Simulations of Pressure Waves induced by Proton Pulses

In search of the answer to the fundamental question:

are materials indeed stronger than what we give them credit ?

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Brookhaven National Laboratory

INPUT also from

H. Kirk, K. McDonald, S. Kahn, H. Ludewig

OVERVIEW

Target Concepts

Simulation Studies

Benchmark Studies

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 have a way of coming back

WHY SIMULATION ?

- **Because of complex geometries the ONLY way to identify trouble spots is through simulation**
- **Given that we DO NOT have the high power yet (we just talk about it) it is hard to know how target materials/target systems will REALY respond**
- **By benchmarking simulations at the available lower beam power we can REASONABLY extrapolate the processes (as much as the state of knowledge allows)**

ONE thing that we cannot really do is identify FAILURE (failure means different things to different people)

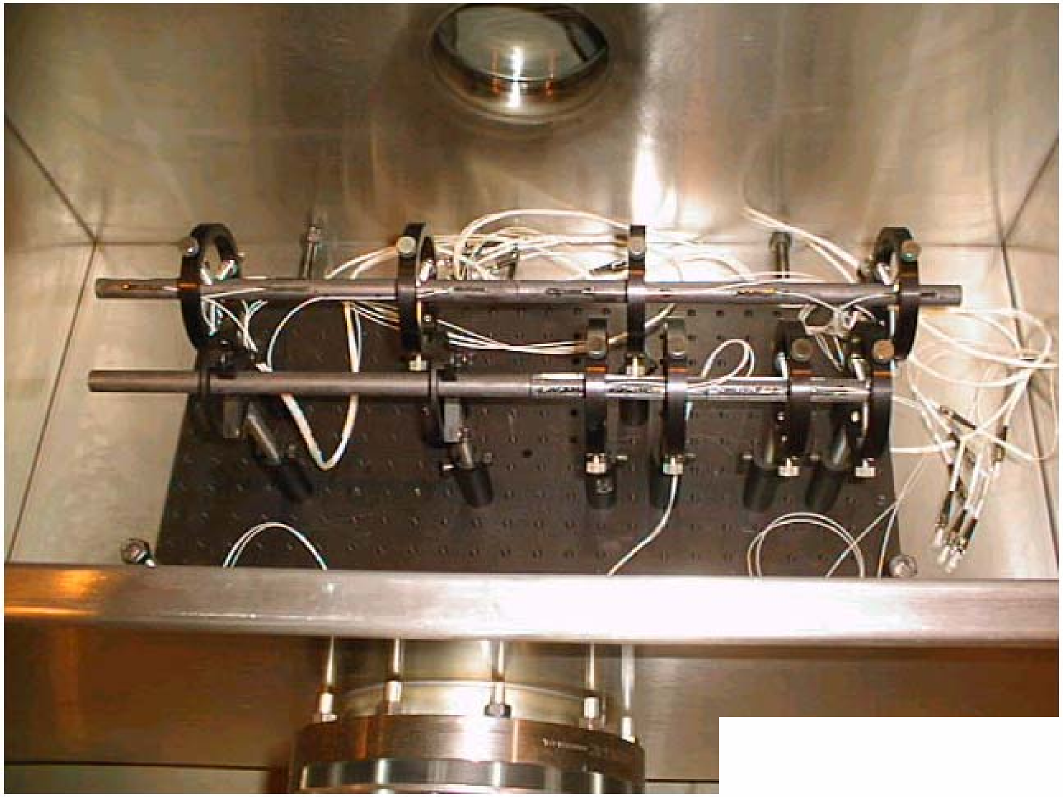
Goals

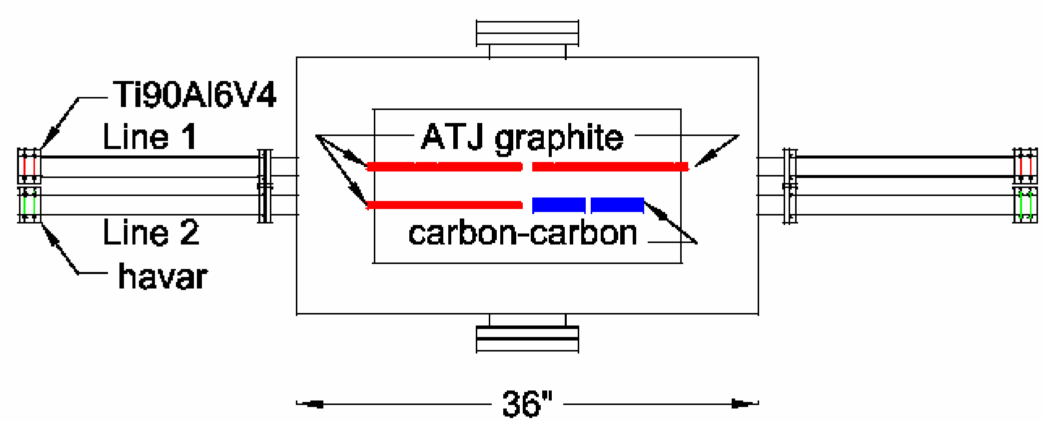
- **Find best possible materials that can be used as targets/beam windows under extreme conditions**
- **Experiment with selected materials, measure responses**
- **Validate prediction models against measurements to gain confidence in predicting material response and/or failure at anticipated extreme conditions**
- **USE experimental results to benchmark energy depositions predicted by the various Monte Carlo codes**

TARGET CONCEPTS

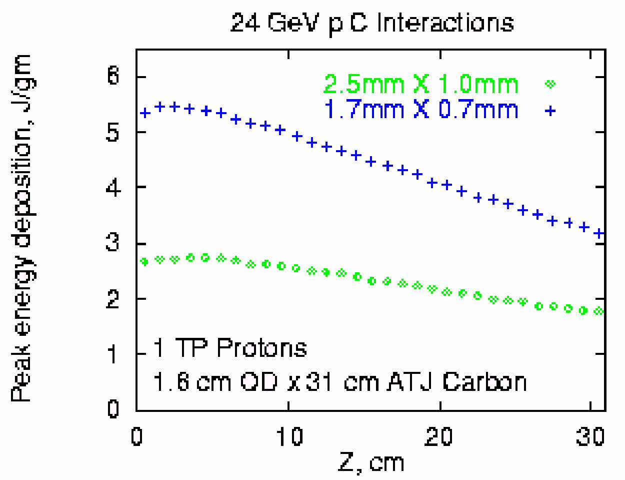
- Solid Targets for Muon Collider/Neutrino Factory
  - Graphite, carbon-carbon, rotating band
  - Beam windows
- Solid Targets for the Neutrino Superbeam (CC composite)
- Targets for Pulsed Neutron Sources

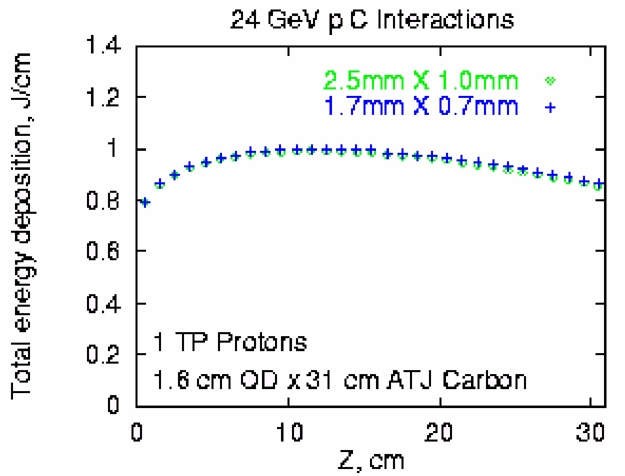
Graphite Targets - E951





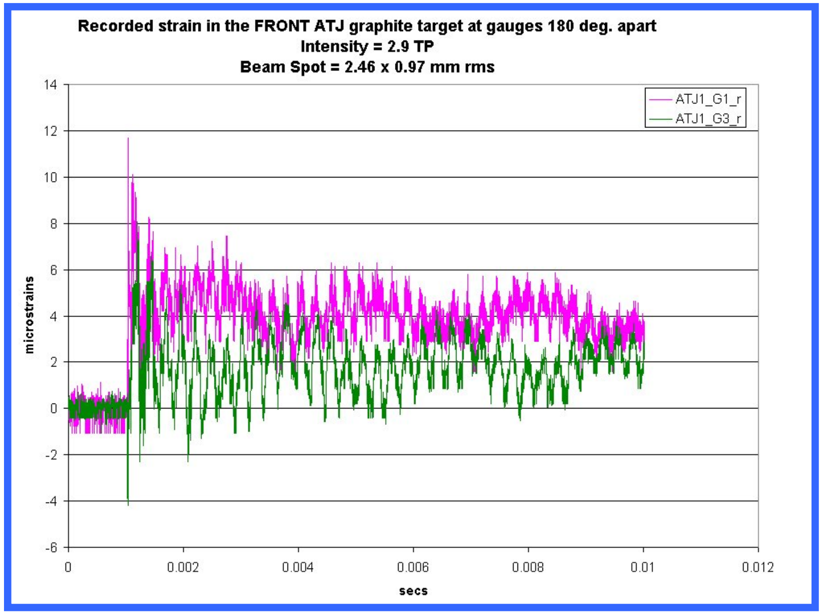
ATJ Graphite Energy Depositions

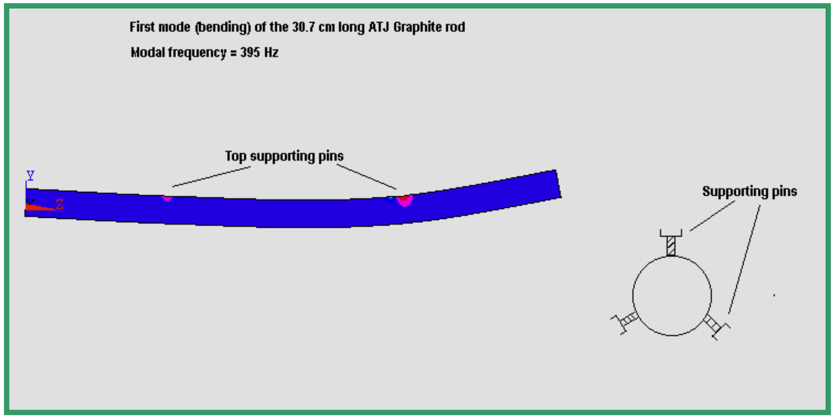




ATJ Graphite Strain Data

Verification of fundamental modes of target response



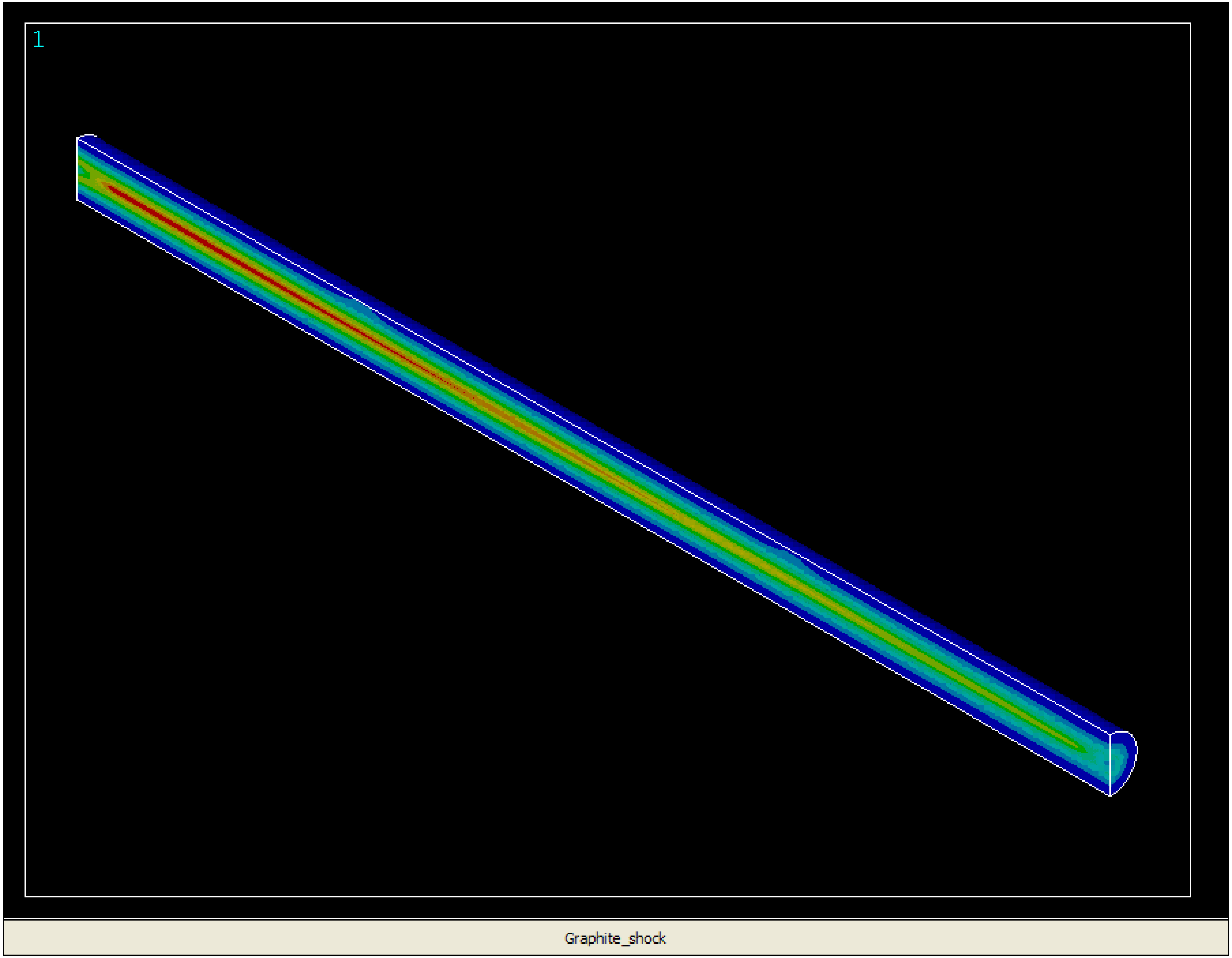


Record of strains in the middle of the graphite rod (left) shows a bending frequency between 380-390 Hz

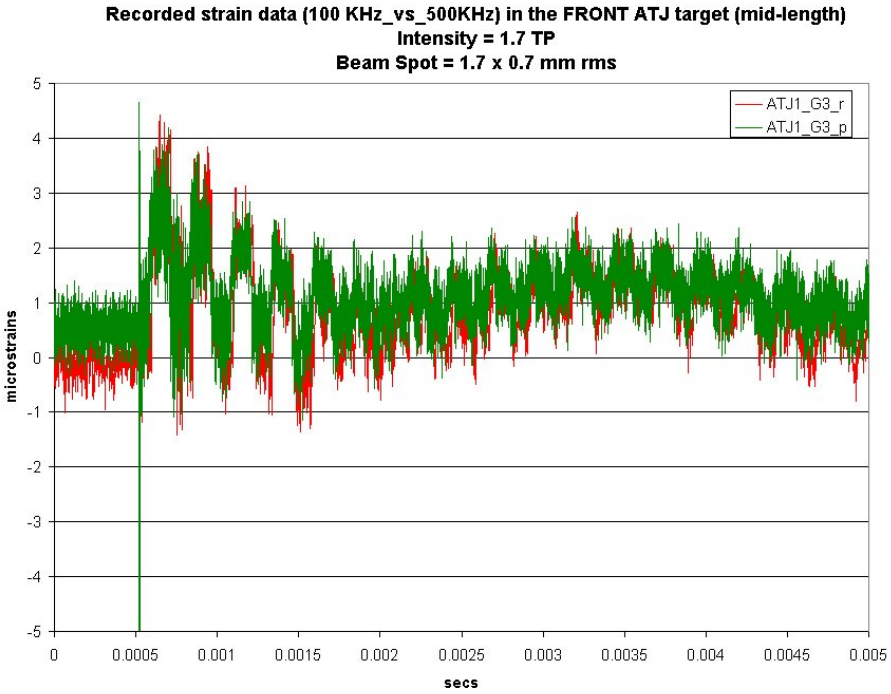
The prediction of the detailed model that implements the supporting/holding fixtures of the target as close to the real setting as possible, predicts a bending frequency of 395 Hz

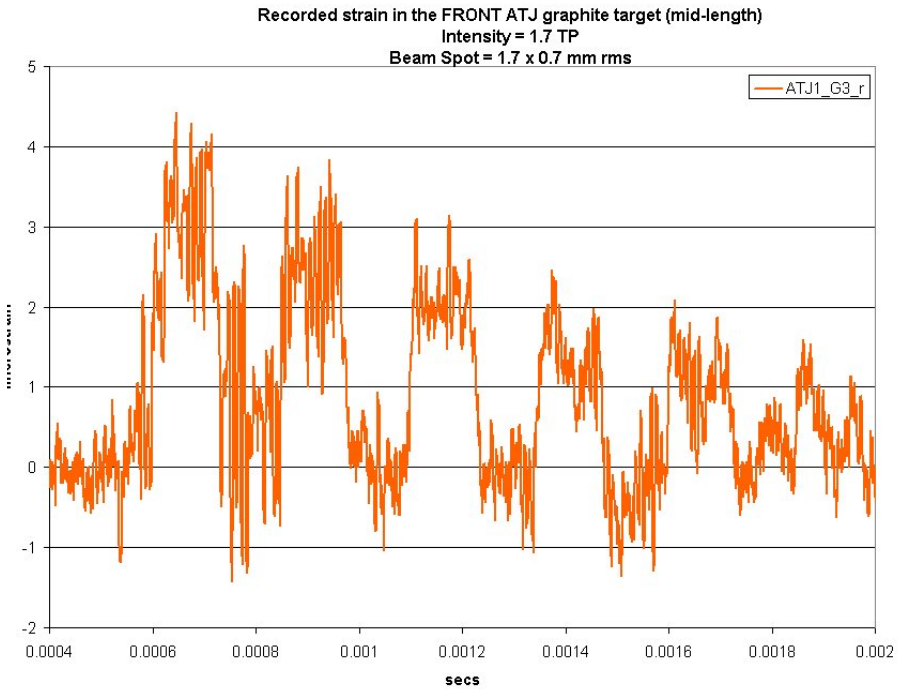
Also from the record, the axial "ringing" of the target has a period of 260 to 265 microseconds. The fundamental axial period T=2L/c (where L is target rod length and c is speed of sound) is approximately 261 microseconds

