E951 Experiment

Target Response Re-evaluation

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E951 Window/Graphite Study Goals

- Test Hg, Graphite and window targets for the Muon collider/neutrino factory
- Push the AGS intensity to 16 TP and the beam spot to 0.5 mm RMS sigma
- Find best possible materials that can be used as beam windows under such 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
- Finally, use experimental results to benchmark energy depositions predicted by the various Monte Carlo codes

Why the Re-evaluation ?

- **Material activation analysis (P. Thieberger) revealed that the beam spot was smaller than originally assumed !!!**
- **OLD beam spot estimated based on FLAG: 0.7mm x 1mm**
- **REVISED beam spot: 0.3 mm x 1mm rms sigma**

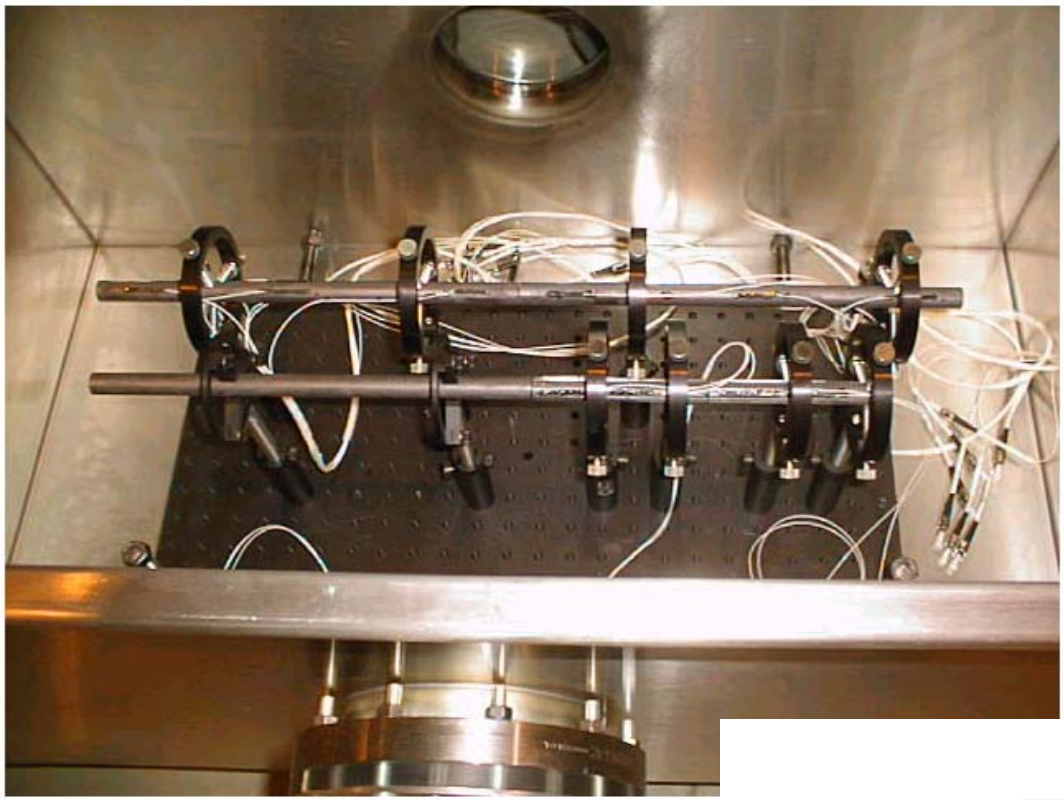
- **QUESTIONS:**
- **What does this mean to the window materials that intercepted the beam ?**
- **Did any window approached a condition that would be considered failure ?**
- **How do the prediction models perform with this new input as they compare to the measured strains ?**

