Superbeam Horn-Target Integration

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EUROnu-IDS Target Meeting

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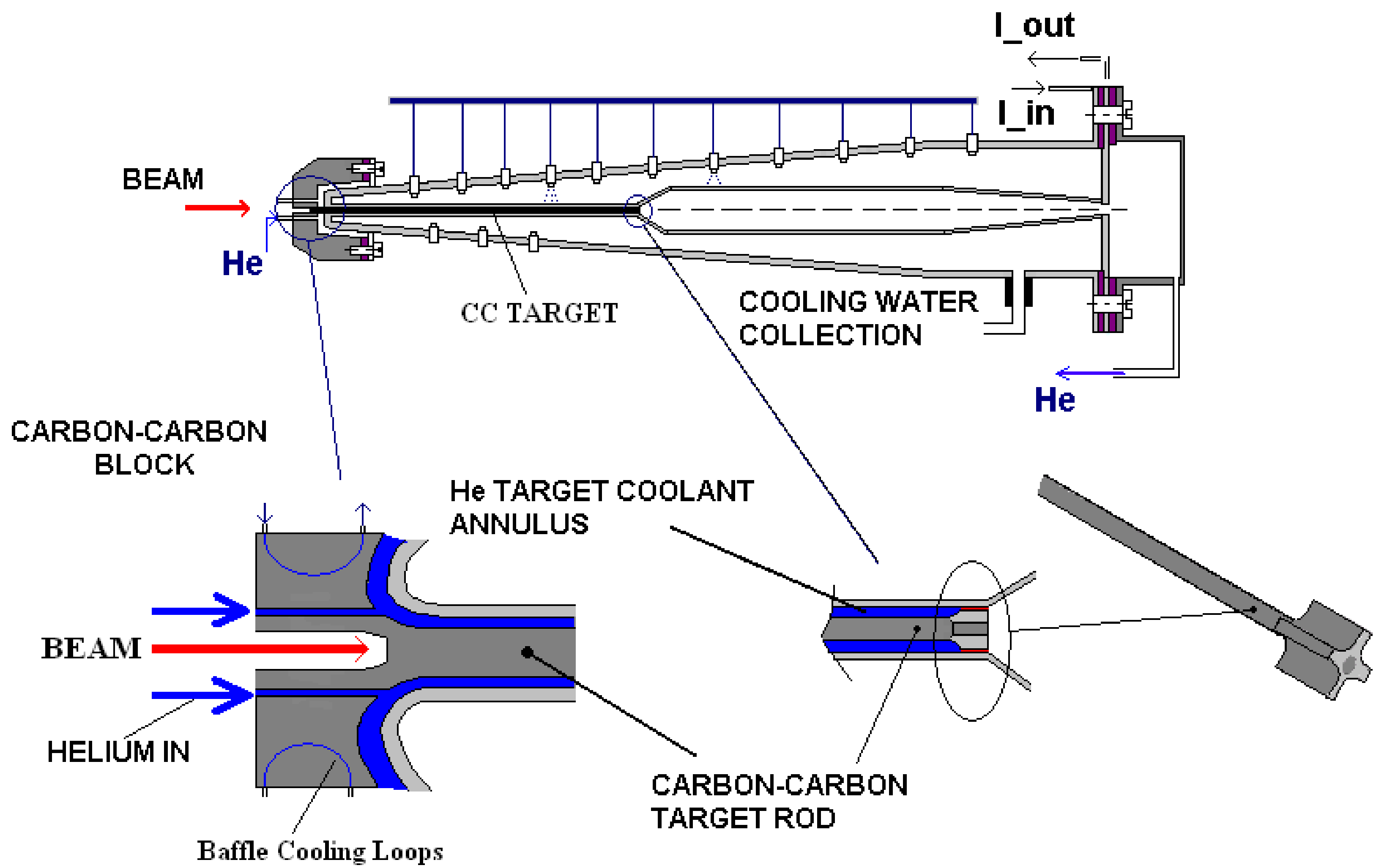
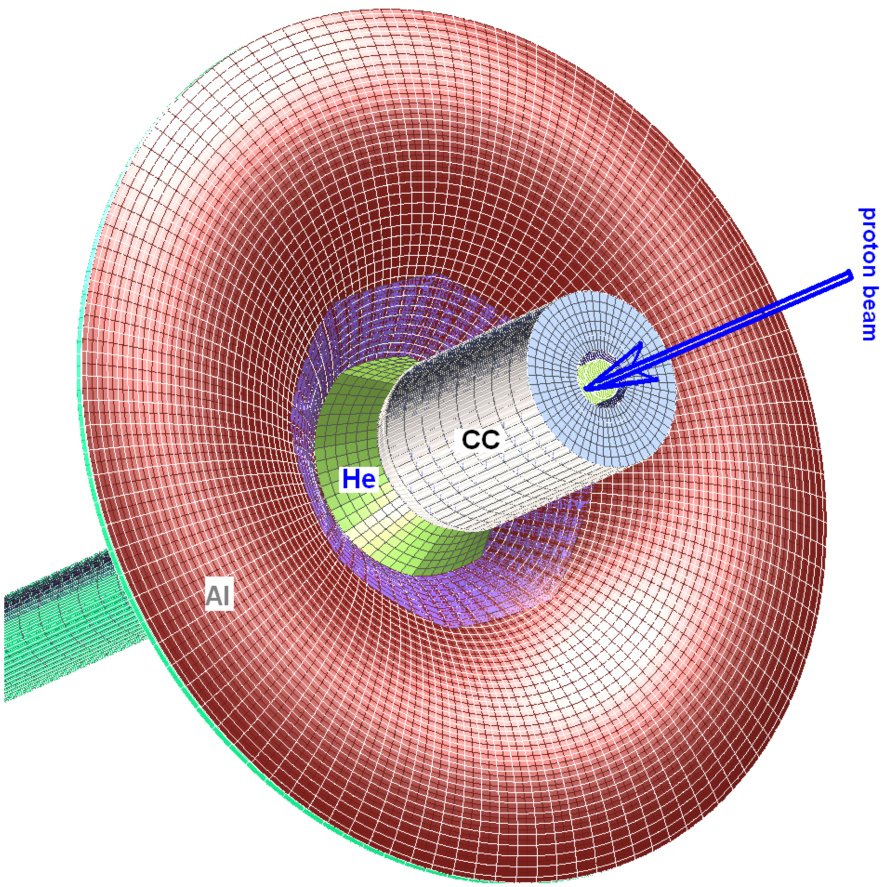
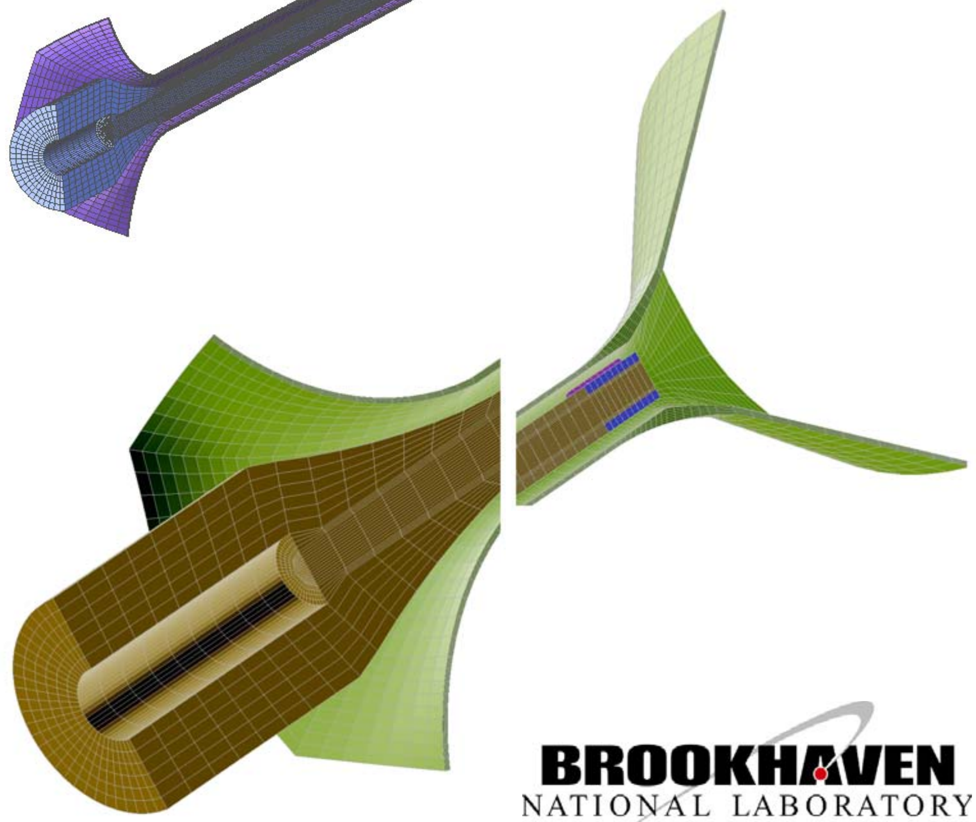
Superbeam Target-Horn Concept – BNL Study



Superbeam Target-Horn Concept – BNL Study

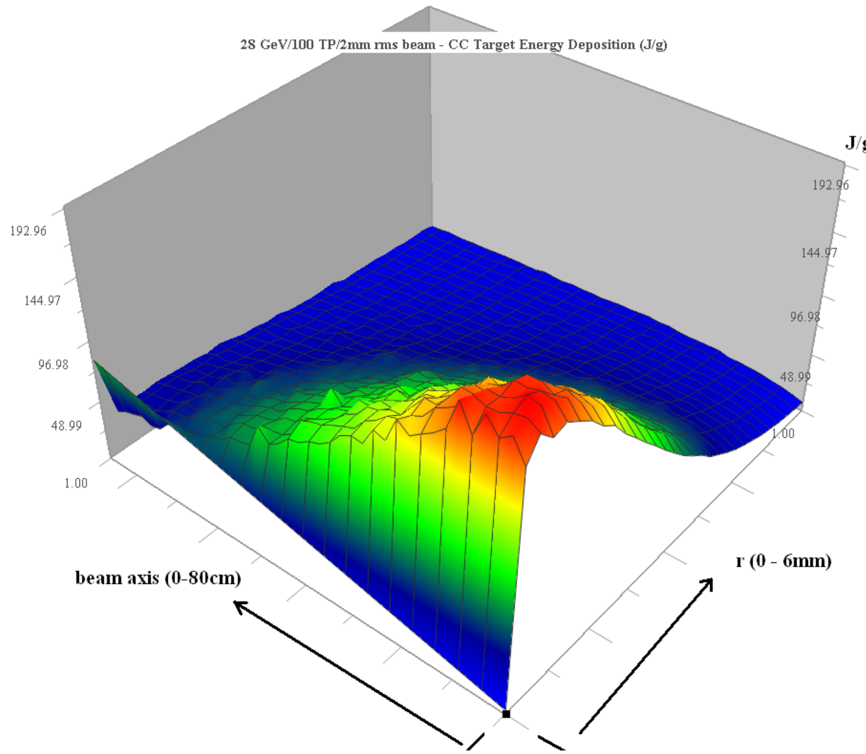




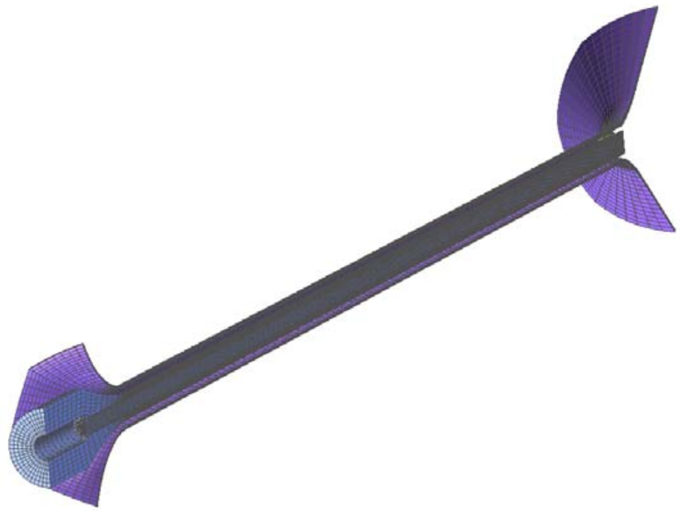
The 1 MW BNL Superbeam Study

Table 6.1: Horn/Target design parameters.

Proton Beam Energy	28 GeV
Protons per Pulse	8.9x10^{13}
Average Beam Current	35.7 μA
Repetition Rate	2.5 Hz
Pulse Length	2.58 μsec
Number of Bunches	23
Number Protons per Bunch	3.87x10^{12}
AGS Circumference	807.1 m
Bunch Length	40 ns
Bunch Spacing	60 ns
Normalized Emittance-X	100 π mm-mrad
Normalized Emittance-Y	100 π mm-mrad
Longitudinal Emittance	5.0 eV-sec
Target Material	carbon-carbon composite
Target Diameter	1.2 cm
Target Length	80 cm
Horn Small Radius	9 mm
Beam Size (Radius) on Target	2 mm (rms)
Horn Smallest Radius	6 mm
Horn Large Radius	61 mm
Horn Inner Conductor Thickness	2.5 mm
Horn Minimum Thickness	1 mm
Horn Length	217 cm
Horn Peak Current	250 kA
Current Repetition Rate	2.5 Hz
Power Supply Wave Form	Sinusoidal, Base Width 1.20 ms



The 1 MW BNL Superbeam Study



ESTIMATES OF HORN inner Conductor Heating

Joule Heat (conservative estimate)   = 1.335 kW (for 2.5 Hz !!)