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


1
Graphite_shock

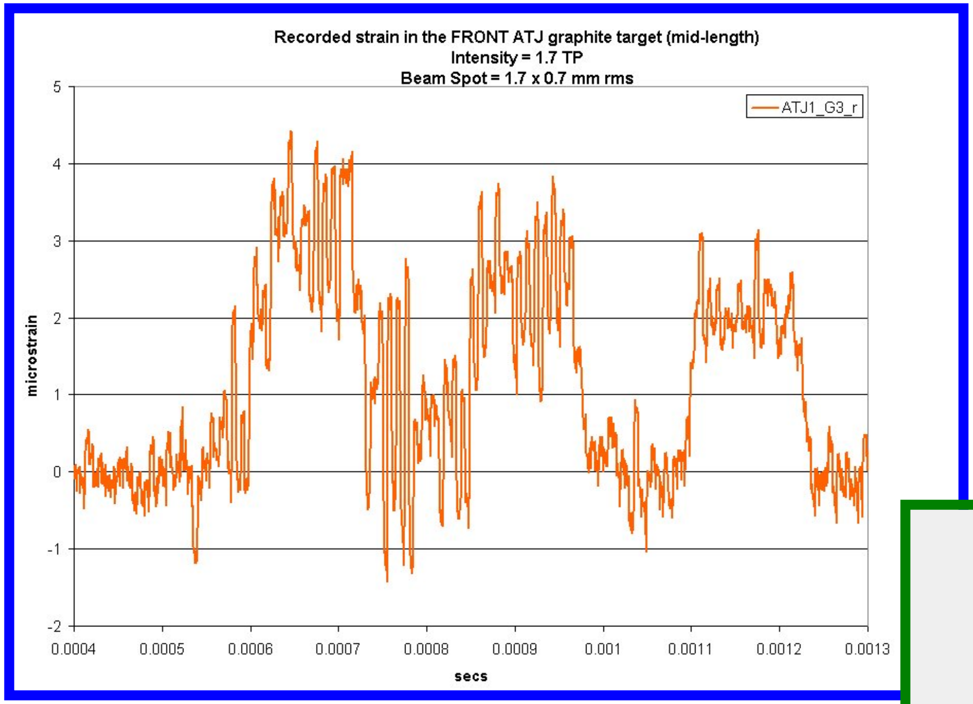
ATJ Graphite Strain Data

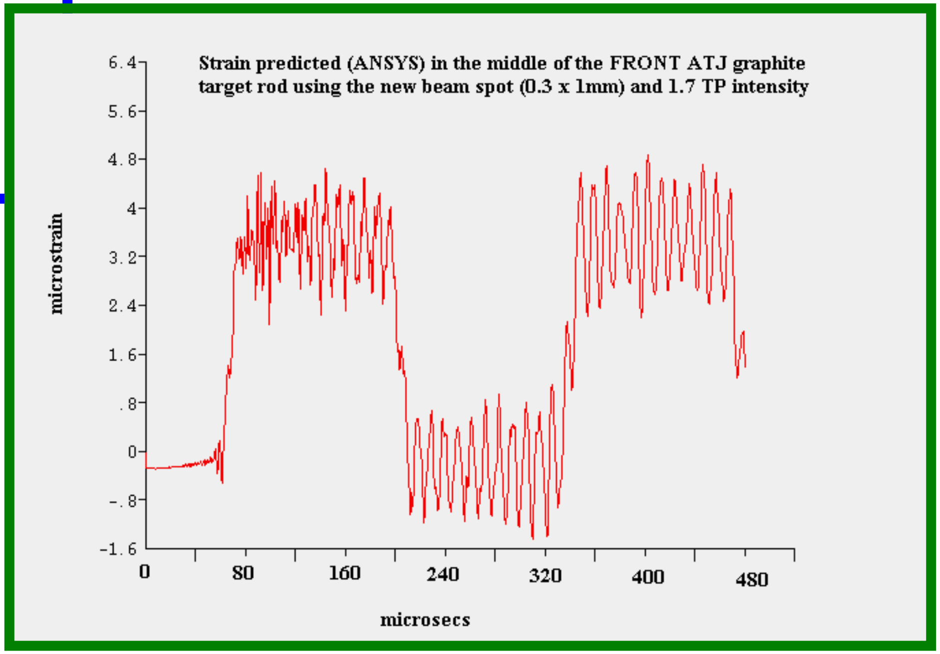




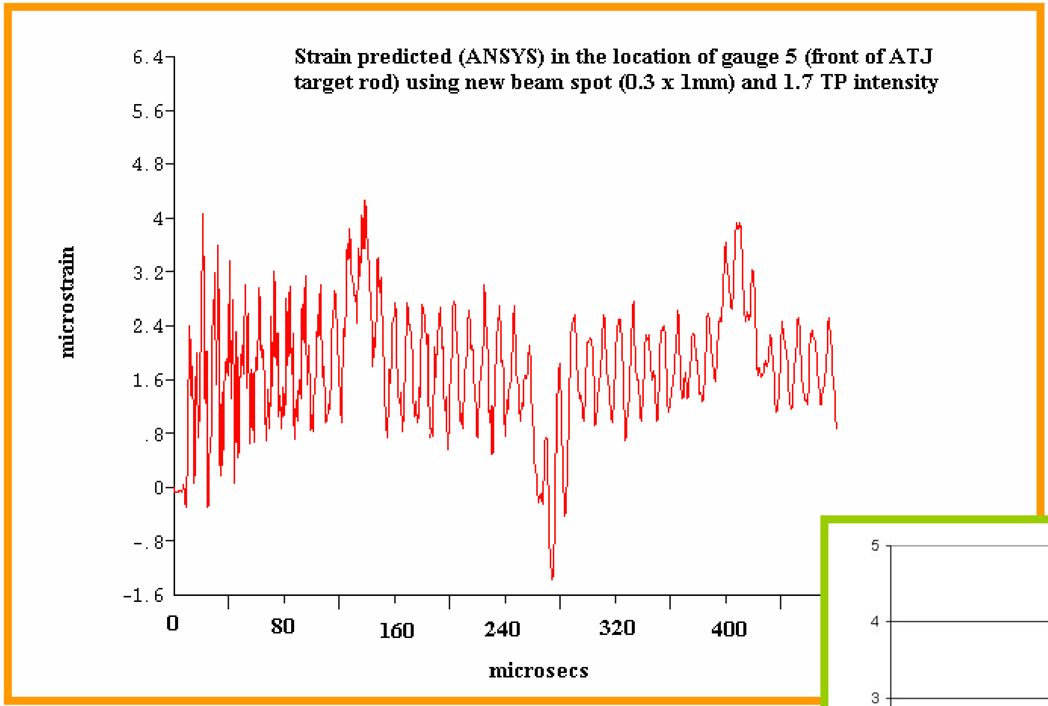
ATJ Graphite Strain Comparison

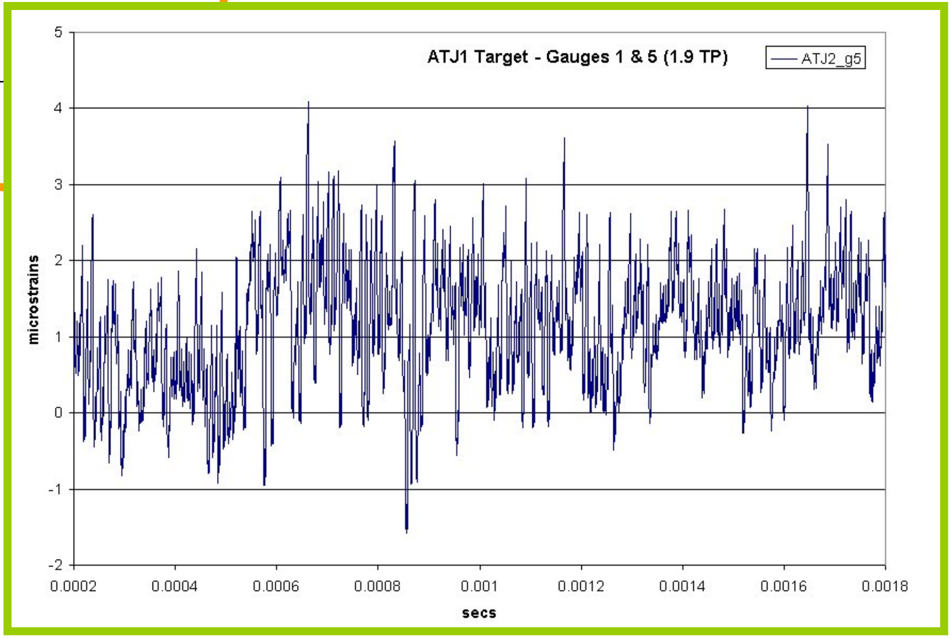
Prediction model has not implemented damping from supports or material



