MATERIAL R&D FOR HIGH-INTENSITY PROTON BEAM TARGETS

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BACKGROUND

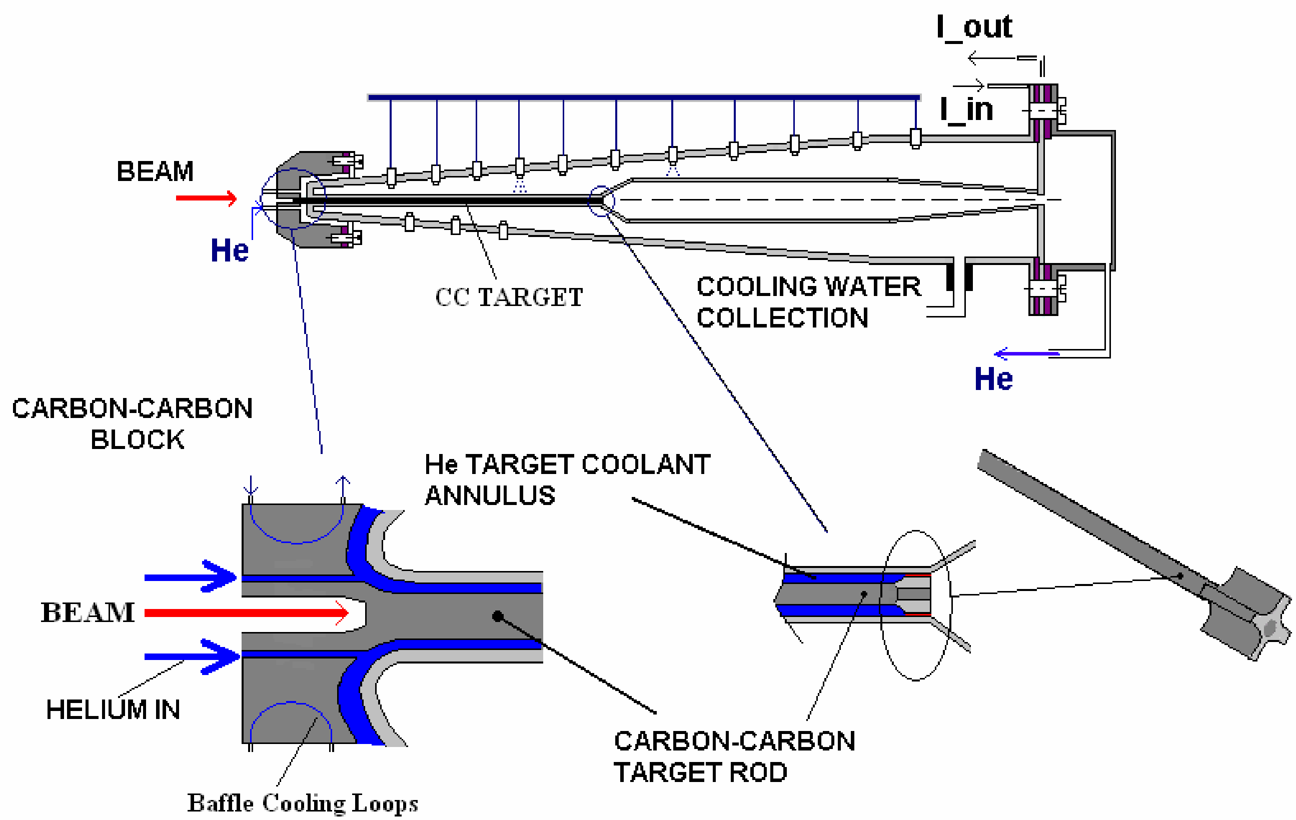
•**All studies suggest that, to push frontier in proton drivers to an order higher than the existing ones, one must maximize the yield at the source**

•**Proton drivers with beam power up to 4 MW could become reality**

•**Challenge in finding suitable target material/configurations that will withstand intense heating, shock waves and radiation damage**

•**Experience suggests that without R&D surprises are not far behind**

Neutrino SuperBeam, an example where R&D is a MUST



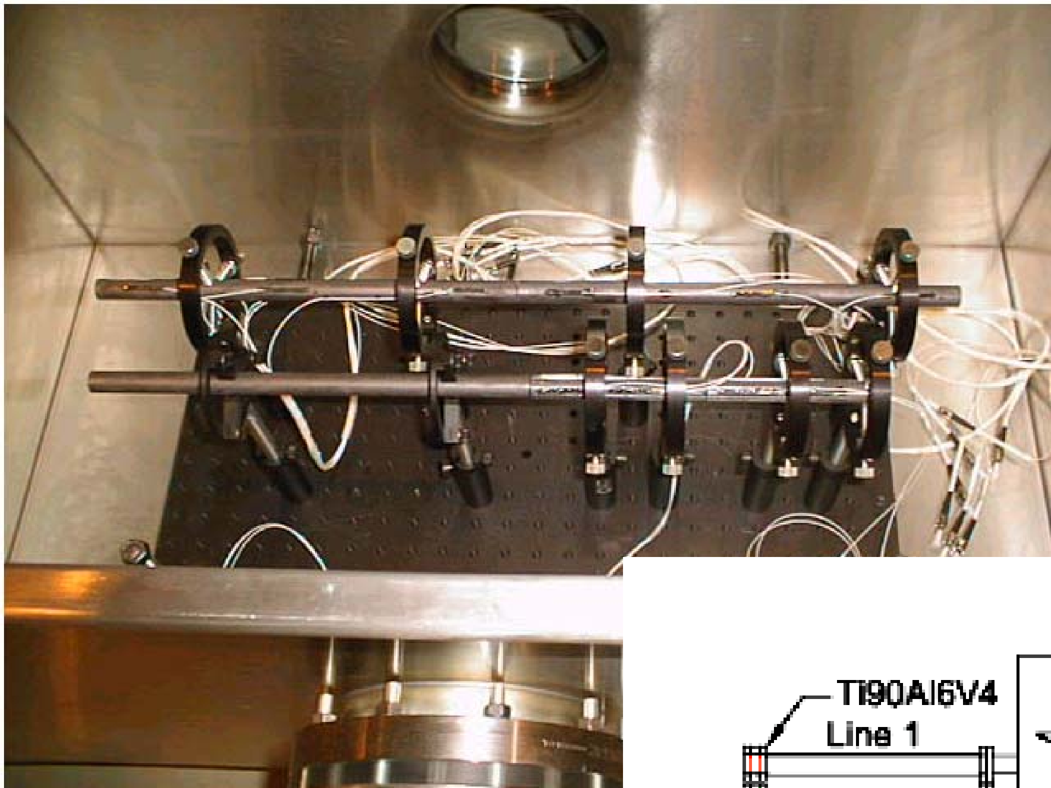
GOALS

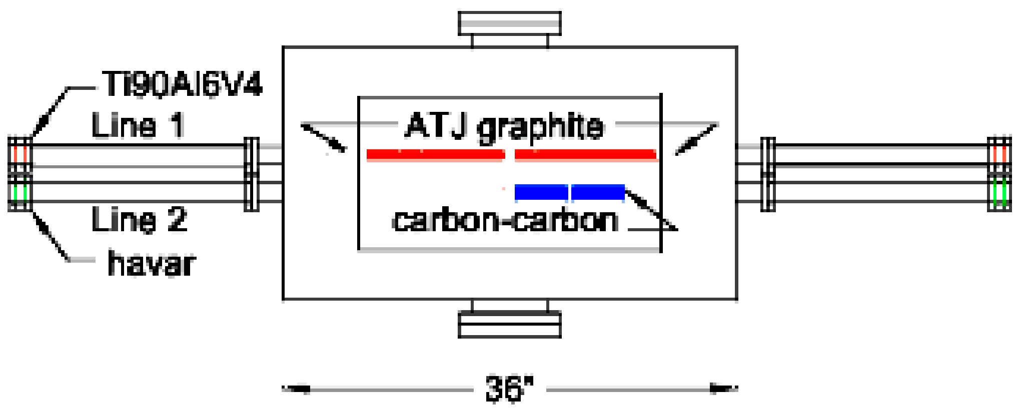
- **Find best possible materials that can be used as accelerator targets under extreme conditions**
- **ONLY experimentation with such materials can ensure longevity**
  - **Irradiation effects on physical & mechanical properties**
    - **Materials are known to lose conductivity in excess of 90% !!!**
  - **Resistance to shock**
- **Validate prediction models against measurements to gain confidence in predicting material response and/or failure at anticipated extreme conditions**
- **USE experimental results to benchmark energy depositions predicted by tMonte Carlo codes**