Heat from secondary particles = 10.3 kW

Radiation from target = 0.885 kW

TOTAL = 12.52 kW.

The removal of the generated heat using only the forced helium in the annulus, that is also cooling the target, high helium velocities will be required. Helium with inlet Temp of 144 K and with the surface temperature of the horn maintained at ~ 90 C, the required heat transfer film coefficient is 1624 W/m2-C requiring He velocities >150 m/s

ISSUES

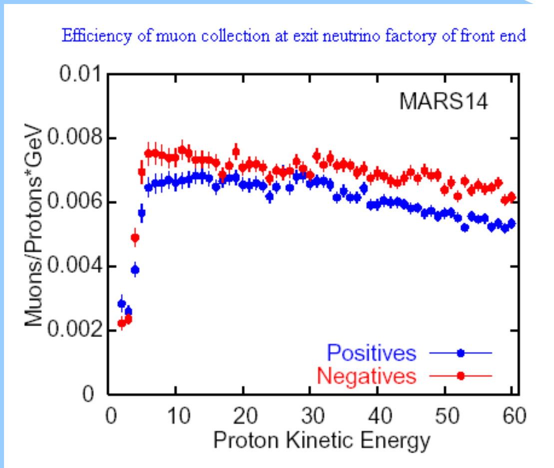
- Target
  - – 4 MW and solid target (?)
- Horn
  - – How will any horn perform at 4 MW?
    - Radiation damage and electrical property degradation
    - Integration with target and heat removal
    - Heat removal from the inner conductor (water deluge to cool it)

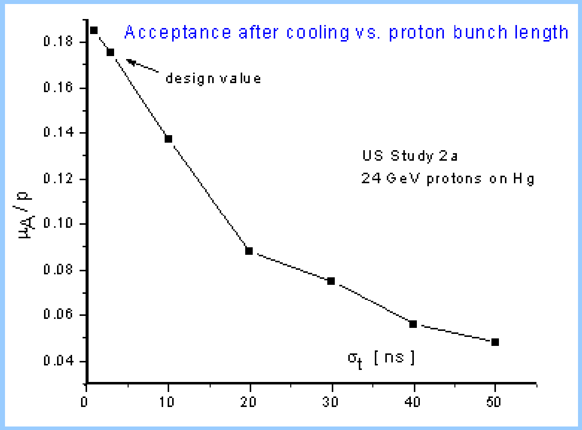
Parameter Space

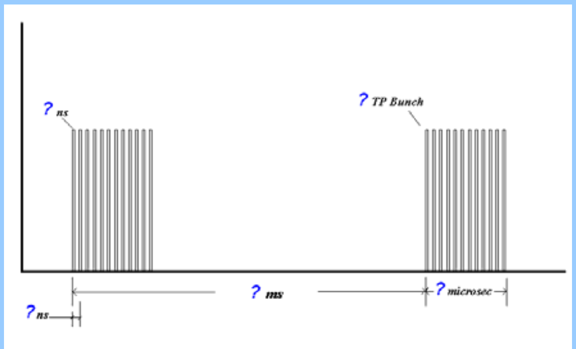
Protons per pulse required for 4 MW

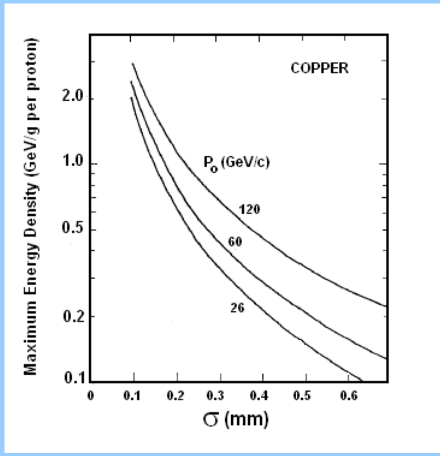
$$\overline{P}_{arc}(w) = E[eV] \times N \times e \times f_{rep}[Hz]$$

	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}







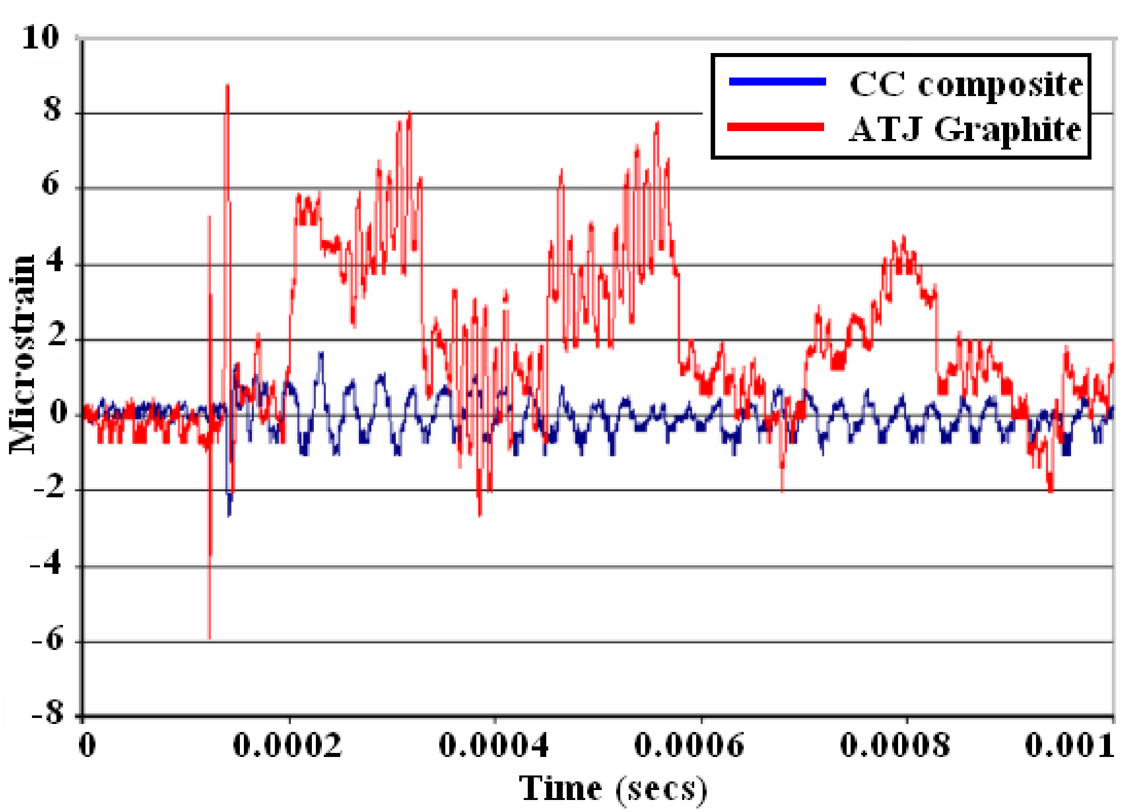


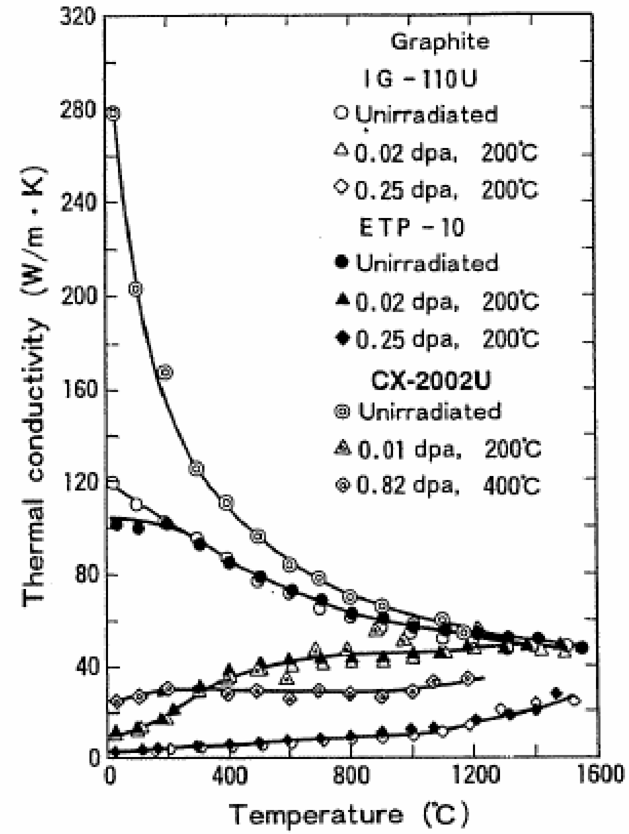
Solid Targets – How far we think they can go?

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 is 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

Irradiation Effects on CRITICAL Target Properties

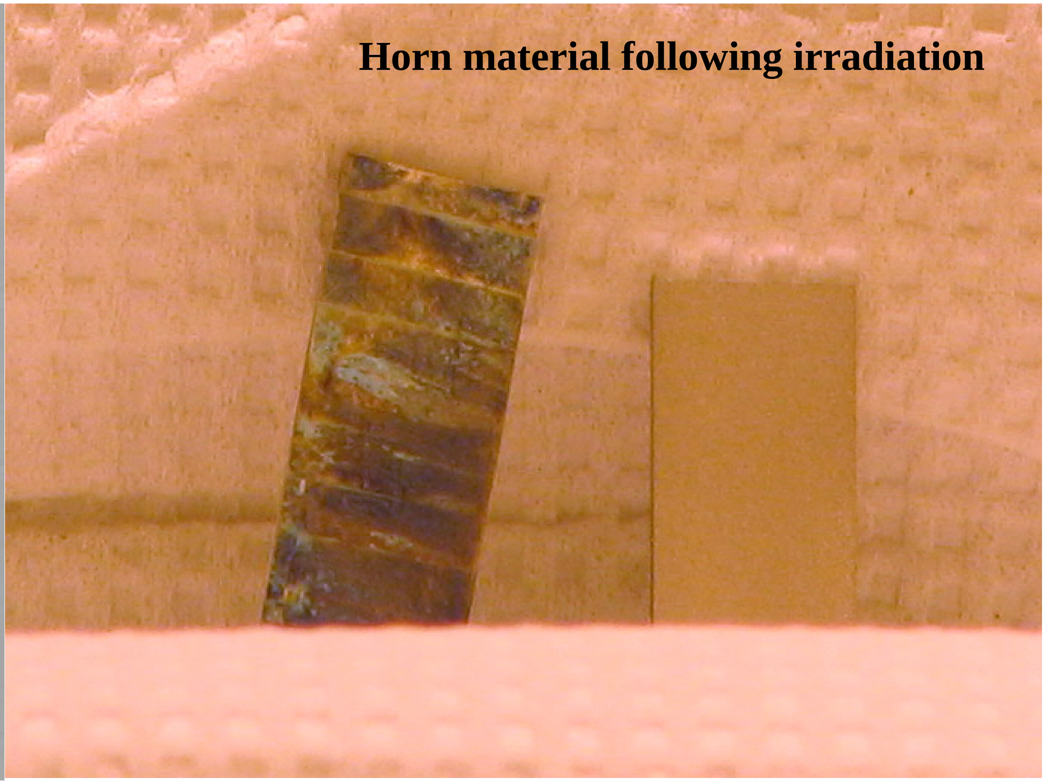
- Graphite vs. Carbon-Carbon Composite (it may be that CC is a viable alternative to graphite !!!! NOT SO FAST)



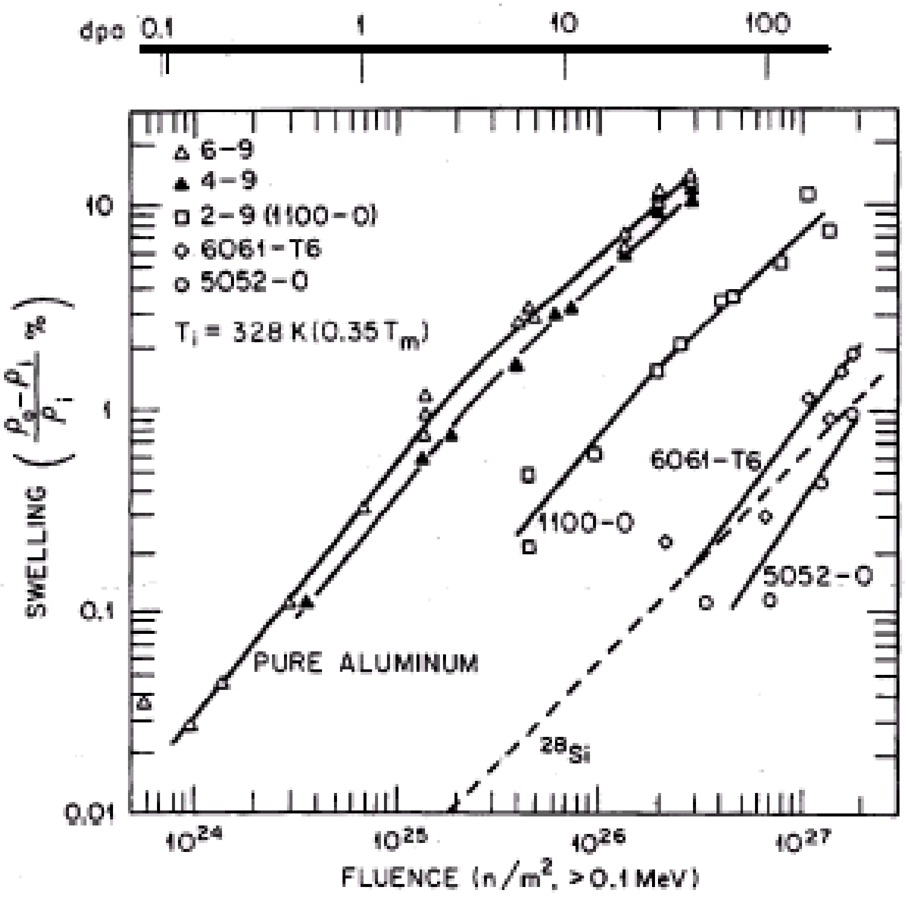


Thermal conductivity of neutron-irradiated graphites.