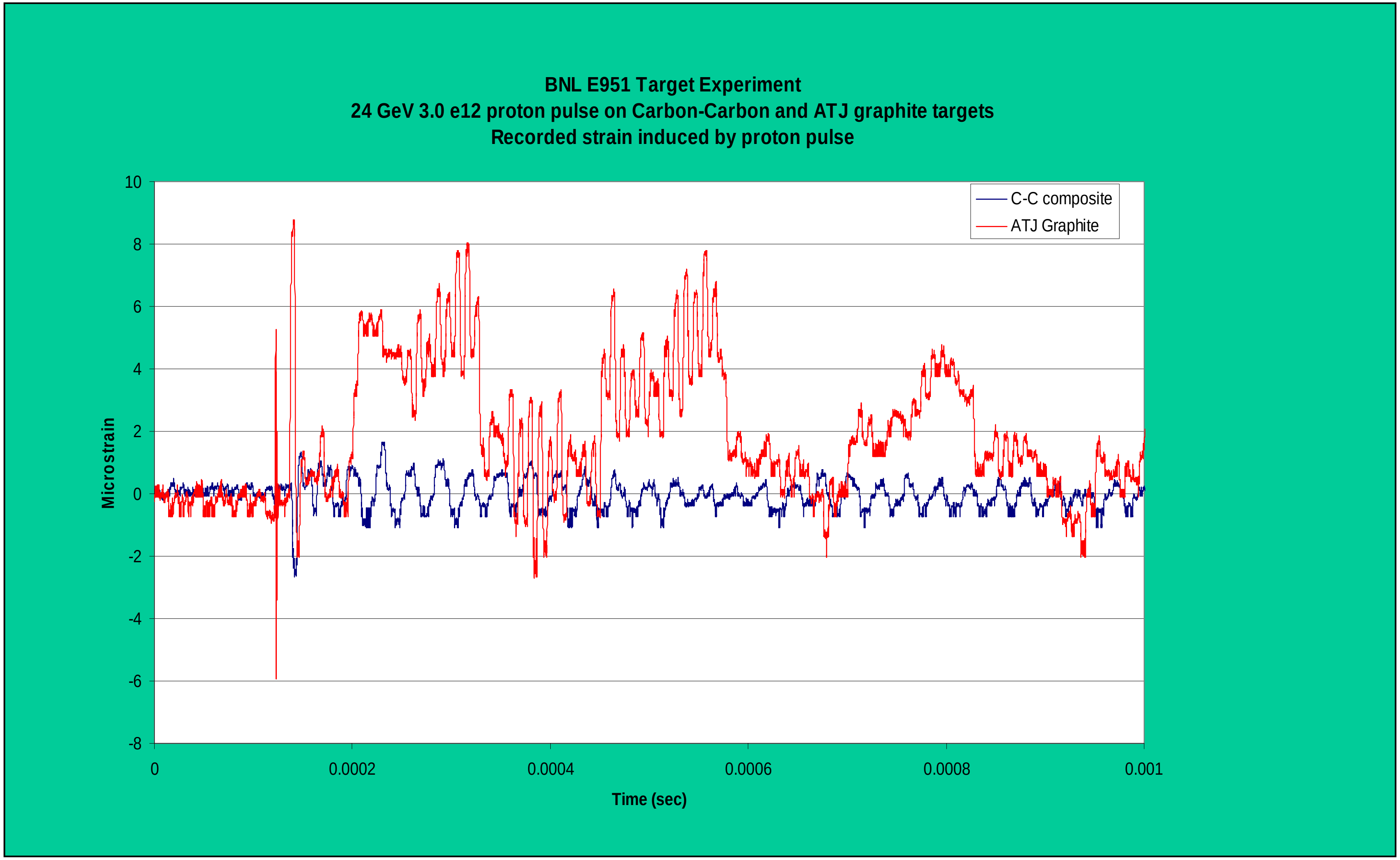


ATJ Graphite Strain Data - Predictions

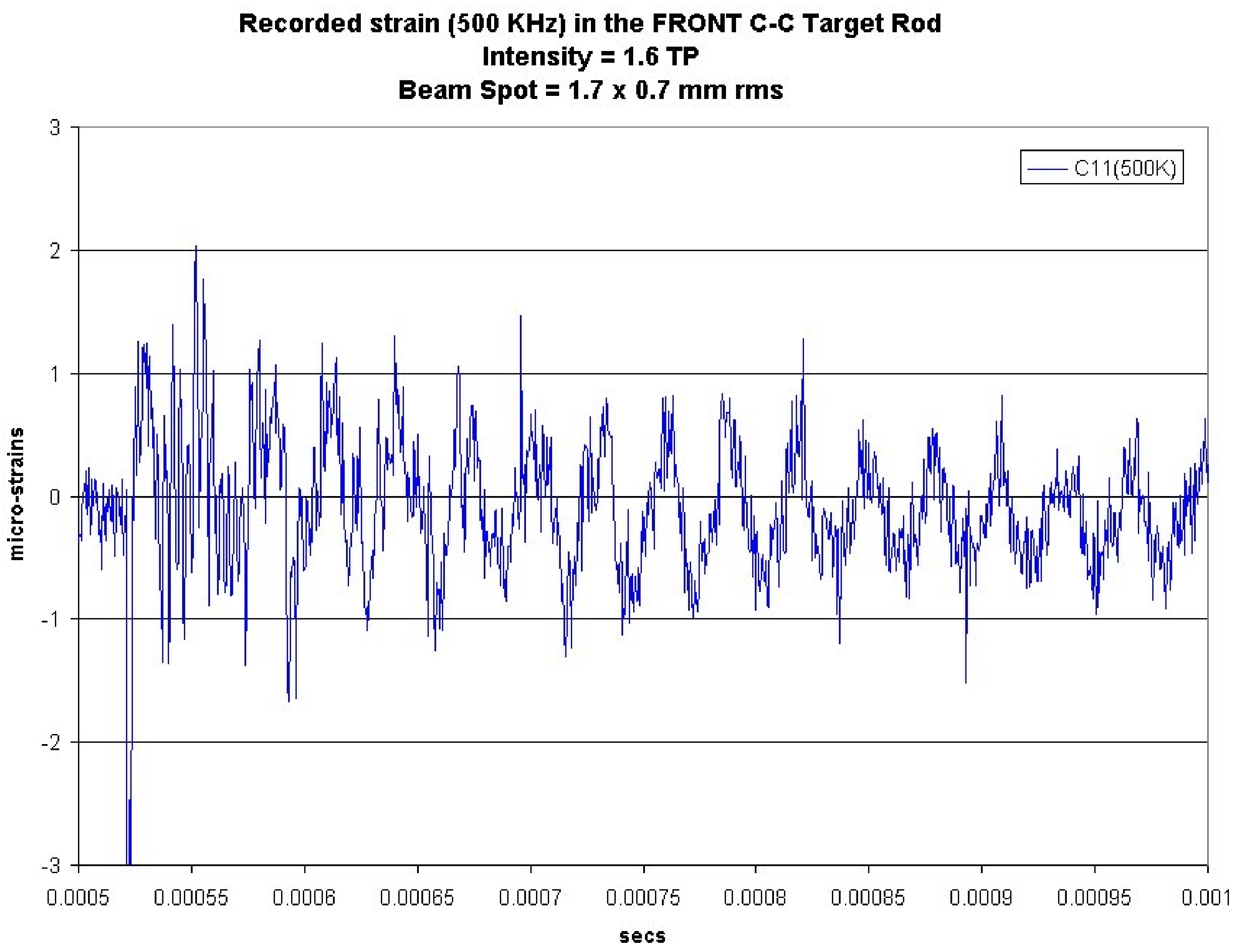


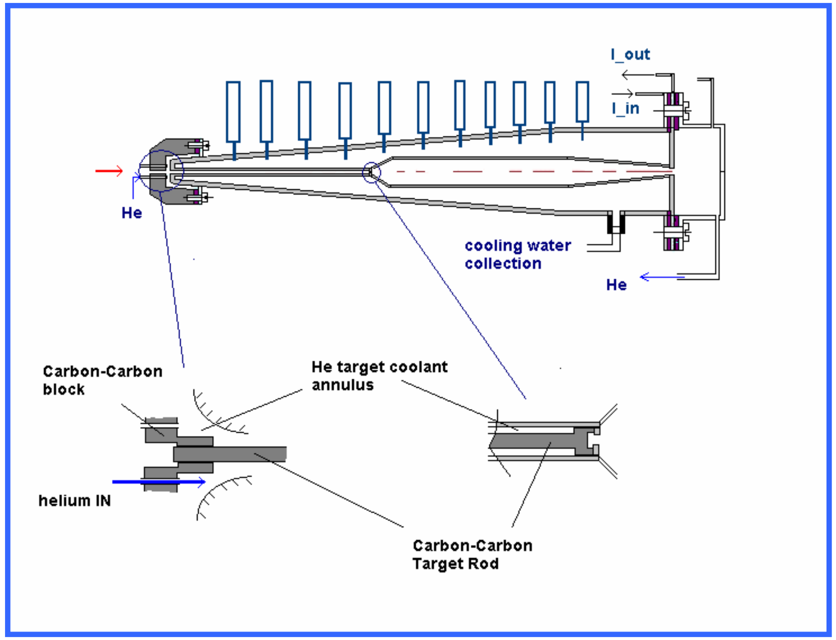


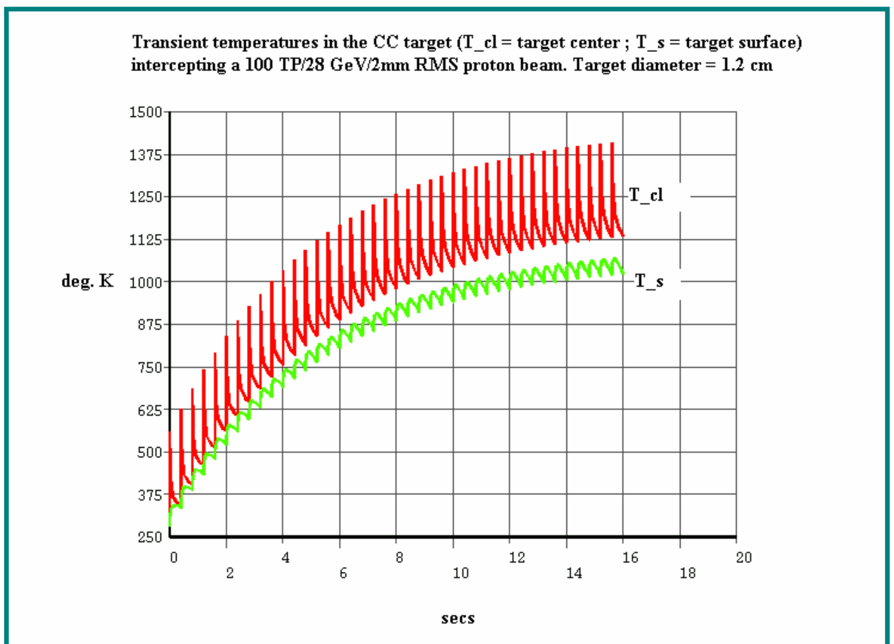
Strain Comparison: Graphite vs. Carbon-Carbon



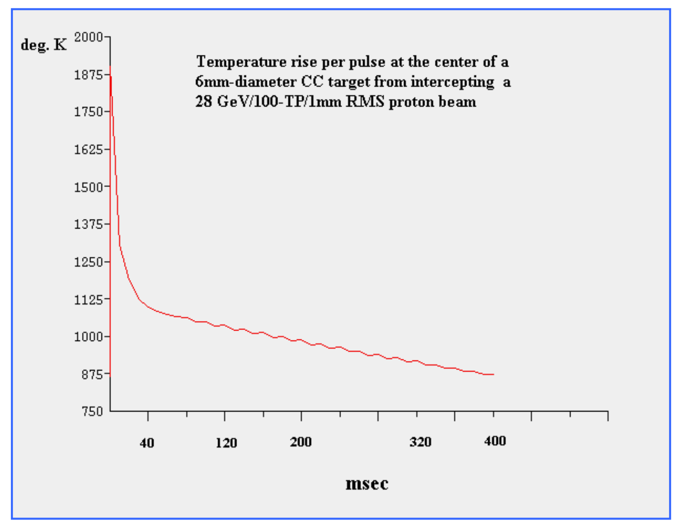
Carbon-Carbon Strain Data



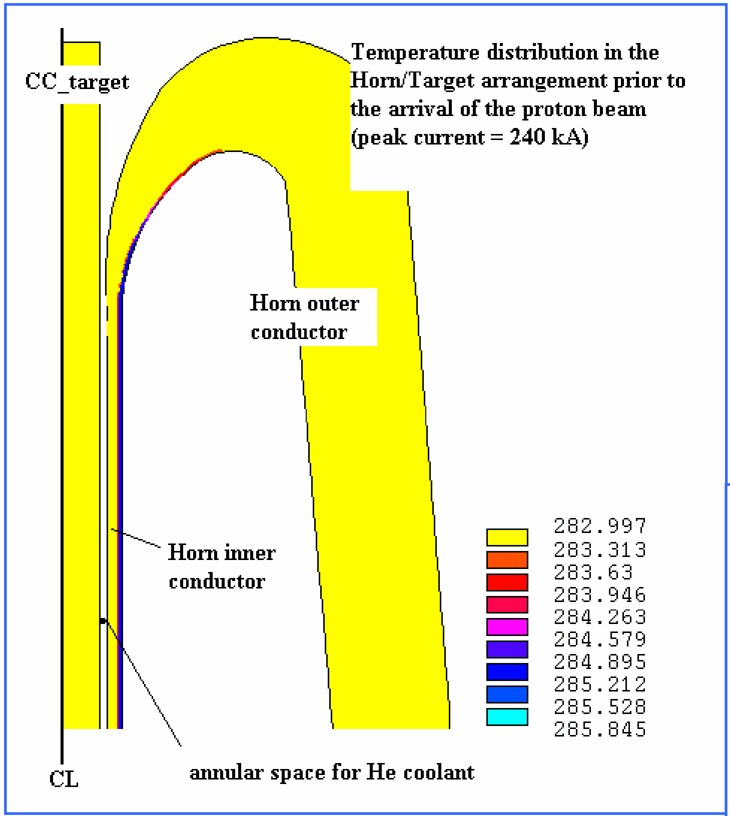




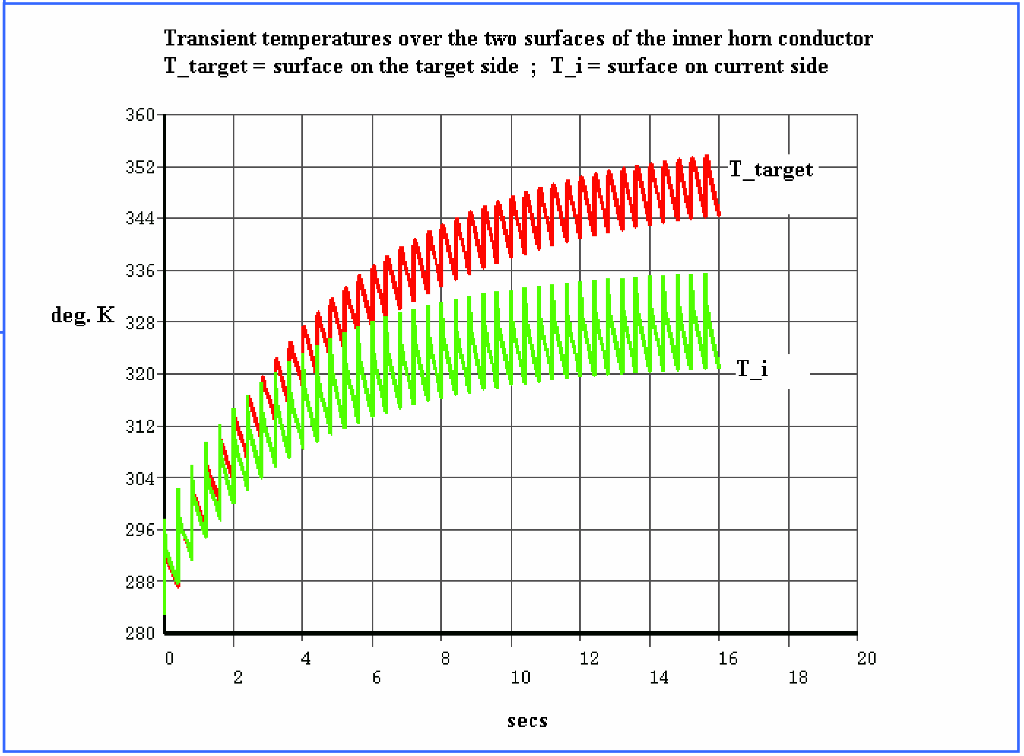
Transient temperatures in the CC target (T_cl = target center ; T_s = target surface) intercepting a 100 TP/28 GeV/2mm RMS proton beam. Target diameter = 1.2 cm



Temperature rise per pulse at the center of a 6mm-diameter CC target from intercepting a 28 GeV/100-TP/1mm RMS proton beam



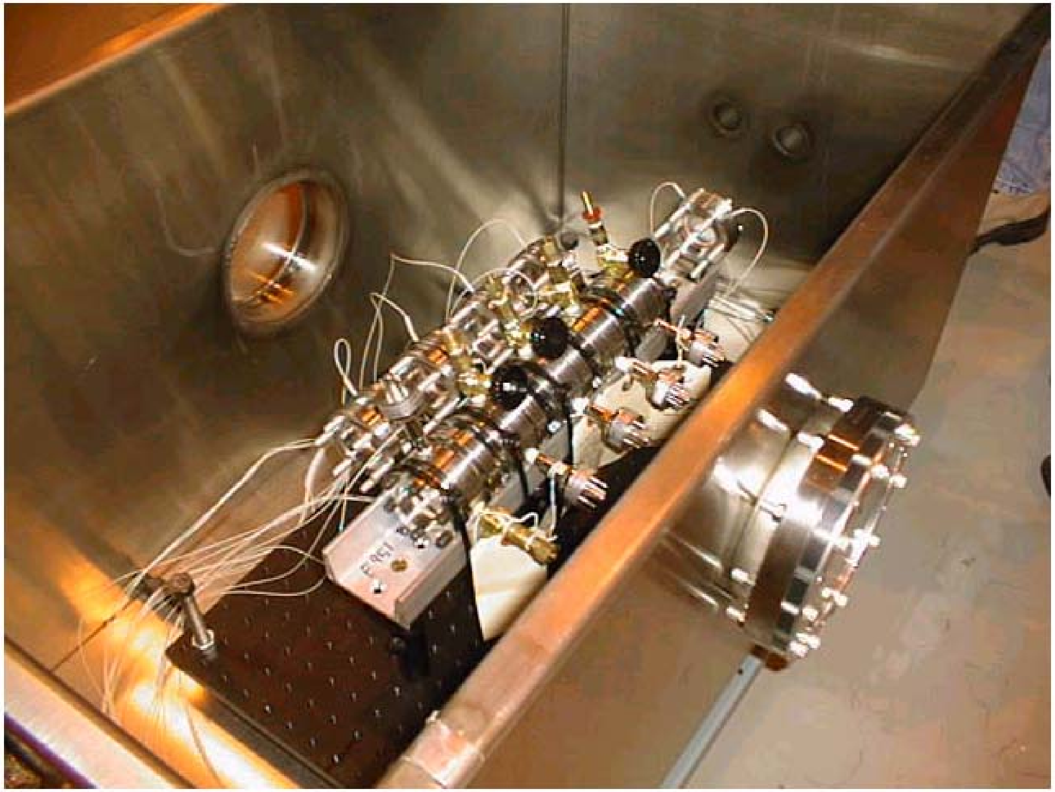
CC_target
Temperature distribution in the Horn/Target arrangement prior to the arrival of the proton beam (peak current = 240 kA)
Horn outer conductor
Horn inner conductor
282.997
283.313
283.63
283.946
284.263
284.579
284.895
285.212
285.528
285.845
CL
annular space for He coolant



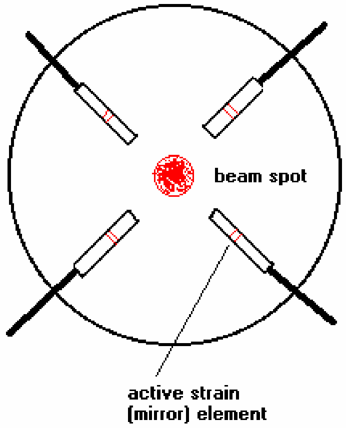
Transient temperatures over the two surfaces of the inner horn conductor
T_target = surface on the target side ; T_i = surface on current side
deg. K
360
352
344
336
328
320
312
304
296
288
280
T_target
T_i
0
2
4
6
8
10
12
14
16
18
20
secs

E951 WINDOW TEST Station Set-Up

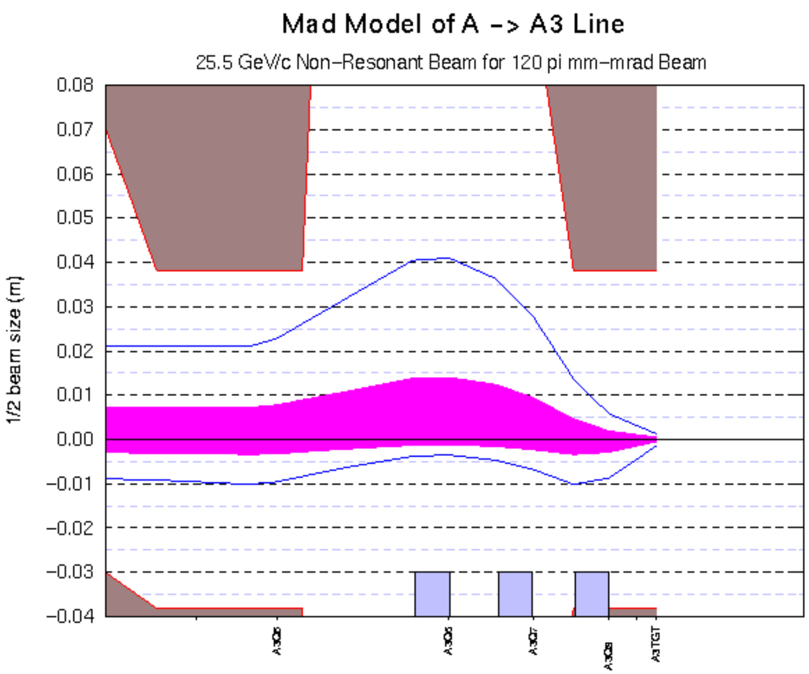
Fiber-optic Strain Gauges & Double window vacuum monitoring

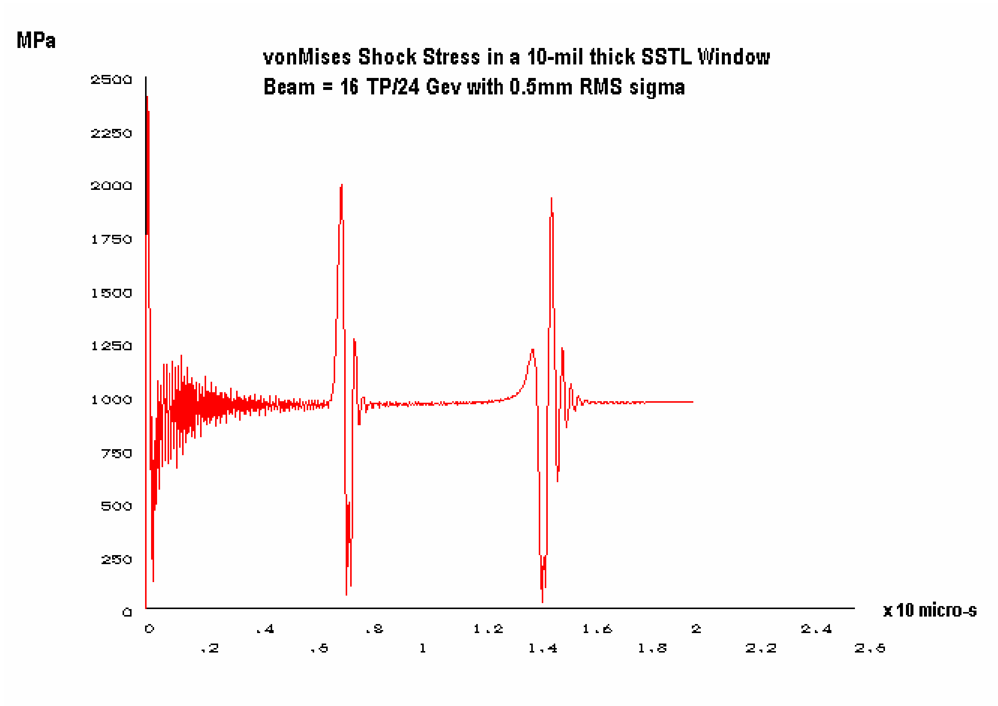


Fiberoptic Strain Gauge Arrangement in the 2" diam. Beam Window



What Triggered the Window Experimental Effort





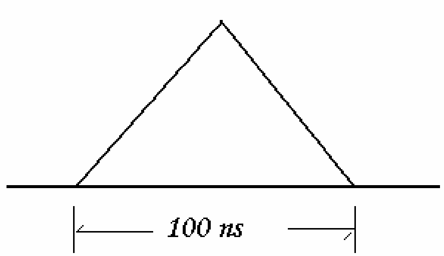
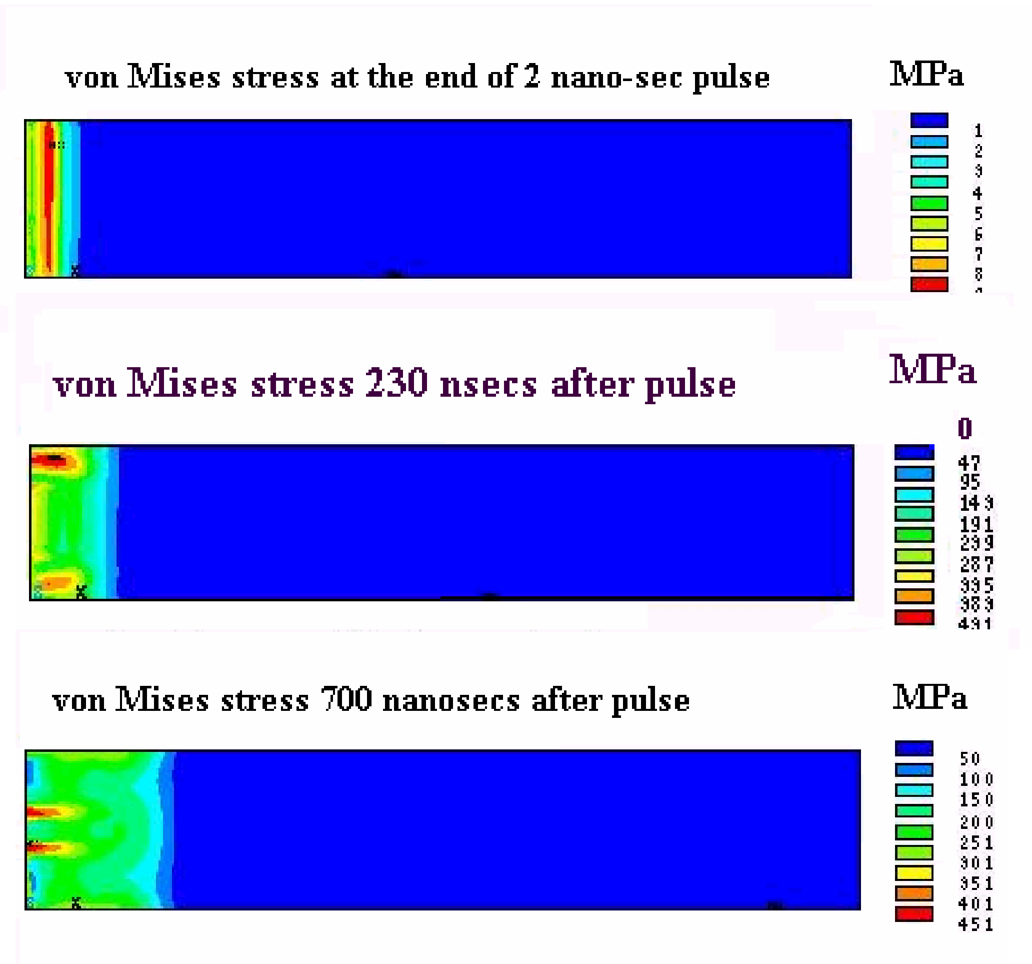