TARGET CONCEPTS UNDER CONSIDERATION

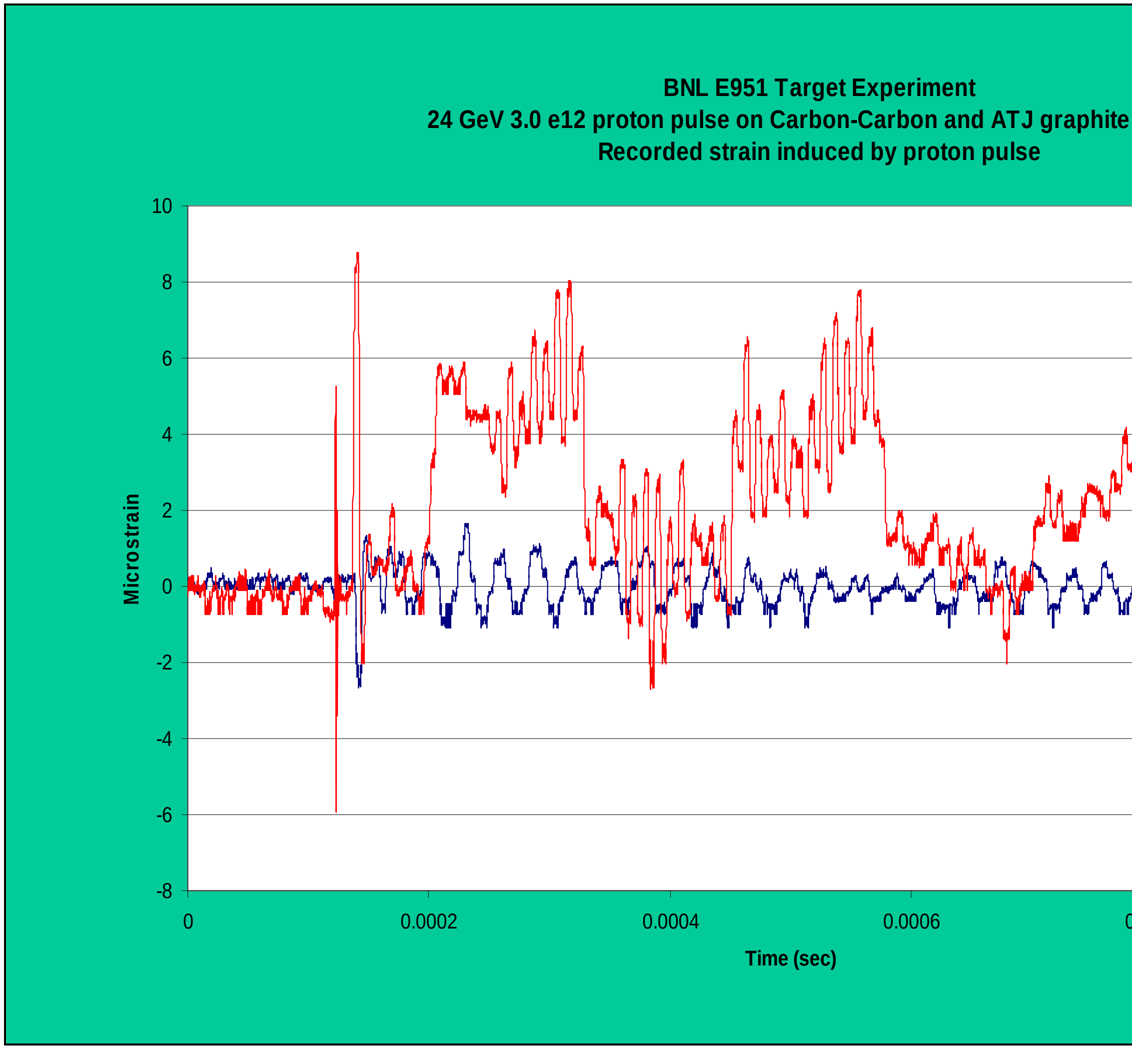
- Solid Targets for Muon Collider/Neutrino Factory
  - Graphite, CC composite
- Target-like (beam windows) for Muon Collider/Neutrino Factory
  - Host of materials that expect to see same beam (Inconel, Havar, Ti_alloy, etc)
- Solid Targets for the Neutrino Superbeam
  - CC composite, Graphite, AlBeMet, Gum Metal
- Targets for Pulsed Neutron Sources (iridium)

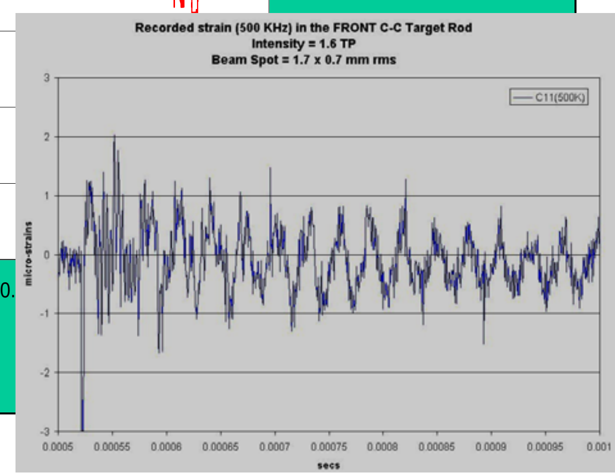
Experimentation with Graphite & CC Targets (BNL E951)



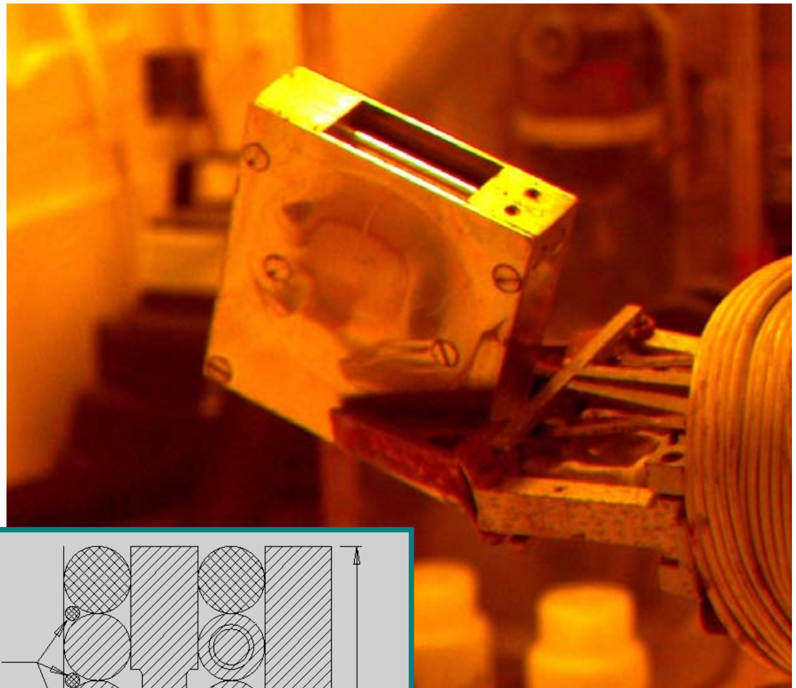


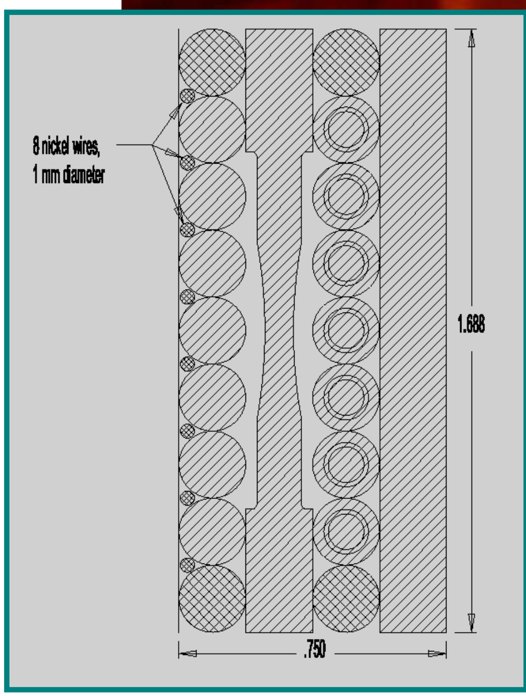
Graphite vs. Carbon-Carbon – A Clear Choice ….. really?