Irradiation & Oxidizing Environment Effects on Horn Conductor



Irradiation & Oxidizing Environment Effects on Horn Conductor



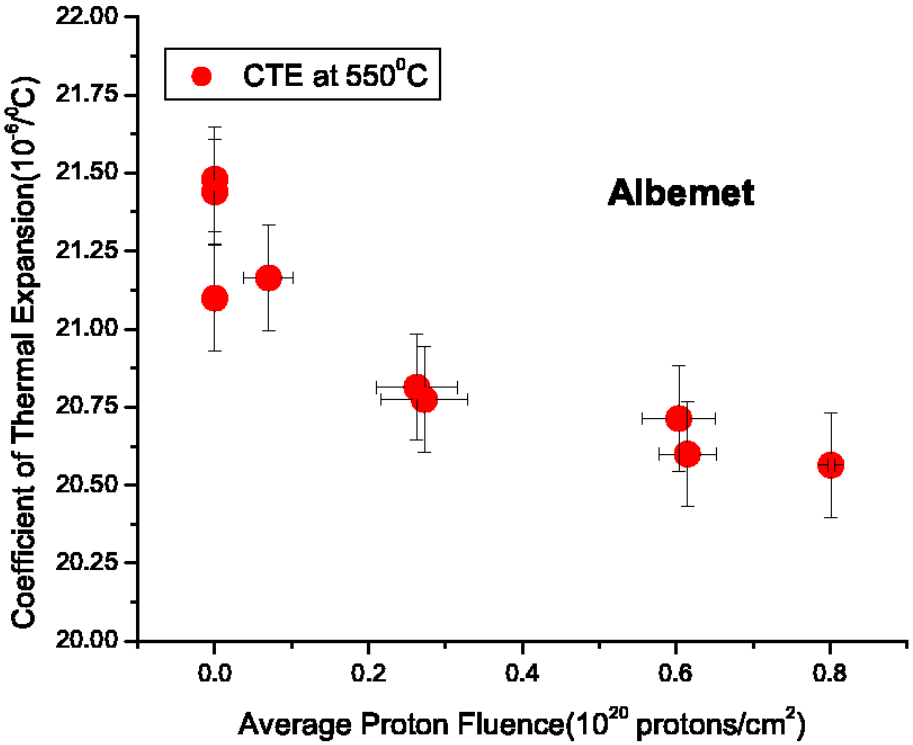
Radiation-induced swelling of various aluminum alloys

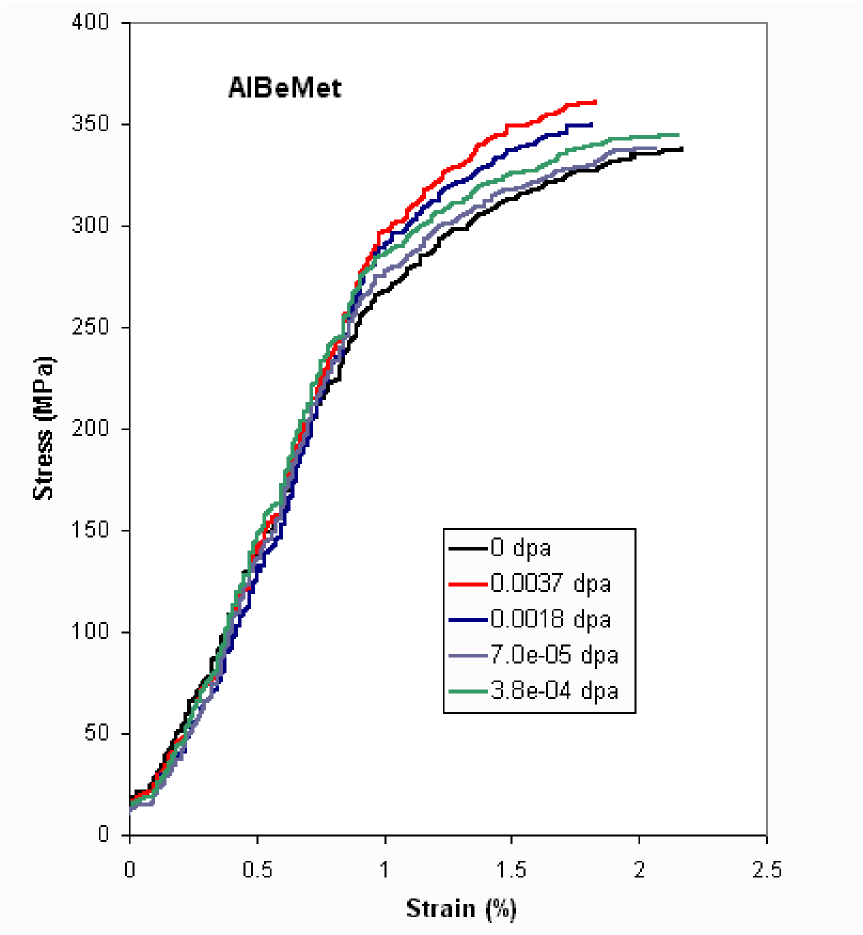
The AlBeMet Choice

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	6	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

The AlBeMet Choice

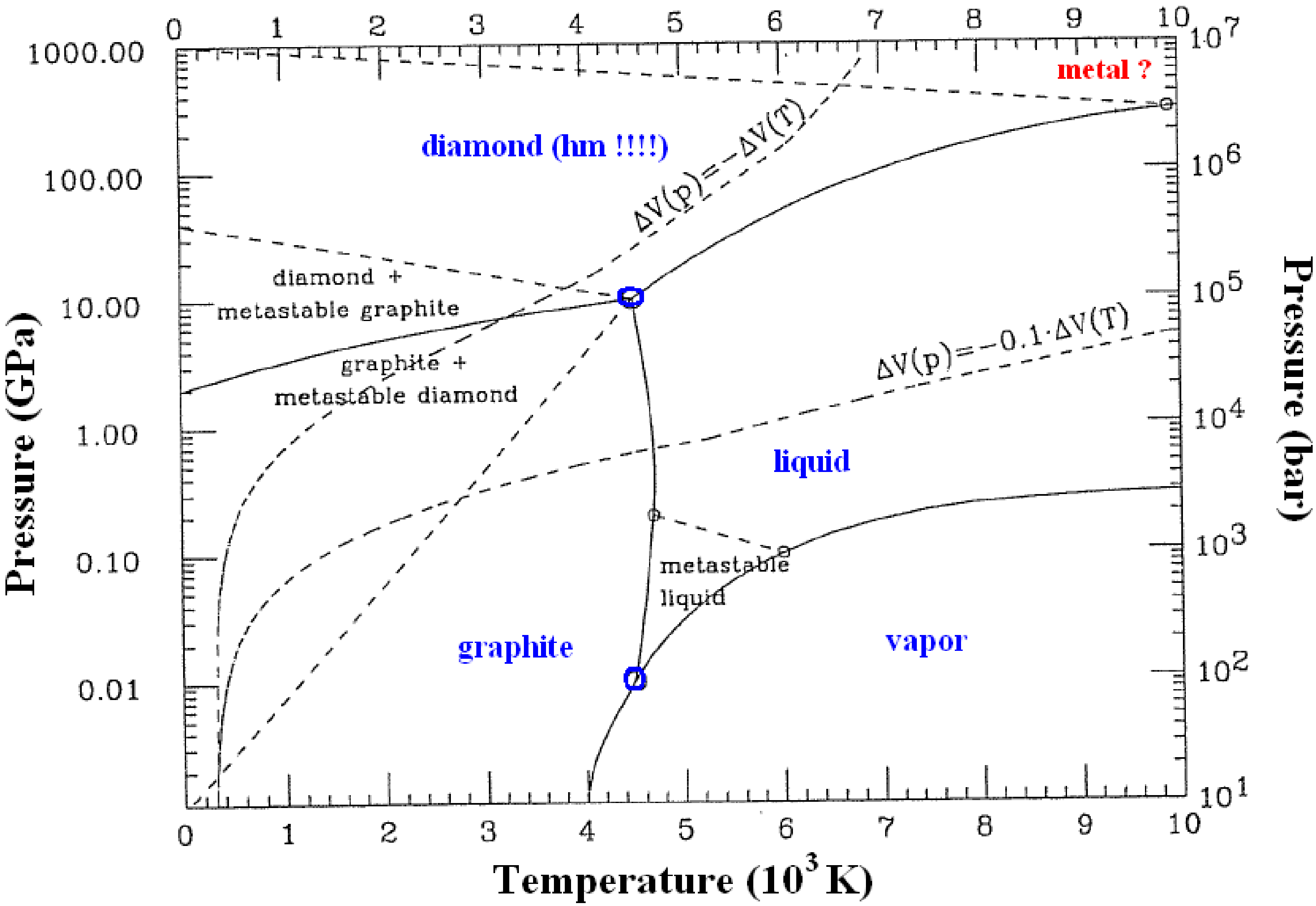




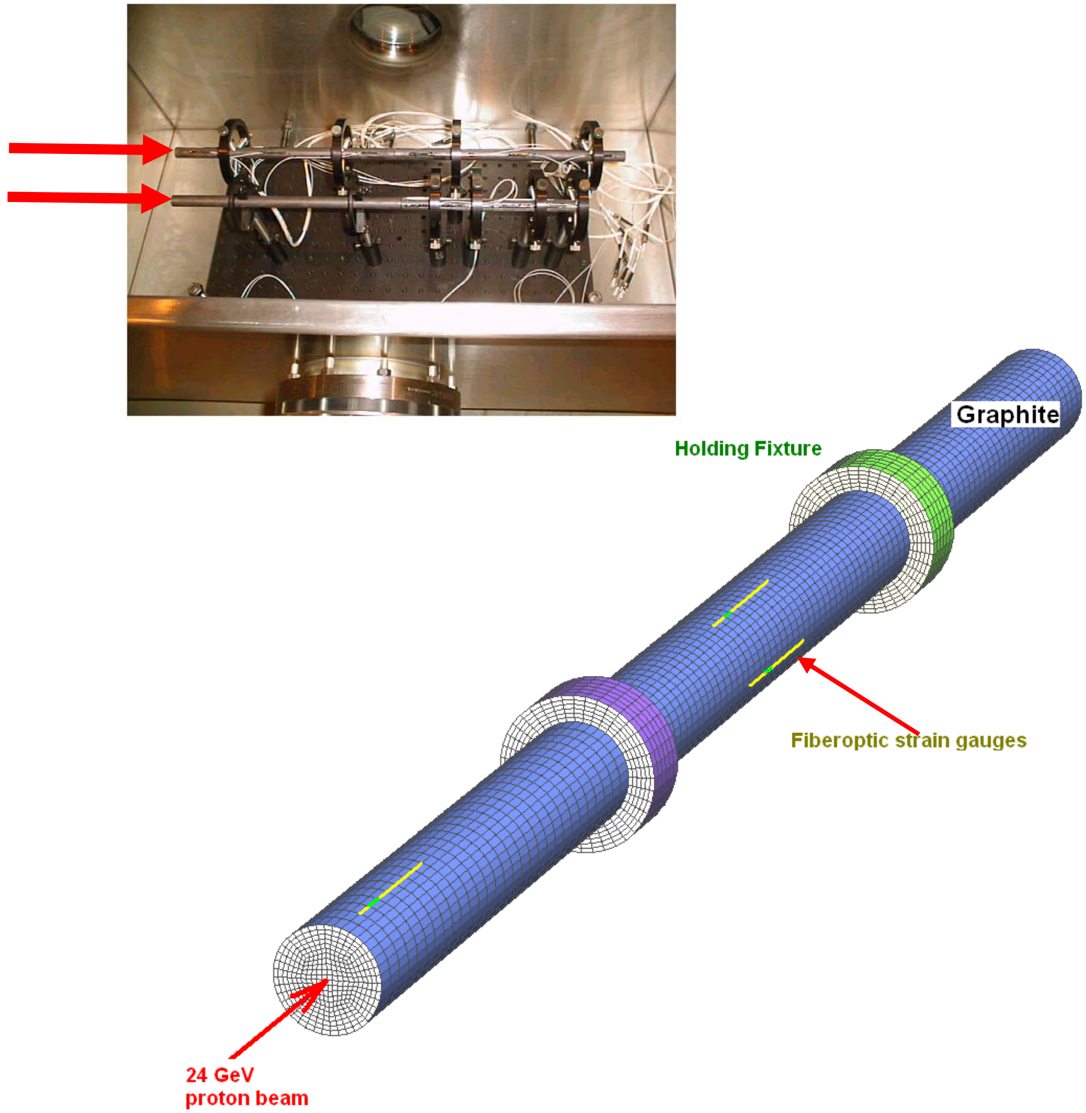
Overview of R&D Realized to-date on Solid Targets

