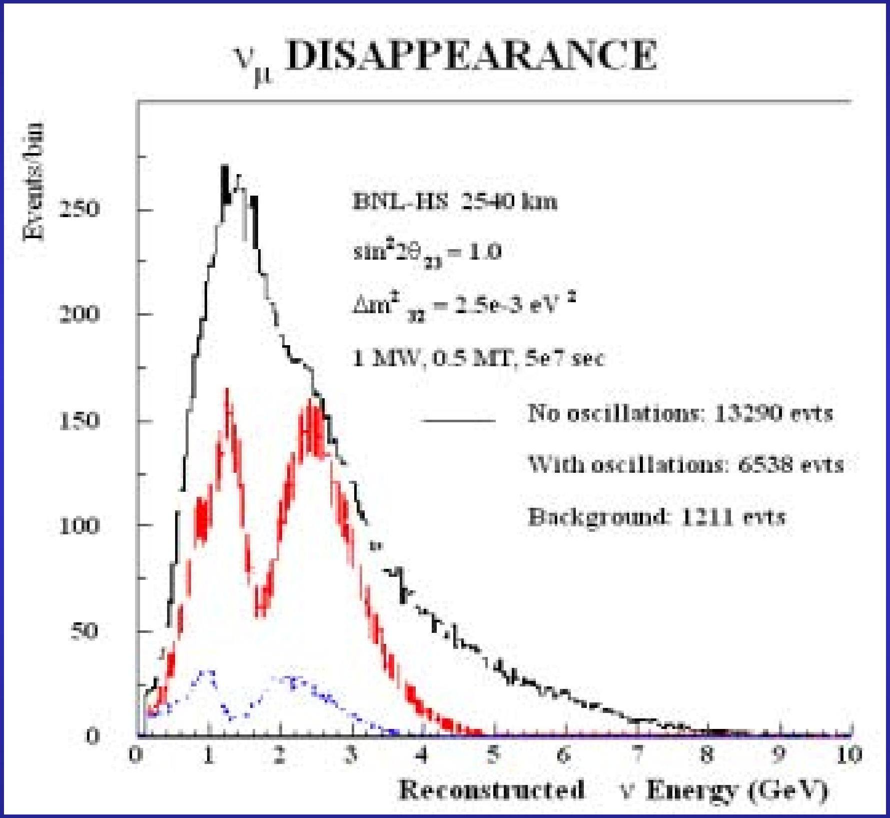
BNL Neutrino Long Baseline Neutrino Initiative

N. Simos, BNL NWG

WHERE WE ARE

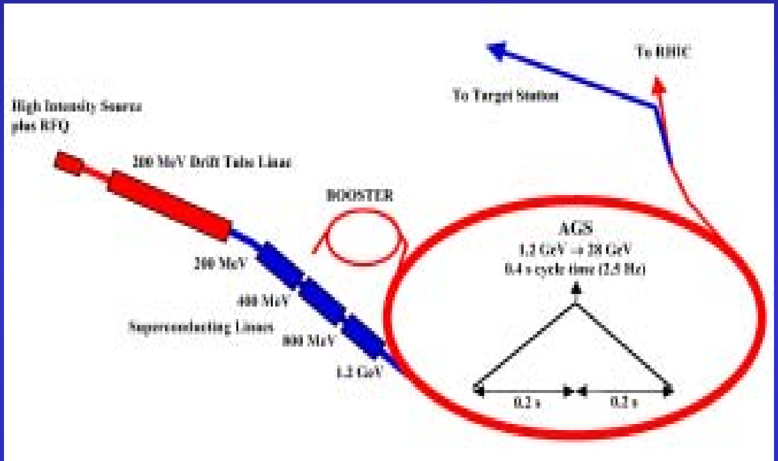
- Making the physics case for the Very Long Baseline Neutrino Beam
- Conceptualizing AGS upgrade schemes that will lead to high power (1+ MW)
- Developing target/horn ideas
- Embarking on an material R&D

BNL Long Baseline Neutrino Beam - Physics



- The dominant term governing the oscillations is $\sin^2(\Delta m_{32}{}^2\ L\ /\ 4E)$
- Longer Length allows oscillations to be seen at higher Energy
- Cross sections are larger and energy resolutions are better at higher Energy
- A broad band beam allows coverage of multiple oscillation periods and observation of a distinct oscillation signature
- The multiple node structure alows $\Delta m_{32}{}^2$ to be precisely measured by a *wavelength* rather than an amplitude (reducing systematic errors)

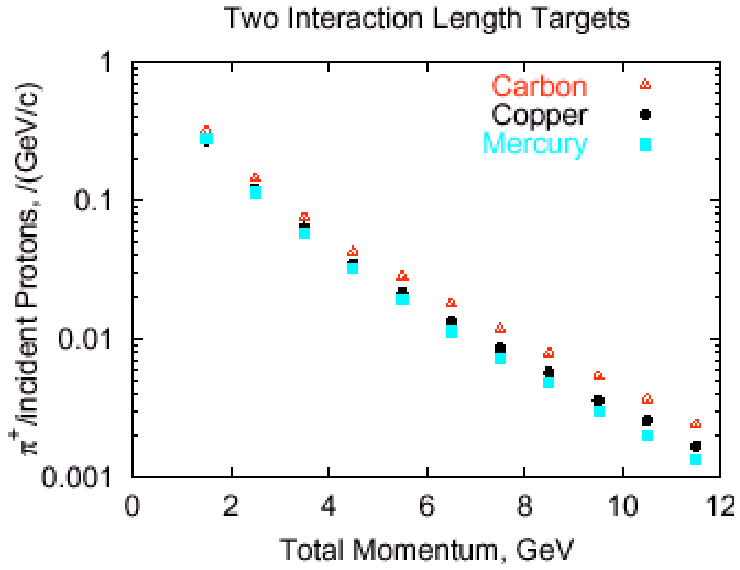
BNL Super-Beam – Baseline Parameters

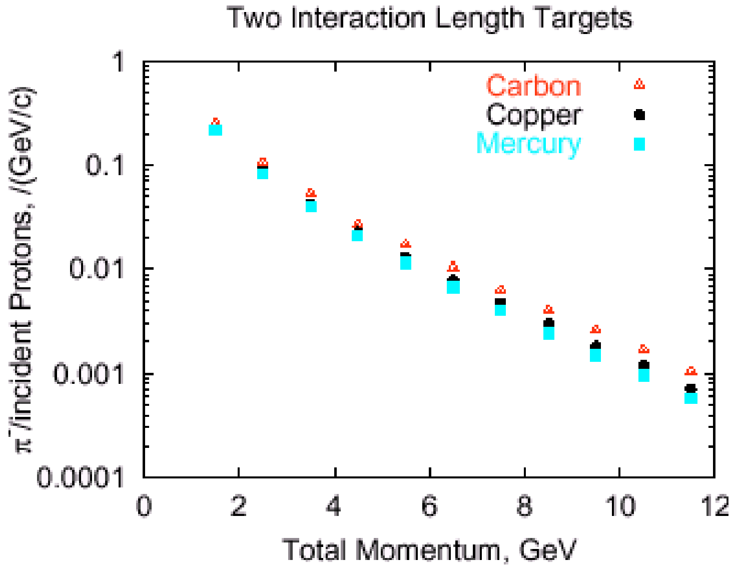


Proton Beam Energy	28 GeV
Protons per Pulse	8.9×10^{13}
Average Beam Current	35.7 μA
Repetition Rate	2.5 Hz
Pulse Length	2.58 μsec
Number of Bunches	23
Number Protons per Bunch	3.87×10^{12}
AGS Circumference	807.1 m
Bunch Length	40 ns
Bunch Spacing	60 ns
Normalized Emittance-X	100 π mm-mrad
Normalized 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	7 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

BNL Super-Beam – Baseline Parameters

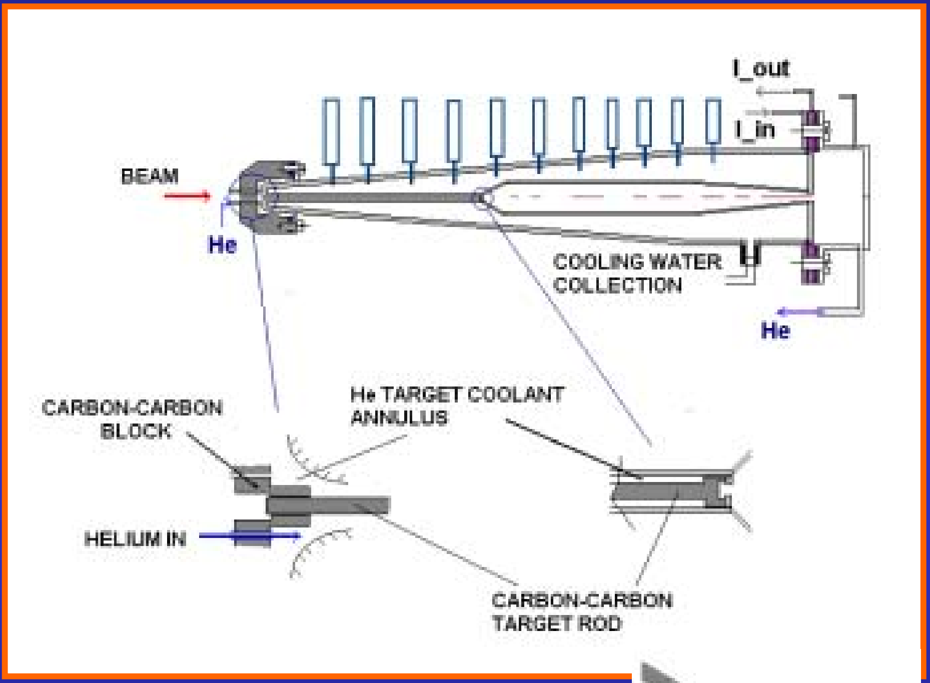




Machine	Power	Proton/Pulse	Repetition Rate	Protons/SSC year
Current AGS	0.17 MW	6×10^{13}	0.625 Hz	3.75×10^{20}
AGS Proton Driver	1 MW	1×10^{14}	2.5 Hz	2.5×10^{21}
Japan Hadron Facility	0.77 MW	3.3×10^{14}	0.29 Hz	9.6×10^{20}
Super AGS Prot Driver	4 MW	2×10^{14}	5.0 Hz	1.0×10^{22}