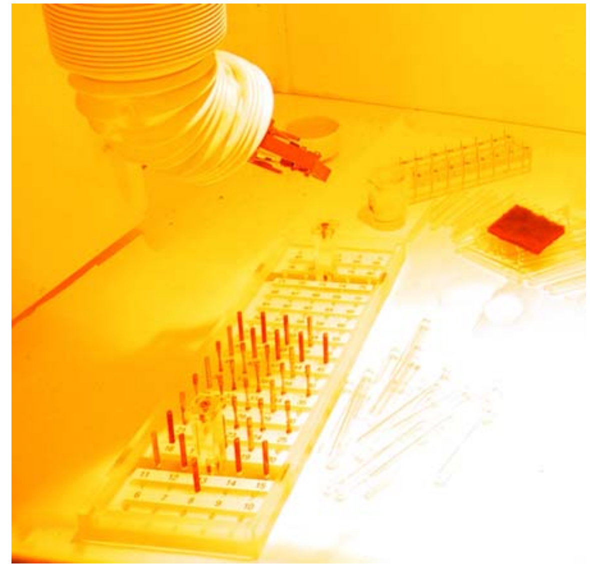


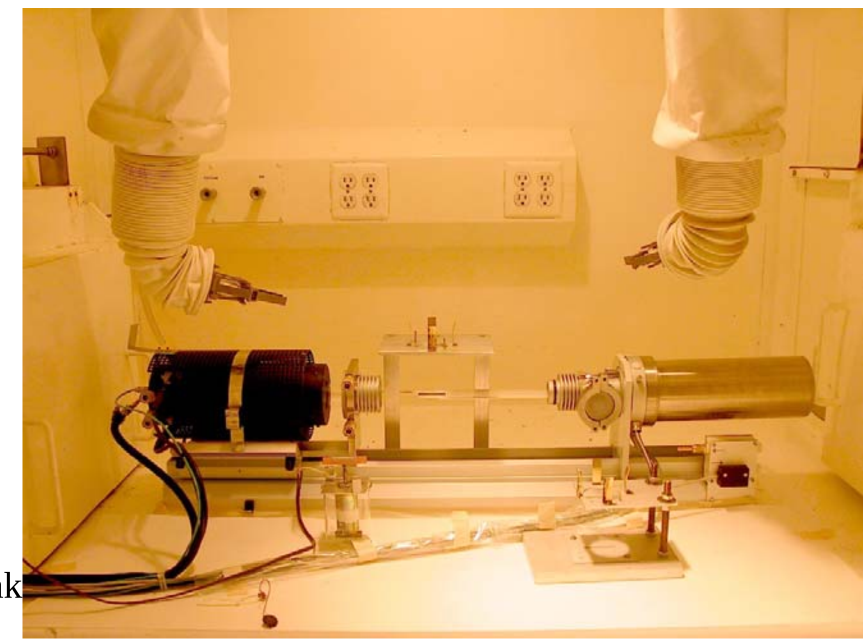


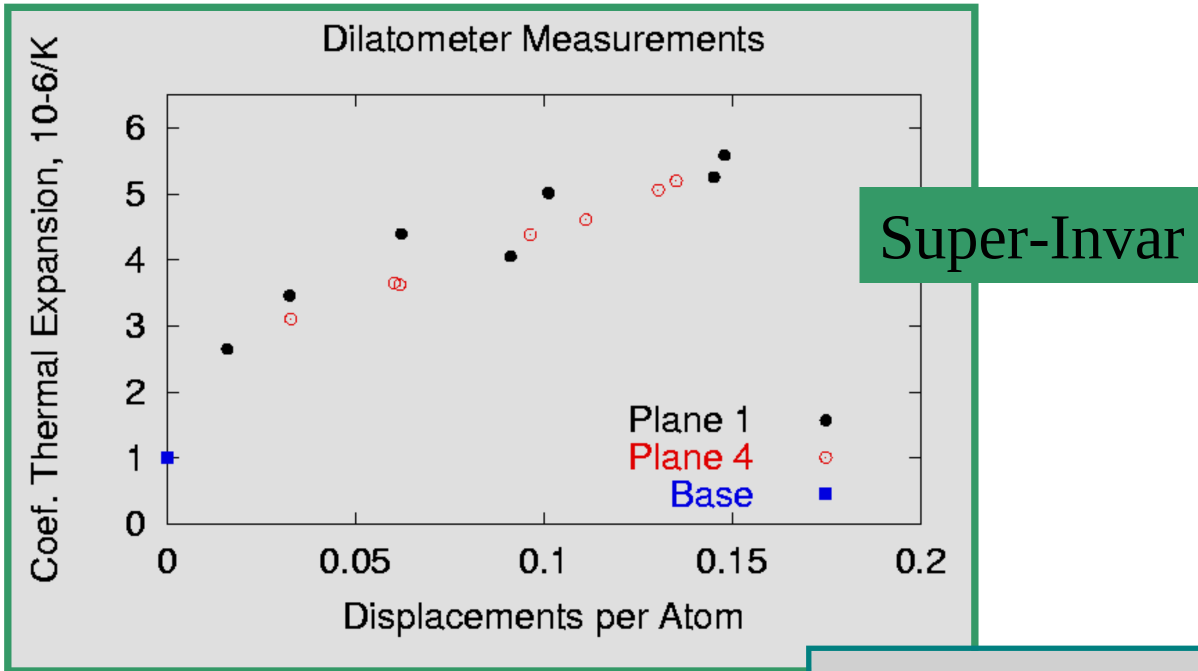
PHASE I of BNL Irradiation Studies

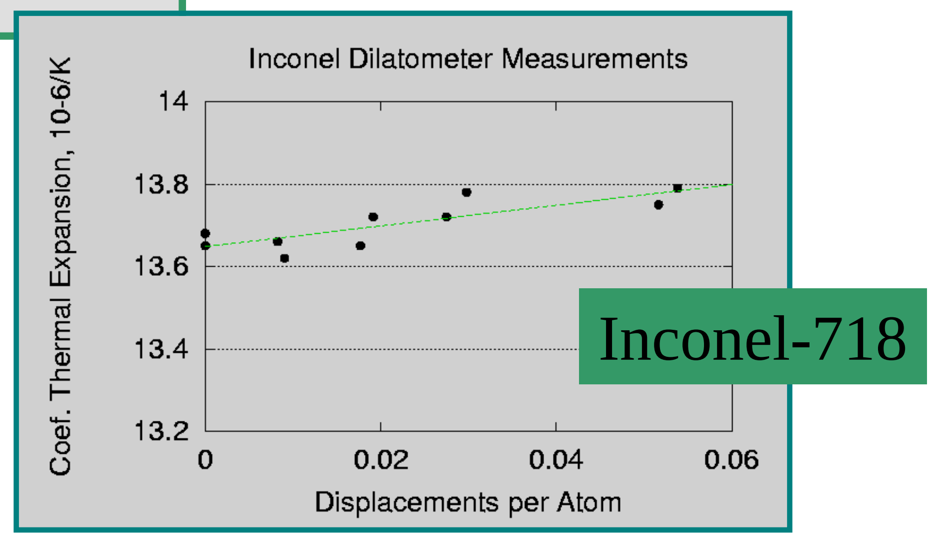


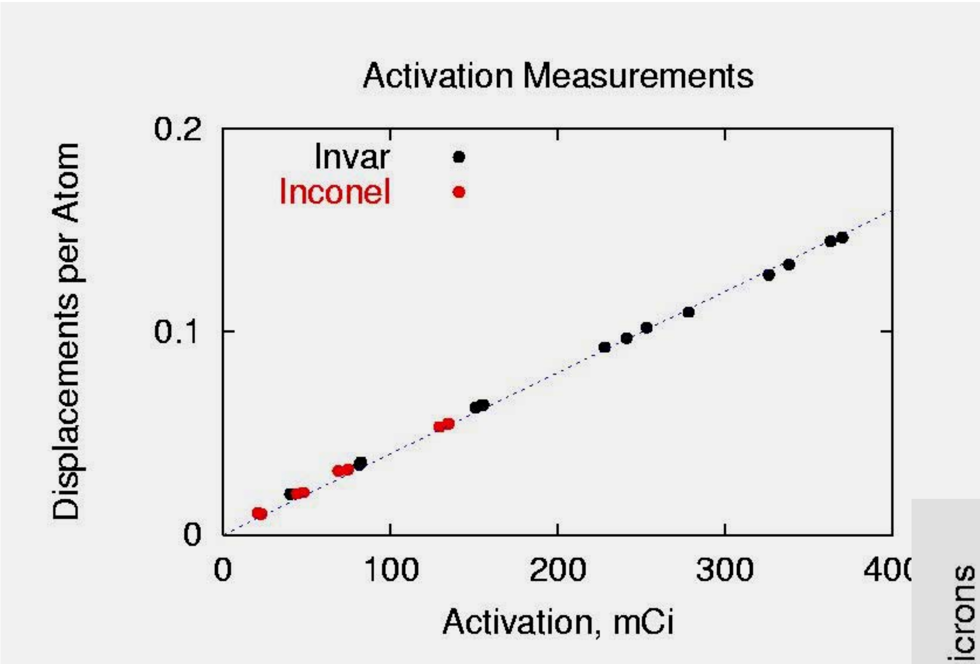


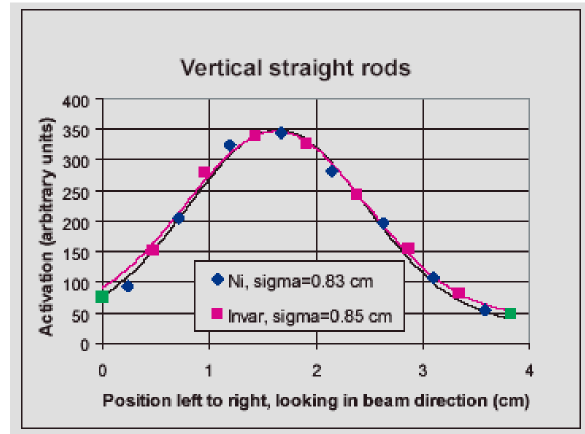


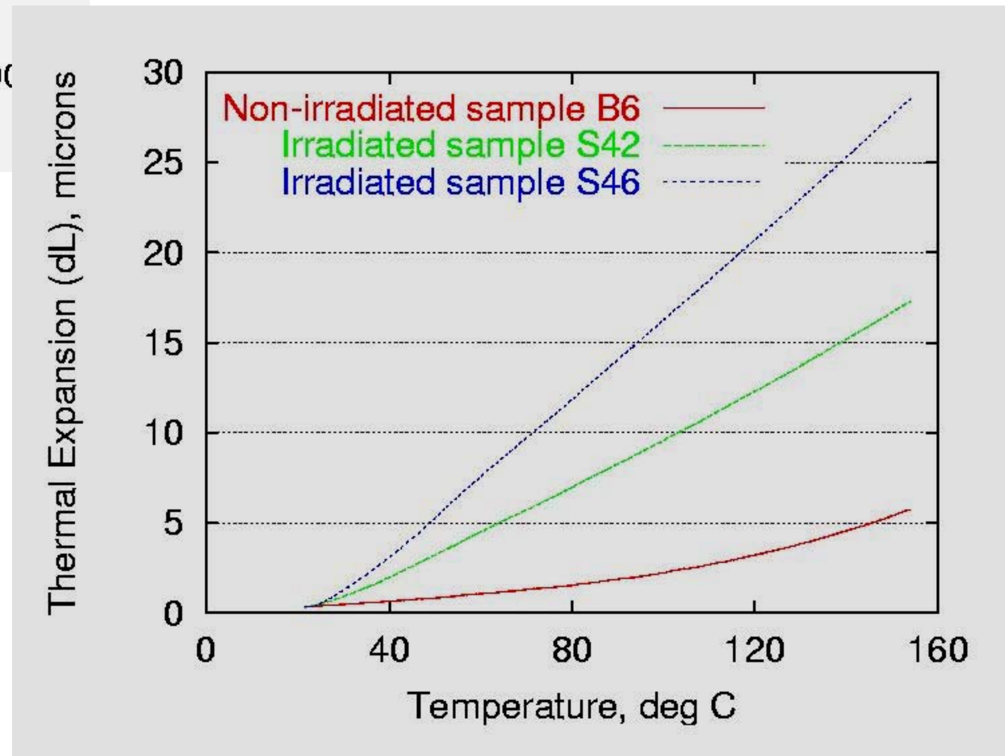


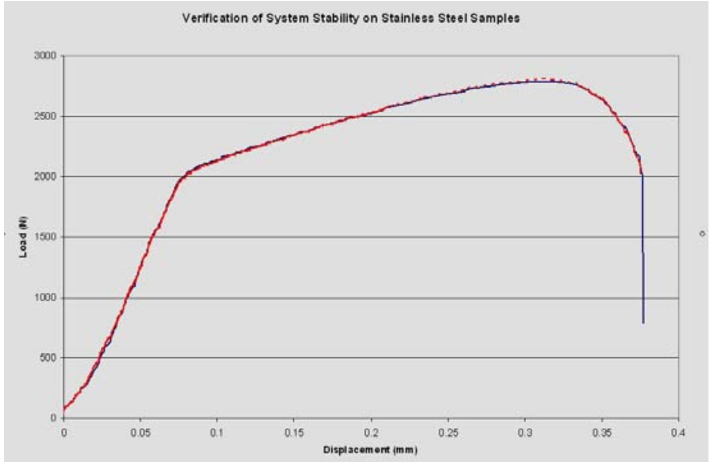

Dilatometer Measurements
Coef. Thermal Expansion, 10-6/K
Displacements per Atom
0
1
2
3
4
5
6
0
0.05
0.1
0.15
0.2
Plane 1
Plane 4
Base
Super-Invar