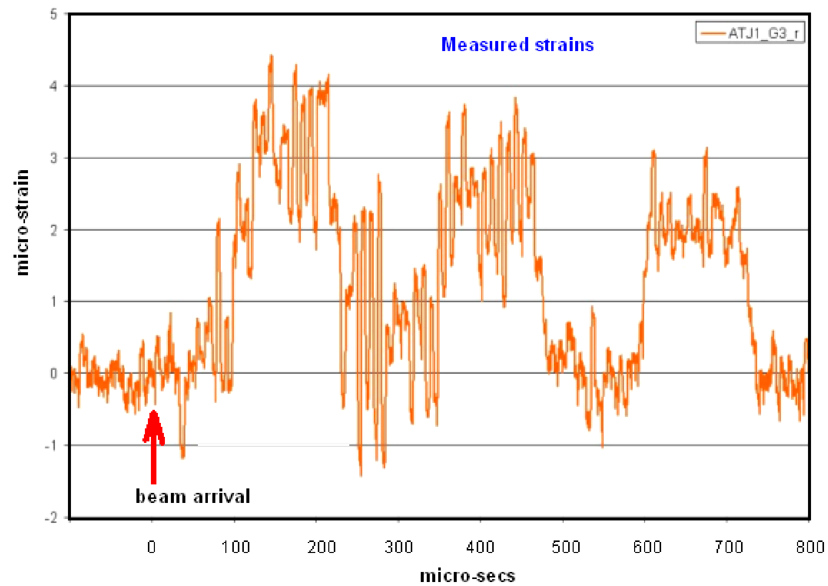
- Target Shock Studies
- Radiation damage to target & horn

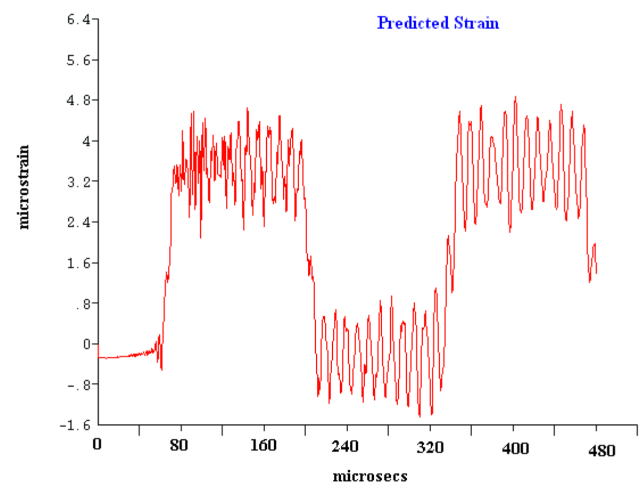
Solid Targets



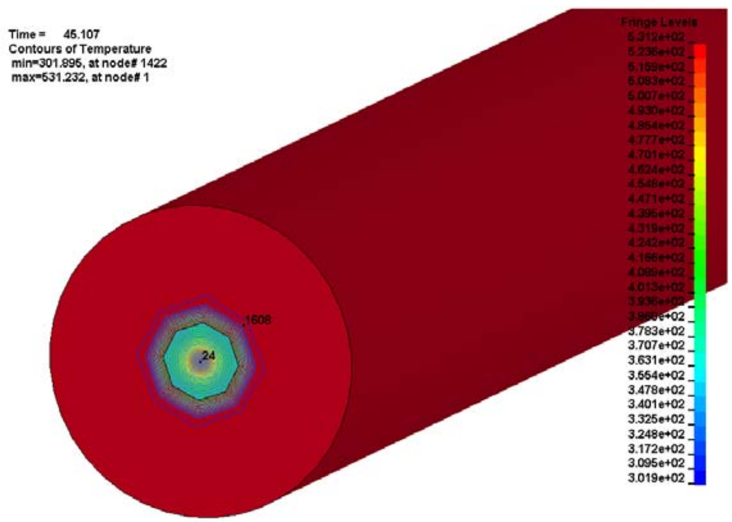
Target Shock Studies

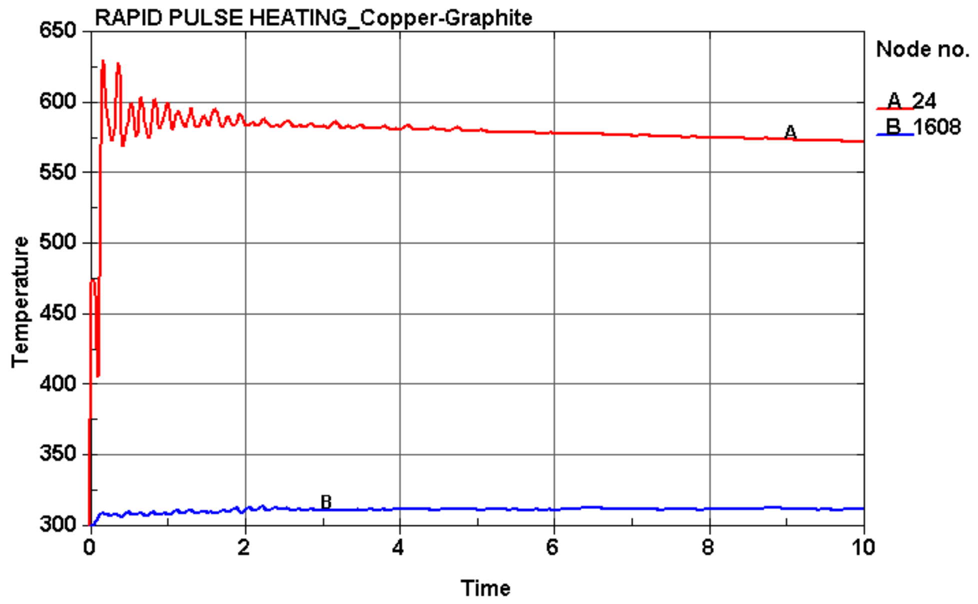


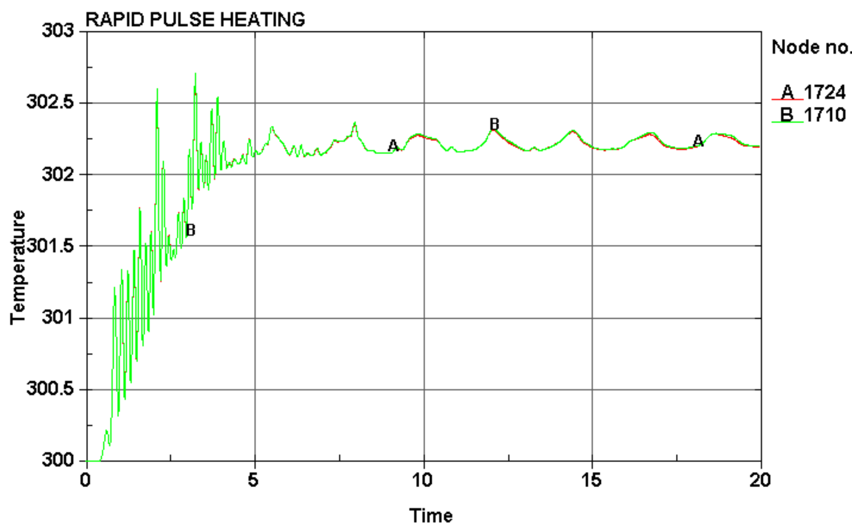




Beam-induced shock simulation







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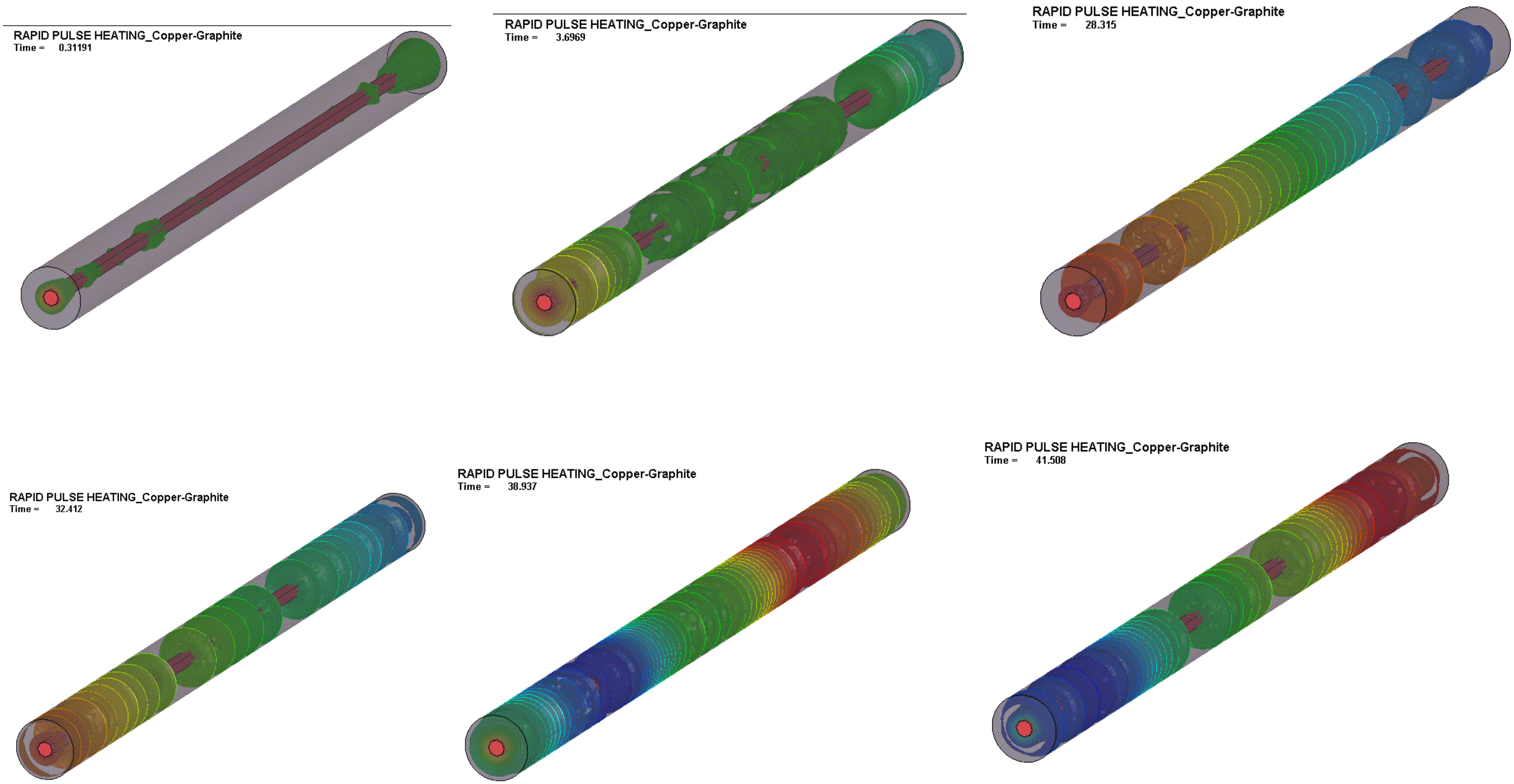
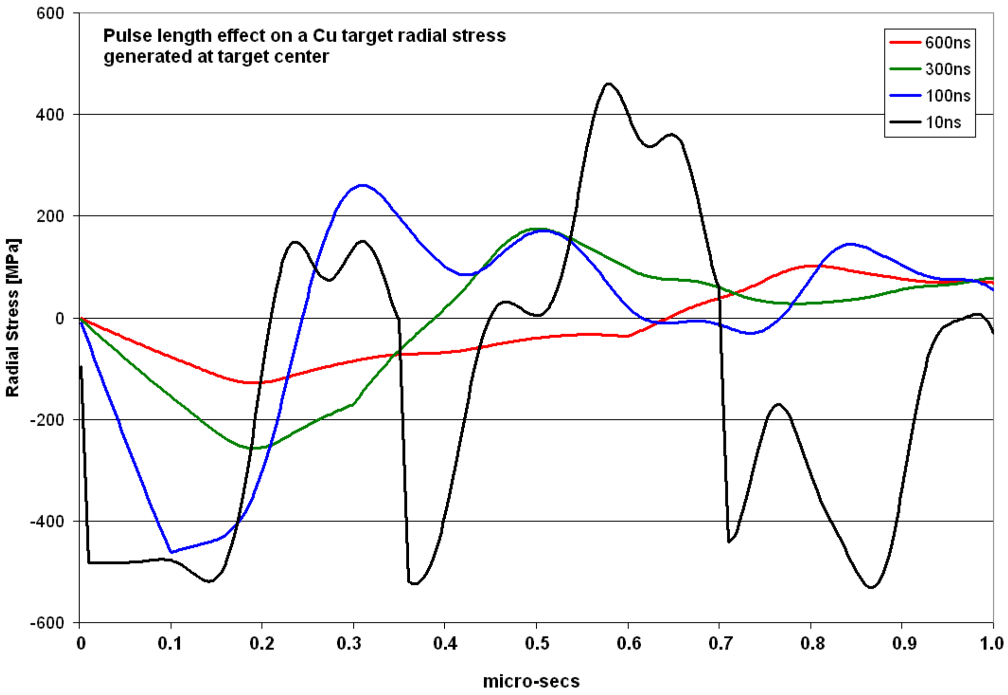
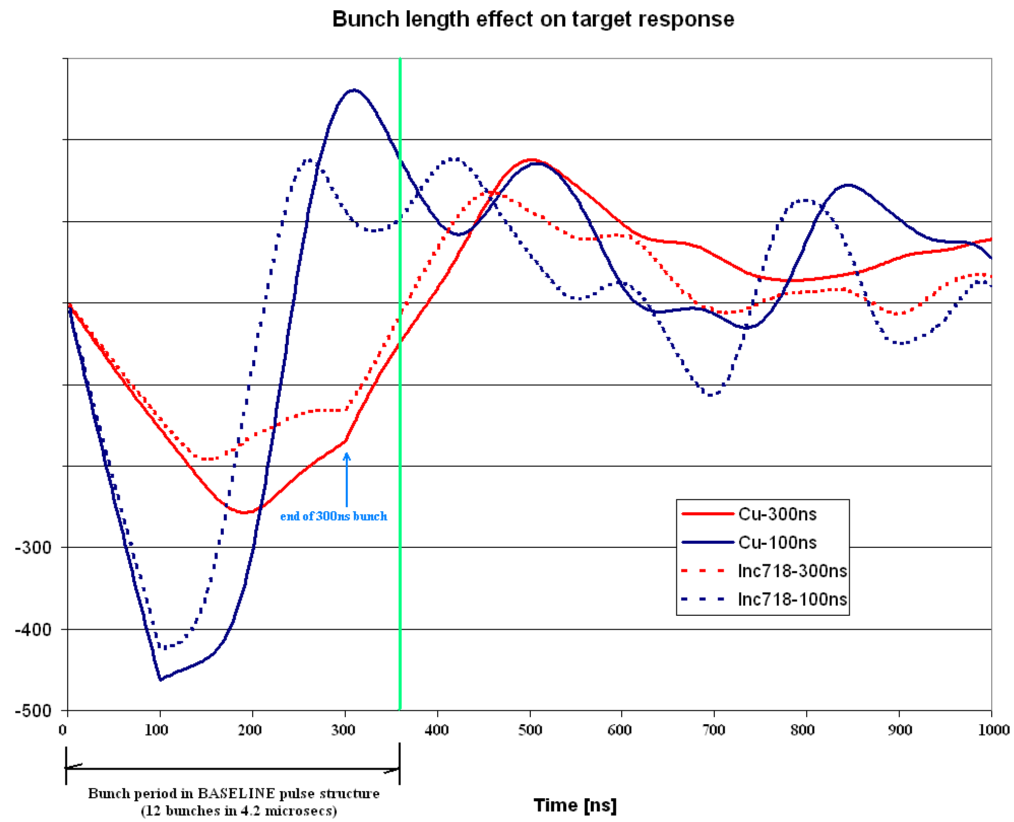
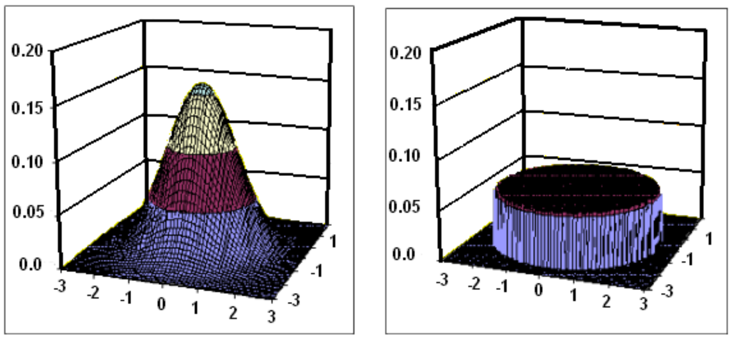


