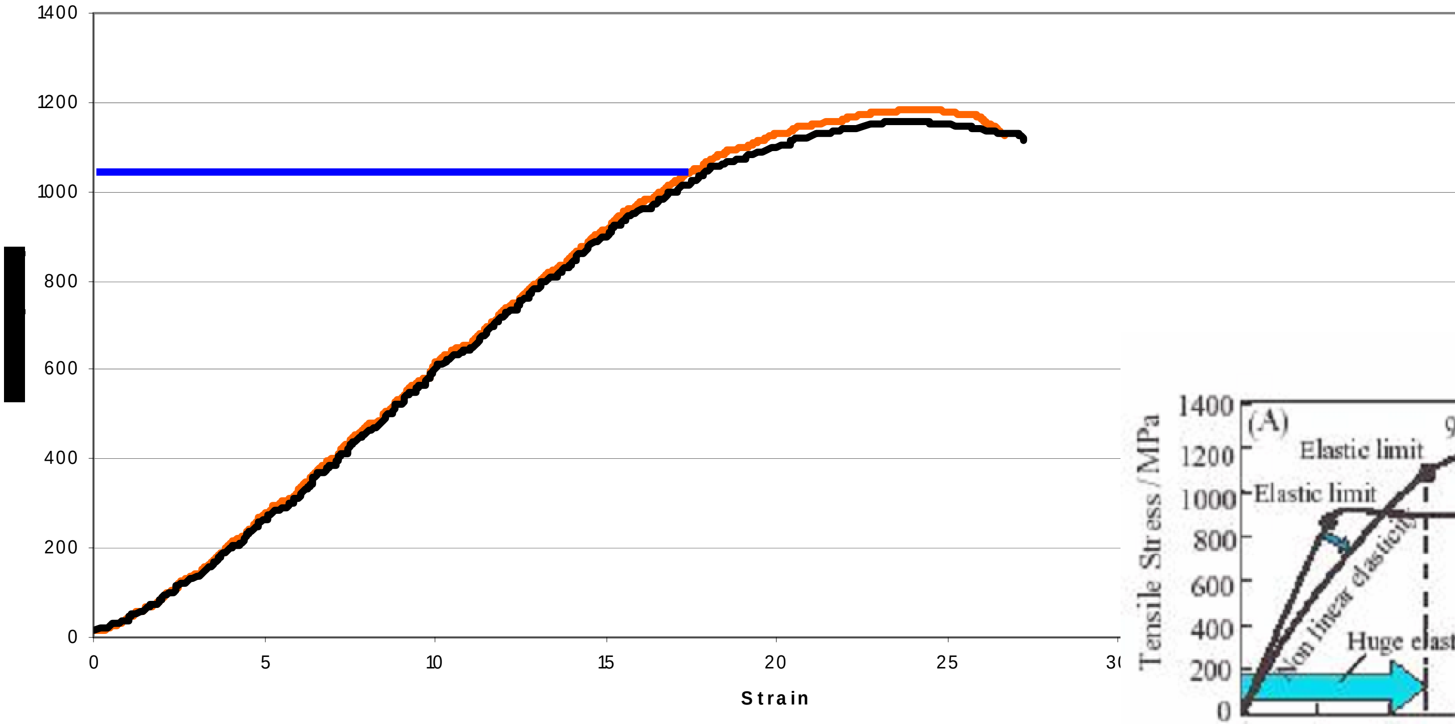


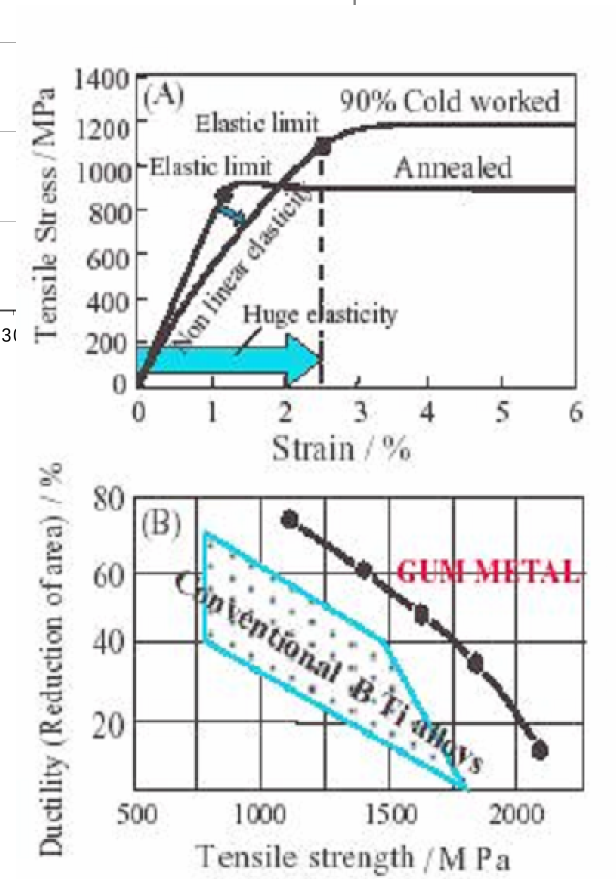