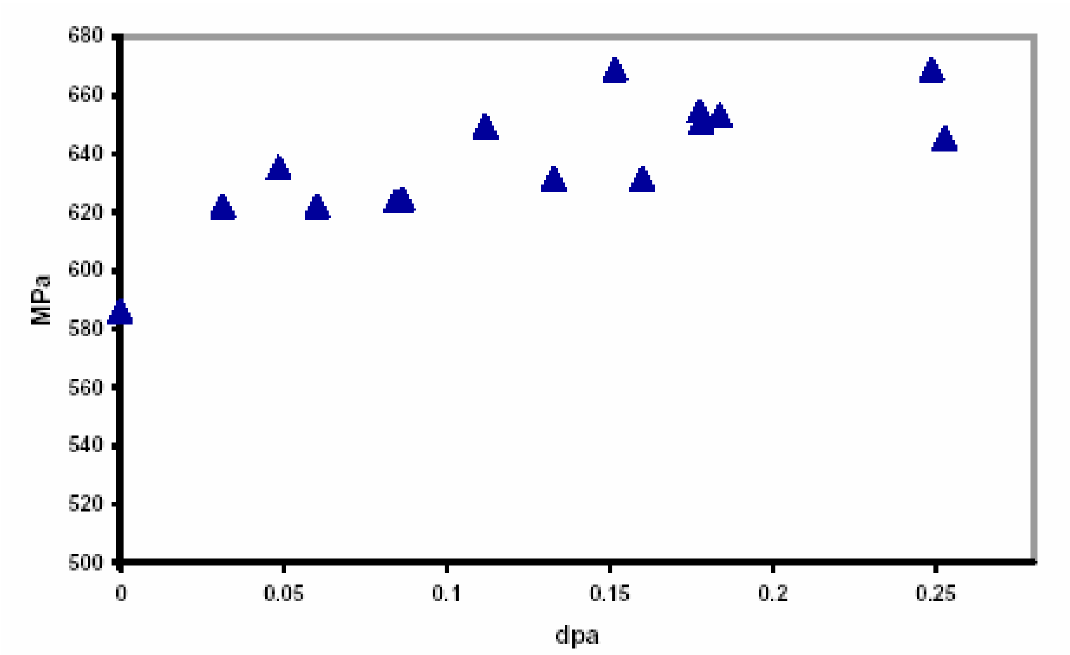

Inconel Dilatometer Measurements
Coef. Thermal Expansion, 10-6/K
Displacements per Atom
13.2
13.4
13.6
13.8
14
0
0.02
0.04
0.06
Inconel-718

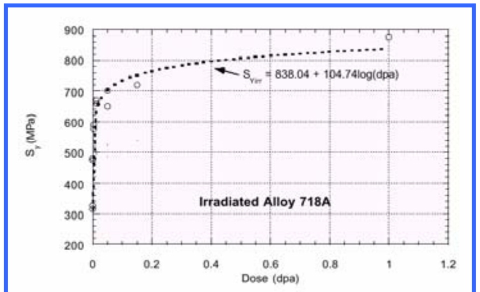

Activation Measurements
Invar
Inconel
Displacements per Atom
0.2
0.1
0
0
100
200
300
400
Activation, mCi


Vertical straight rods
Activation (arbitrary units)
400
350
300
250
200
150
100
50
0
0
1
2
3
4
Ni, sigma=0.83 cm
Invar, sigma=0.85 cm
Position left to right, looking in beam direction (cm)


Non-irradiated sample B6
Irradiated sample S42
Irradiated sample S46
Thermal Expansion (dL), microns
30
25
20
15
10
5
0
0
40
80
120
160
Temperature, deg C

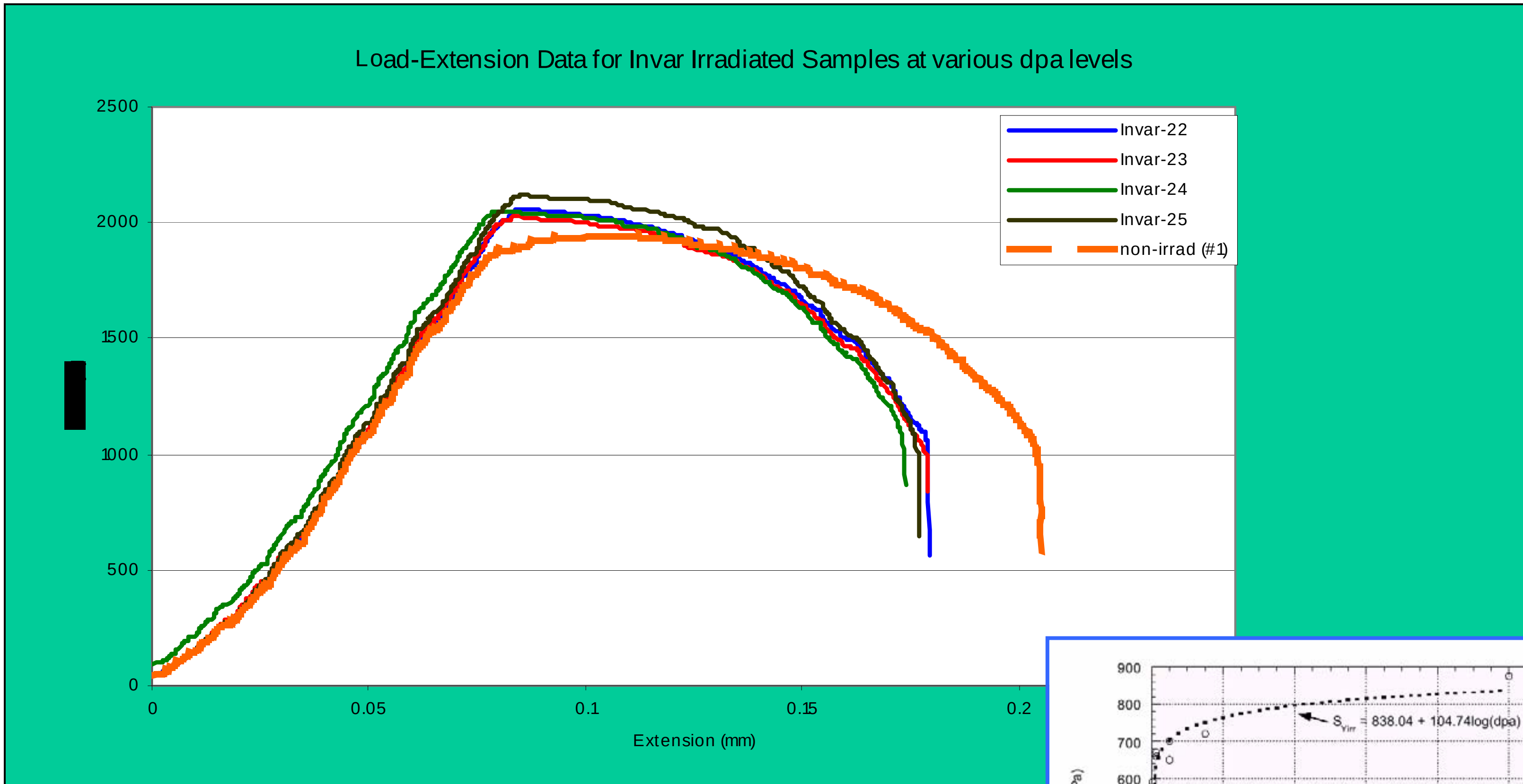


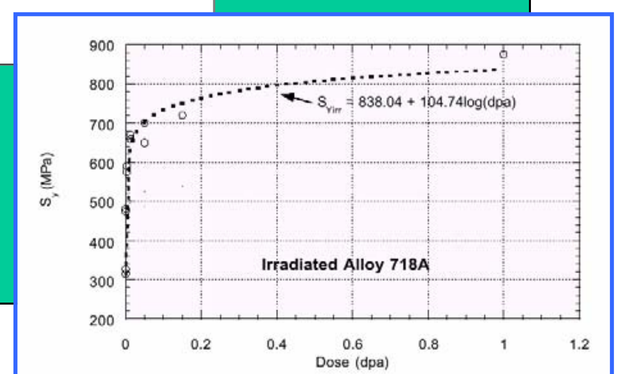




Effect of irradiation in HFIR on the room-temperature yield strength of Alloy 718A

Solid Target Option: Super-Invar Irradiation Study



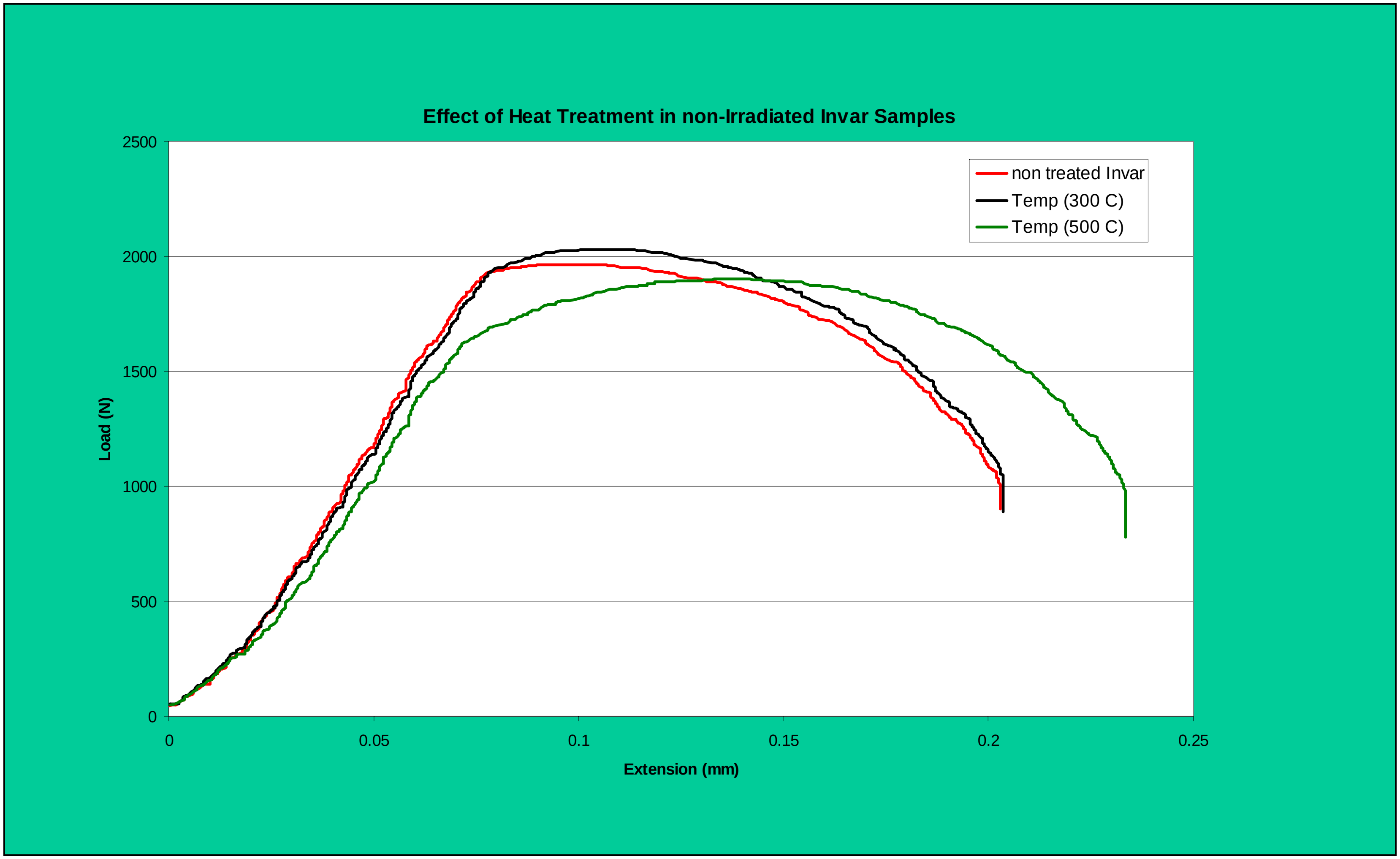


Effect of irradiation in HFIR on the room-temperature yield strength of Alloy 718A

WHY STUDY super Invar ?