Figure above depicts the tight beam spot requirement (0.5 x 0.5 mm rms) for target experiment at AGS

Induced shock stress in a window structure by 16 TP intensity beam and the spot above will likely fail most materials in a single short pulse (~ 2 ns)

Figure (right) depicts prediction of vonMises stress in a stainless steel window for the above conditions. Initial shock stress is ~ 3 x yield strength of material !!

Mechanism of induced shock stress in windows



•No matter how thin the window is, the reverberation of stress between surfaces is the key issue

• vonMises stress amplitude depends on the spot size (initial compressive load amplitude), thickness of window, speed of sound and pulse shape

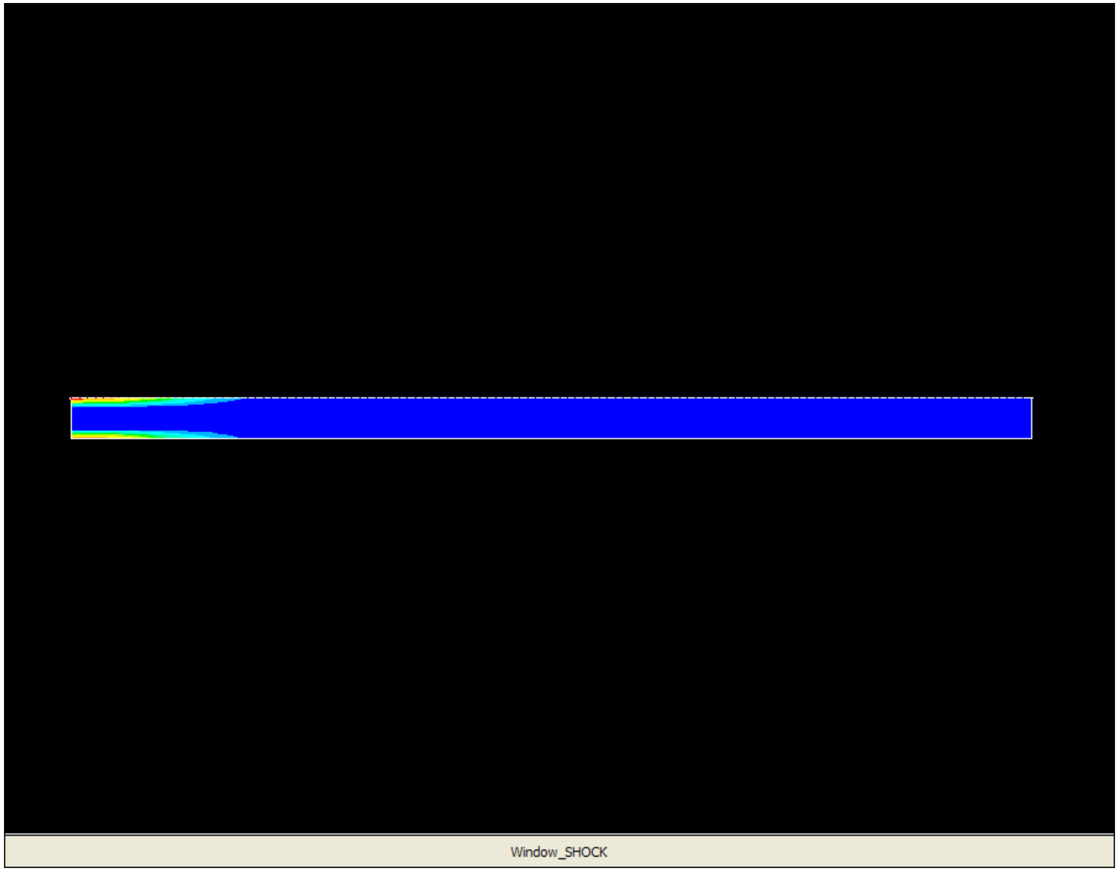
• the measurement of strain on the surface is to be used as benchmark of the ability of the model to predict the stress field in the heated zone

• the radial response (stress/strain) and the ability of the pulse to relax depends on the spot size and the pulse structure

• smaller spot size does not necessarily mean larger response at a distance

• smaller spot size definitely means higher stress field in the vicinity of the heated zone

Mechanism of induced shock stress in windows

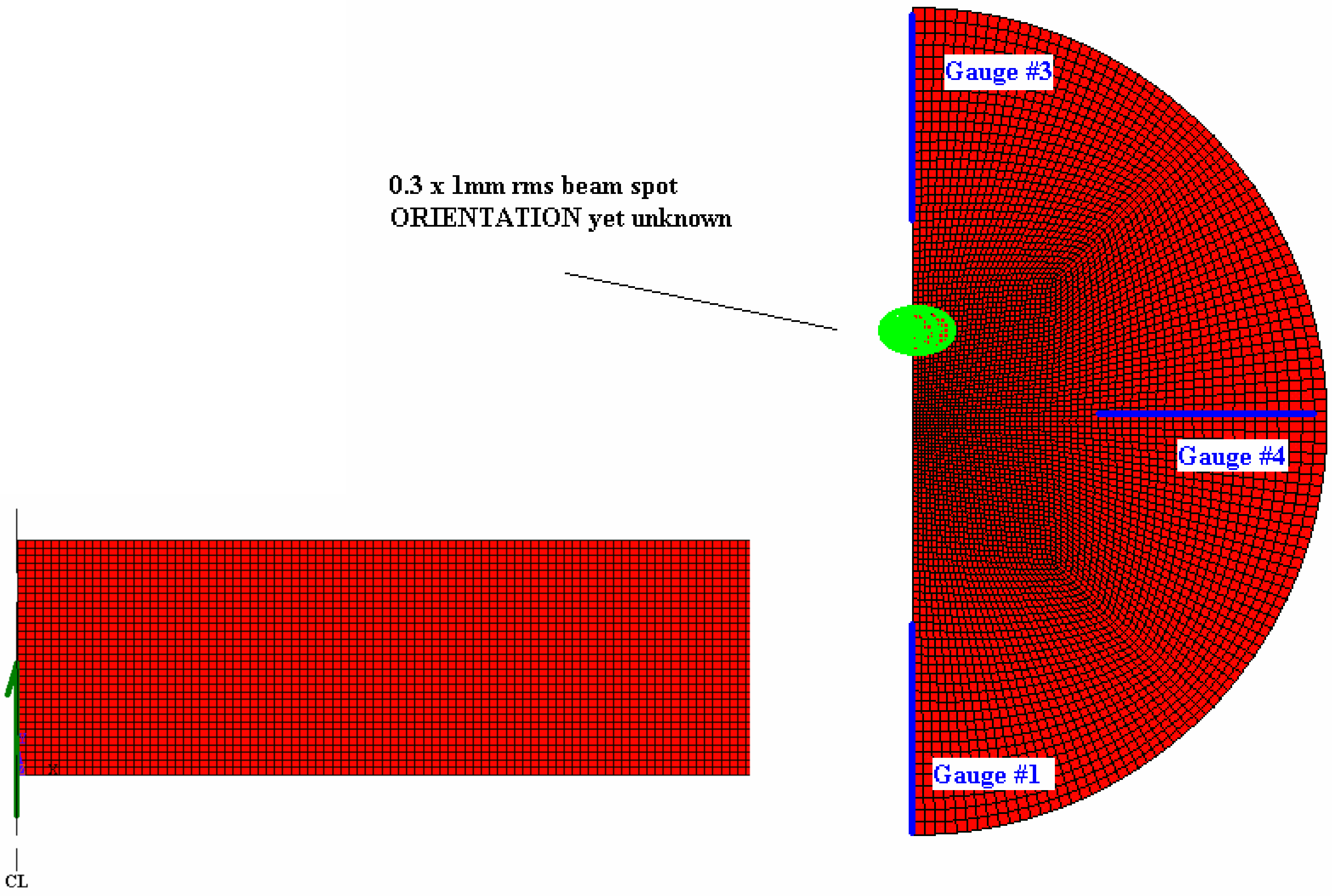


Window_shock2

Issues and Material Matrix selection

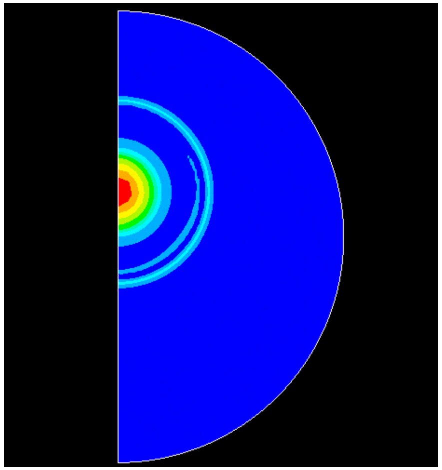
- FAST proton beam interacting with window and depositing energy in small spot inducing shock waves
- Based on a 24 GeV/16 TP/0.5 mm rms beam MOST materials could fail with a single pulse
- Though thin, failure in window governed by through-thickness response
- **Sound speed**, **material thickness** and **pulse structure** are critical elements
- Material search combined with analytical predictions led to the following materials for testing
  - Inconel 718 (1mm and 6mm thickness to study the effect)
  - Havar
  - Titanium Alloy (highest expectation of survivability)
  - Aluminum
- Aluminum (3000 series) selected as the one that COULD fail under realistic expectations of AGS beam during E951 (~ 8 TP and 1mm rms)

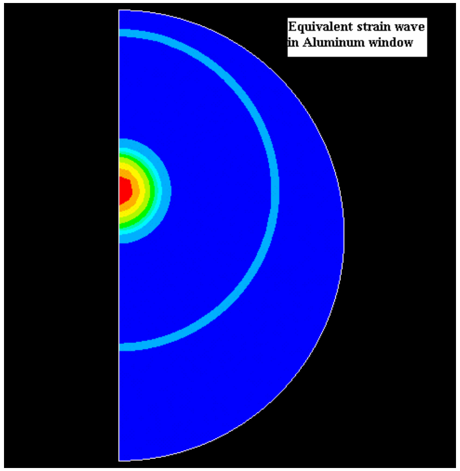
Finite Element Models to Capture the Dynamic Response of Windows

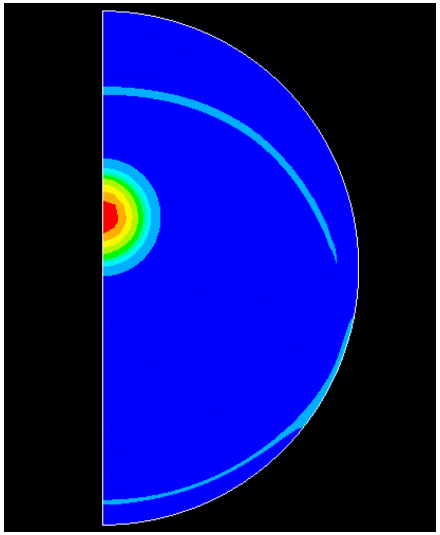


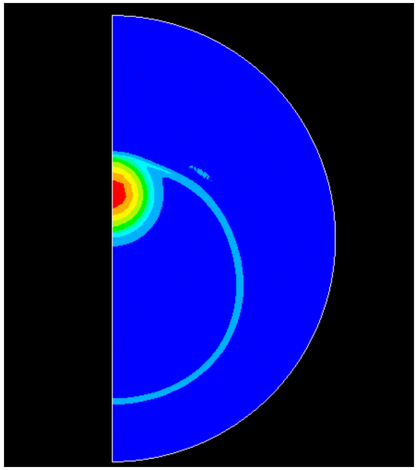
Aluminum Window Strain Waves

(beam spot ~ 0.3 x 1mm)