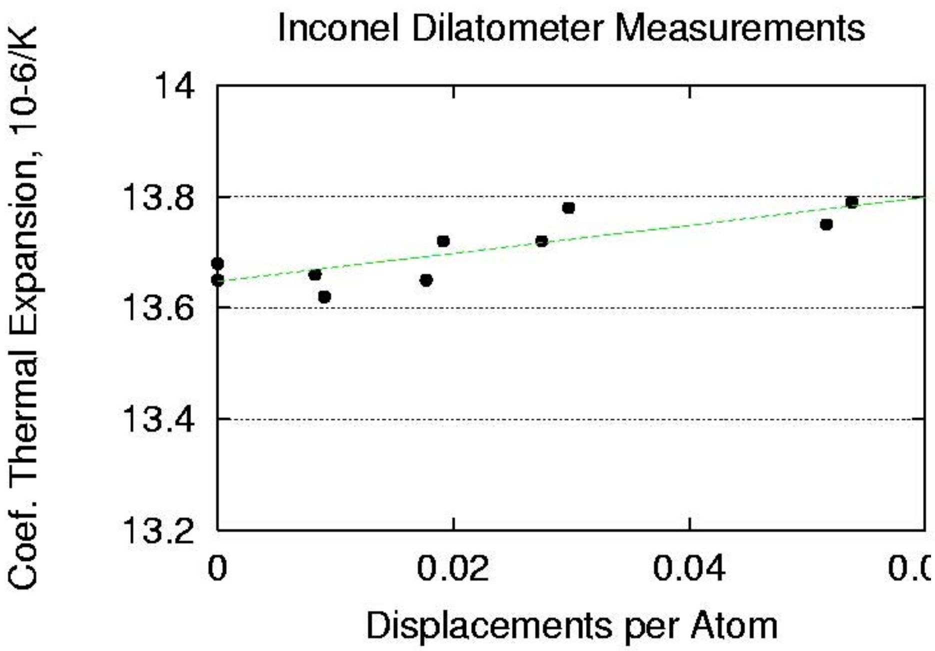
We would like to test (next irradiation phase) the 90% cold-worked material