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

Super-Invar Irradiation Study – Temperature Effects



LESSON LEARNED FROM PHASE I

Attractive properties of some wonder materials may be thrown out the window very quickly once on line

Do not give up … There are more "wonder" materials out there.

And that brings us to PHASE II …………………………..

PHASE II -TARGET MATERIAL R&D

- **Carbon-Carbon Composite (BNL)**
- **Toyota "Gum Metal" (KEK)**
- **Graphite (IG-43) (KEK)**
- **AlBeMet (BNL)**
- **Beryllium (BNL)**
- **Ti Alloy (6Al-4V) (SLAC)**
- **Vascomax (BNL)**
- **Nickel-Plated Alum. (BNL-FNAL-KEK)**

WHAT IS OF INTEREST TO US IN POST-IRRADIATION PHASE

Resilience in terms of strength/shock absorption

- CTE evaluation
- Stress-strain
- Fatigue
- Fracture Toughness and crack development/propagation

•Corrosion Resistance

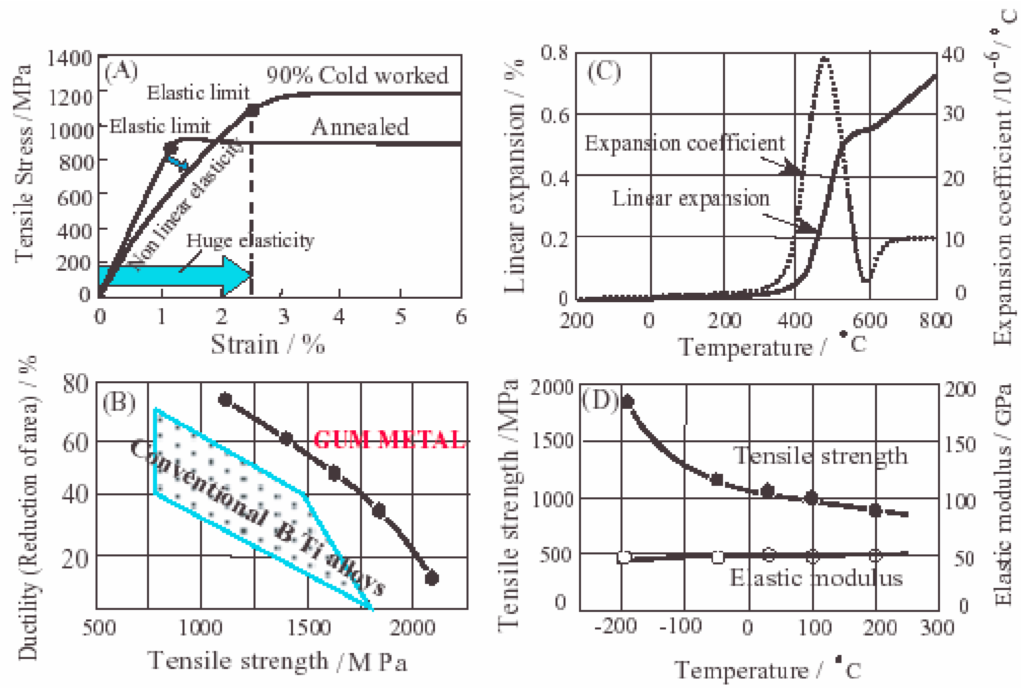
•De-lamination (if a composite such as CC or plated HORN conductor) – Use of ultrasonic technology to assess changes

•Degradation of conductivity

All of the above can/will be done in Hot Cell.

Other tests are also in the planning for scrutiny of the successful candidates (laser induced shock and property measurements)

WHY "GUM" Metal, Vascomax, or AlBeMet ?



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TECHNICAL DATA SHEET

VASCOMAX® C-200/C-250/C-300/C-350

Nominal Mechanical Properties of Small Diameter Bars Following Aging Heat Treatment
Figure 1

	VascoMax C-200	VascoMax C-250	VascoMax C-300	VascoMax C-350
Ultimate Tensile Strength, psi	210,000	260,000	294,000	350,000
0.2% Yield, psi	206,000	255,000	290,000	340,000
Elongation, %	12	11	11	7
Reduction of Area, %	62	58	57	35
Notch Tensile (K_t= 9.0), psi	325,000	380,000	420,000	330,000
Charpy V-Notch, ft-lb	36	20	17	10
Fatigue Endurance Limit (10^6 Cycles), psi	110,000	110,000	125,000	110,000
Rockwell "C" Hardness	43/48	48/52	50/55	55/60
Compressive Yield Strength, psi	213,000	280,000	317,000	388,000

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 (206)	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 (206)	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 (96)	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 (.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

PHASE-II TARGET MATERIAL STUDY

WHAT'S DIFFERENT FROM PHASE-I?

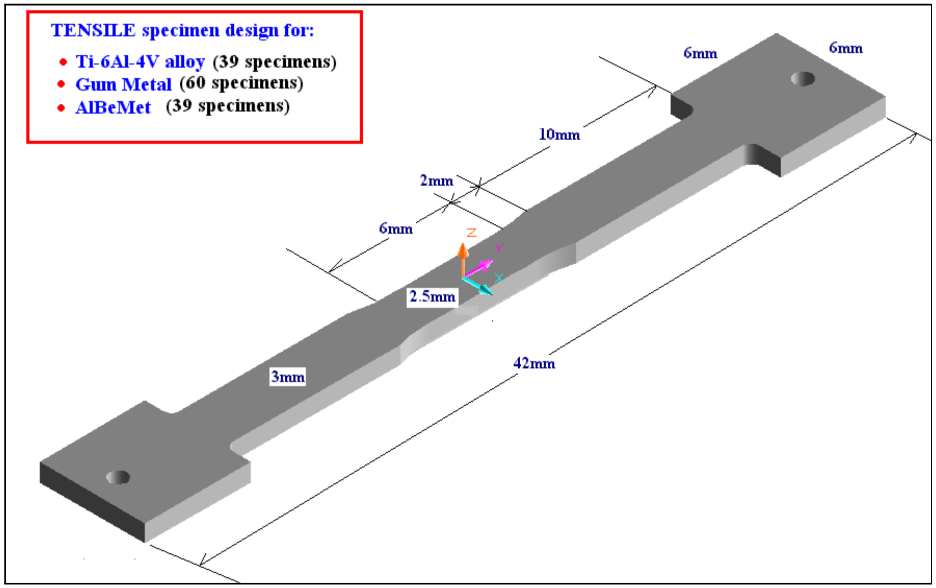
~ 100 MeV of Proton Beam (200 to 100 MeV)

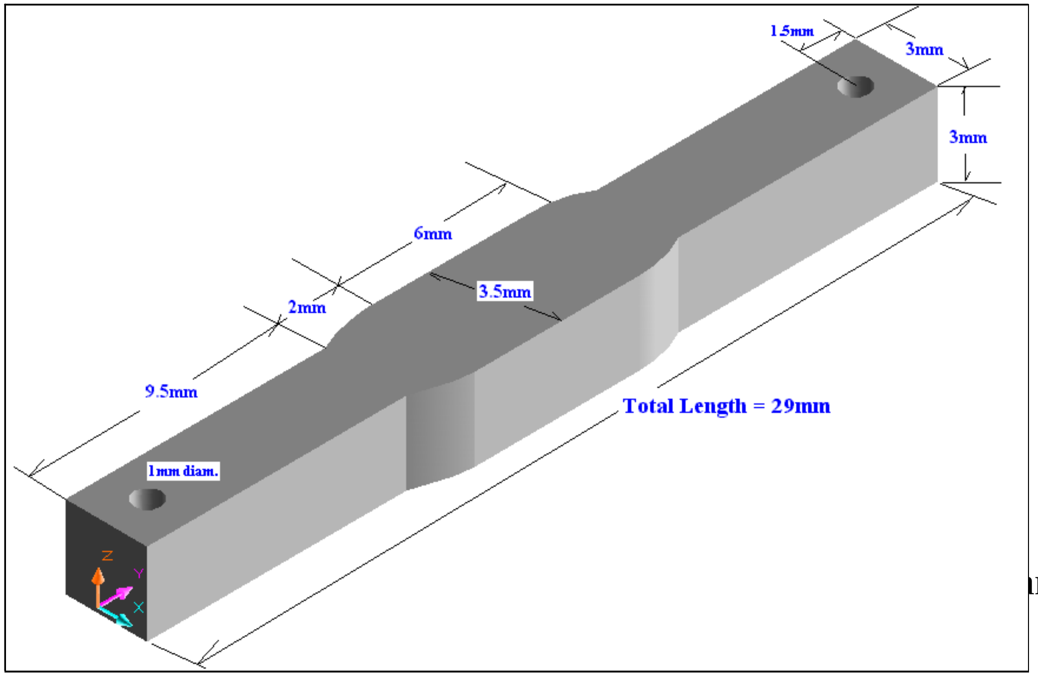
Challenge of inducing UNIFORM Beam degradation

MORE Material to go in (optimization of dE/dx for range 200 MeV-100 MeV)

OPEN Issue: Study of Fracture Toughness for some materials ?
ORIGINAL THOUGHT was YES
dE/dx budget pushed it to next round