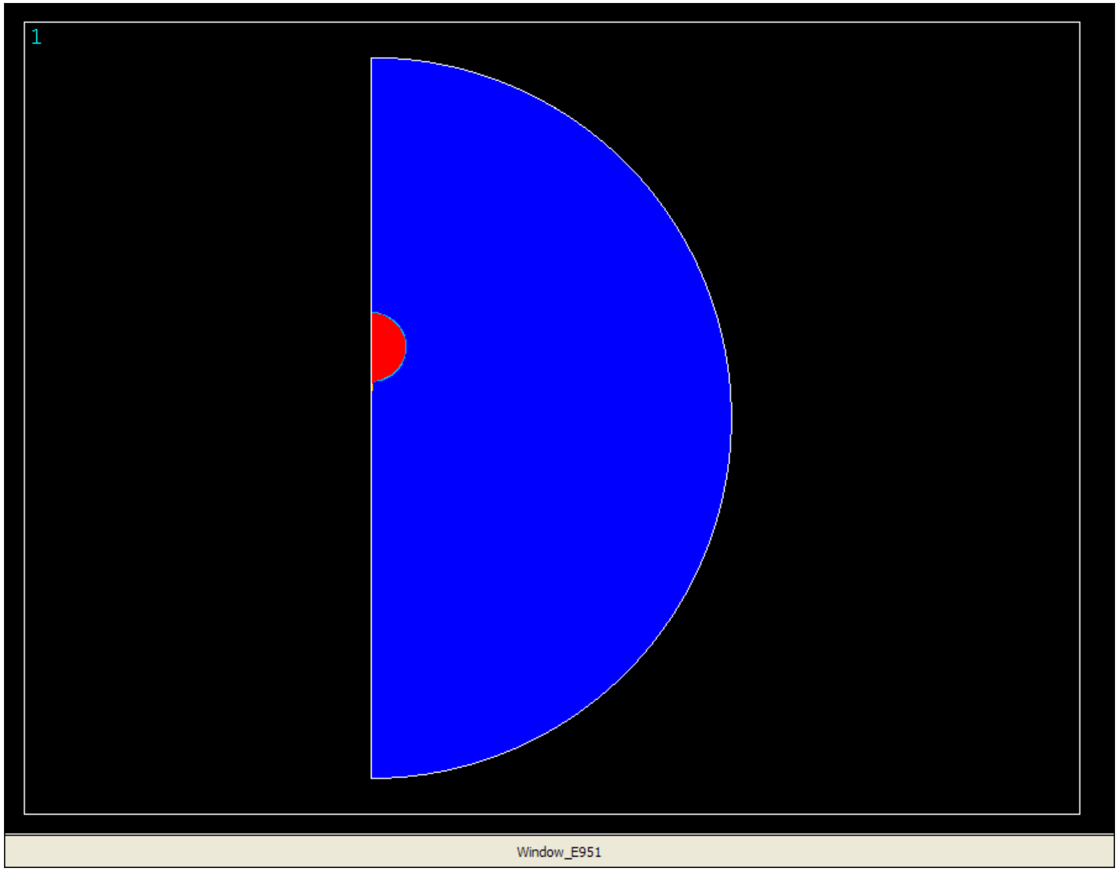






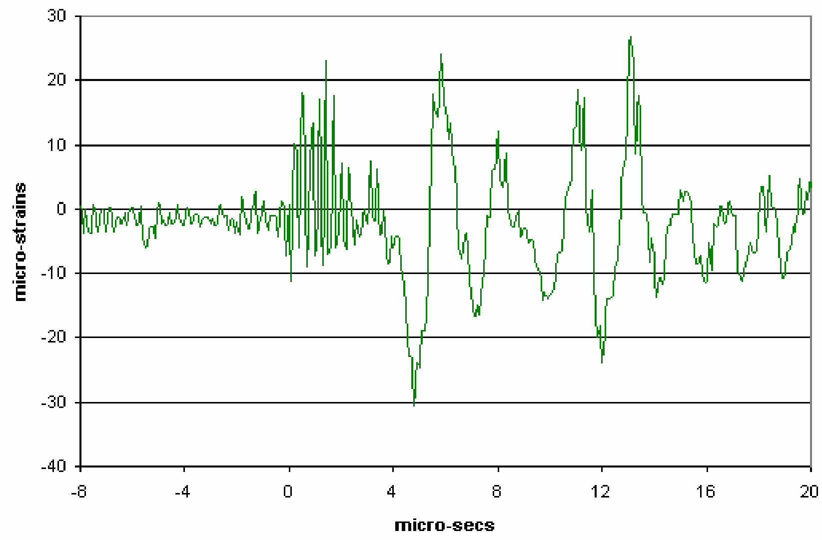


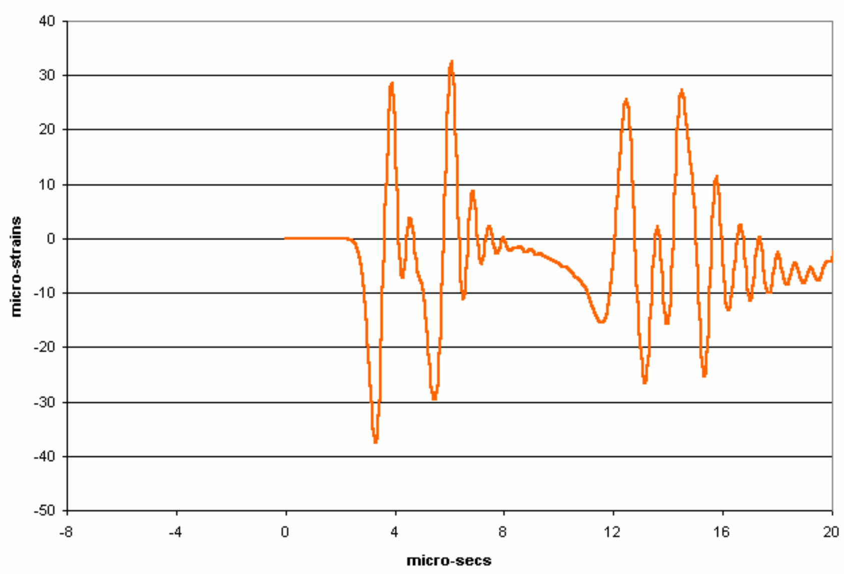
Aluminum Window Strain Wave Simulation



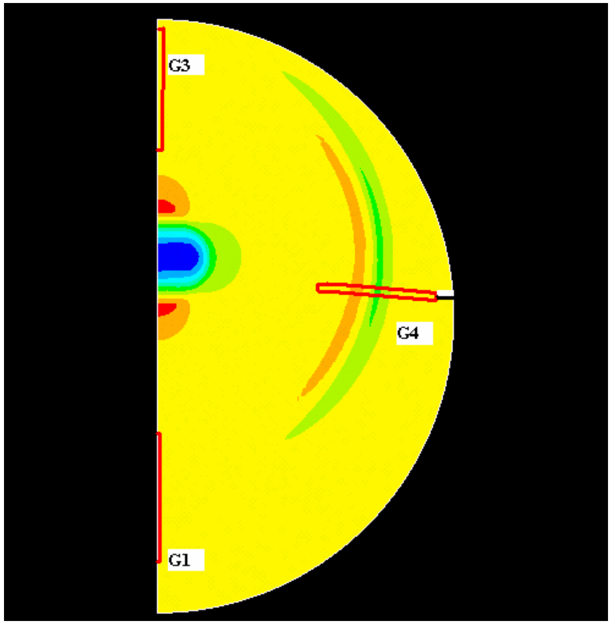
Aluminum Window Strain Data

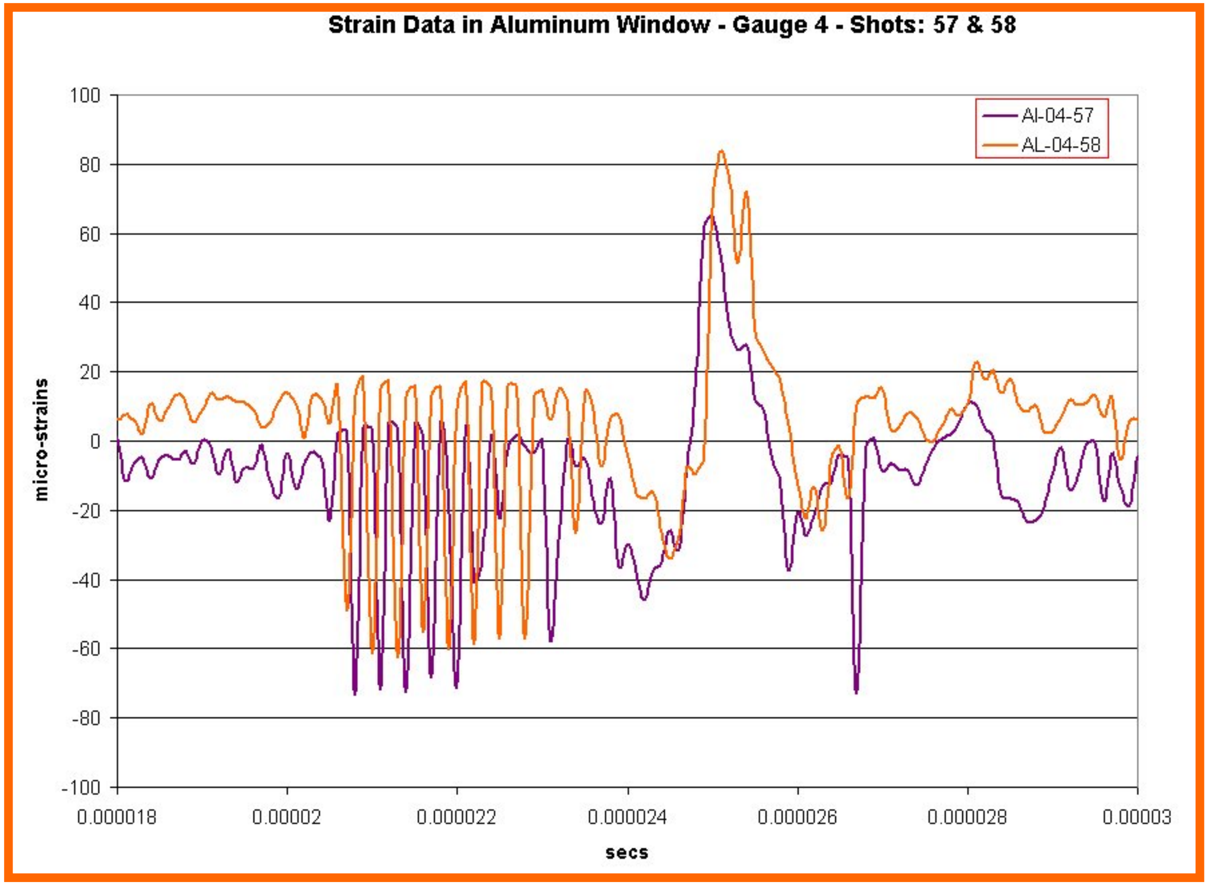
Experimental data vs. prediction using the new beam spot (0.3 x 1mm)



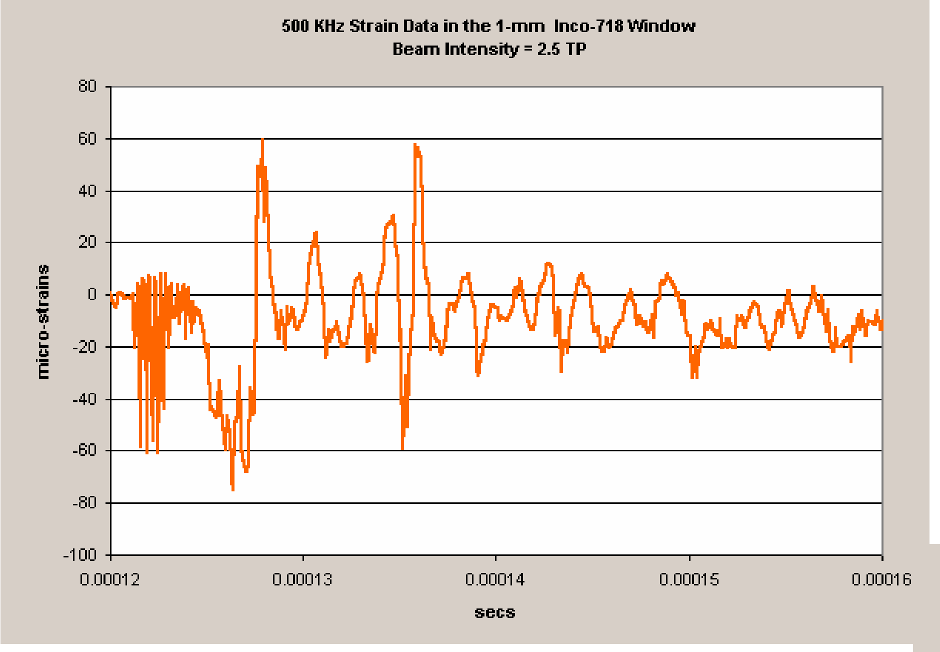


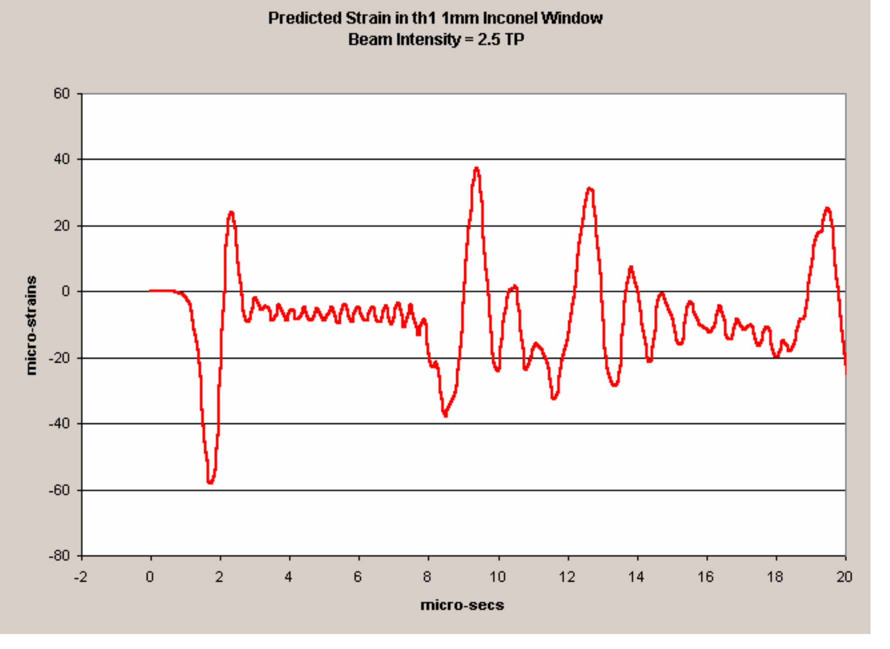
Recorded Aluminum Window Strain Data in back-to-back pulses



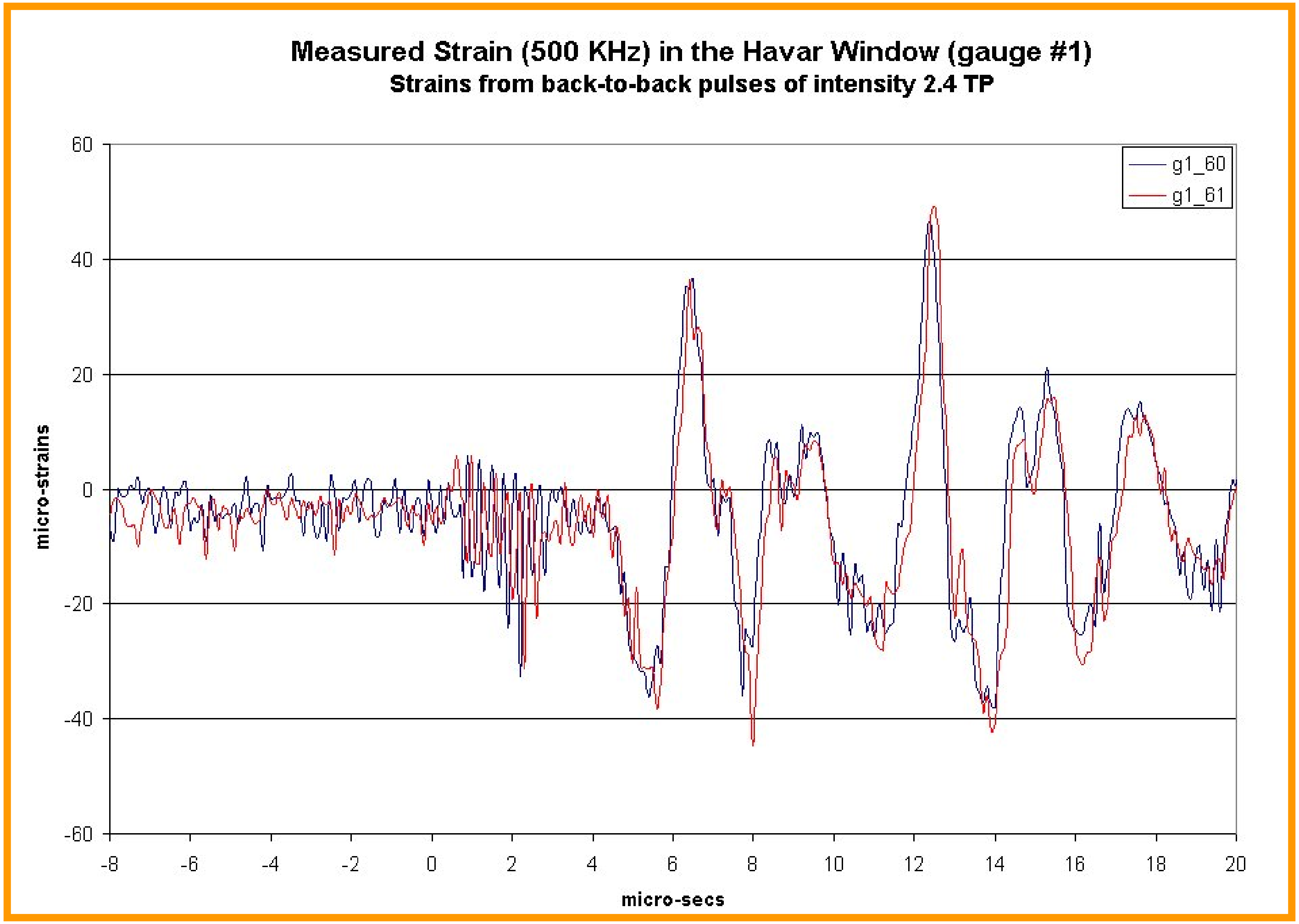


Measured and predicted strains in the 1mm thick Inconel-718

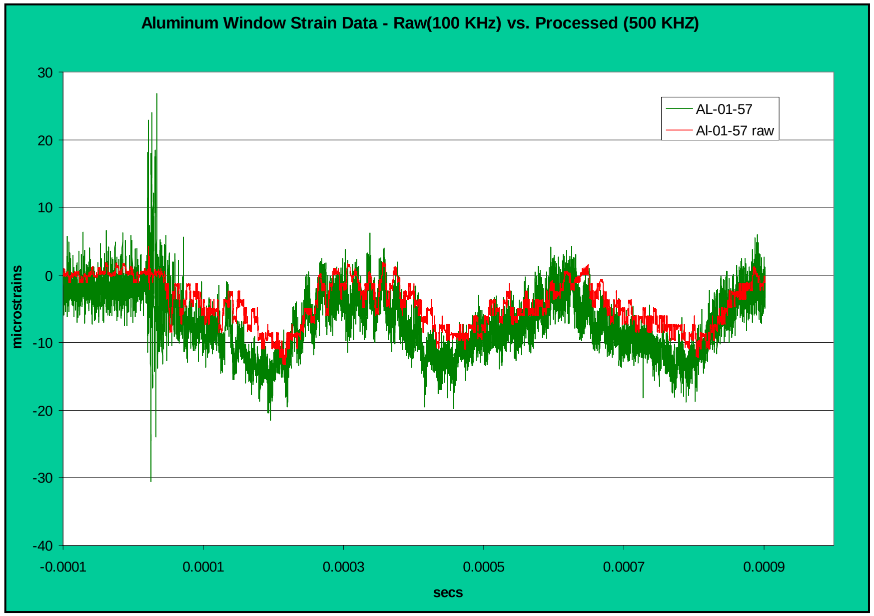




RECORDED strains in the Havar Window (back-to-back pulses)