BNL Target/Horn Working Concept

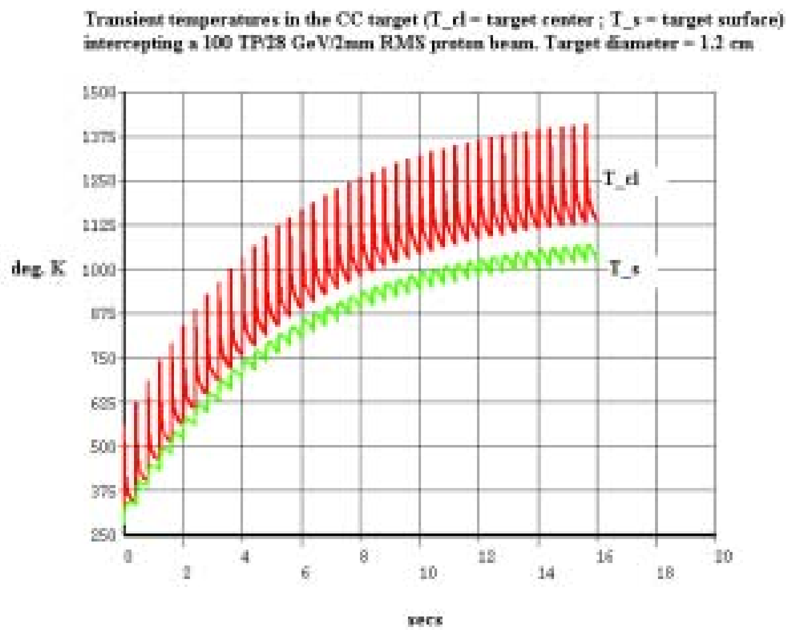
TARGET CONCEPTUAL DESIGN - CHALLENGES

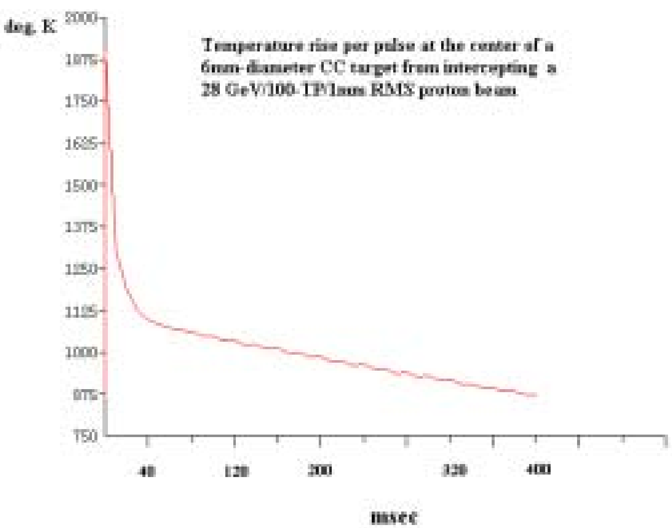


- Carbon-Carbon composite target (80cm long, 6mm radius)
- Selected over graphite for superior strength and low thermal expansion
- Experimental verification of graphite and carbon-carbon response
- Sublimation issues are potentially avoided
- Forced He gas in annular space cools target operating at ~ 800C
- ΔT per 10^{14} proton pulse ~ 170^{o} C

Carbon-Carbon Composite Target

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%





IS THERE AN OPTIMAL BEAM SIZE/TARGET SIZE RELATION ?

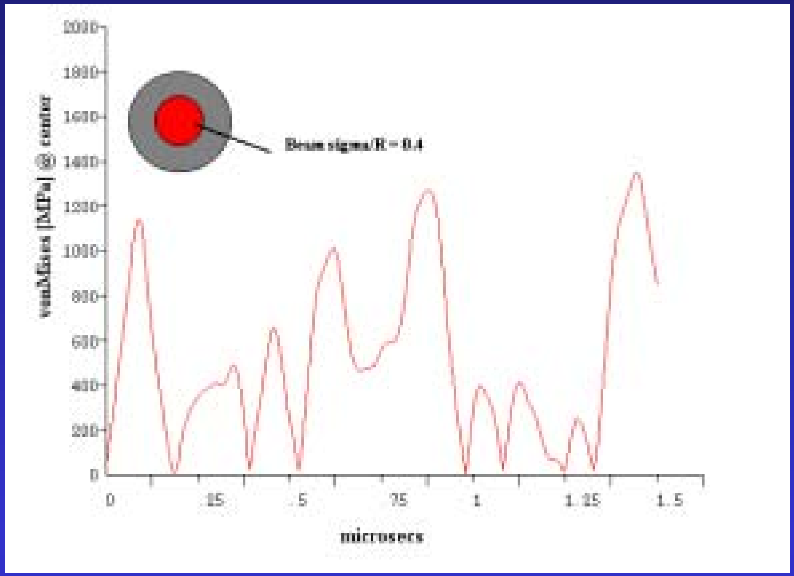
Two Beam sizes are considered – 1mm & 2mm beam spots (6mm & 12mm diam. targets respectively)

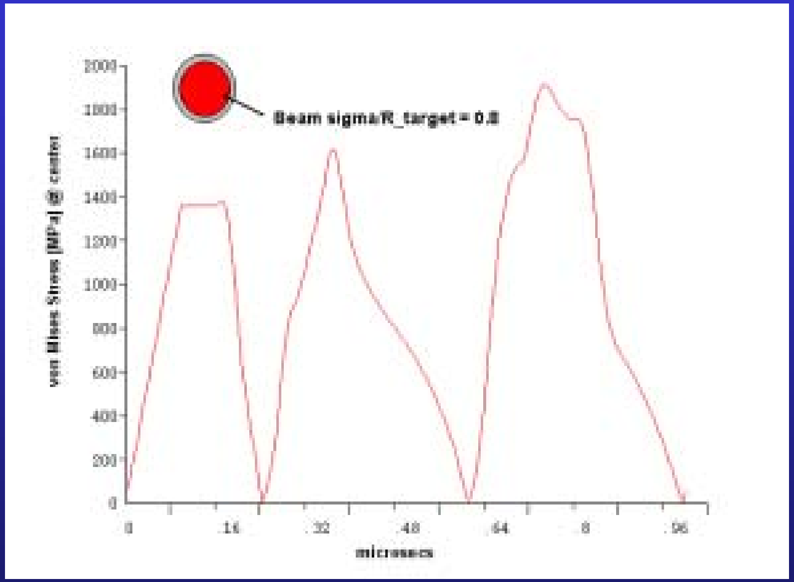
Total energy deposited on target is 5.1 & 7.3 kJ respectively

Corresponding peak DTs on target are 960 C and 260 C

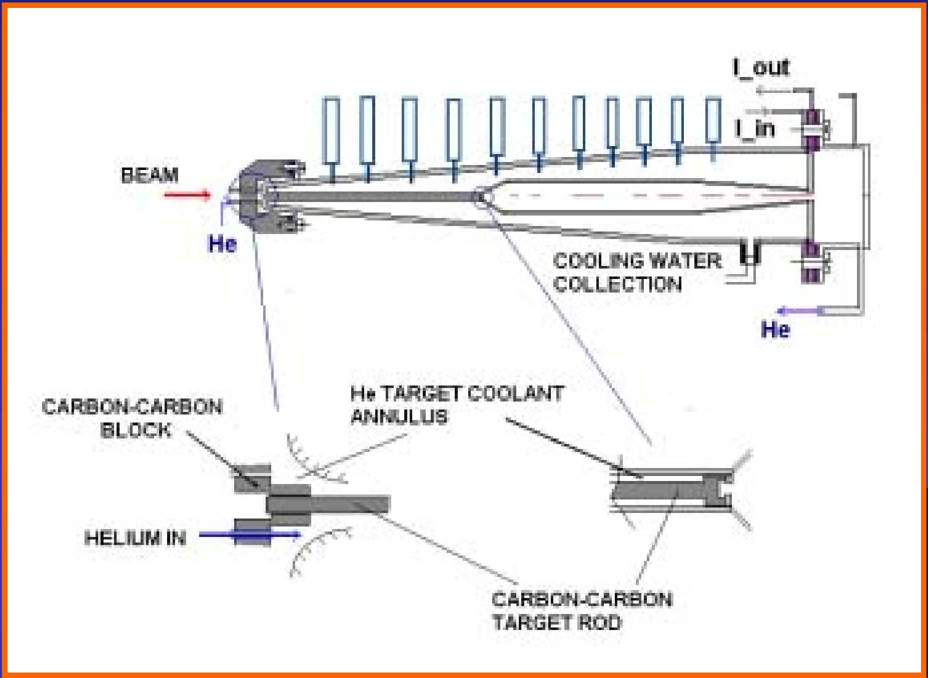
Yield of secondaries is being optimized. That may lead to a beam spot/target diameter somewhere in between

Option of Gaussian beam to flat beam is also assessed



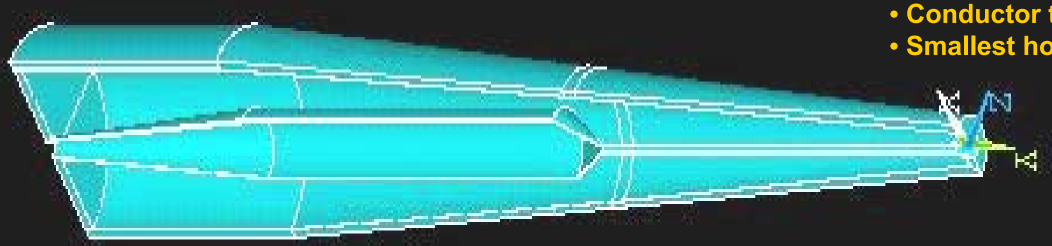


BNL Target/Horn Working Concept



HORN CHALLENGES

- Current pulse structure - Joule heating
- Gamma ray heating - long term irradiation effects
- Material degradation due to forced water cooling combined with thermal fatigue
- Maintaining operating temperature at safe levels



- Baseline material is Aluminum (6061 T6 or 3000 series)
- New alloys are considered (e.g. AlBeMet)
- Task is keeping resistivity low while maintaining strength as well as resistance to fatigue, corrosion
- Heat transfer through water spray (baseline)
- Horn inner conductor diameter = 14mm
- Conductor thickness narrowest section = 2.5mm
- Smallest horn thickness = 1mm

CHALLENGES FOR THE INTEGRATED TARGE/HORN SYSTEM

AS WE GET TO 1+ MW SYSTEM

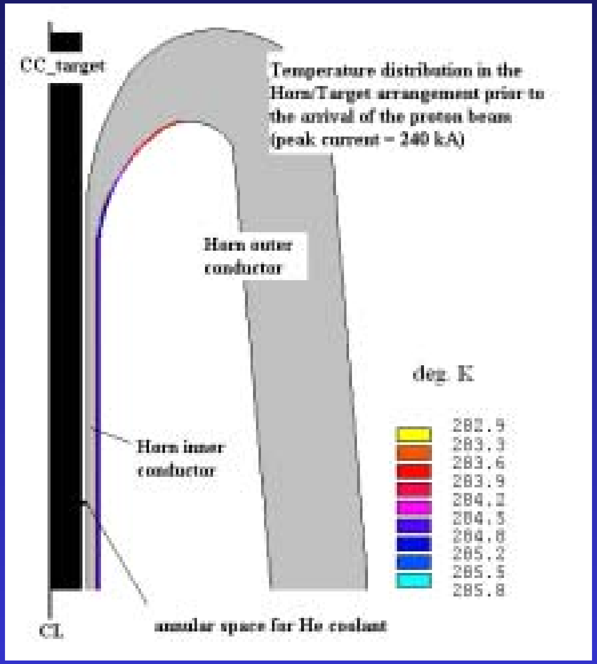
Heat generation and removal from the target/horn system