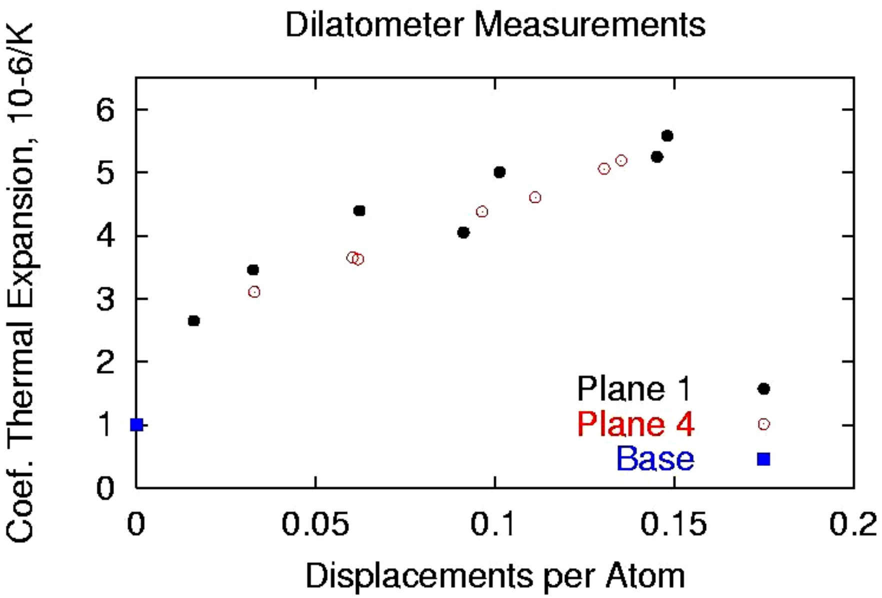
Unirradiated Gum Metal Stress-Strain



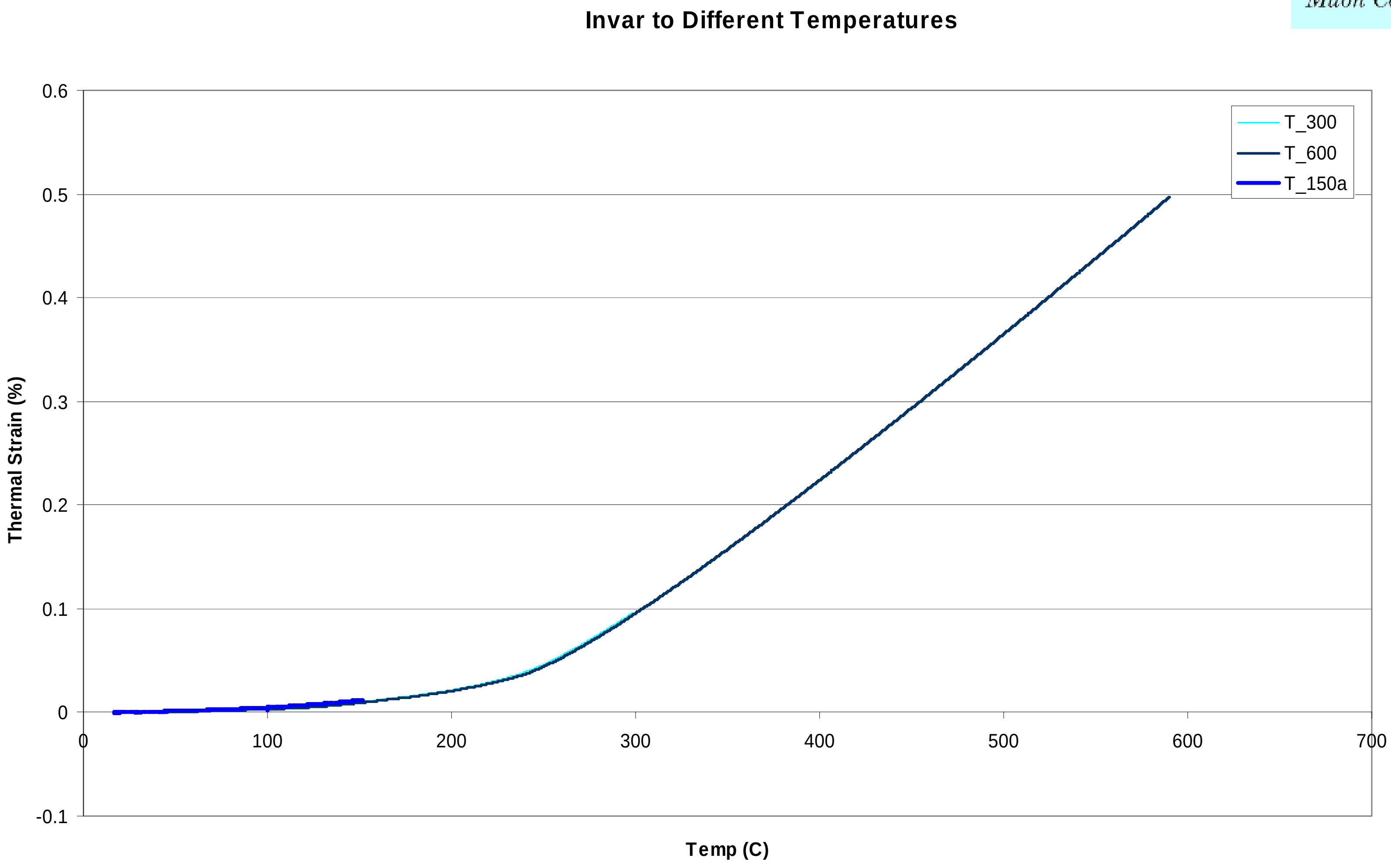


Some Alloys Change Drastically and some Don't
Reassessment of Super Invar
New tests with Temp ➔ 600 C