Pulse Structure



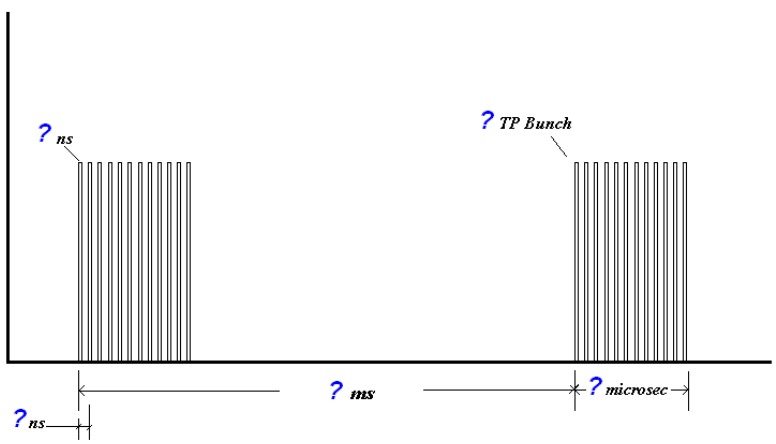


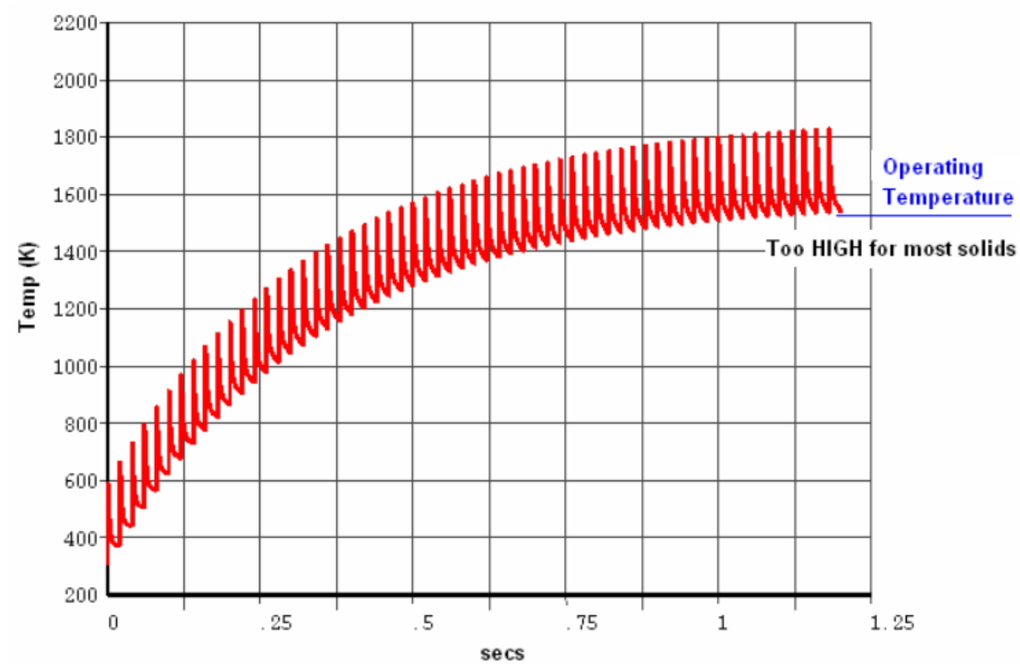
Why is Pulse Structure Important?



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





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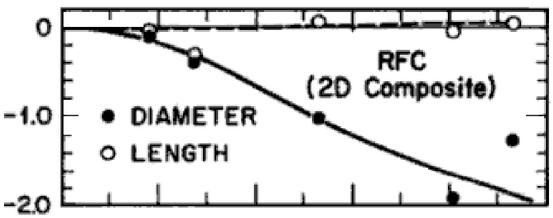
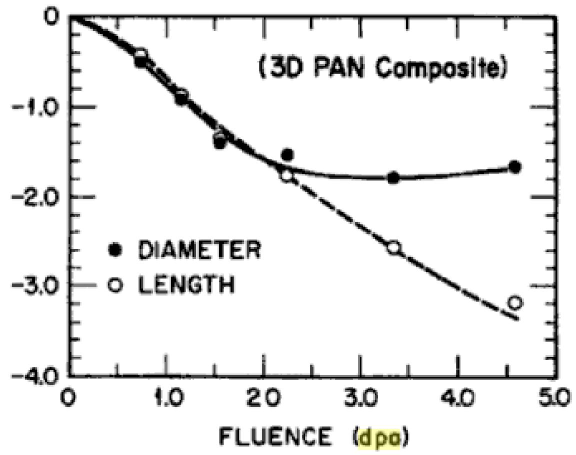
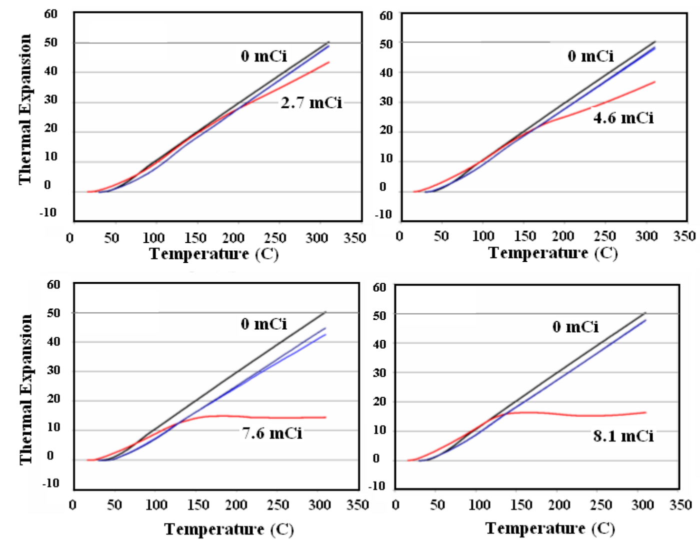
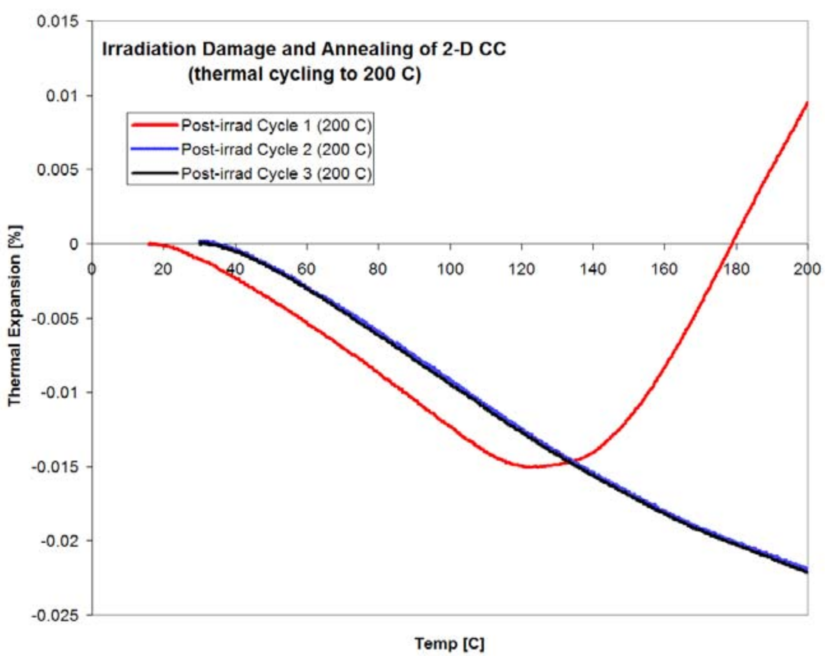
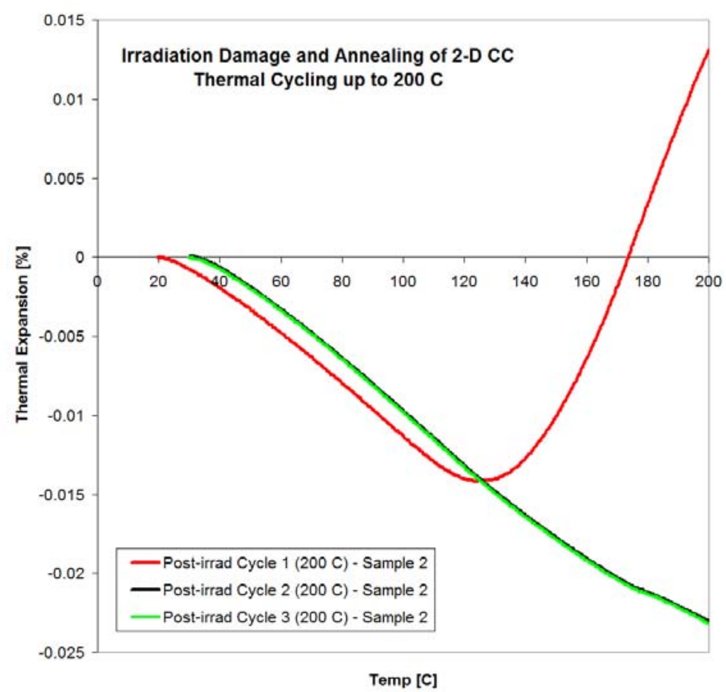
Graphite-CC experience