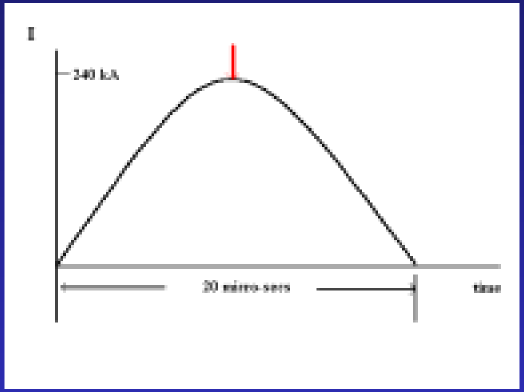
Target thermo-mechanical response from energetic, high intensity protons

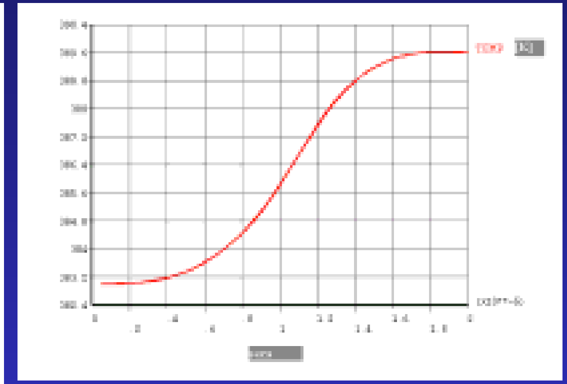
Irradiation and corrosion effects on materials

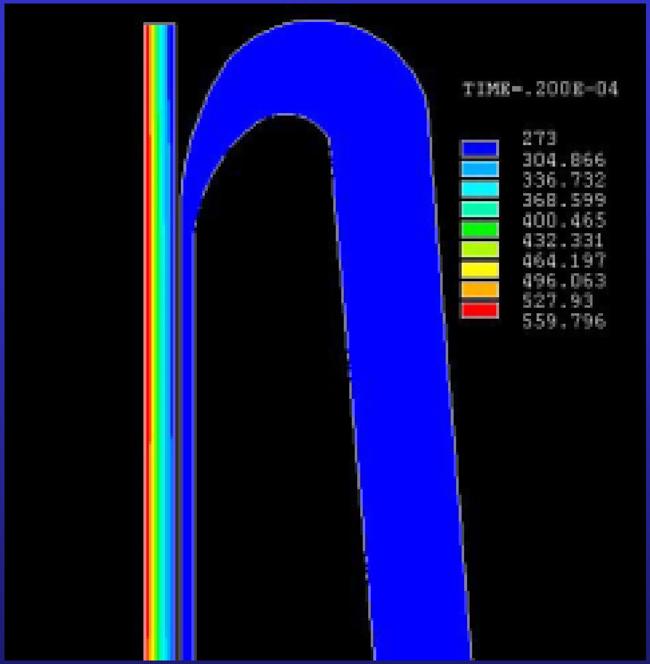
Horn/target integration issues
Horn mechanical response and long term integrity (irradiation, corrosion and thermal fatigue)

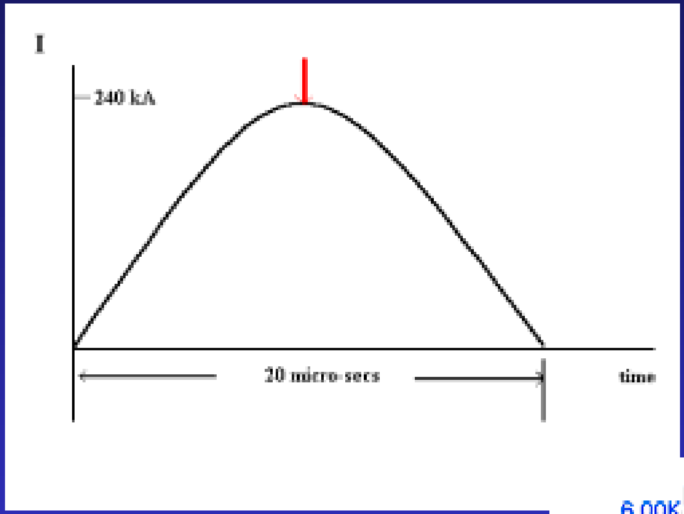
Beam windows integrated in the system to (a) separate the vacuum space in the transfer line from the final beam line to the target and (b) to maintain the coolant around the target in a close-system loop

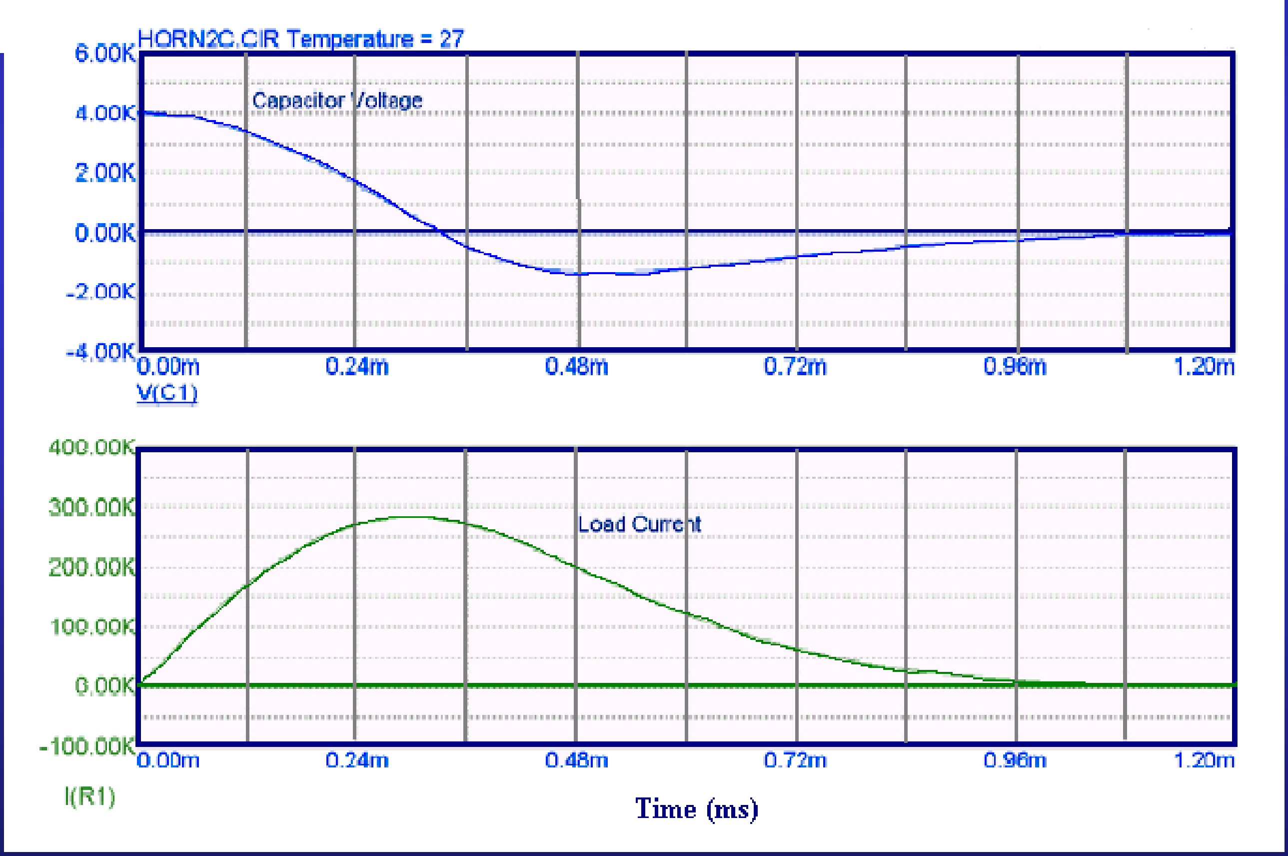

CC_target
Temperature distribution in the Horn/Target arrangement prior to the arrival of the proton beam (peak current = 240 kA)
Horn outer conductor
deg. K
282.9
283.3
283.6
283.9
284.2
284.5
284.8
285.2
285.5
285.8
Horn inner conductor
CL
annular space for He coolant

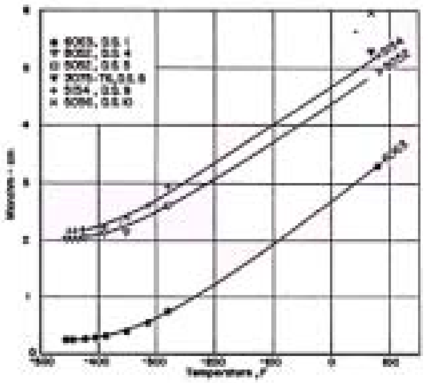

I
240 kA
20 micro-secs
time




TIME=.200E-04
273
304.866
336.732
368.599
400.465
432.331
464.197
496.063
527.93
559.796


I
240 kA
20 micro-secs
time

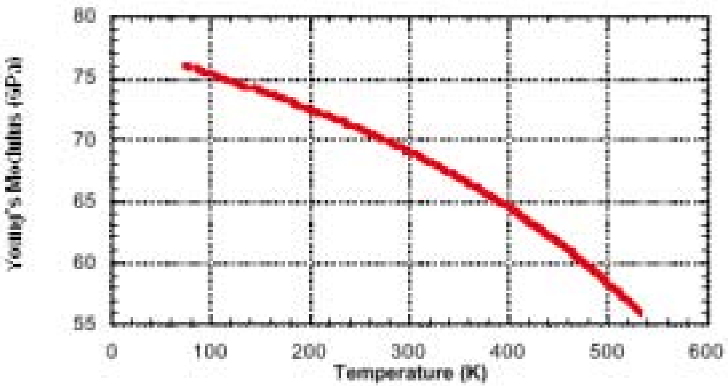

HORN2C.CIR Temperature = 27
Capacitor Voltage
6.00K
4.00K
2.00K
0.00K
-2.00K
-4.00K
0.00m
0.24m
0.48m
0.72m
0.96m
1.20m
V(C1)
Load Current
400.00K
300.00K
200.00K
100.00K
0.00K
-100.00K
0.00m
0.24m
0.48m
0.72m
0.96m
1.20m
I(R1)
Time (ms)



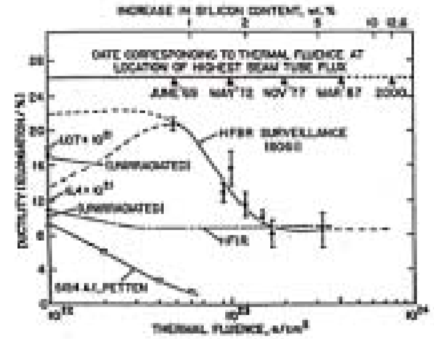
Electrical resistivity of aluminum as a function of temperature

Table 4-21. Temperature Dependence of 0.2% Yield Strength (Typical and Conservative) of 6061-T6 Aluminum