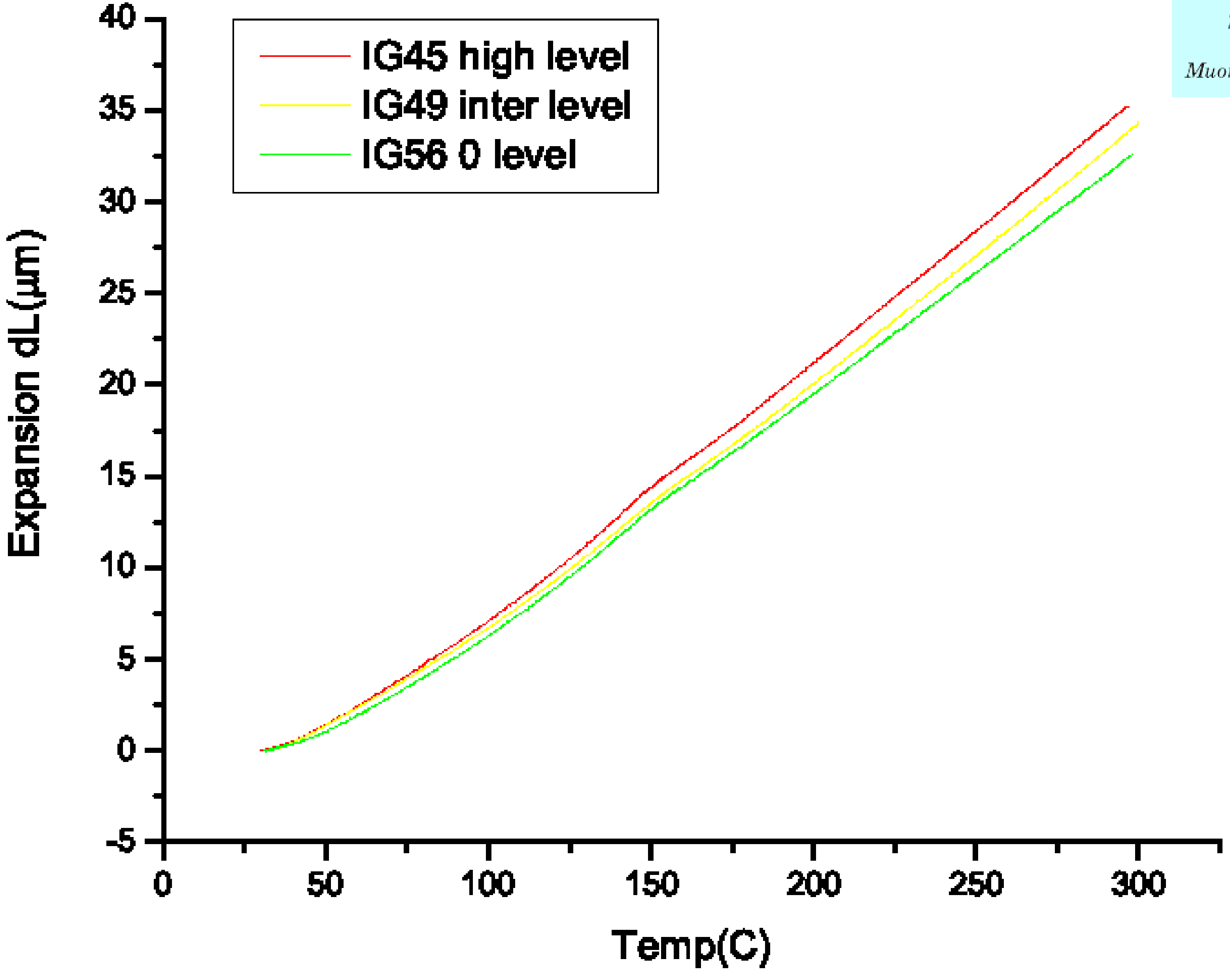




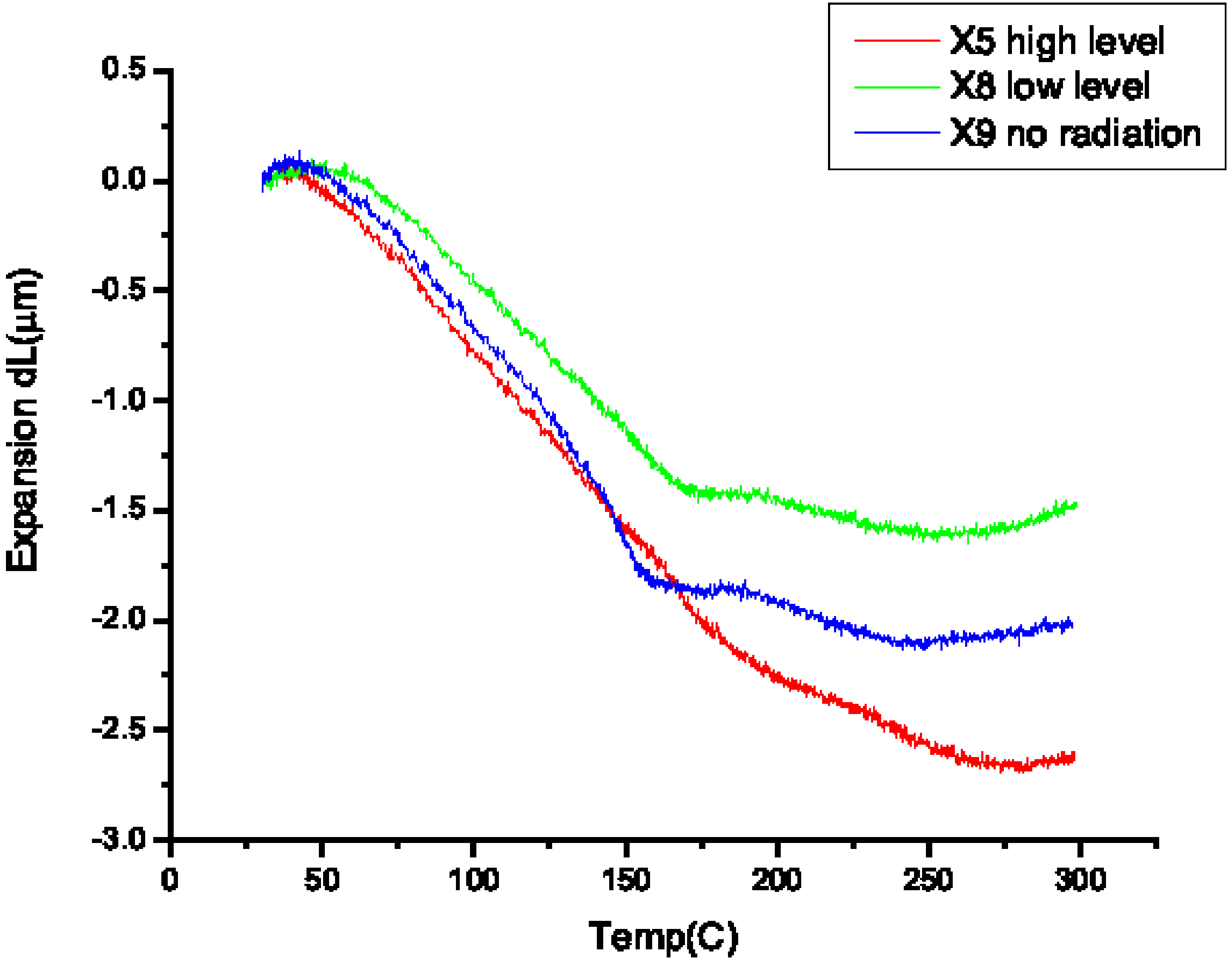