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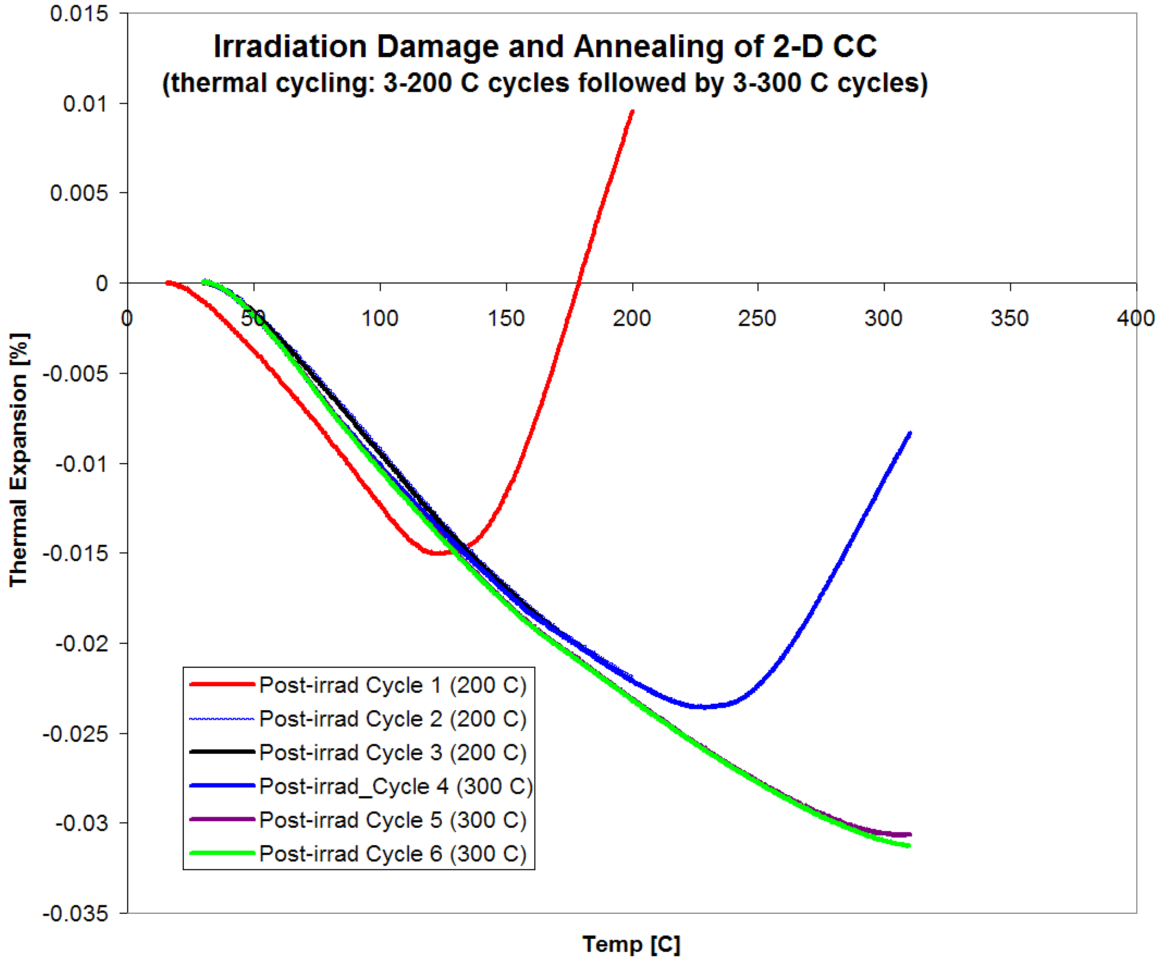

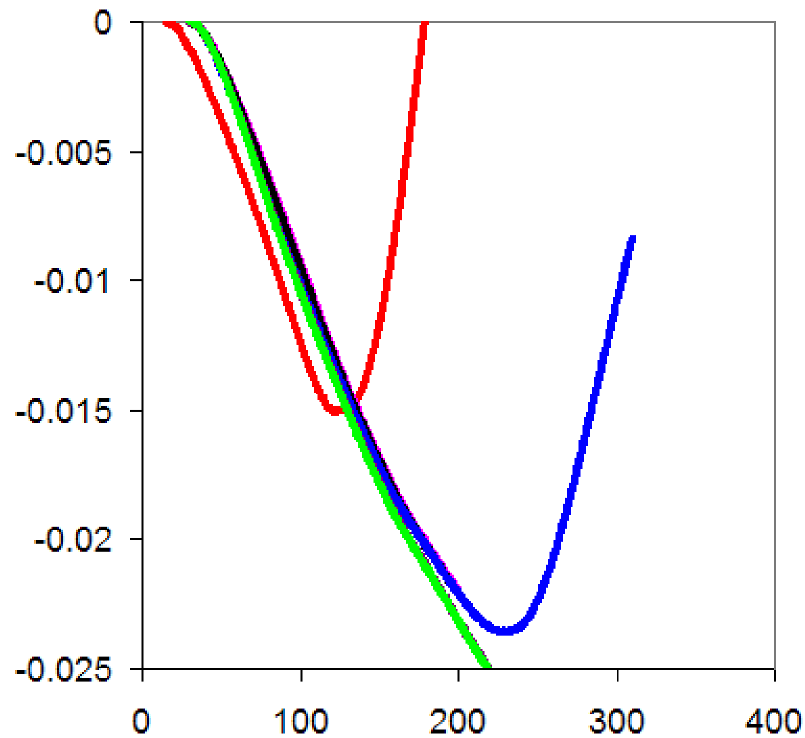

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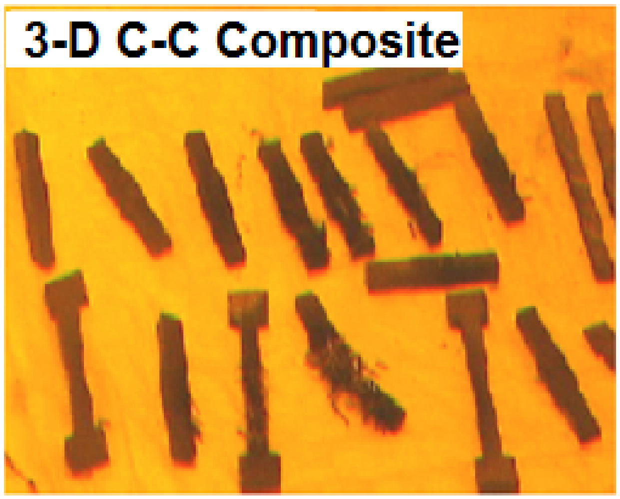
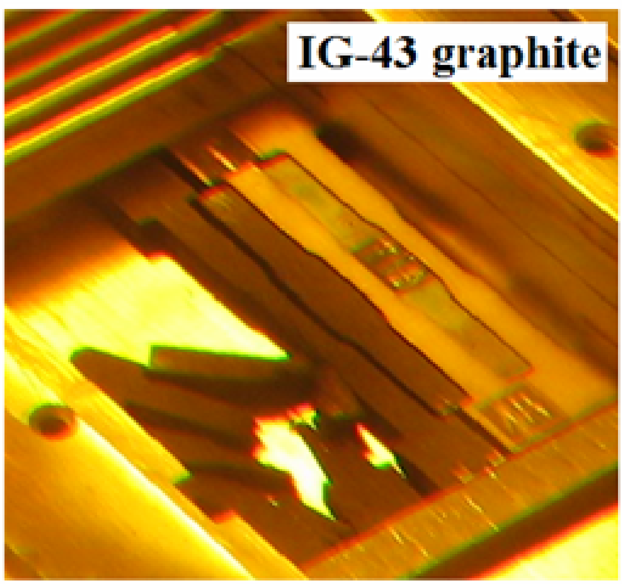
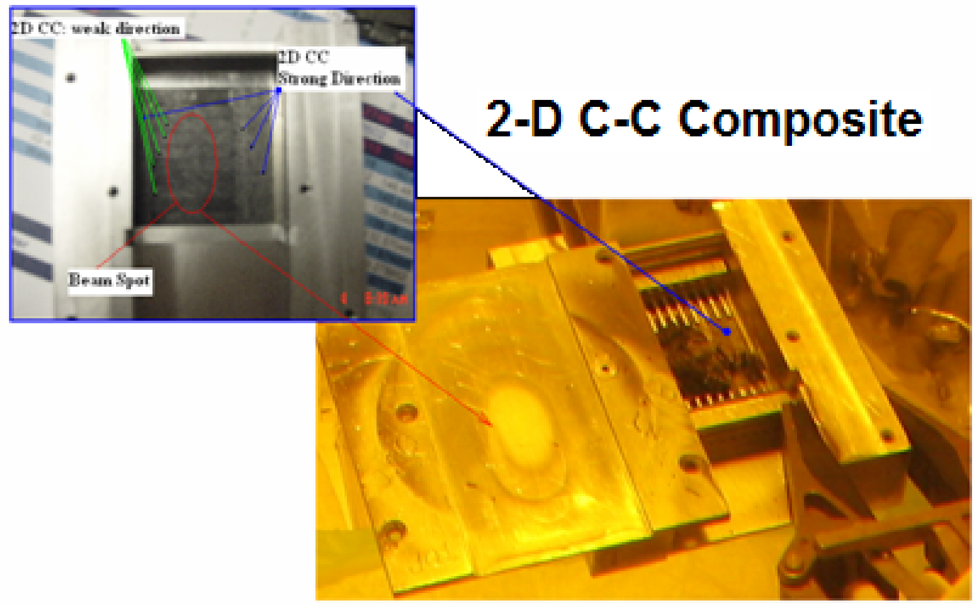
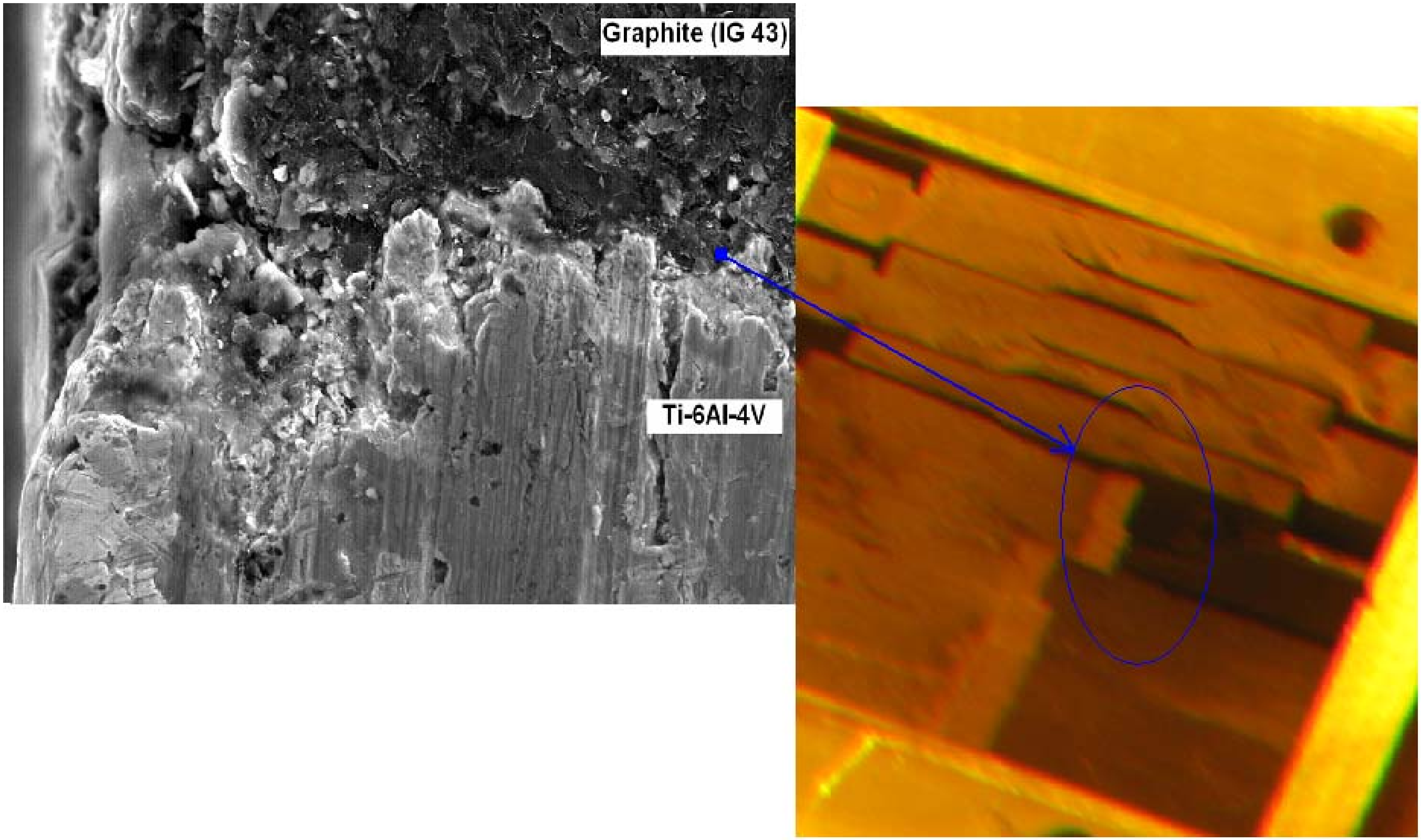






Threshold ~ 10^21 p/cm2

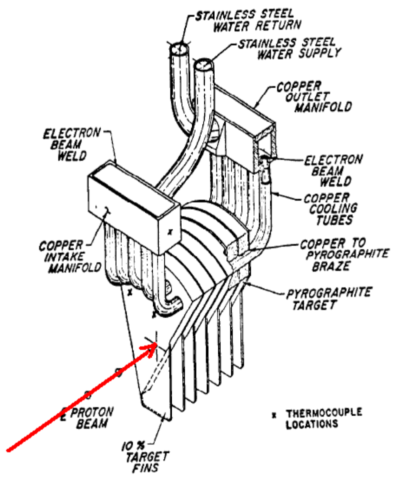
Graphite-CC experience



Graphite-CC experience

Accelerator Experience:

TRIUMF Target; LANL Target; PSI Target

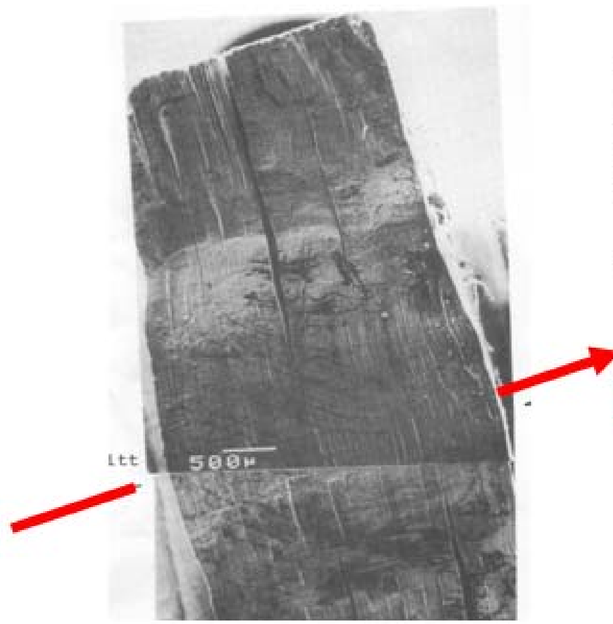


The cracks running through the plates develop at proton fluences above about $2x10^{25}$ P/m^2. Plates from targets irradiated to about 0.5 of this fluence show extensive delamination, but lack the macroscopic cracks across the a-b planes. These results indicate that pyrolytic graphite is very susceptible to delamination, as would be expected from the low tensile strength in the c direction.