Lesson: You better have the necessary resolution, or …



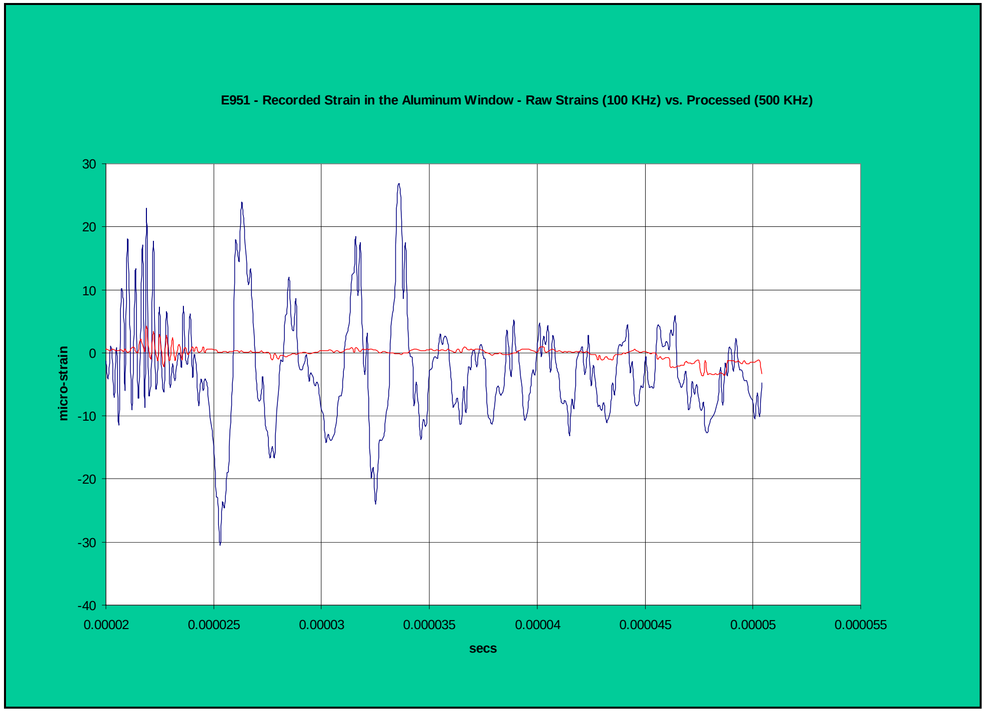
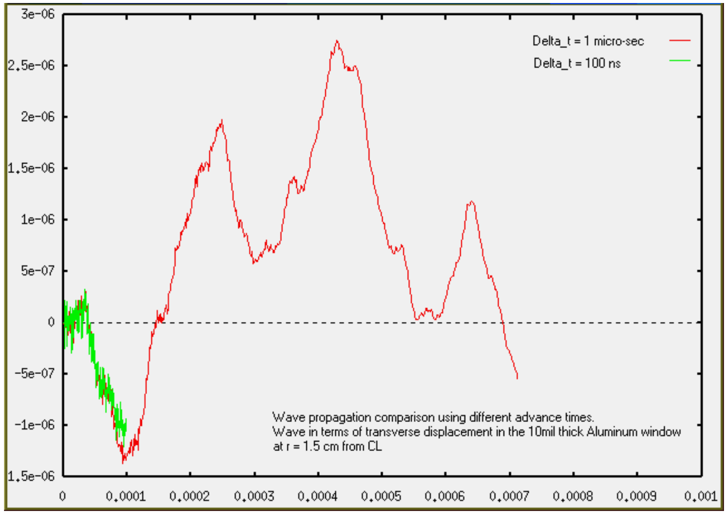
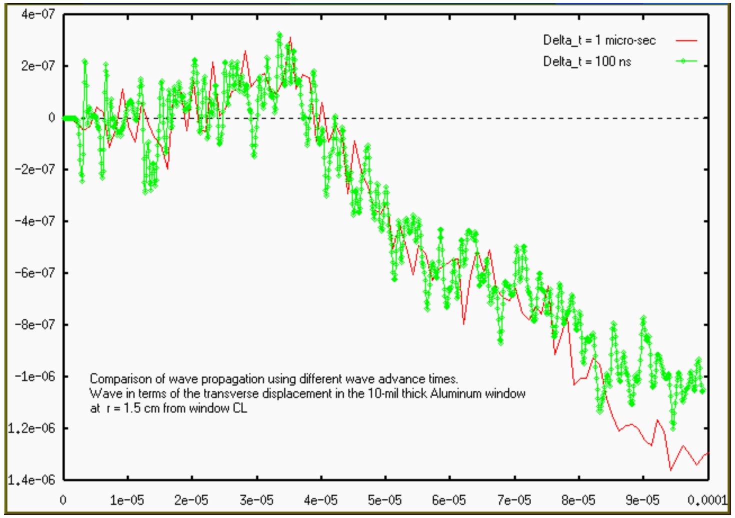
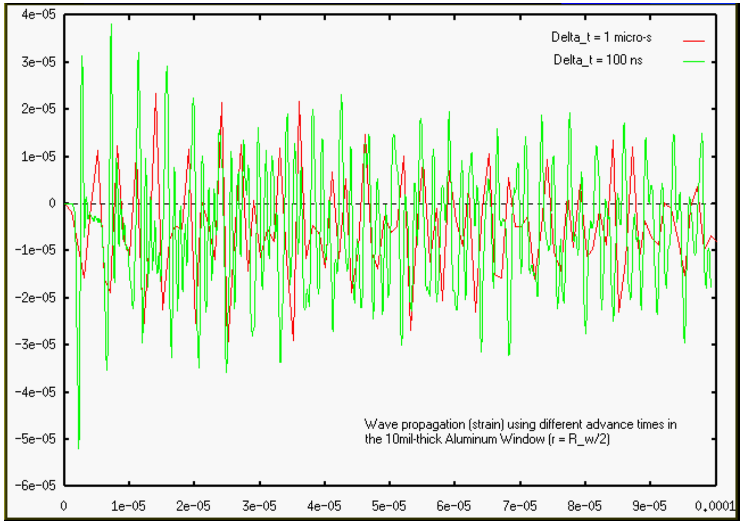
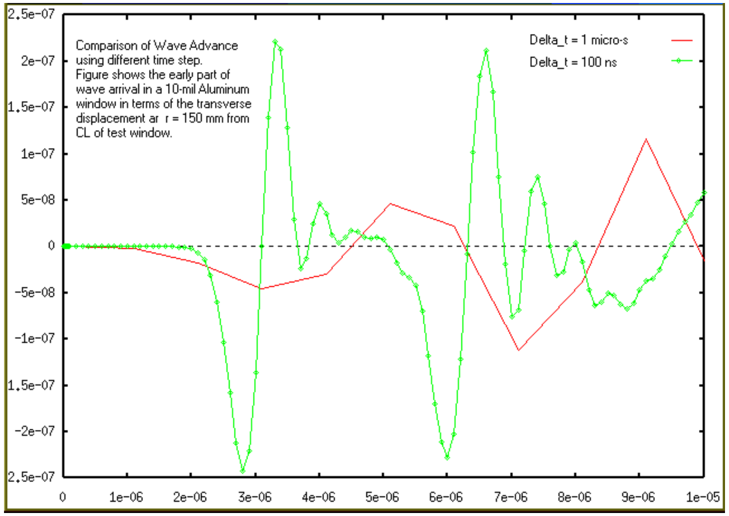


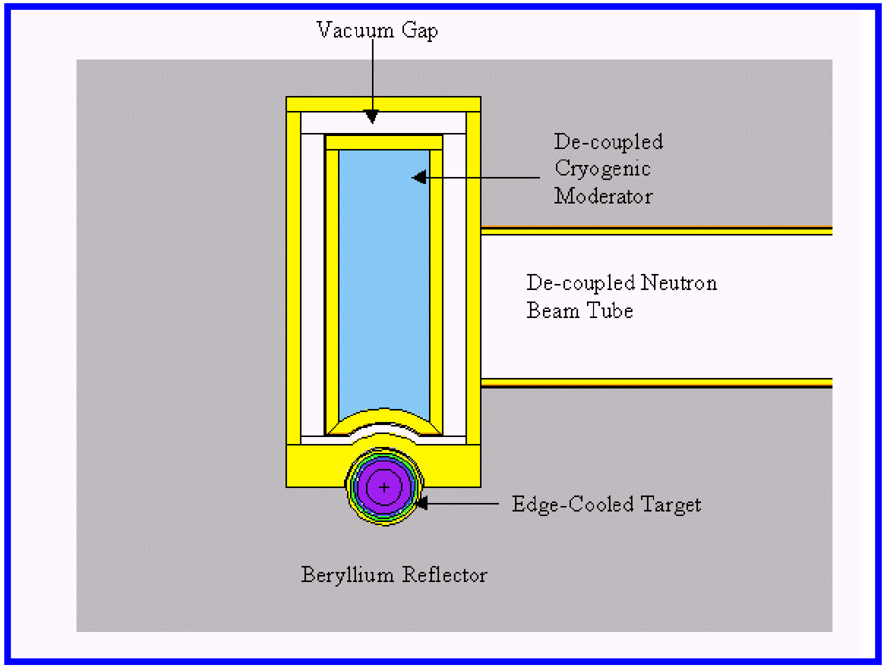
Illustration of sampling rate on data prediction











SOURCE CHARACTERISTICS

PROTON SOURCE

- ENERGY = 24 GeV
- MAXIMUM SINGLE PULSE INTENSITY ~ 16 x 10^{12} PROTONS
- IMPLIED MAXIMUM ENERGY PER PULSE = 64 kJ
- PULSES CAN BE DELIVERED IN A VARIETY OF SEQUENCES AND FREQUENCIES

PROPOSED NEUTRON SOURCE

- MAXIMUM NEUTRON PRODUCTION IN FIRST 15 cm OF TARGET
- REQUIRES DENSE TARGET DUE TO HIGH PROTON ENERGY
- IMPLIES EDGE COOLED TARGET CONFIGURATION
- POSSIBLE TARGET MATERIALS

Material	Density (g/cc)	Thermal capture (b)	Resonance Integral (b)
Tantalum	16.6	20.5	660.0
Tungsten	19.3	18.4	352.0
Rhenium	20.53	89.7	831.0
Osmium	22.48	16.0	180.0
Iridium	22.42	425.0	2150.0
Mercury	13.55	372.0	73.0
Lead	11.35	0.171	0.12
Thorium	11.3	7.37	85.0

OPERATING EXPERIENCE WITH A SOLID IRIDIUM ANTI-PROTON TARGET AT CERN WILL FORM BASIS FOR CURRENT DESIGN

TARGET REFLECTOR AND MODERATOR DESCRIPTION

- EITHER TARGET IS EDGE COOLED - COOLANT FLOWS IN A SPIRAL COOLANT DUCT
- INNER REFLECTOR OF BERYLLIUM - EXTENDS 10 cm IN ALL DIRECTIONS BEYOND TARGET AND MODERATOR.
- OUTER REFLECTOR OF LEAD - EXTENDS 25 cm BEYOND THE BERYLLIUM INNER REFLECTOR IN ALL DIRECTIONS.
- CRYOGENIC MODERATOR EMBEDDED IN THE BERYLLIUM REFLECTOR. - TWO TYPES TO BE CONSIDERED
  - o LIQUID HYDROGEN (PARA) 20 K (REPRESENTED BY APPROPRIATE SCATTERING KERNEL)
  - o AMMONIA AT 20 K (REPRESENTED BY A GAS MODEL AT 20 K)
  - o MODERATORS ENCLOSED IN A DOUBLE WALLED VESSEL WITH A CADMIUM DE-COUPLER.
- TARGET DIAMETER DETERMINED BY A PERFORMANCE FIGURE OF MERIT - BASED ON NEUTRON CURRENT LEAVING FRONT FACE OF MODERATOR (NORMALIZED TO CASE 1)

		Solid iridium		Iridium particle	
Case	Target OD (cm)	FOM*	n/p^{+}	FOM	n/p^{+}
1	1.0	1.0	237	0.942	226
2	2.0	1.351	264	1.187	249
3	3.0	1.434	281	1.250	262

- TARGETS WITH 3 cm OD WILL BE CONSIDERED IN THIS STUDY.

POWER DEPOSITED IN THE TARGET REFLECTOR AND MODERATOR ASSEMBLY

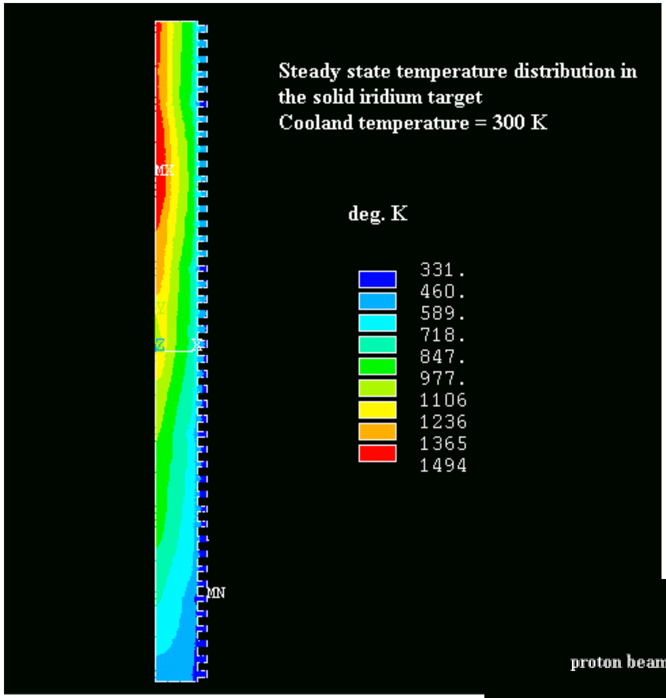
COMPONENT	POWER (WATTS)*
Solid Iridium target	31,848
Titanium clad	407
Cooling water	531
Aluminum containment	257
Vacuum chamber	510
Cd de-coupler	1,253
Moderator container	125
Liquid hydrogen moderator	90
Total Be	7,111

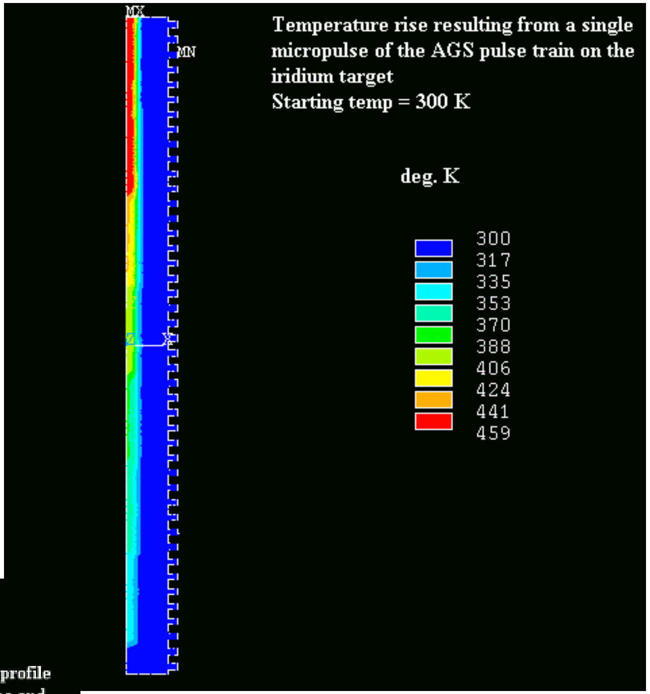
* Assuming an average power of 100 kW

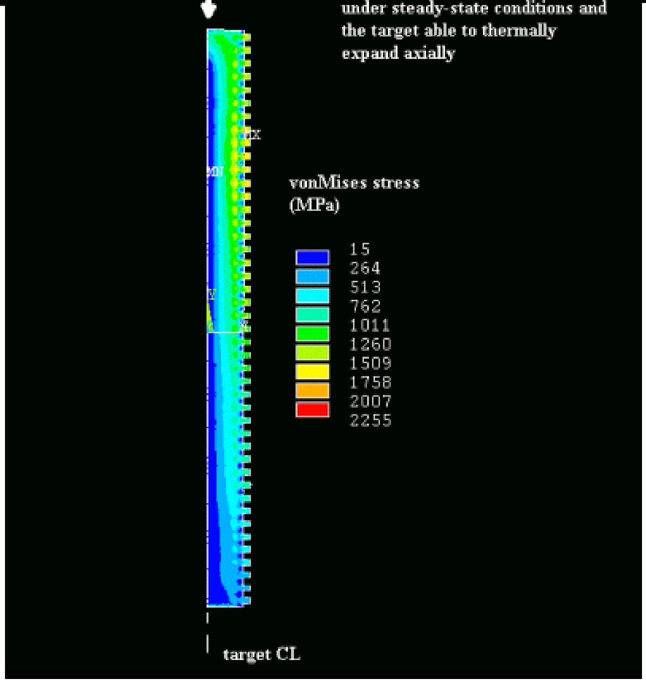
ENERGY DEPOSITED IN PARTICLE BED TARGET PER PULSE

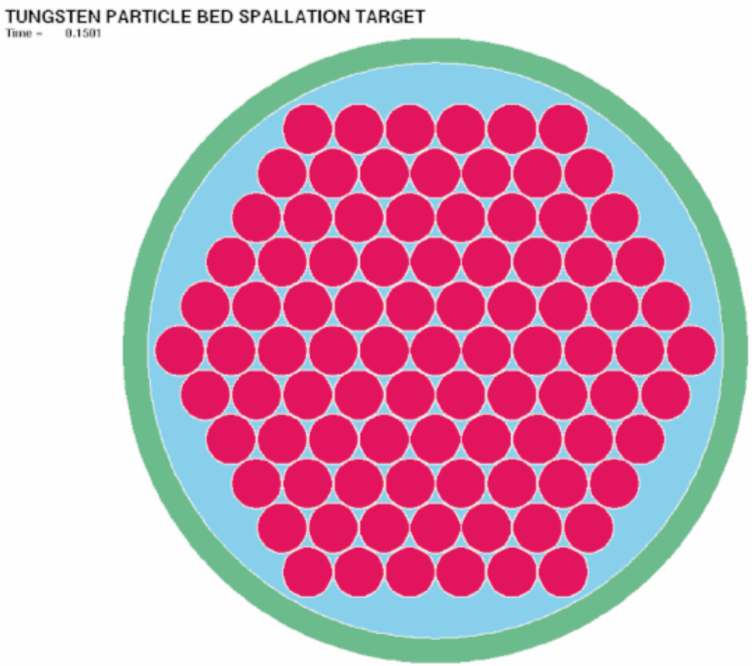
ENERGY DEPOSITED PER PARTICLE AND ASSOCIATED LEAD, FOR THE VARIOUS LAYERS IN A HEXAGONALLY ORDERED PARTICLE BED, PER PULSE (ASSUMING 6.242 X 10^{12} PROTONS PER PULSE)