Temperature		Yield Strength: Typical Value		Yield Strength: Minimum Value	
K	°F	MPa	ksi	MPa	ksi
77	−320	324	47	—	—
193	−112	290	42	—	—
245	−18	283	41	242	35
249	75	276	40	242	35
373	212	262	38	232	33.7
422	300	214	31	189	27.4
477	400	103	15	91.8	13.3
533	500	34	5	—	—
589	600	19	2.7	—	—
644	700	12	1.8	—	—

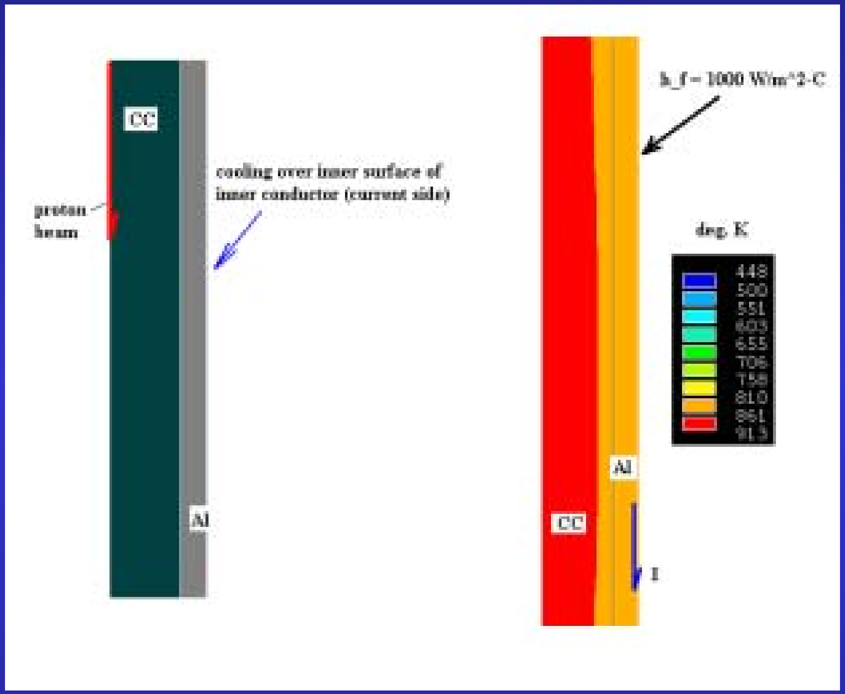


Effects of Irradiation on Crystal Structure/Phase of Al-6061

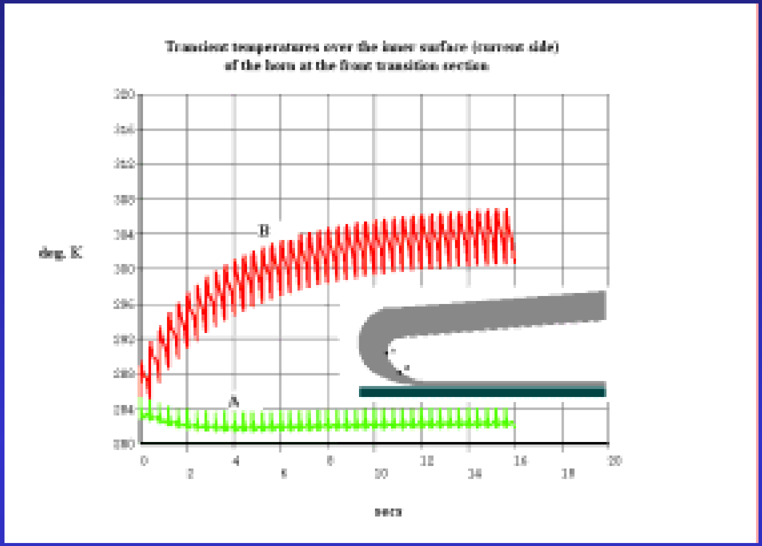


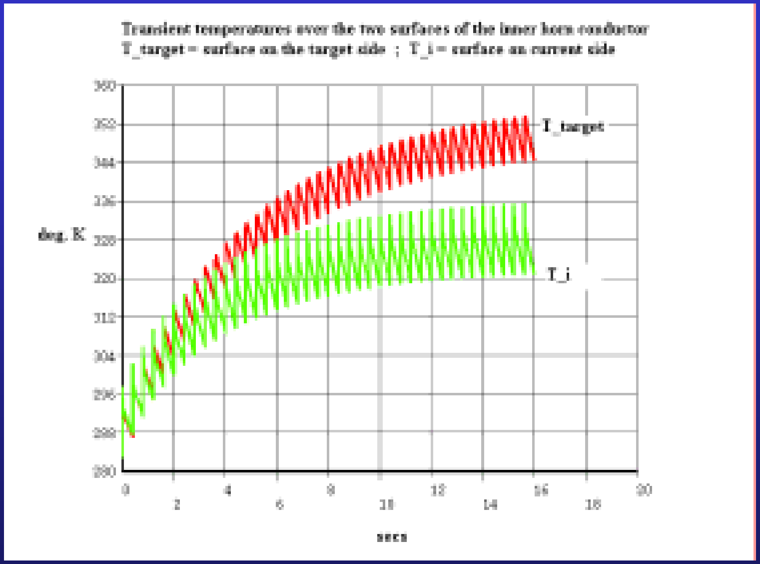
Effect of thermal neutron radiation on silicon content of 6061 Al. Note: Thermal fluence is not in SI units. Thermal Fluence (n/m^2) = Thermal Fluence (n/cm^2) × 10000. $F_{fast}/F_{thermal}$ = 0.6 (HFIR), $F_{fast}/F_{thermal}$ = 0.05 (HFBR)

Temperature distribution for HORN/Target in contact



Horn temperature transients





OPTIMIZATION EFFORT TO MEET THE CHALLENGE OF 1+ MW SYSTEM

Alternative new materials (e.g. AlBeMet, Toyota “Gum Metal”, etc) are being considered and will be experimentally evaluated

Nano-structured surface film embedment is being considered as option to protect the horn base-material – Examine other techniques for surface treatment (e.g. culsterizing ???)

Heat transfer enhancement is being evaluated through the use of nano-particles in the cooling medium

Relevant Lessons from BNL E951 Experiment

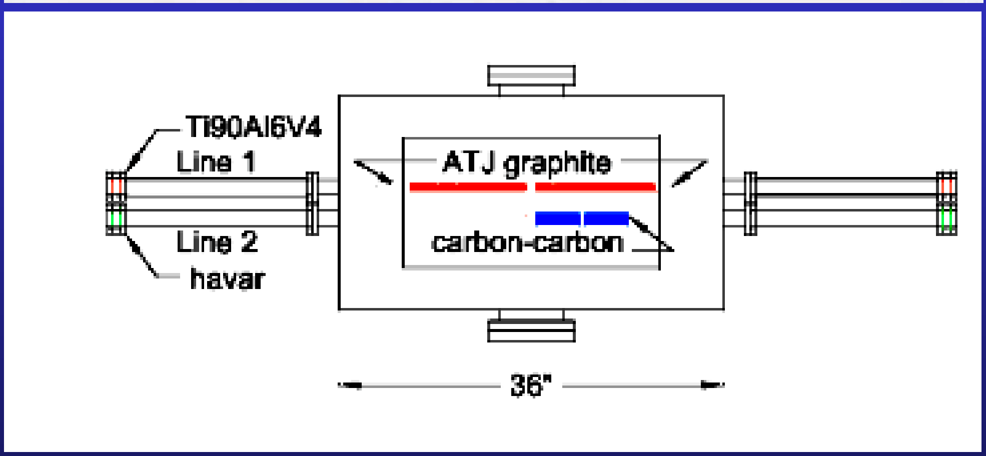
Set out to assess:

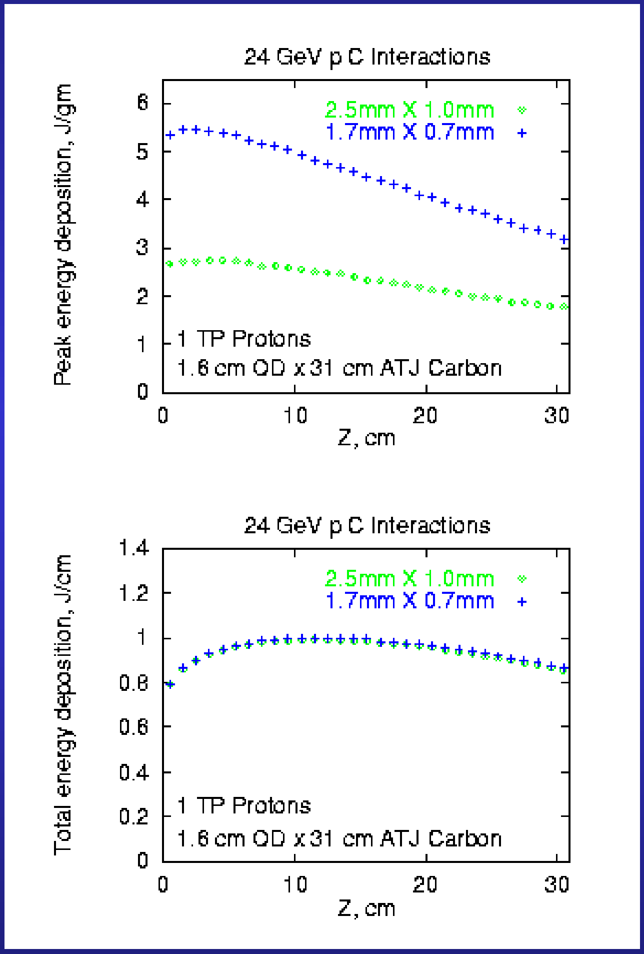
- **Solid target survival chances (graphite, carbon-carbon, inconel, superInvar, etc.)**
- **Beam window survival (critical due to Hg)**

And while at it ……

- **Push the AGS intensity to 16 TP and beam spot to 0.5 mm RMS sigma**
- **Experiment with and identify best candidate materials through measured responses**
- **Validate prediction models against measurements to gain confidence in predicting material response and/or failure at extreme conditions**
- **Use experimental results to benchmark energy depositions predicted by the various Monte Carlo codes**

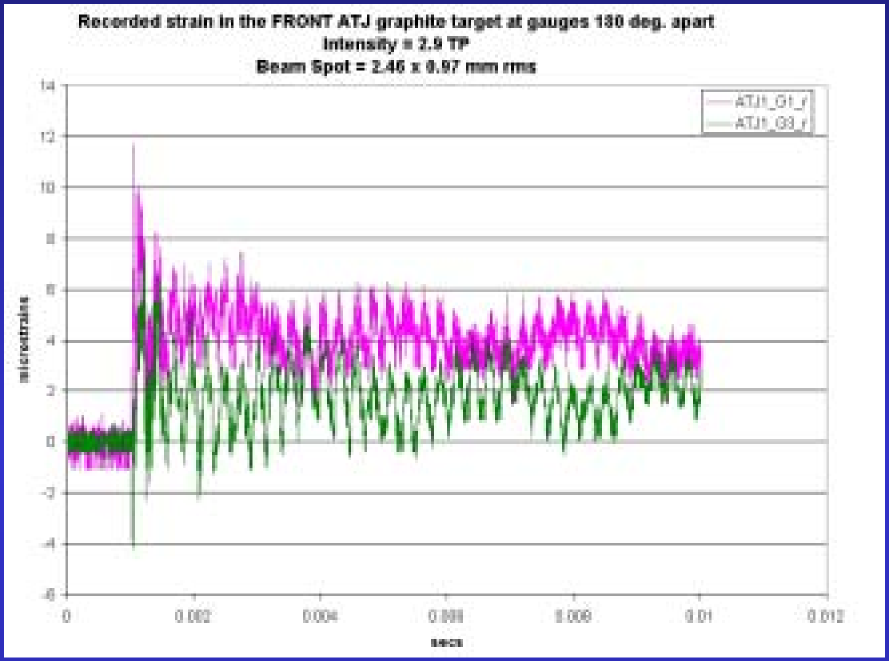
E951Target Station Set-Up
Graphite & Carbon-Carbon Targets