Tensile and CTE Specimen Design





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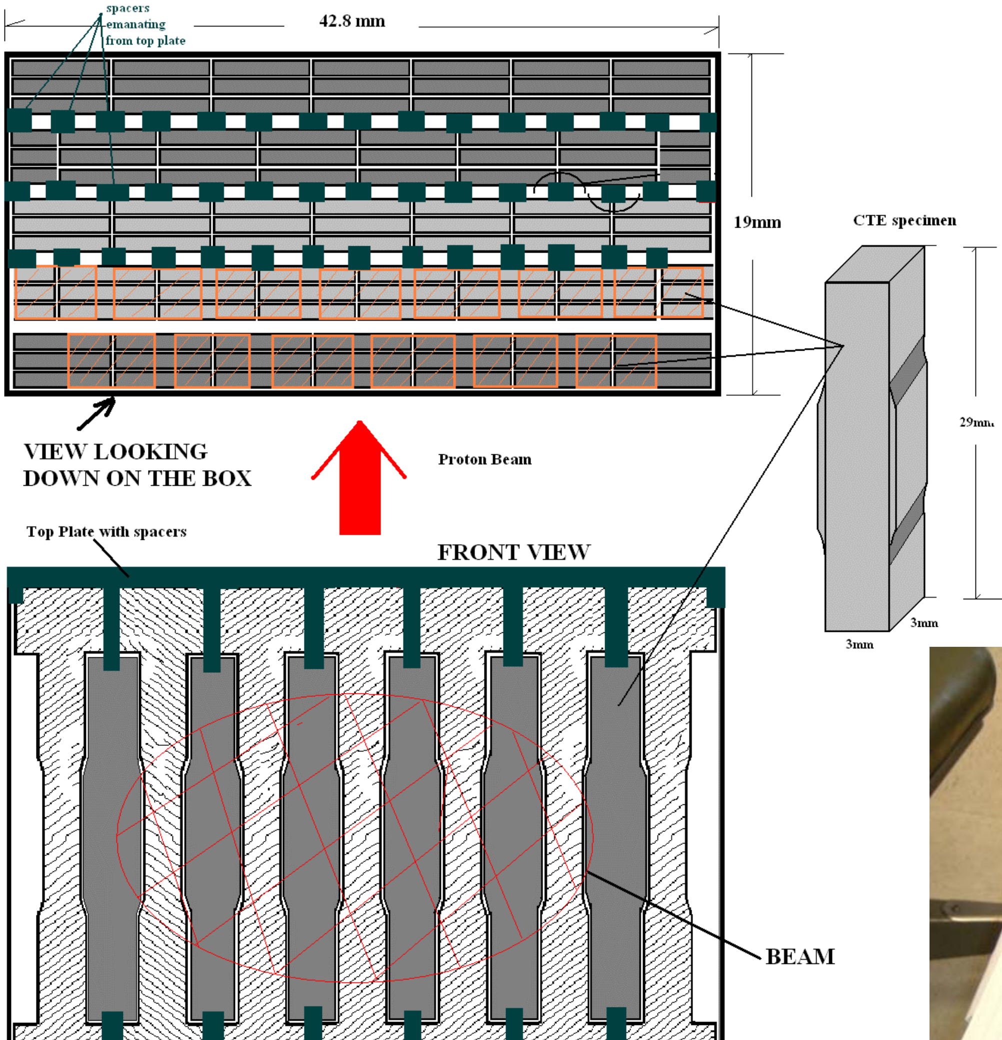
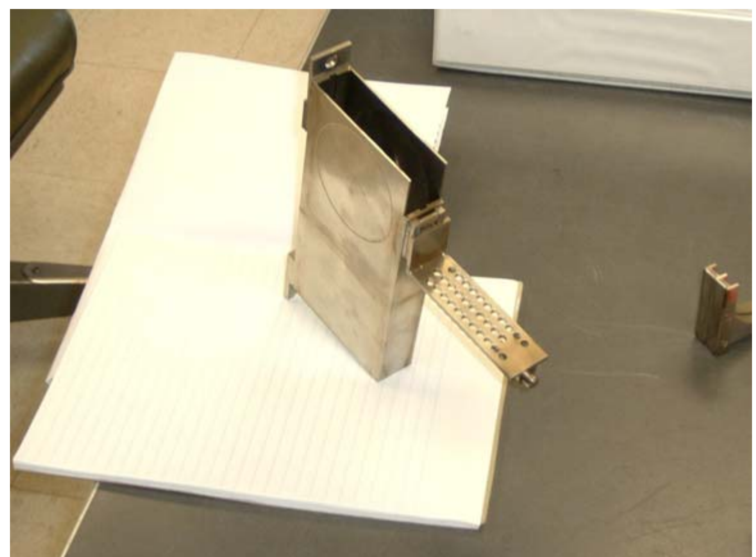
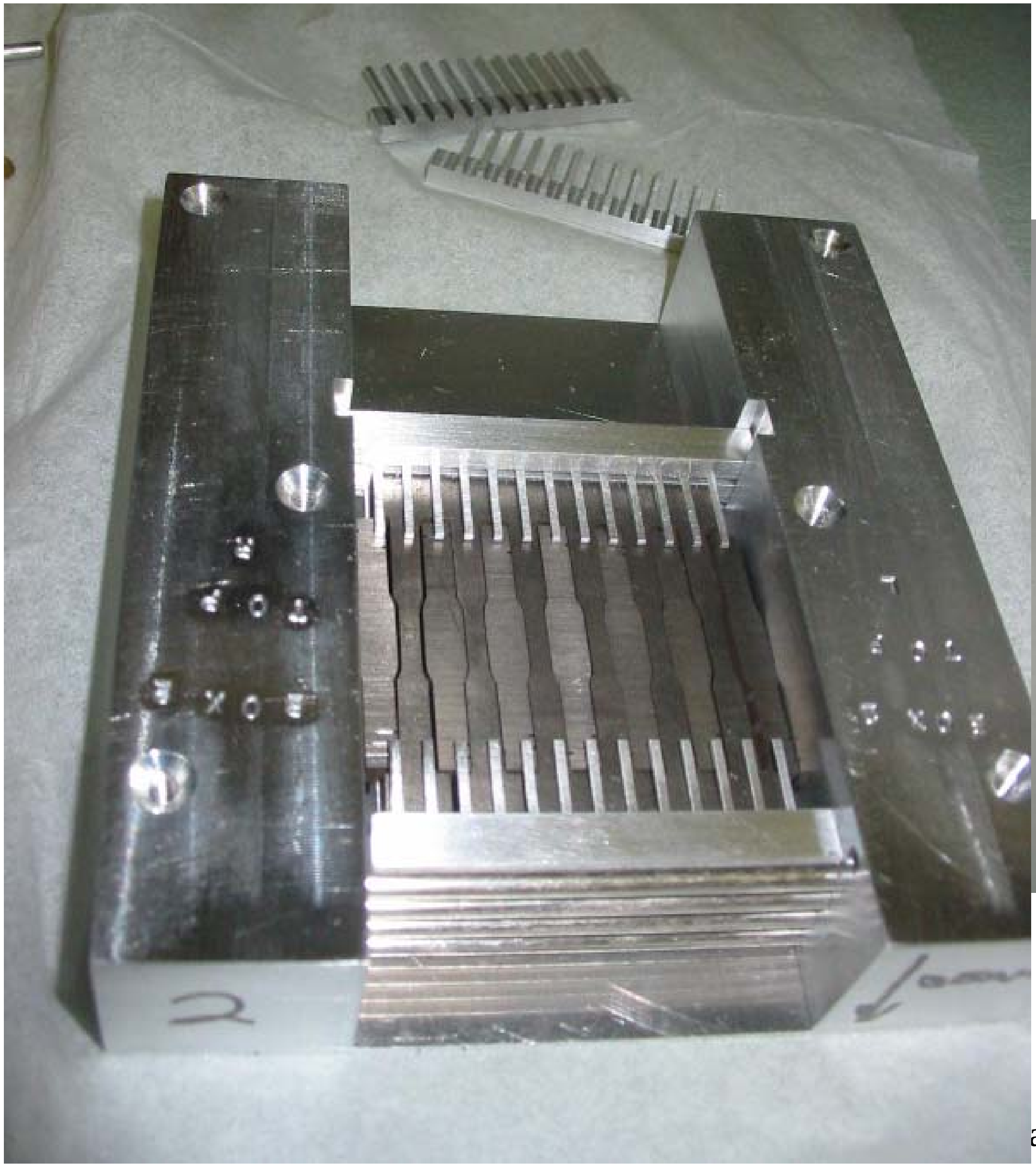
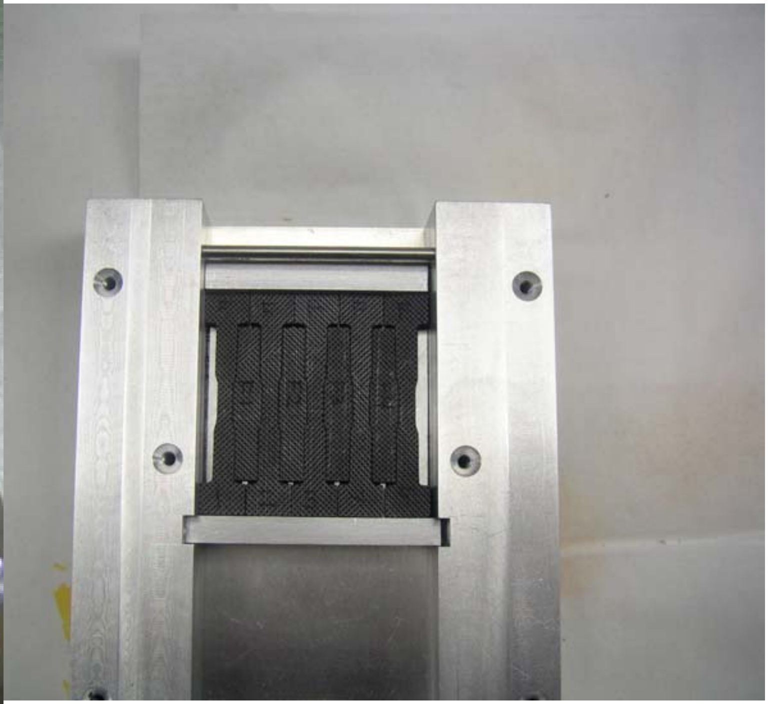
Tensile and CTE Specimen Assembly into the Target Box During Irradiation