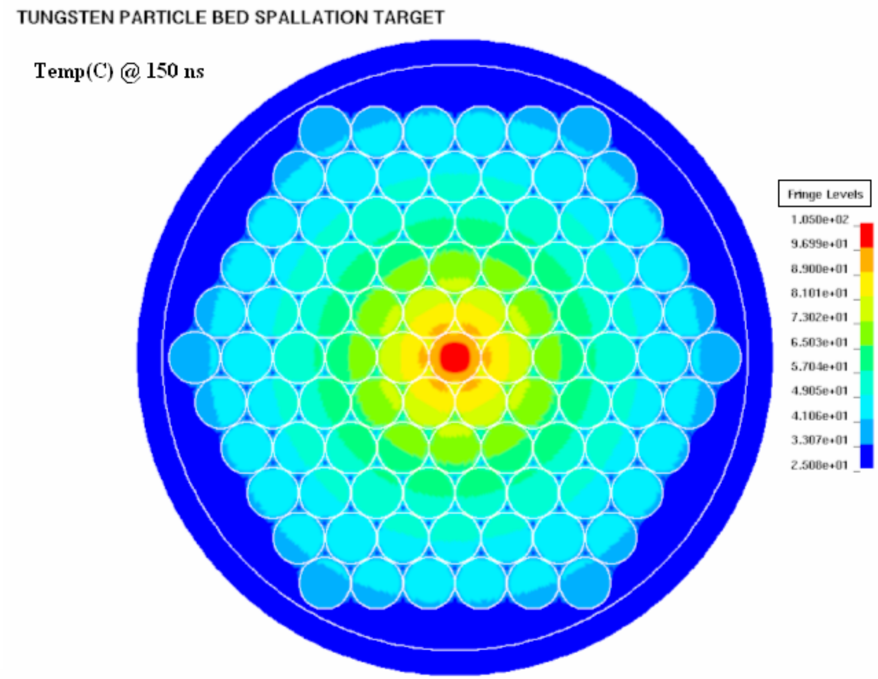
Layer number	Number of units	Particles (J/cc)	Lead (J/cc)
1	1	438	257
2	6	386	229
3	12	59	46
4	18	7	4
5	24	3	2
6	30	1	1
Remainder		~	1

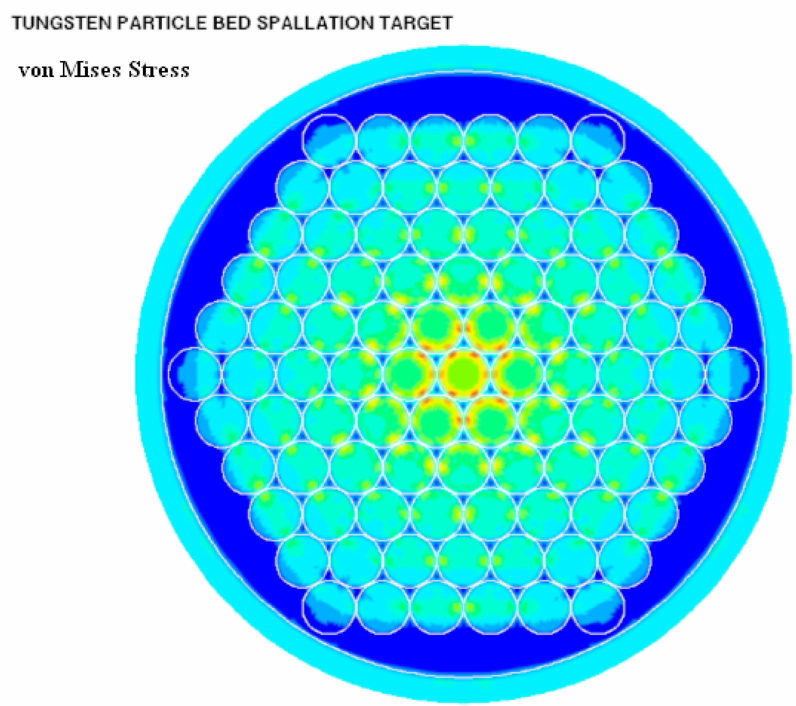

Steady state temperature distribution in the solid iridium target
Cooland temperature = 300 K
deg. K
331.
460.
589.
718.
847.
977.
1106
1236
1365
1494
MX
MN

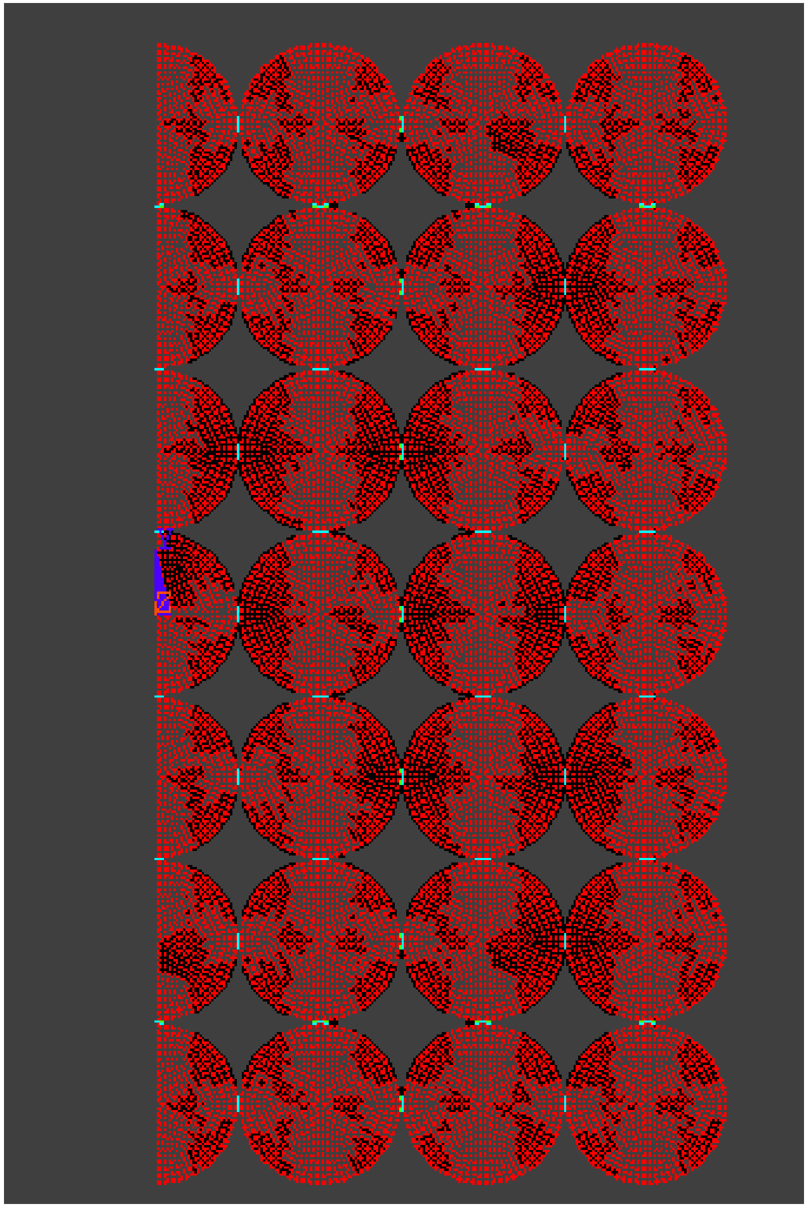

Temperature rise resulting from a single micropulse of the AGS pulse train on the iridium target
Starting temp = 300 K
deg. K
300
317
335
353
370
388
406
424
441
459
MX
MN


proton beam
Estimated vonMises stress profile under steady-state conditions and the target able to thermally expand axially
vonMises stress
(MPa)
15
264
513
762
1011
1260
1509
1758
2007
2255
MX
MN
target CL

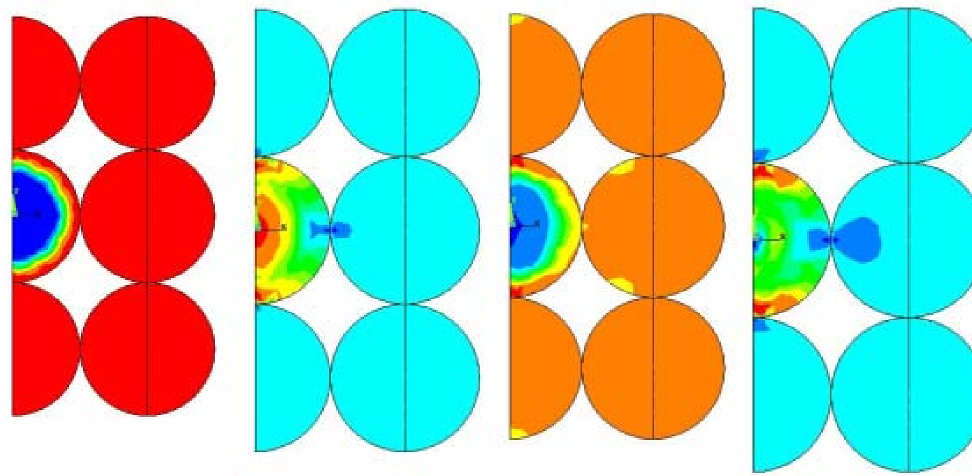

TUNGSTEN PARTICLE BED SPALLATION TARGET
Time = 0.1501


TUNGSTEN PARTICLE BED SPALLATION TARGET
Temp(C) @ 150 ns
Fringe Levels
1.050e+02
9.699e+01
8.900e+01
8.101e+01
7.302e+01
6.503e+01
5.704e+01
4.905e+01
4.106e+01
3.307e+01
2.508e+01


TUNGSTEN PARTICLE BED SPALLATION TARGET
von Mises Stress

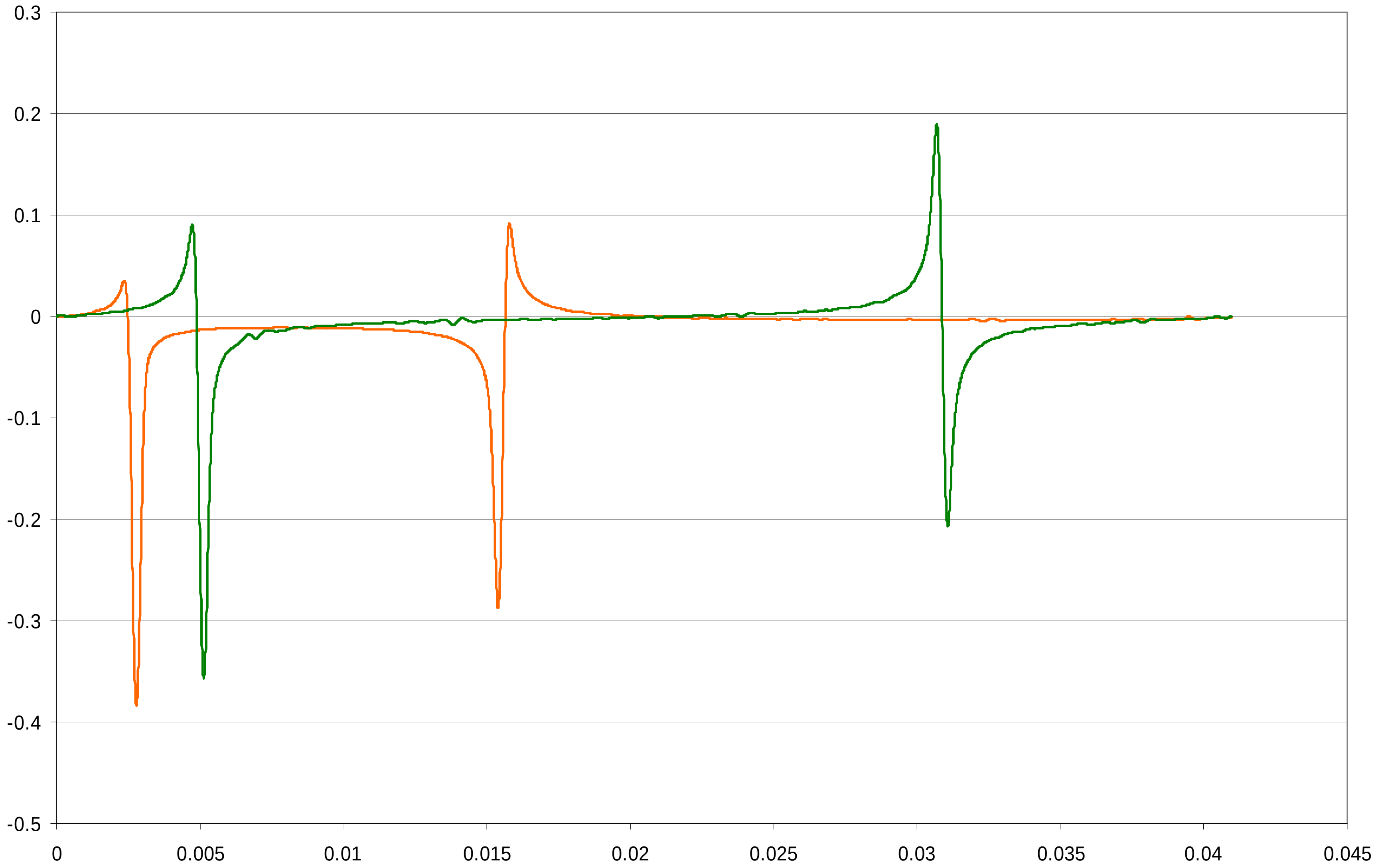


Microscopic Evaluation Of a Particle Bed Target



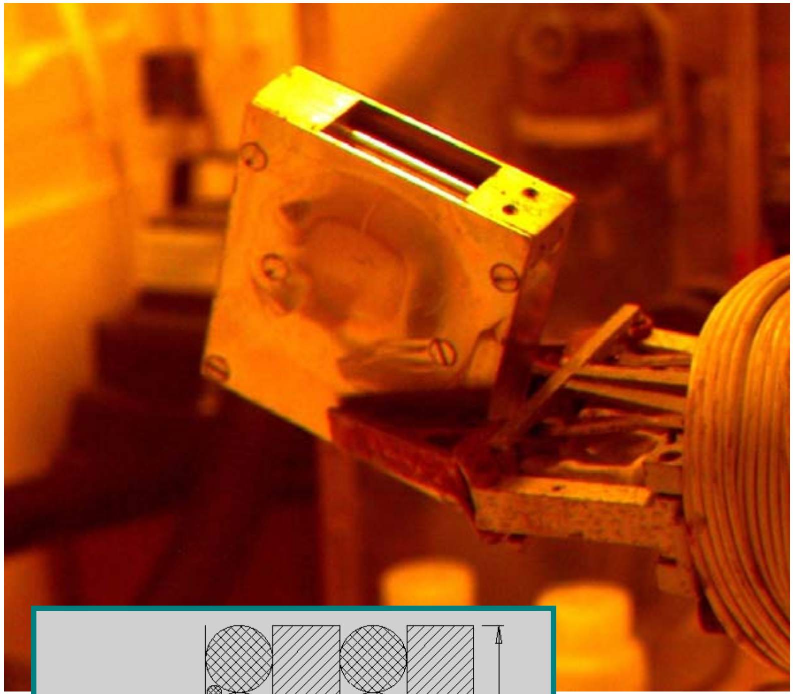
MACROSCOPIC ASSESSMENT OF A PARTICLE BED OPTION

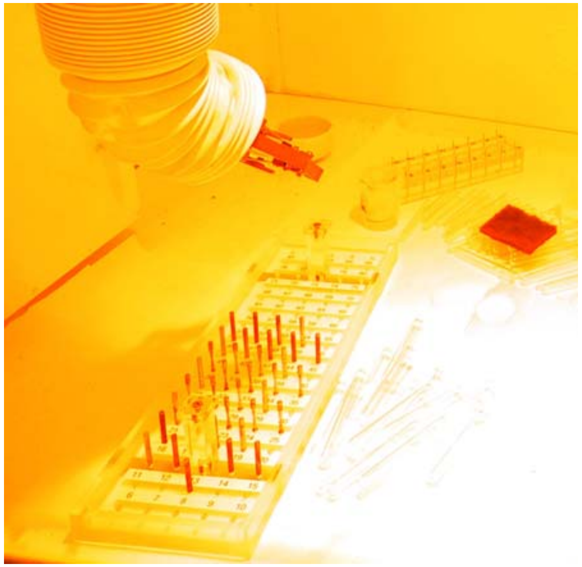
- Utilize poroelastic equations of saturated medium
- Assess pulse attenuation vs. microscopic geometric parameters
- Validate using a controlled experiment