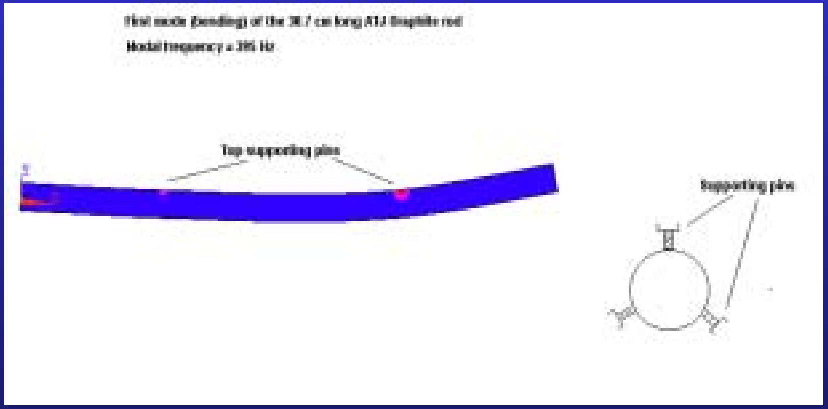




ATJ Graphite Strain Data

Verification of fundamental modes of target response





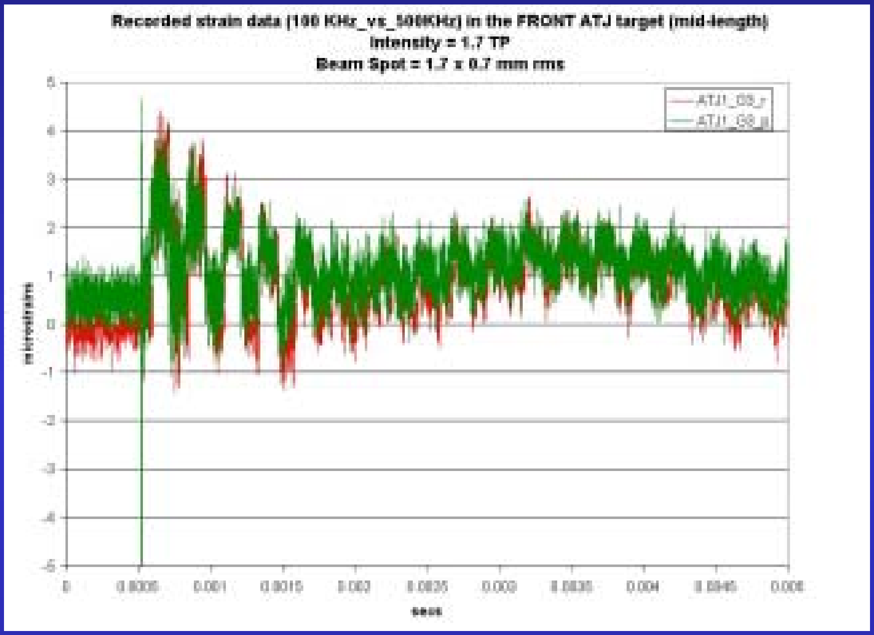
Recorded strains in the middle of the graphite rod (left) shows a bending frequency between 380-390 Hz

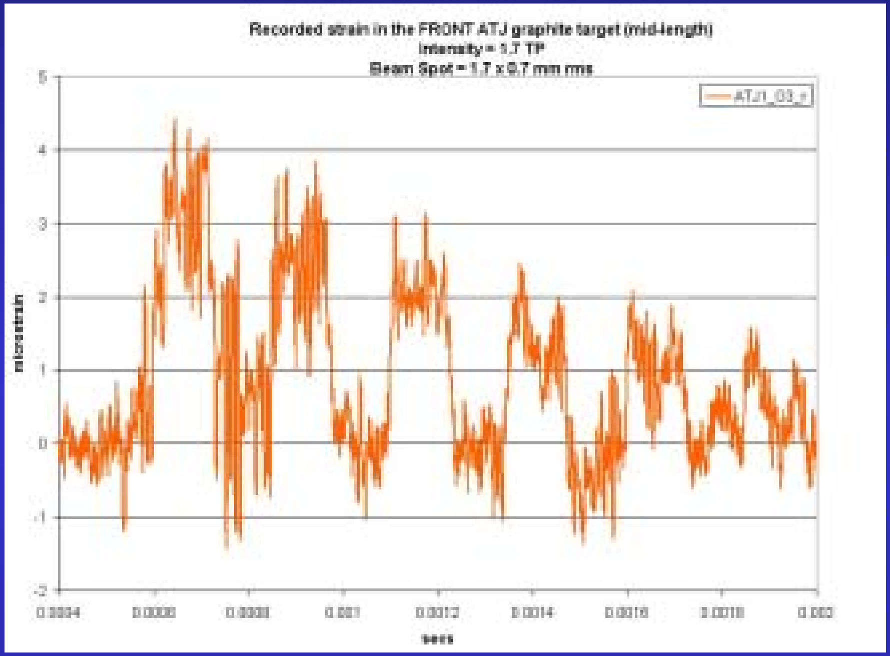
The prediction of the detailed model that implements the supporting/holding fixtures of the target as close to the real setting as possible, predicts a bending frequency of 395 Hz

Also from the record, the axial "ringing" of the target has a period of 260 to 265 microseconds. The fundamental axial period T=2L/c (where L is target rod length and c is speed of sound) is approximately 261 microseconds

The radial "ringing" on the other hand, which from theory is calculated at 150 KHz (or 6.625 microsecond period), is visible only in the strain record filtered by the 500 KHz acquisition