TARGET BOX ASSEMBLY DETAILS





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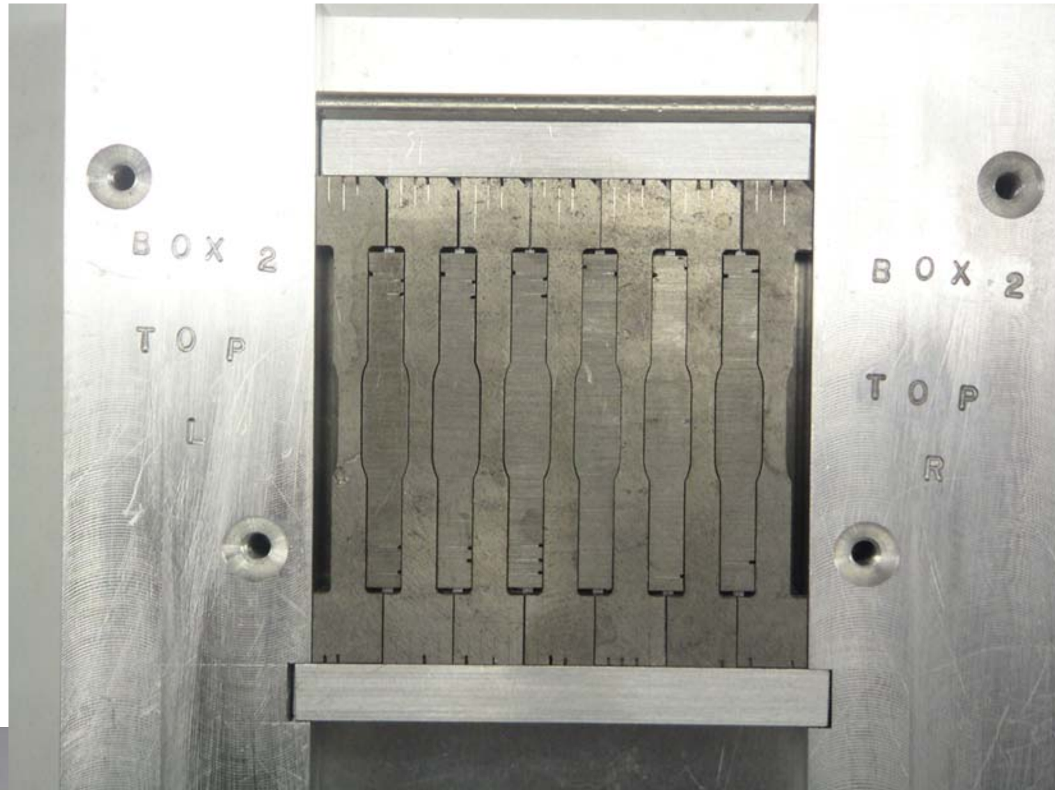
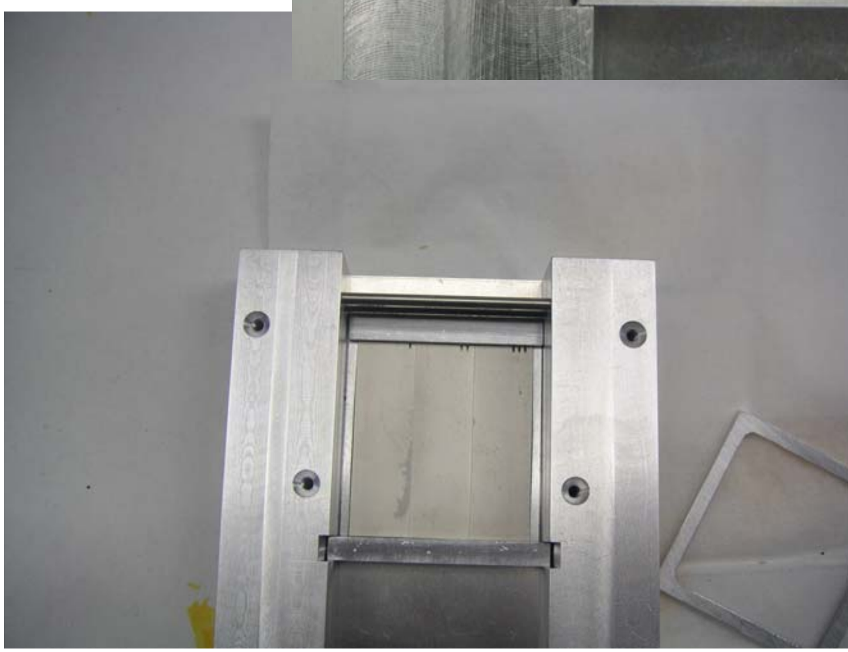
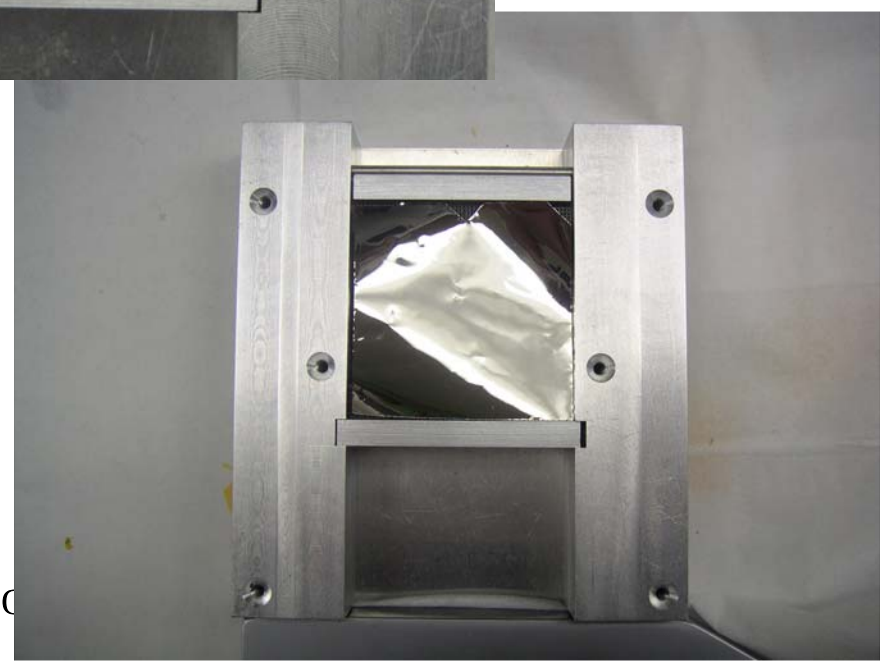
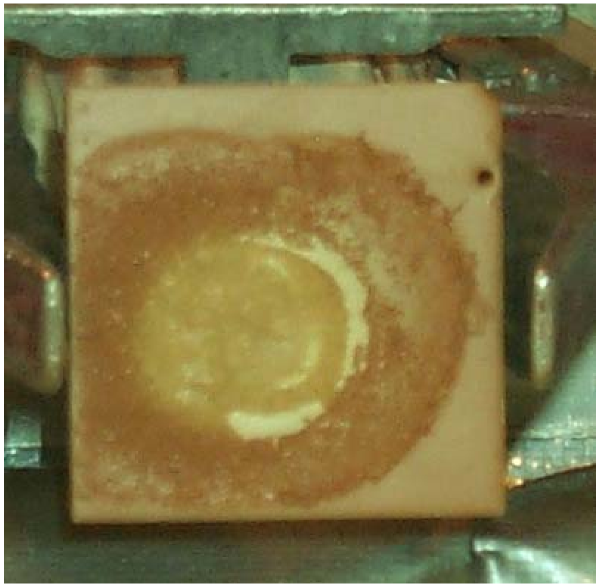
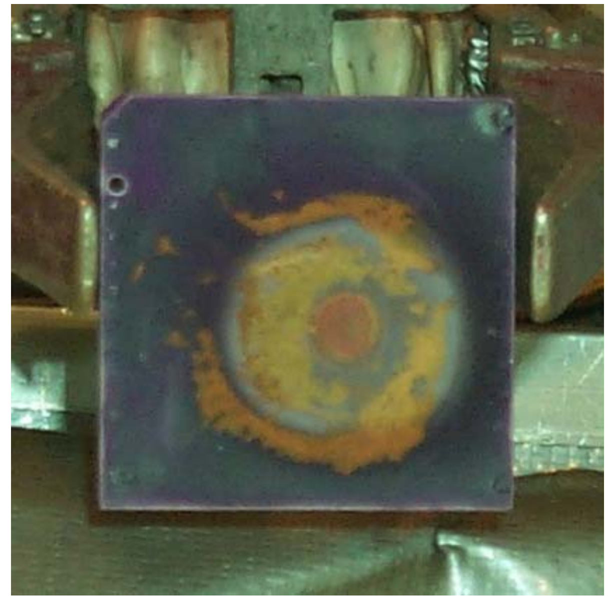