= 10^21 p/cm2

Water-cooled/Edge-cooled TRIUMF target

Fluence: somewhere 10^21 -10^22 p/cm2



Swelling of the target after irradiation

10^{22} p/cm2

radiation-cooled

High operating temp ~1100 C

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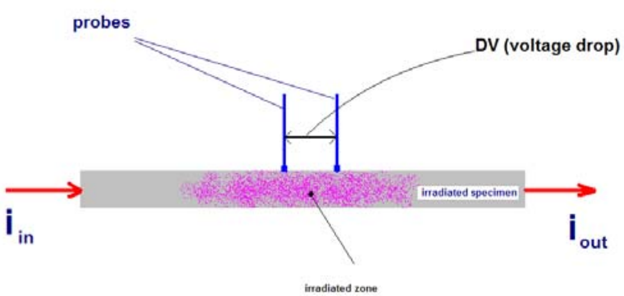
Graphite-CC experience



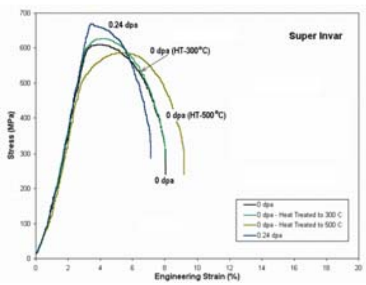
3-D CC (~ 0.2 dpa) conductivity reduces by a factor of 3.2

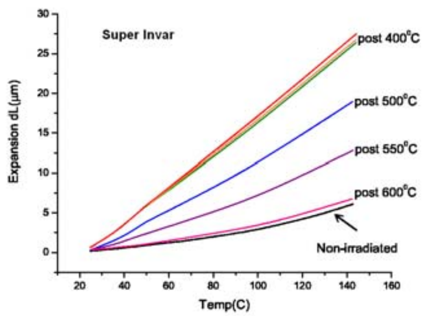
2-D CC (~0.2 dpa) measured under irradiated conditions (to be compared with company data)

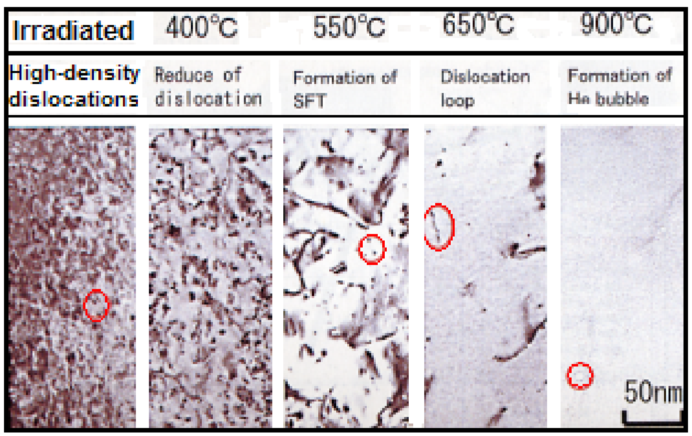
Graphite (~0.2 dpa) conductivity reduces by a factor of 6

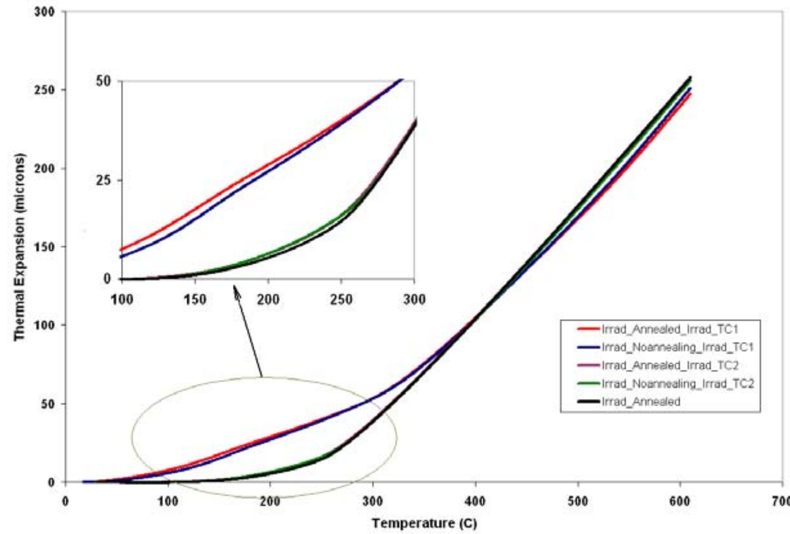
W (1+ dpa)	➔	reduced by factor of ~4
Ta (1+ dpa)	➔	~ 40% reduction
Ti-6Al-4V (~ 1dpa)	➔	~ 10% reduction

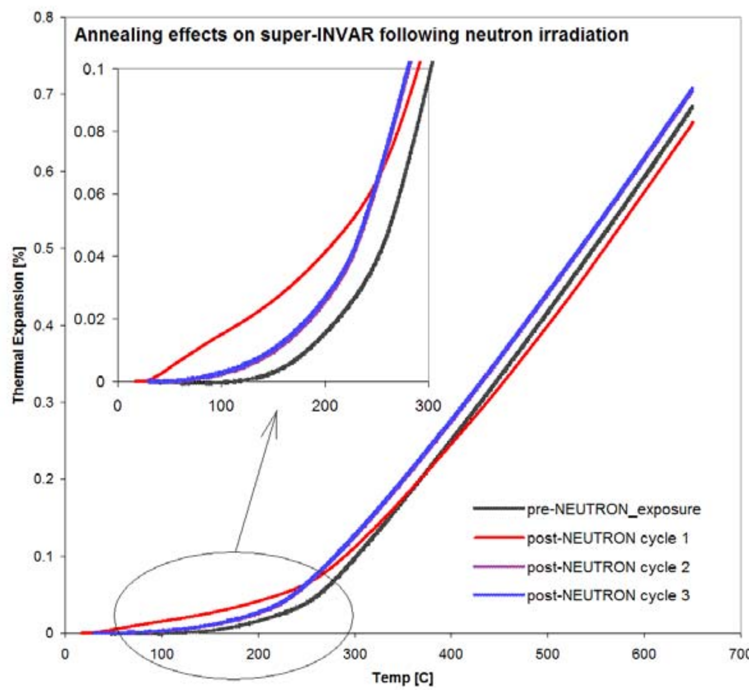
super-Invar


Super Invar
0.24 dpa
0 dpa (HT-300°C)
0 dpa (HT-500°C)
0 dpa
Stress (MPa)
Engineering Strain (%)

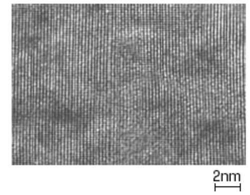

Super Invar
post 400°C
post 500°C
post 550°C
post 600°C
Non-irradiated
Expansion dL(μm)
Temp(C)


Irradiated
400°C
550°C
650°C
900°C
High-density dislocations
Reduce of dislocation
Formation of SFT
Dislocation loop
Formation of He bubble
50nm

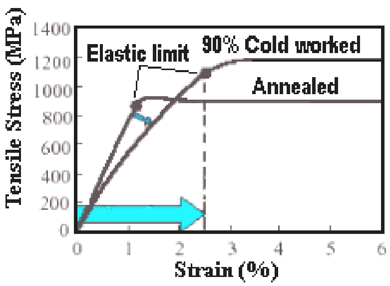

Thermal Expansion (microns)
Temperature (C)
Irrad_Annealed_Irrad_TC1
Irrad_Noannealing_Irrad_TC1
Irrad_Annealed_Irrad_TC2
Irrad_Noannealing_Irrad_TC2
Irrad_Annealed


Annealing effects on super-INVAR following neutron irradiation
Thermal Expansion [%]
Temp [C]
pre-NEUTRON_exposure
post-NEUTRON cycle 1
post-NEUTRON cycle 2
post-NEUTRON cycle 3

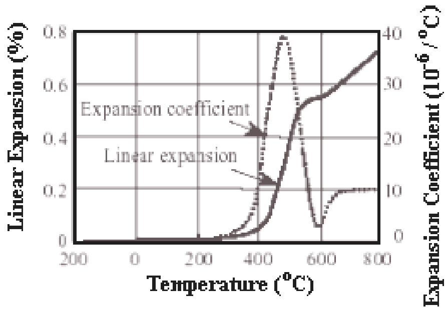
“Gum” metal



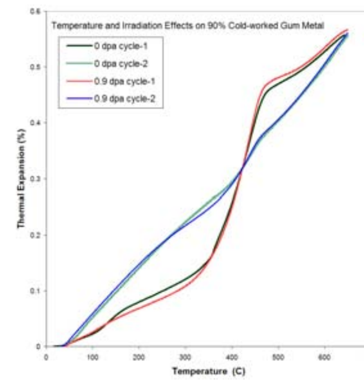
2nm



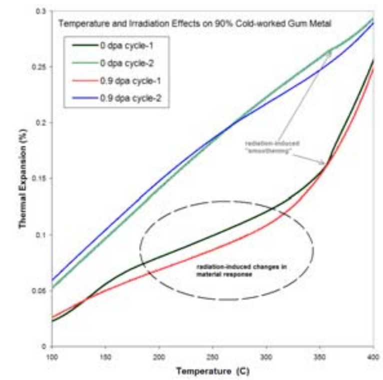
Tensile Stress (MPa)
Elastic limit
90% Cold worked
Annealed
Strain (%)



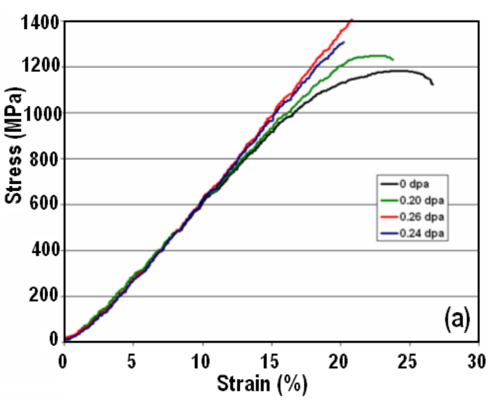
Linear Expansion (%)
Expansion coefficient
Linear expansion
Temperature (°C)
Expansion Coefficient (10⁻⁶ / °C)



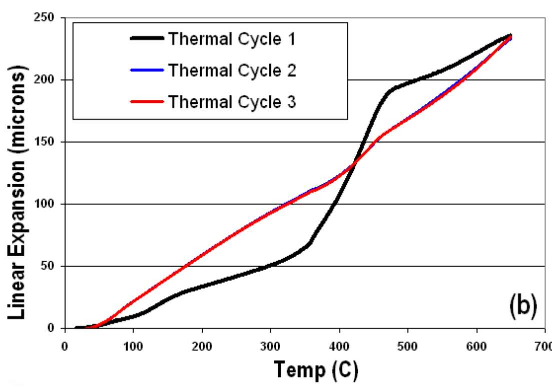
Temperature and Irradiation Effects on 90% Cold-worked Gum Metal
0 dpa cycle-1
0 dpa cycle-2
0.9 dpa cycle-1
0.9 dpa cycle-2
Thermal Expansion (%)
Temperature (C)



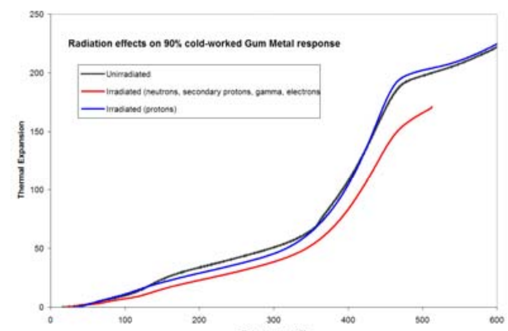
Temperature and Irradiation Effects on 90% Cold-worked Gum Metal
0 dpa cycle-1
0 dpa cycle-2
0.9 dpa cycle-1
0.9 dpa cycle-2
Thermal Expansion (%)
Temperature (C)