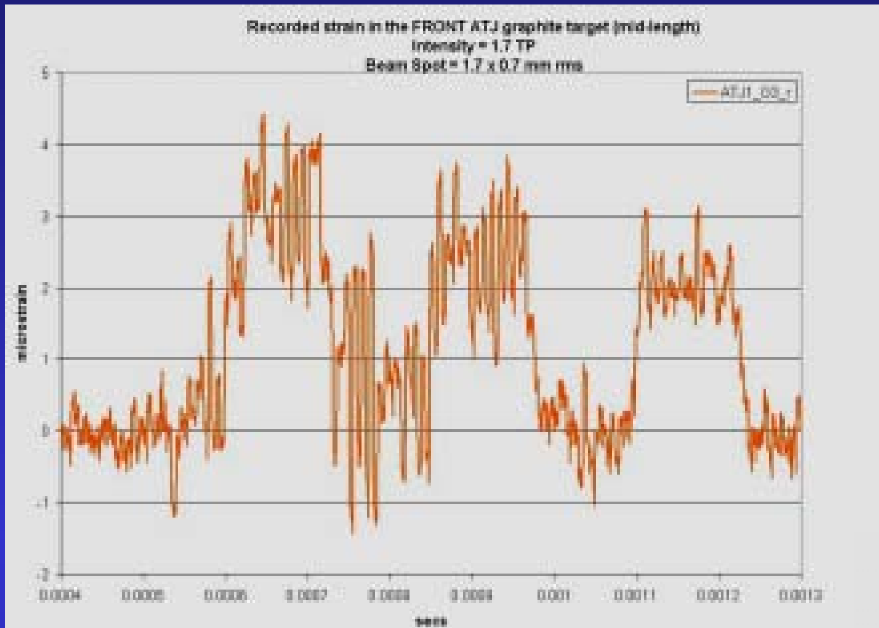
ATJ Graphite Strain Data

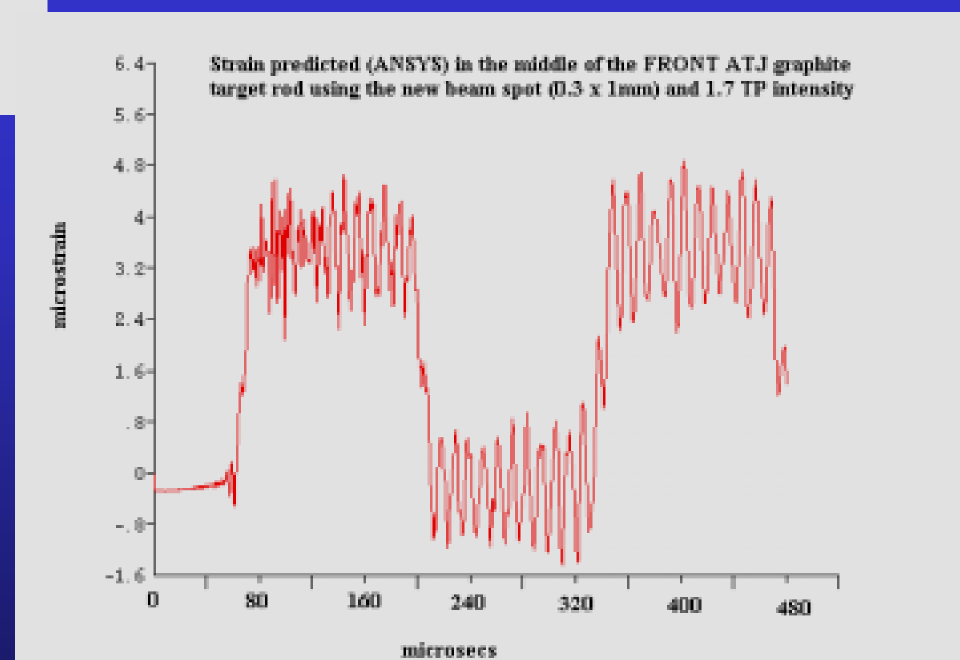




ATJ Graphite Strain Comparison

BASIS FOR HADRON CALCULATIONS BENCHMARKING





ATJ Graphite Strain Comparison

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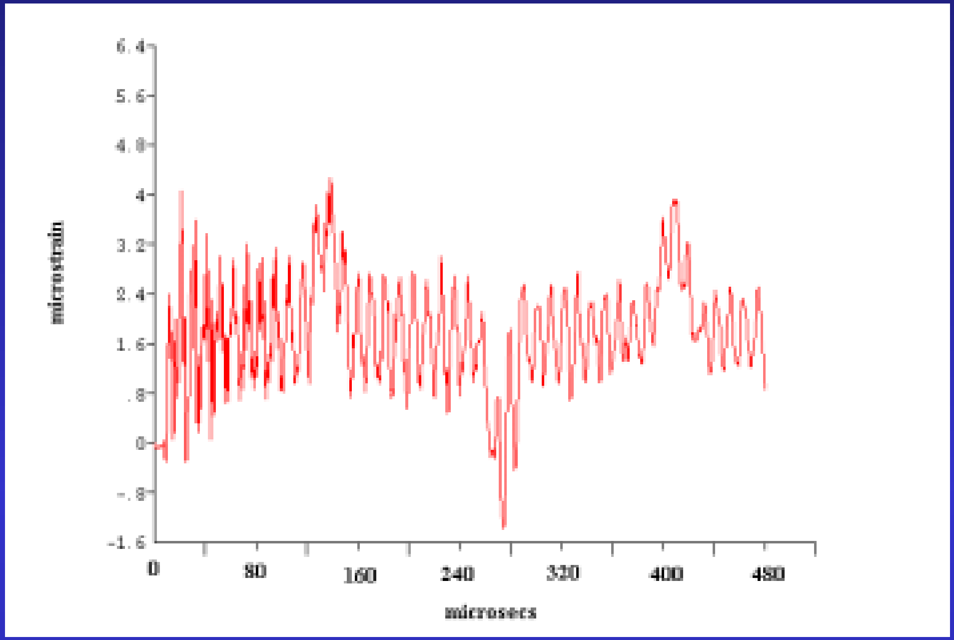
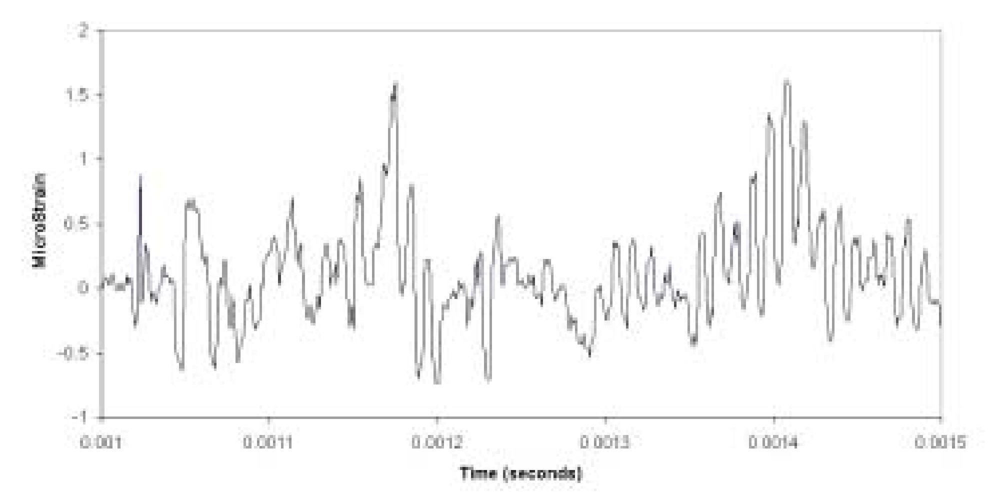
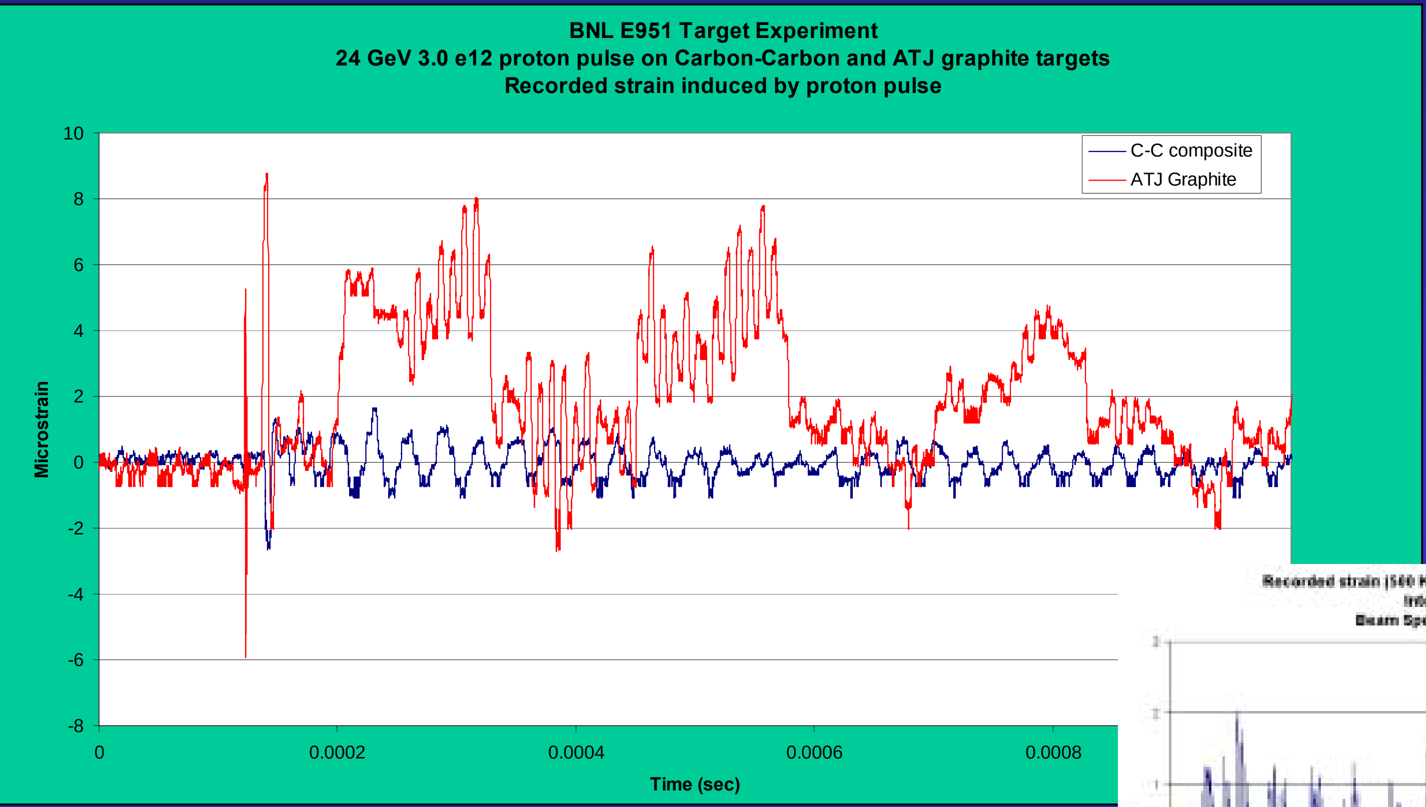
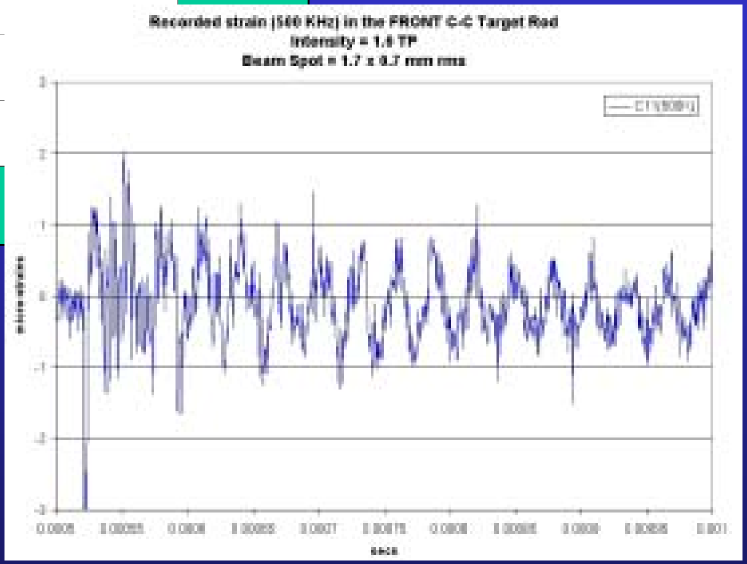


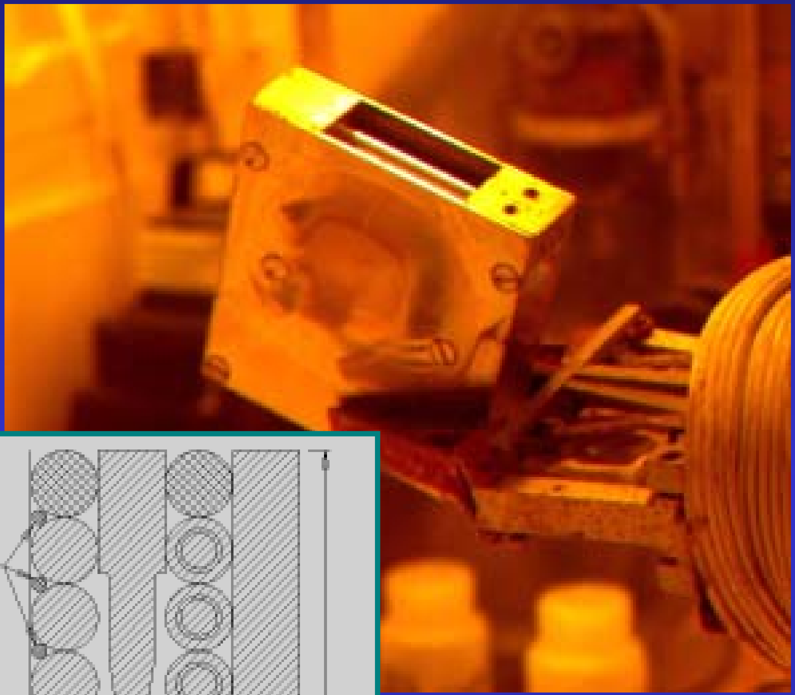


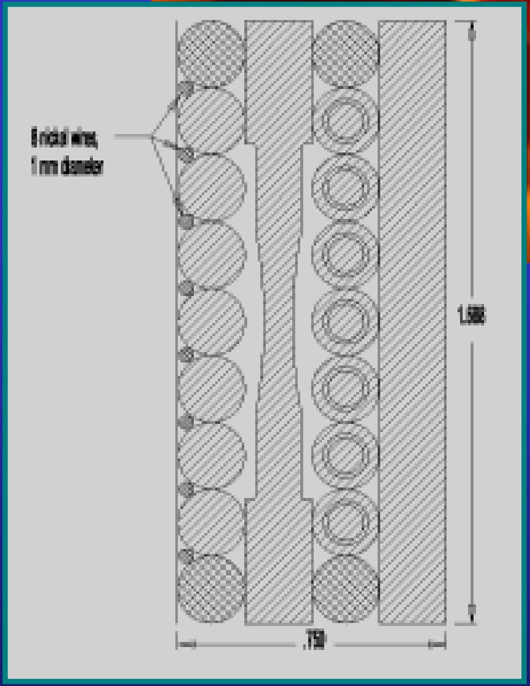
ATJ Graphite vs. Carbon-Carbon Composite