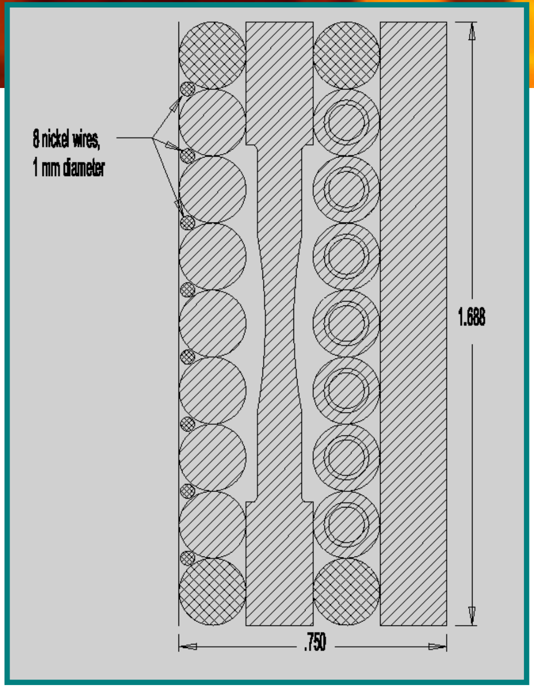


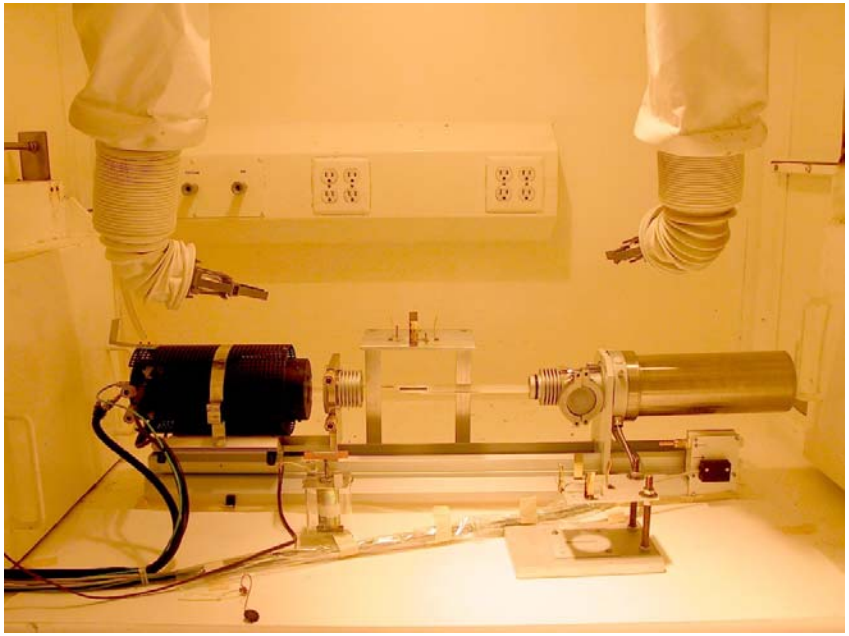
0.3
0.2
0.1
0
-0.1
-0.2
-0.3
-0.4
-0.5
0
0.005
0.01
0.015
0.02
0.025
0.03
0.035
0.04
0.045

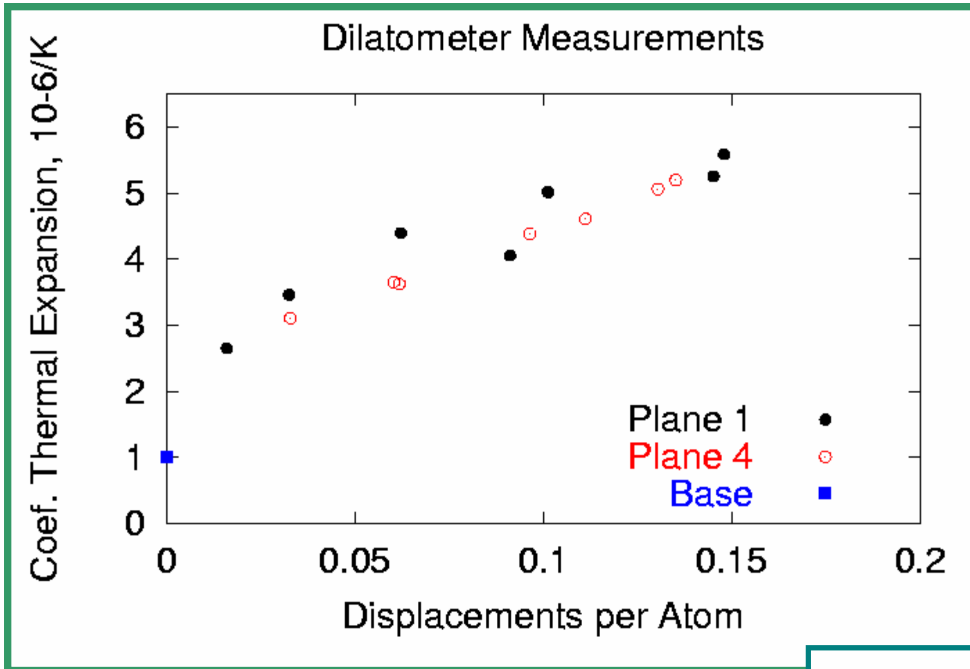
Recent BNL Irradiation Studies



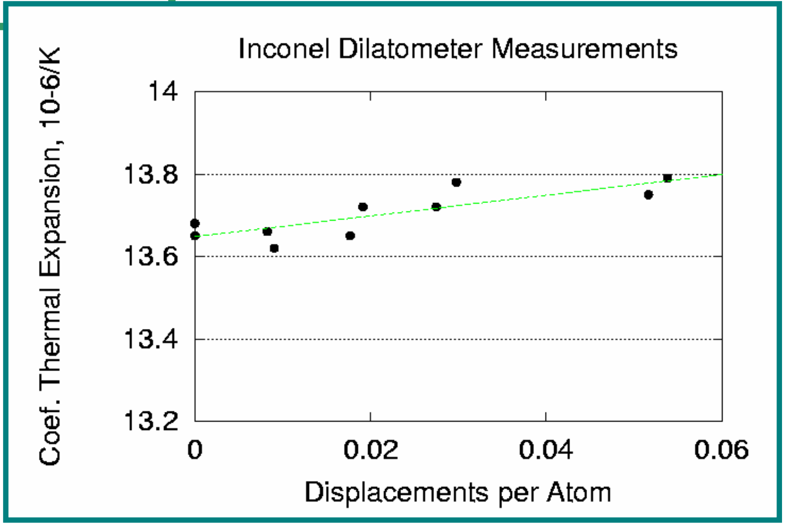




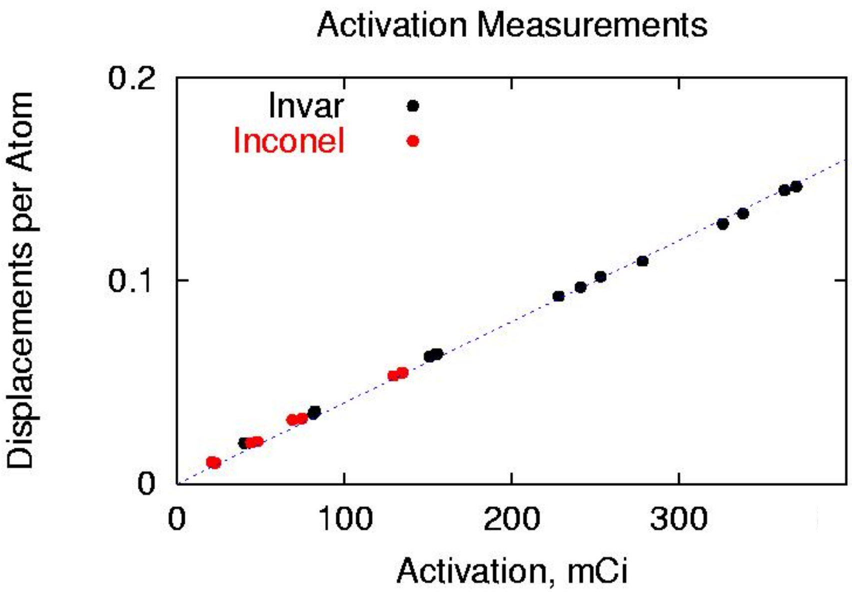


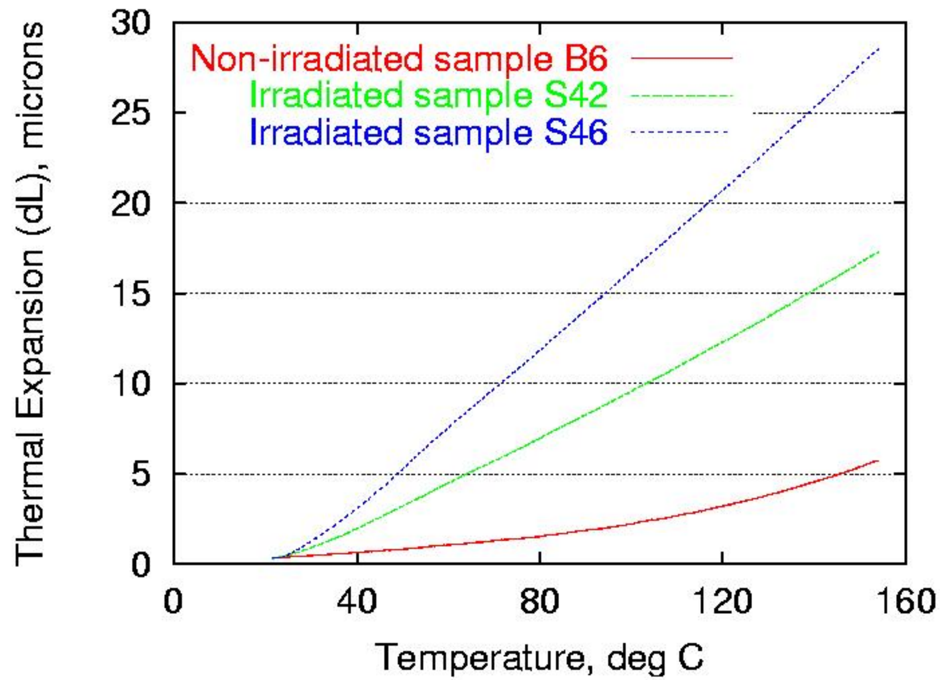


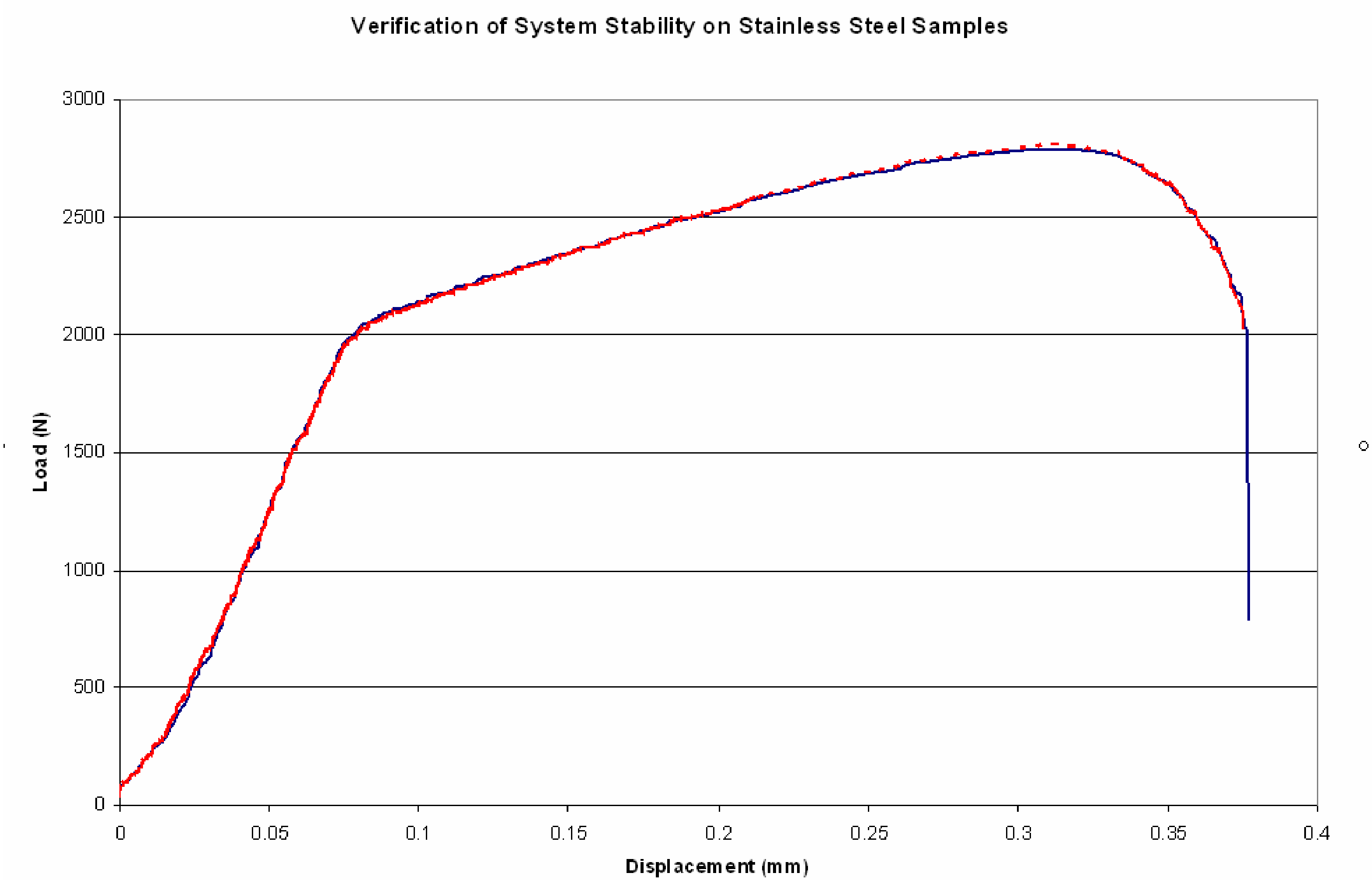
Dilatometer Measurements
Coef. Thermal Expansion, 10-6/K
0
1
2
3
4
5
6
0
0.05
0.1
0.15
0.2
Displacements per Atom
Plane 1
Plane 4
Base



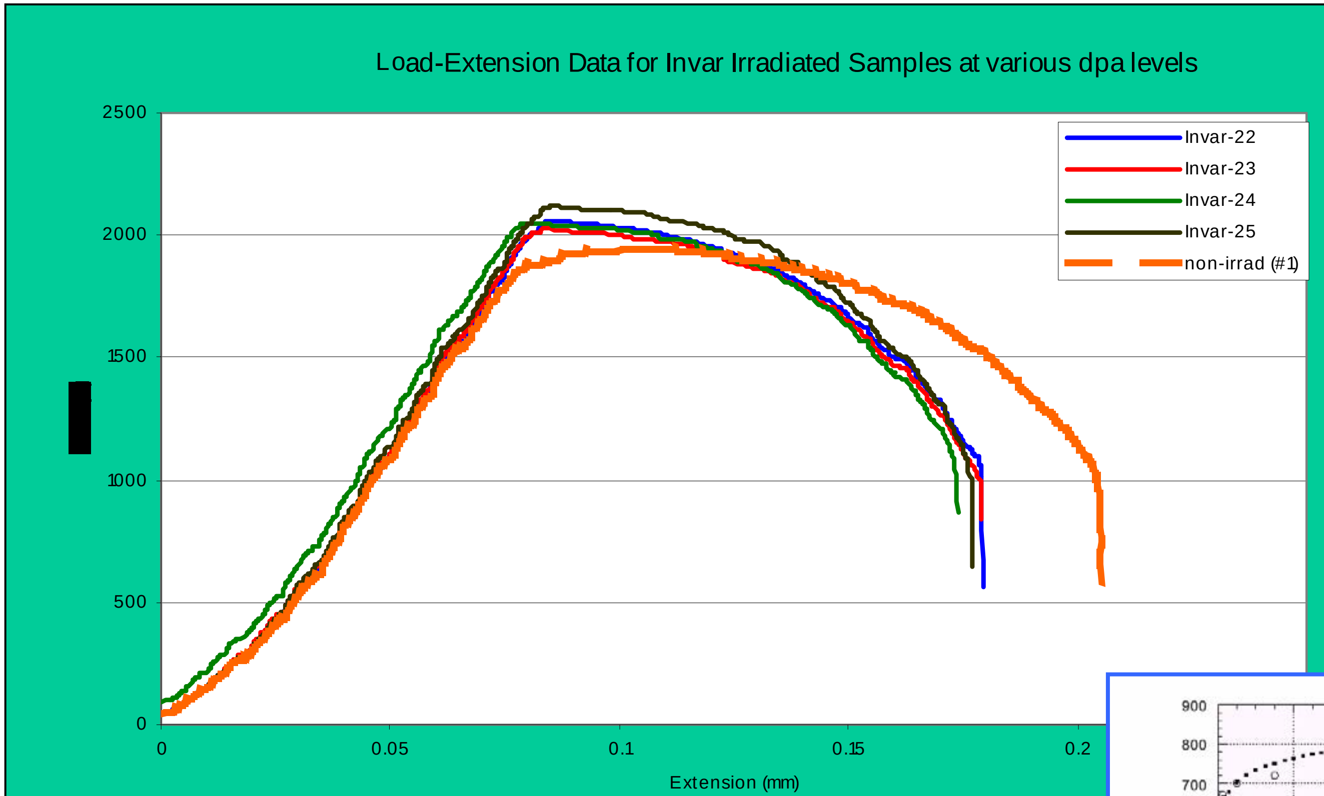
Inconel Dilatometer Measurements
Coef. Thermal Expansion, 10-6/K
13.2
13.4
13.6
13.8
14
0
0.02
0.04
0.06
Displacements per Atom


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


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

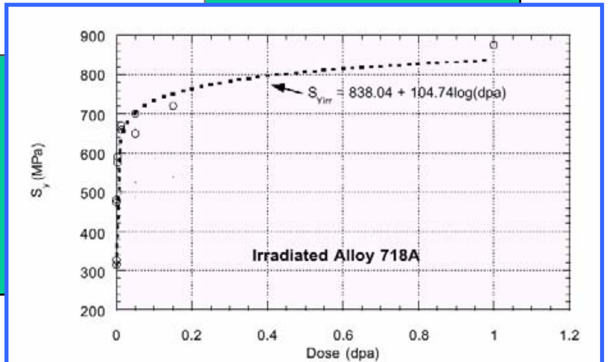

Verification of System Stability on Stainless Steel Samples
3000
2500
2000
1500
1000
500
0
Load (N)
0
0.05
0.1
0.15
0.2
0.25
0.3
0.35
0.4
Displacement (mm)

Solid Target Option: Super-Invar Irradiation Study



WHY STUDY super Invar ?

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



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

Super-Invar Irradiation Study – Temperature Effects