Stress (MPa)
0 dpa
0.20 dpa
0.26 dpa
0.24 dpa
(a)
Strain (%)

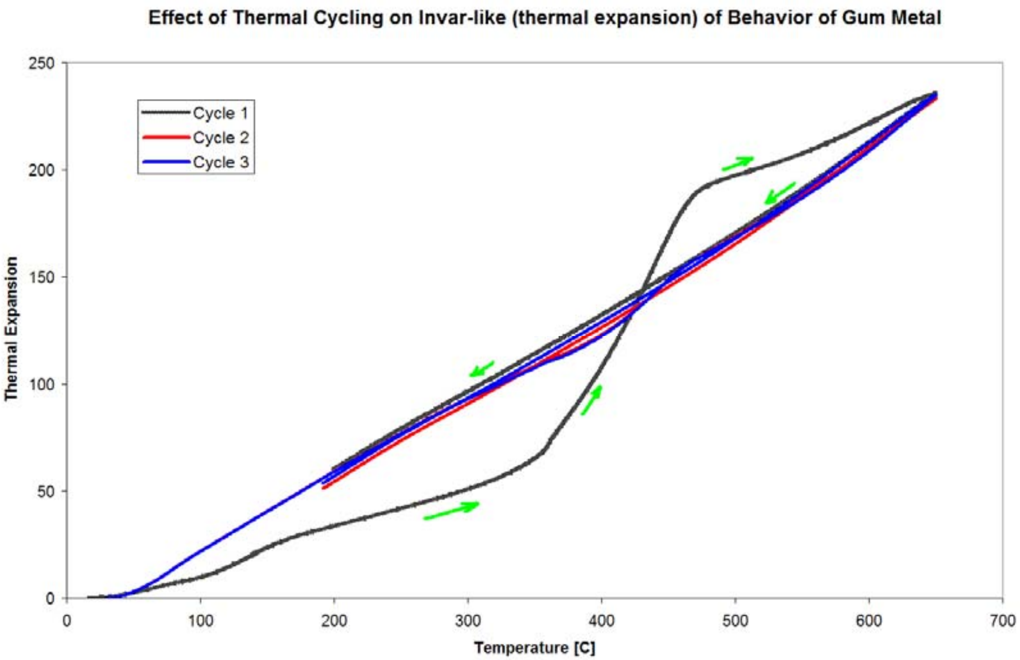


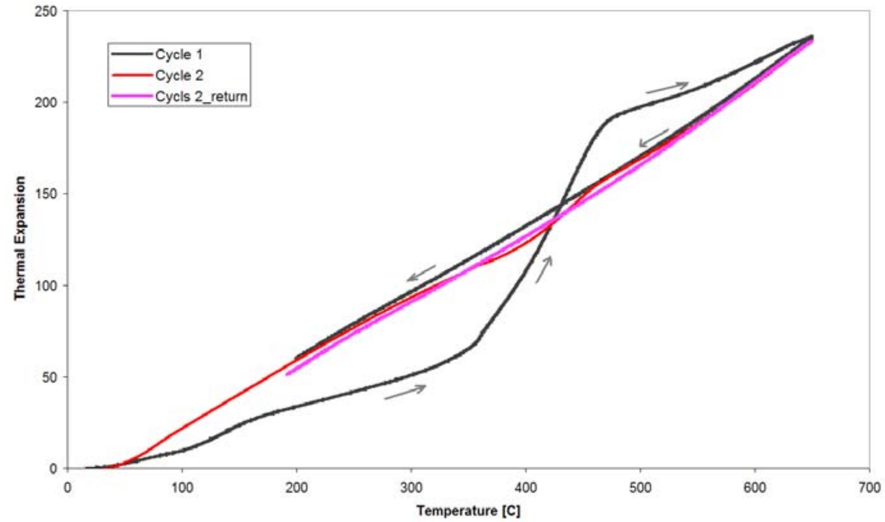
Thermal Cycle 1
Thermal Cycle 2
Thermal Cycle 3
Linear Expansion (microns)
(b)
Temp (C)

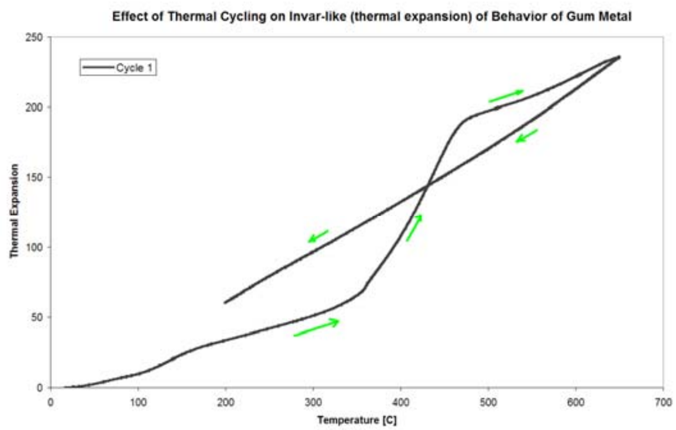


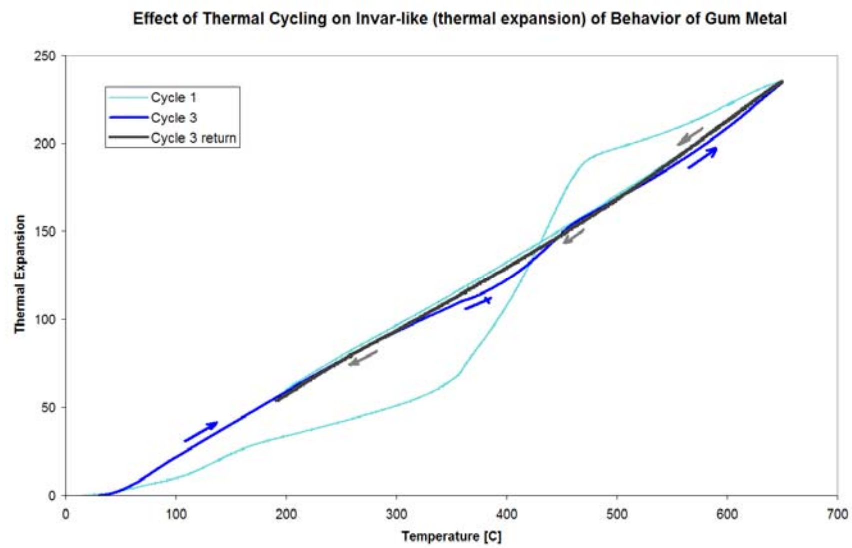
Radiation effects on 90% cold-worked Gum Metal response
Unirradiated
Irradiated (protons)
Thermal Expansion
Temperature [C]

Gum metal

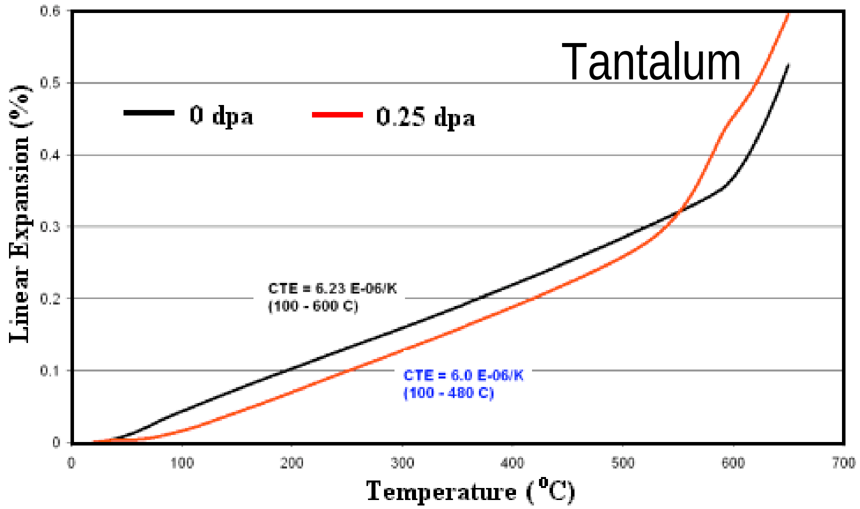

Effect of Thermal Cycling on Invar-like (thermal expansion) of Behavior of Gum Metal
Cycle 1
Cycle 2
Cycle 3
Thermal Expansion
Temperature [C]

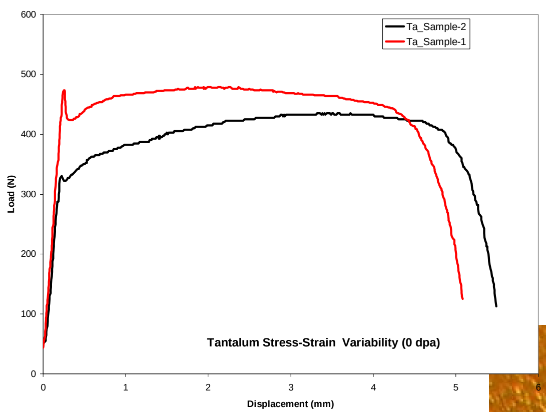

Cycle 1
Cycle 2
Cycls 2_return
Thermal Expansion
Temperature [C]

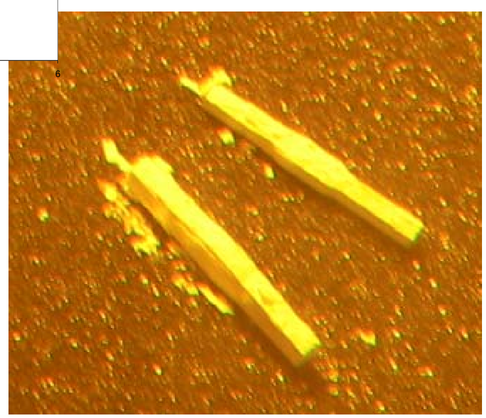

Effect of Thermal Cycling on Invar-like (thermal expansion) of Behavior of Gum Metal
Cycle 1
Thermal Expansion
Temperature [C]

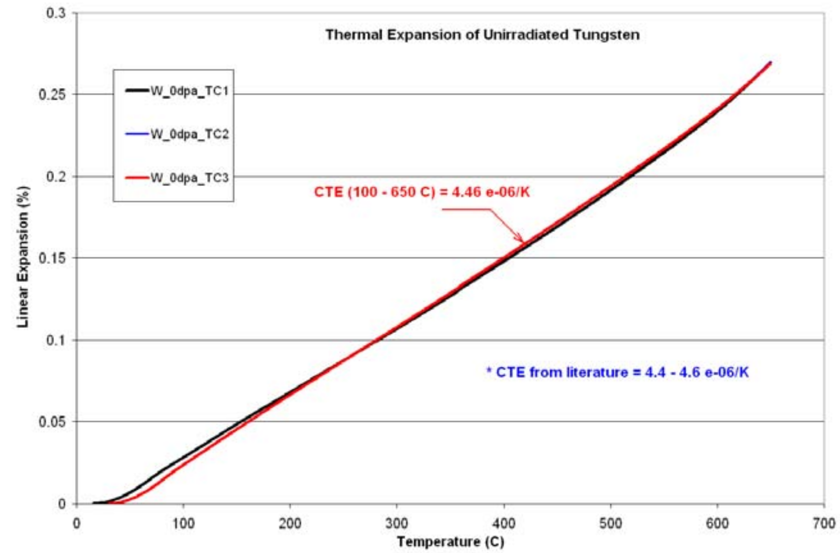

Effect of Thermal Cycling on Invar-like (thermal expansion) of Behavior of Gum Metal
Cycle 1
Cycle 3
Cycle 3 return
Thermal Expansion
Temperature [C]

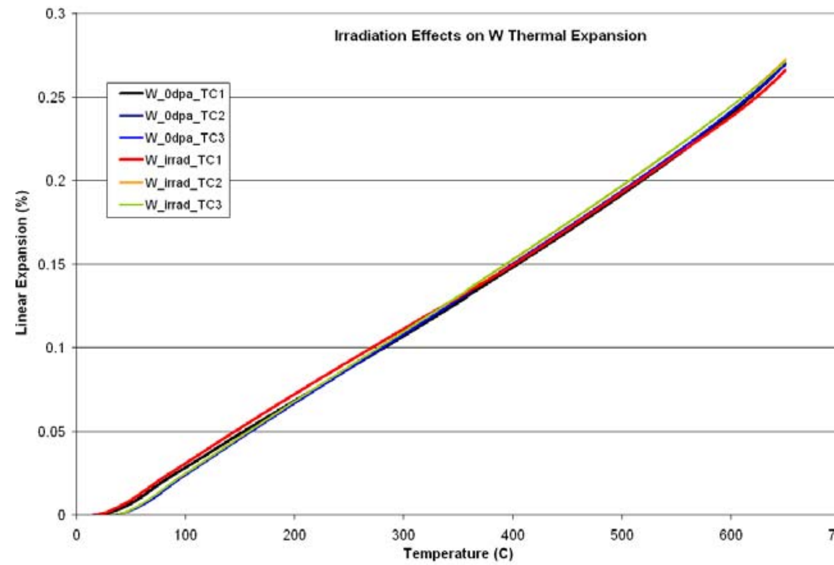
Radiation Damage Studies – High-Z Materials











Urgent R&D

Target material irradiations to 4-MW level fluences

Study of Albemet as Horn and/or Target Material

Irradiation damage of insulators

Heat transfer tests for multi-MW demand