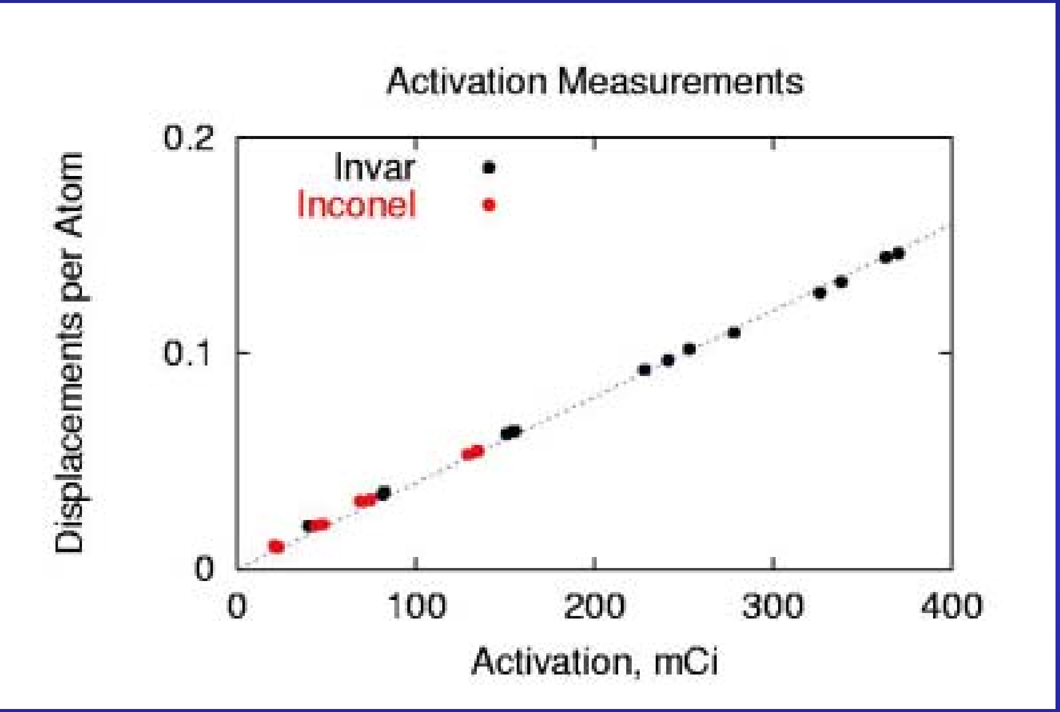


Recent BNL Irradiation Studies on Super Invar & Inconel-718

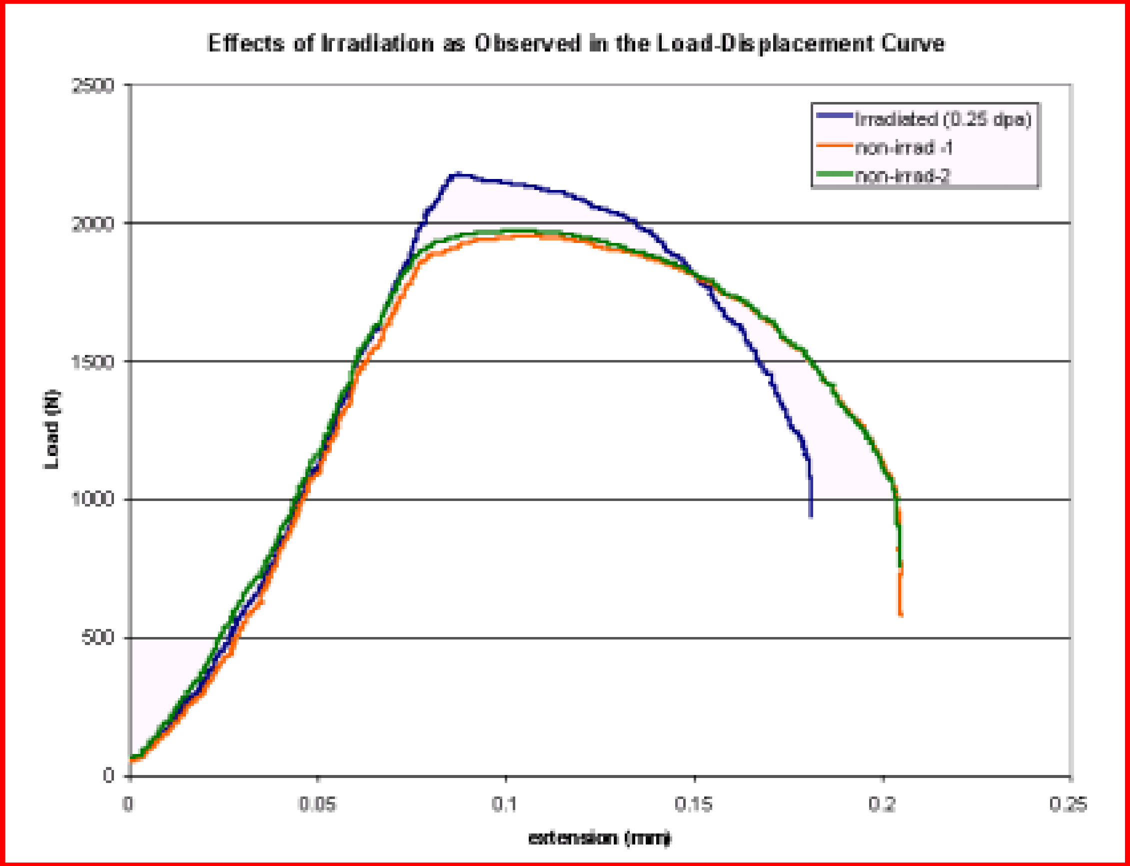


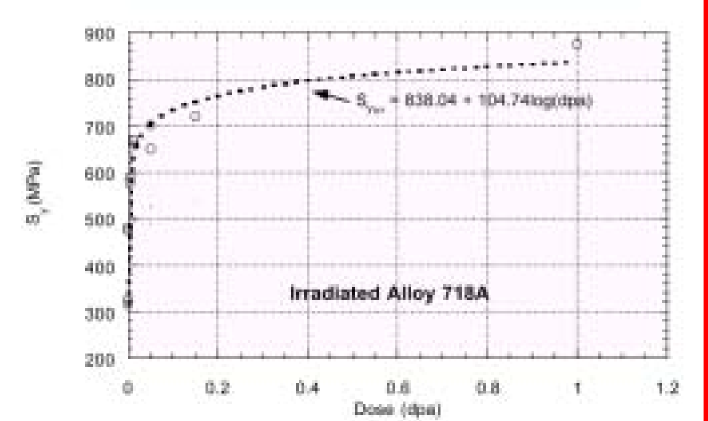


Irradiation Studies at BNL



Super-Invar Irradiation Study



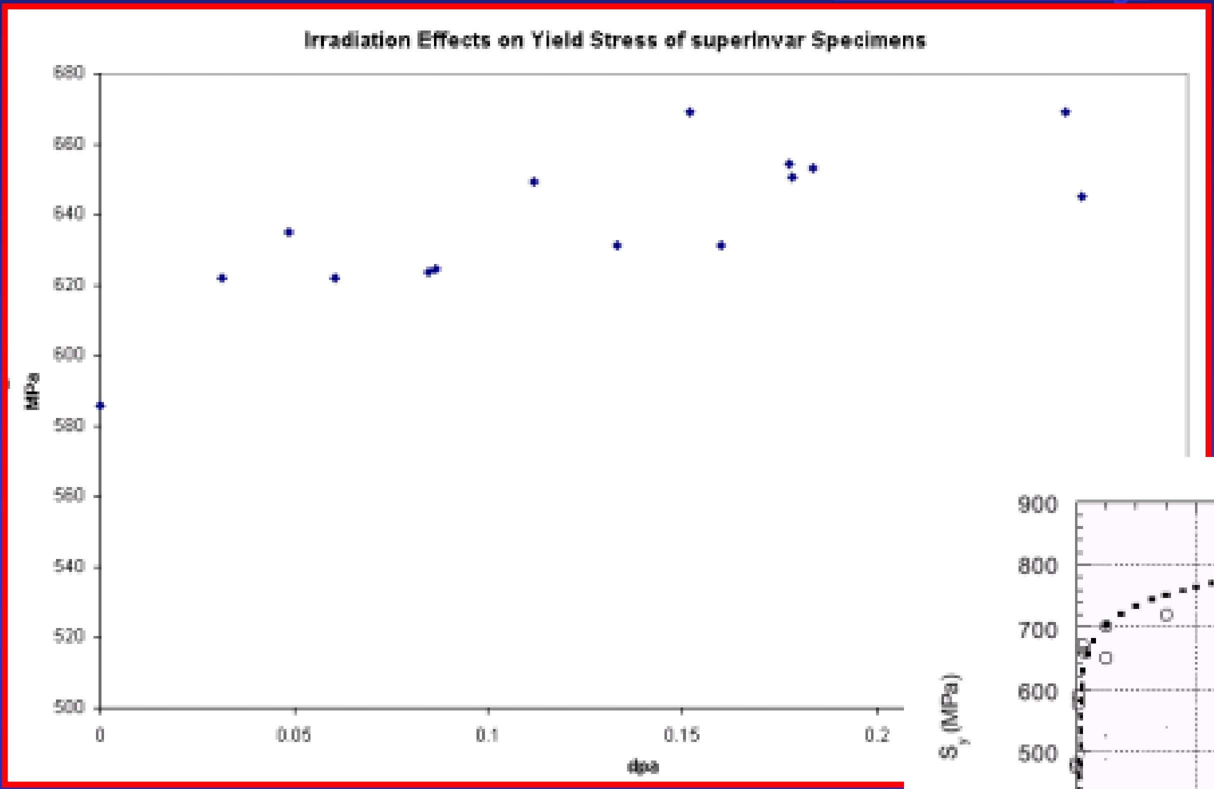


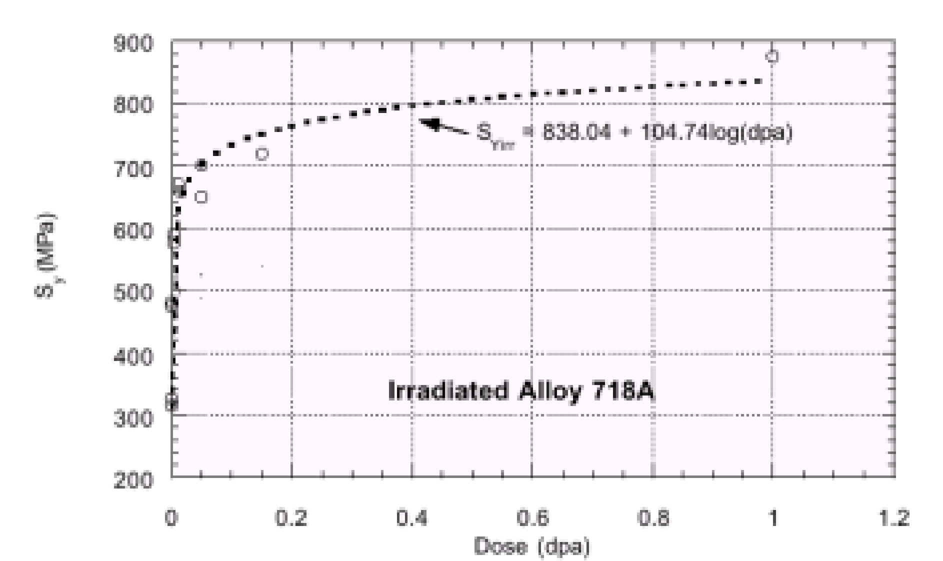
Effect of irradiation in HFIR on the room-temperature yield strength of Alloy 718A

WHY STUDY super Invar ?