BOX 2
TOP
L
BOX 2
TOP
R

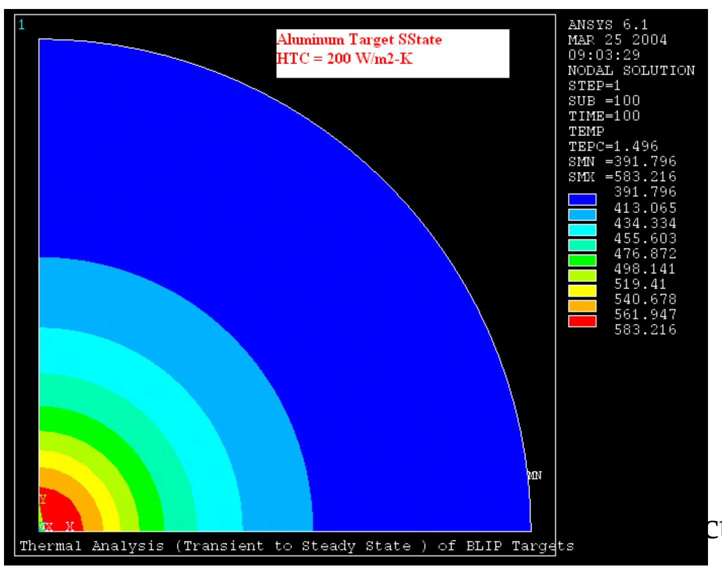


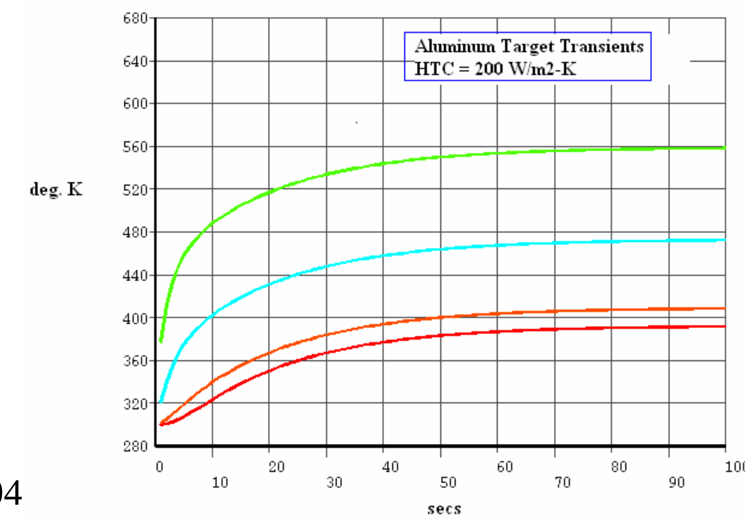


Actual TEST on Estimating Irradiation Temperature
Aluminum Plate

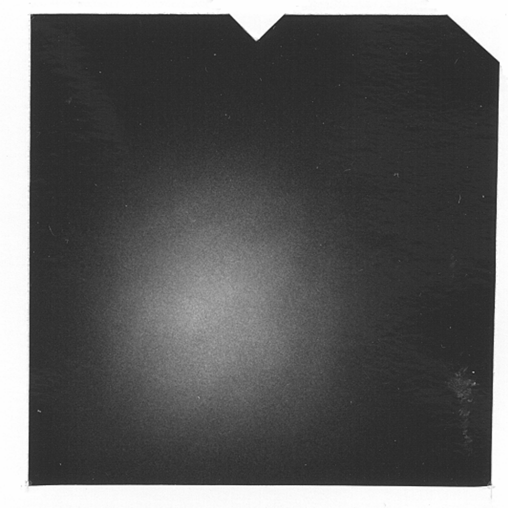


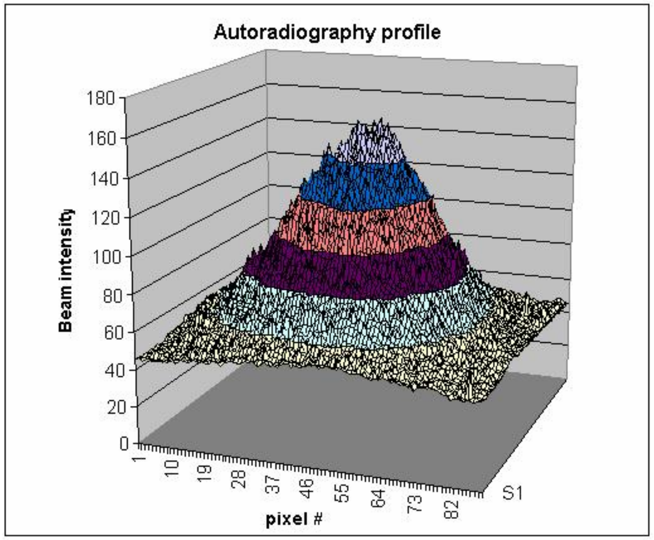


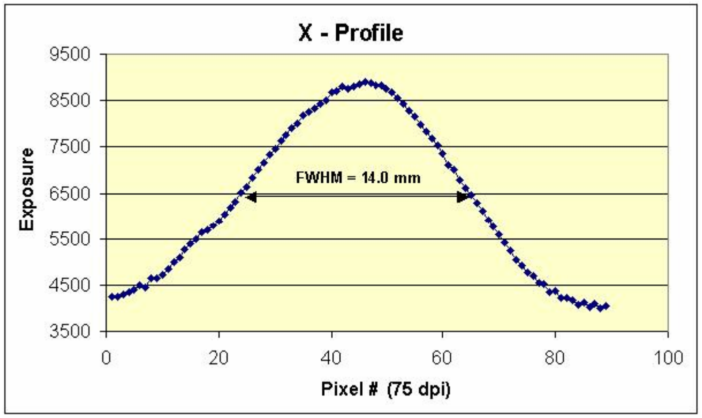


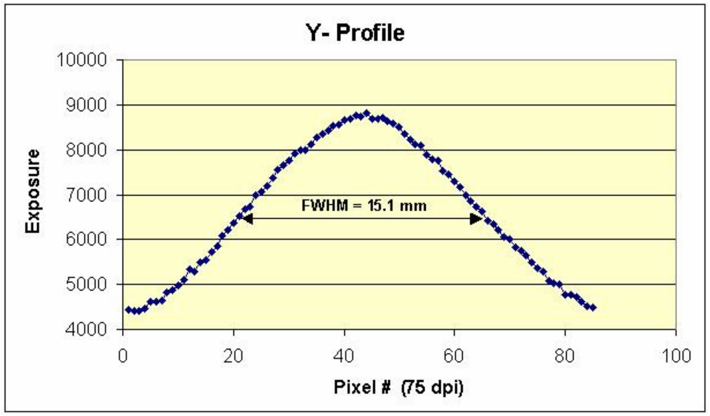


Activation Measurements

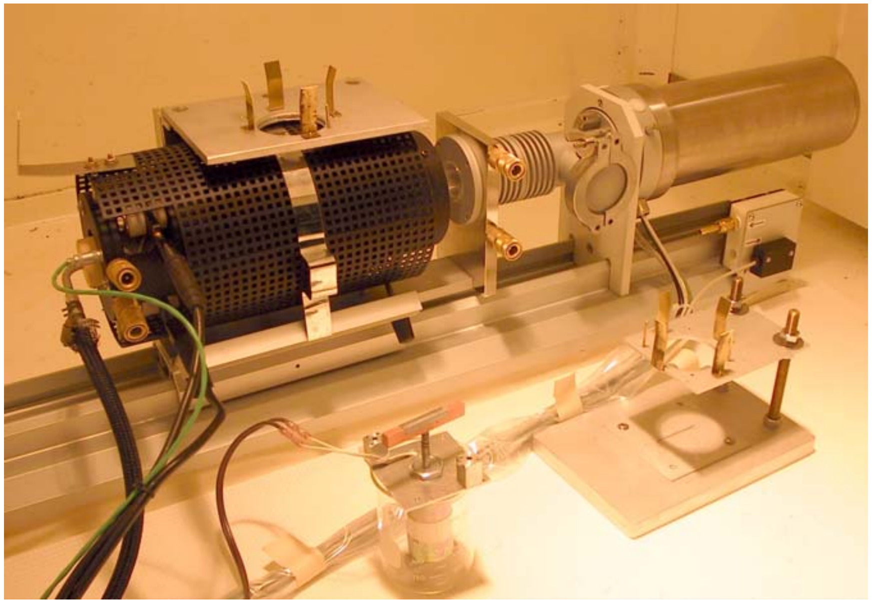


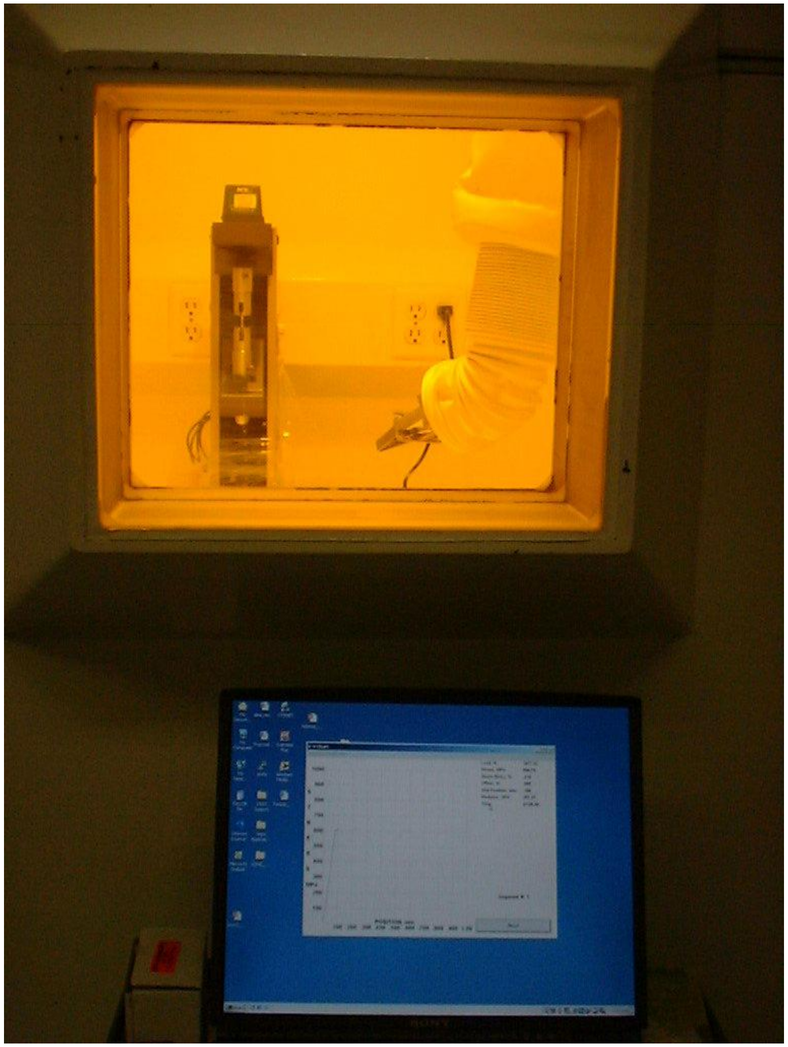






HOT CELL Specimen Analysis





STATUS OF IRRADIATION EXPERIMENT

IRRADIATION PHASE COMPLETED SUCCESSFULLY on March 22nd

2-week irradiation of samples on 200 MeV beam with average current ~ 80 μA

Irradiation exposure expected to induce ~ 0.25 dpa on targets (sufficient in revealing how materials are affected)

We have been sitting-and-waiting for the specimens to "cool-down"

Post-Irradiation evaluation begins in September 2004. Set-up work has begun.

Summary

Results of recent material studies indicate that selecting target material based on it's seemingly attractive properties that appear to be the solution to the daunting task of surviving the high intensity pulses of high-power accelerators (such as coefficient of thermal expansion, fracture toughness, strength, etc.) should be preceded by an assessment of effects that radiation damage can impart on this property.

As many new materials are developed by optimizing key properties that may be of value to the accelerator community (and possibly to the reactor community) the need for assessment of radiation damage potential is paramount.

This material study focuses on some of the new materials and hopes to screen them as possible target candidates. Upon completion of the study those materials that maintain their properties under modest levels of irradiation (that this study can achieve) will undergo further irradiation to levels that are equivalent to those expected during their life expectancy as accelerator targets.