Super Invar RE-ASSESSMENT



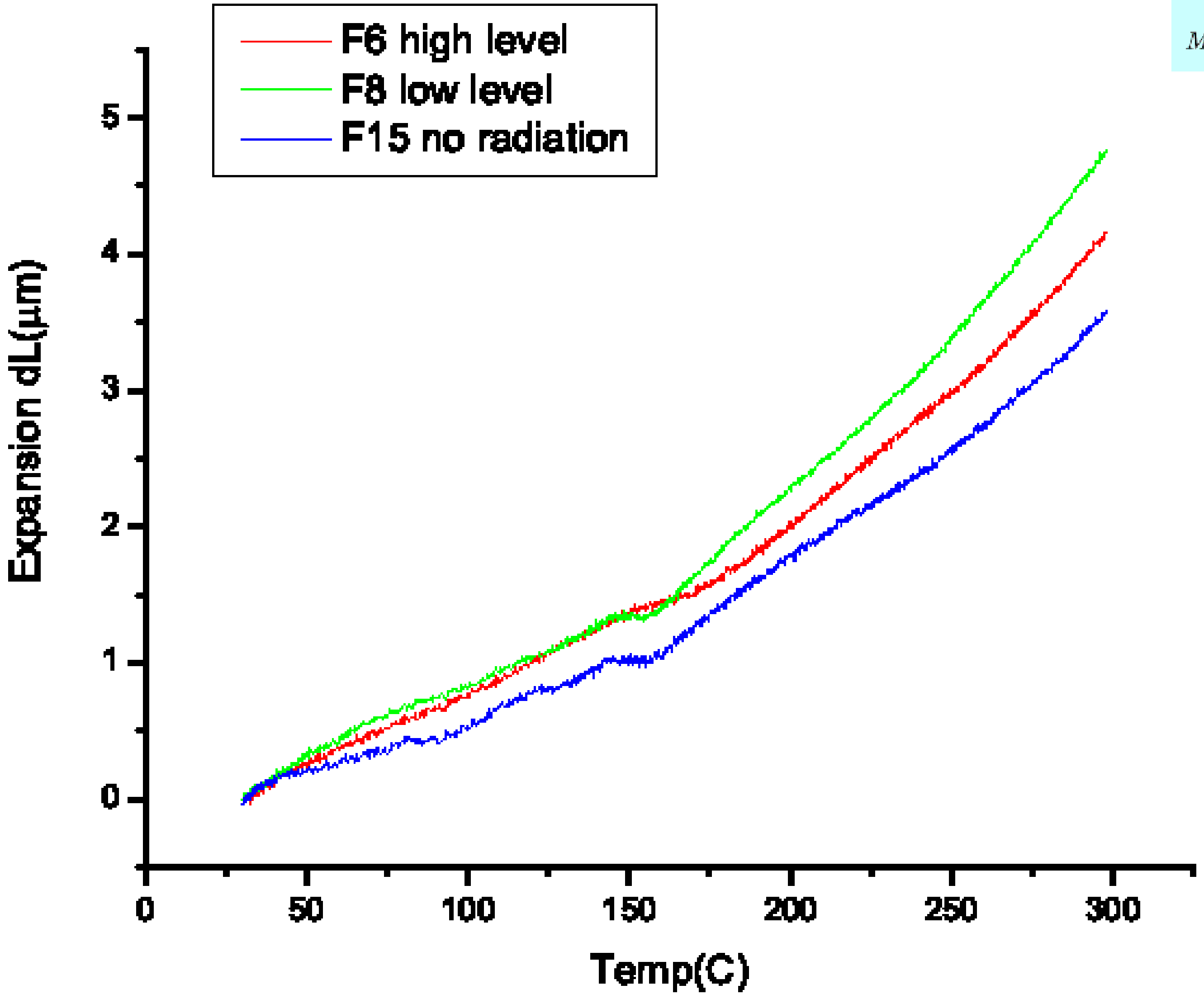
Graphite Preliminary Post-Irradiation Results