- **High-Z with low CTE (0-150 ºC)**
- **How is CTE affected by radiation?**
- **What happens to other important properties?**

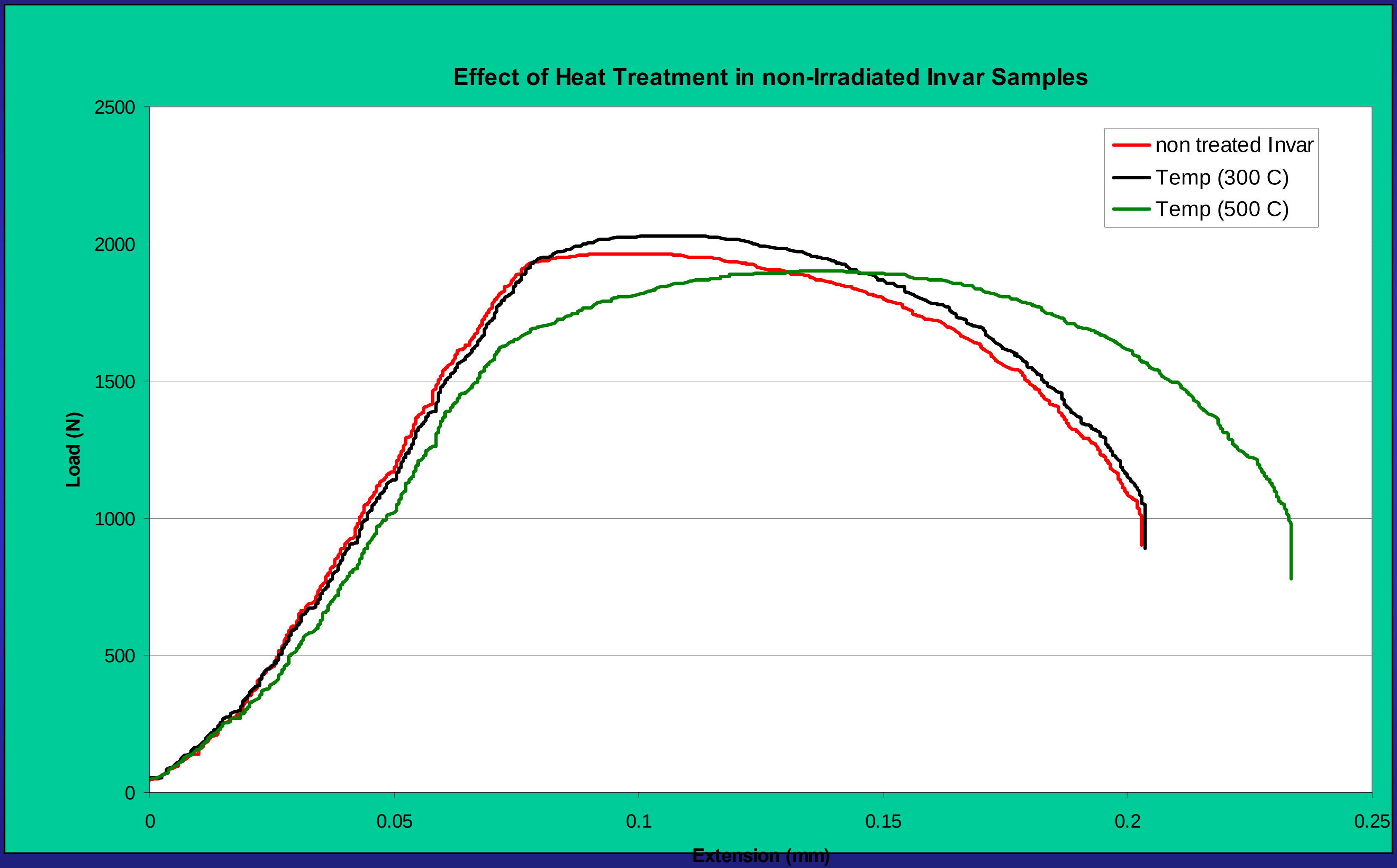
Solid Target Option: Super-Invar Irradiation Study



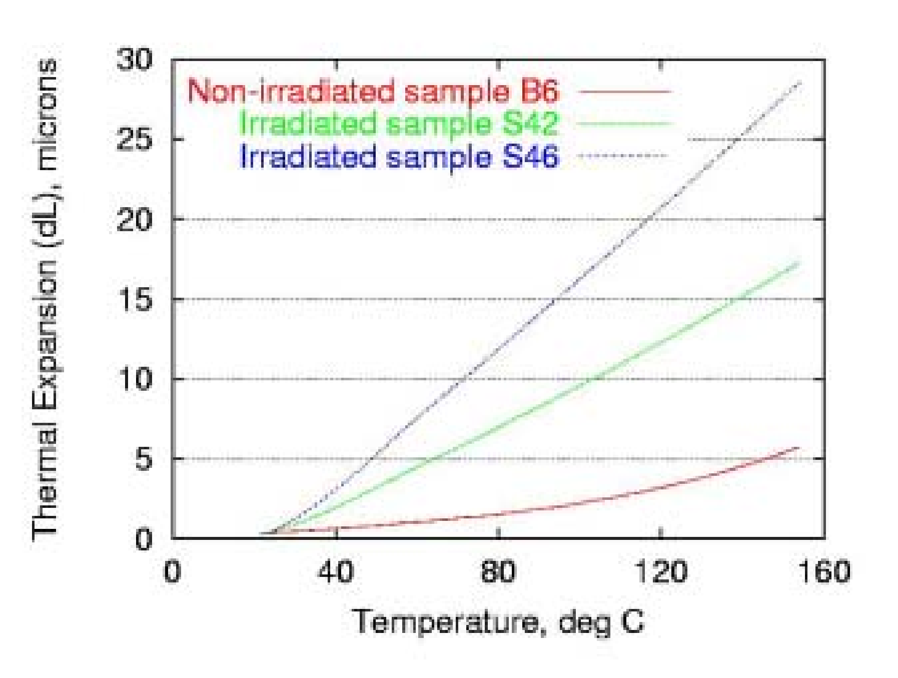


Effect of irradiation in HFIR on the room-temperature yield strength of Alloy 718A

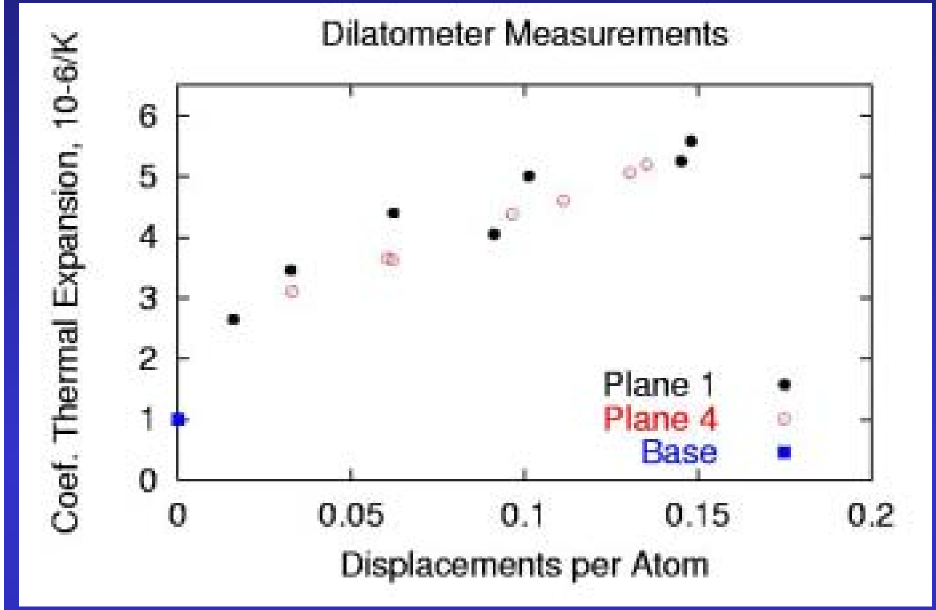
Super-Invar Irradiation Study – Temperature Effects

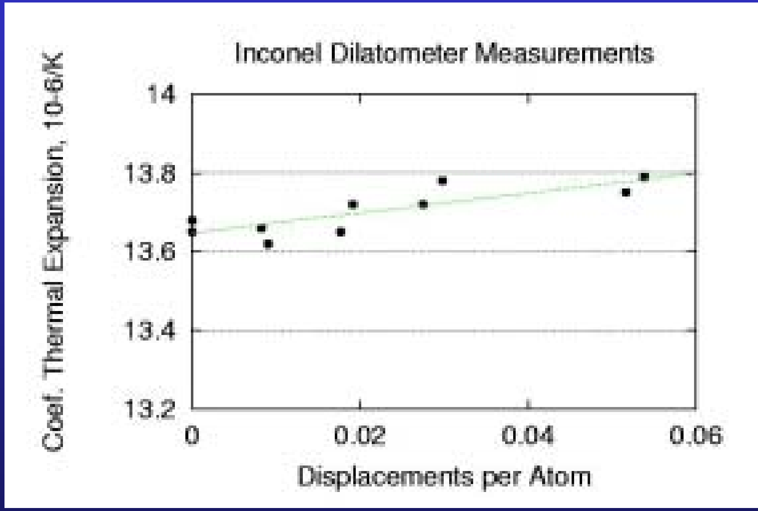


Super-Invar Irradiation Study – CTE assessment



Super-Invar





Inconel 718

WHAT'S NEXT ?

- Assessment of long-term survival of baseline target & horn materials (Aluminum & Carbon-Carbon)
- Repeat irradiation/mechanical property changes experiment for baseline materials
- Experimentally verify the compatibility of cooling agents with baseline materials (corrosion, sublimation)
- Explore innovative schemes to enhance heat transfer and material protection (nano-structured films, nano-fluids, etc.)
- Explore new materials such as AlBeMet, Toyota's "Gum Metal" Titanium Alloy, Vascomax, Titanium (6Al-6Va)
- Explore the possibility of using He for heat removal for the integrated target/horn system

What are some of these new materials we plan to examine ?

AlBeMet®

<u>AM162</u>

- By weight, contains 62% commercially pure beryllium and 38% commercially pure aluminum
- By Metallurgical definition, AlBeMet® is an alloy but can be considered a composite
- AlBeMet® sheet, plate and bar are powder metallurgy products
  - The powder is produced by a gas atomization process which yields spherical powder with a fine beryllium structure
  - The powder is densified by three consolidation processes, each resulting in different mechanical properties, while maintaining AlBeMet's unique physical properties.

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)	225 (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 (.895)	.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