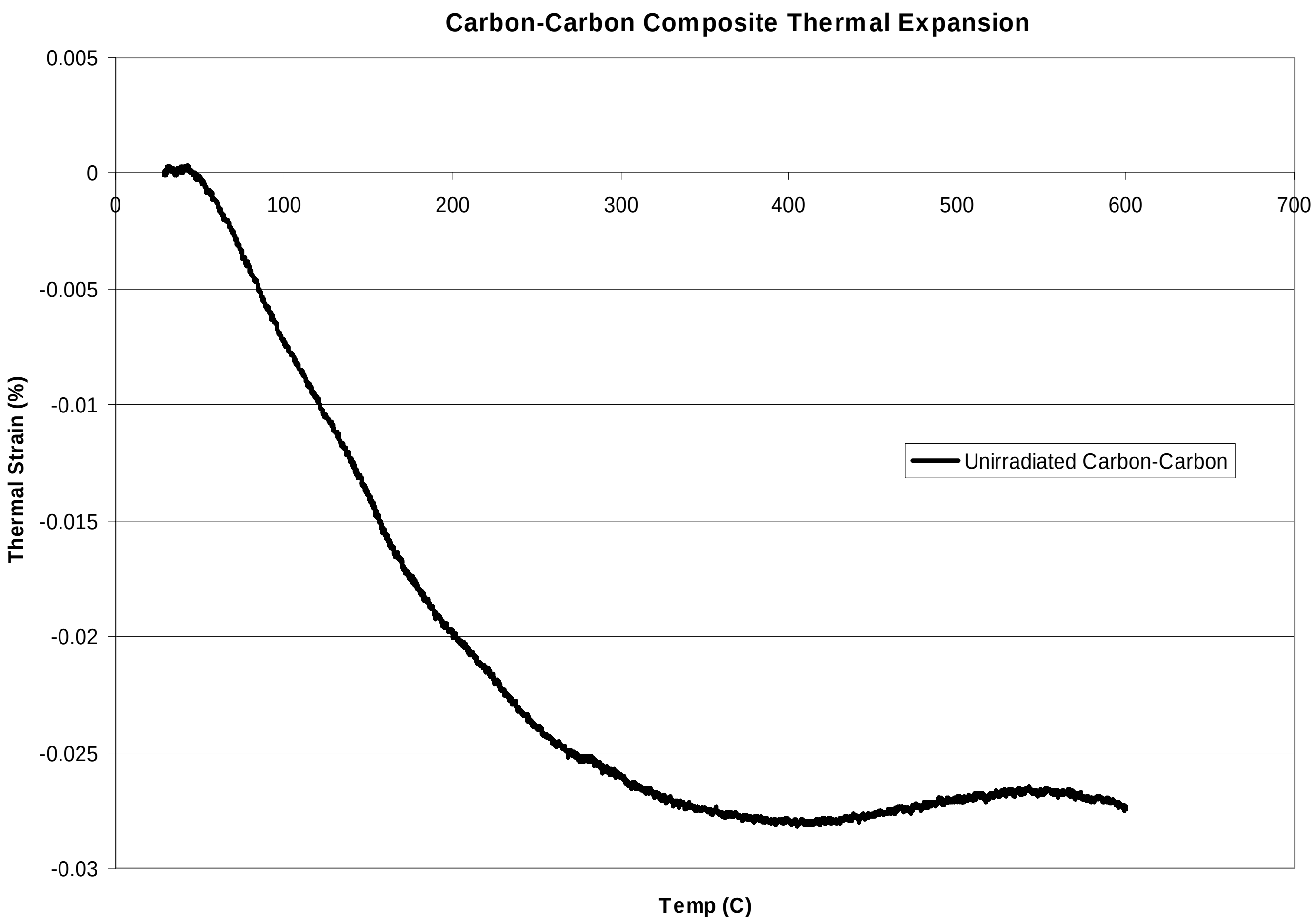
Carbon-Carbon Preliminary Post-Irradiation Results (fiber direction)



Carbon-Carbon Preliminary Post-Irradiation Results
45-degree plane on fiber orientation



Unirradiated Carbon-Carbon BehaviorValidation (fiber direction)



Temp.	% elongation
23 º C	0%
200 º C	-0.023%
400º C	-0.028%
600º C	-0.020%
800º C	0%
1000º C	0.040%
1200º C	0.084%
1600º C	0.190%
2000º C	0.310%
2300º C	0.405%

What do we propose ?

For PHASE I collimator materials

- Scrutinize graphite & carbon-carbon for
  - Diffusivity changes
  - Resistivity
  - Dimensional changes
  - SHOCK (laser-induced)

- Based on ongoing BNL studies on types of these two materials (not exactly those of LHC collimators) assess how drastic is the effect of irradiation (proton-based) on these parameters
- Assess the need for further irradiation (or irradiation of the LHC Phase I graphite & CC composite)
- Communicate with the LHC team and revisit the technical assessment on the current design

What do we propose for Phase II?

- Assess the current baseline (Cu) for driving physical properties (resistivity, diffusivity, CTE, damage)
- Limited knowledge on irradiation effects
- Assess the need for irradiation tests specifically designed to address the Cu baseline
- Enhance the post-irradiation analysis of the possible alternatives:
  - AlBeMet
  - superInvar
  - Gum Metal
  - Beryllium
- Focus on the effects of irradiation on the properties controlling the design/constraints
- Evaluate the need for more irradiation tests (at BNL of FNAL)
  - It will be prudent to delineate between proton energies and the damage effects associated with them (a lot of available info from neutron irrad.)