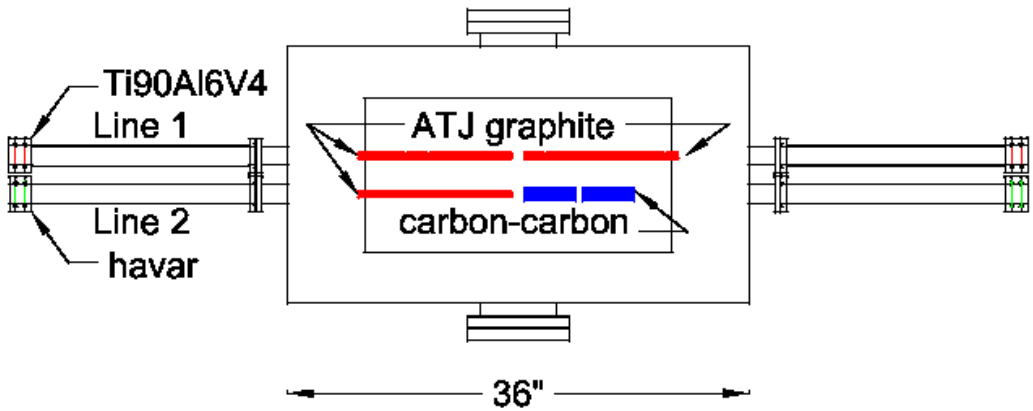
Some Answers and new facts !!!

- **Examination of the actual windows showed that the beam did not intercept the window at dead center (~ 3.7 mm offset toward gauge 3)**
- **Orientation of the ellipse representing the energy deposition on the windows relative to the gauges not known yet (this is important info in trying to predict the response using the FEA model)**
- **While no beam-spot measurement was made for the graphite target tests, the new spot was used to re-assess the response of these targets**

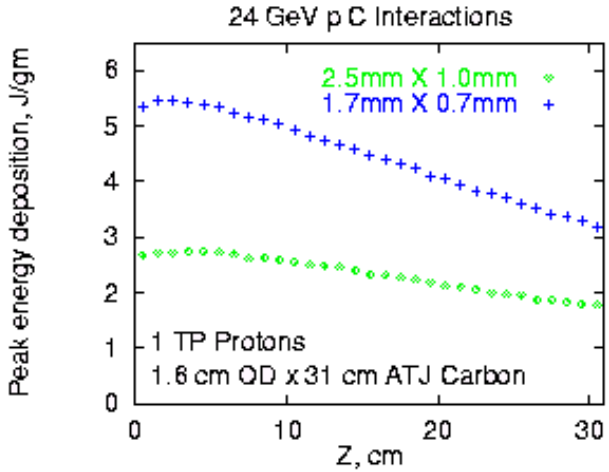
- **ANSWERS to some of the QUESTIONS:**
- **There was no loss of vacuum in any of the double windows, indicating that no FAILURE has occurred !!**
- **The utilized model also predicts that no window material (given the intensity achieved < 2.7 TP and the pulse length ~ 100 ns base) would approach yield**

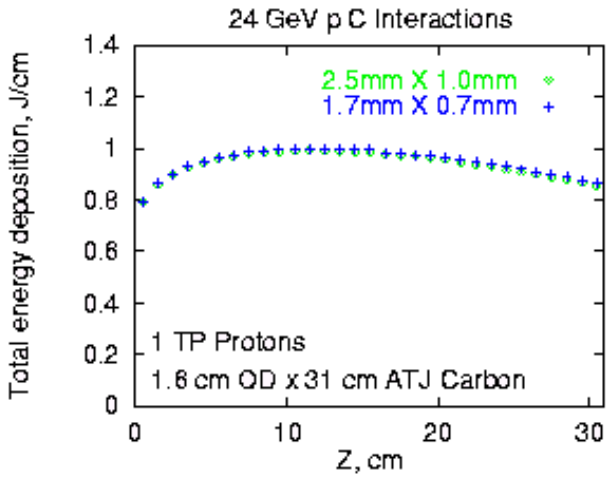
E951Target Station Set-Up
Graphite Targets





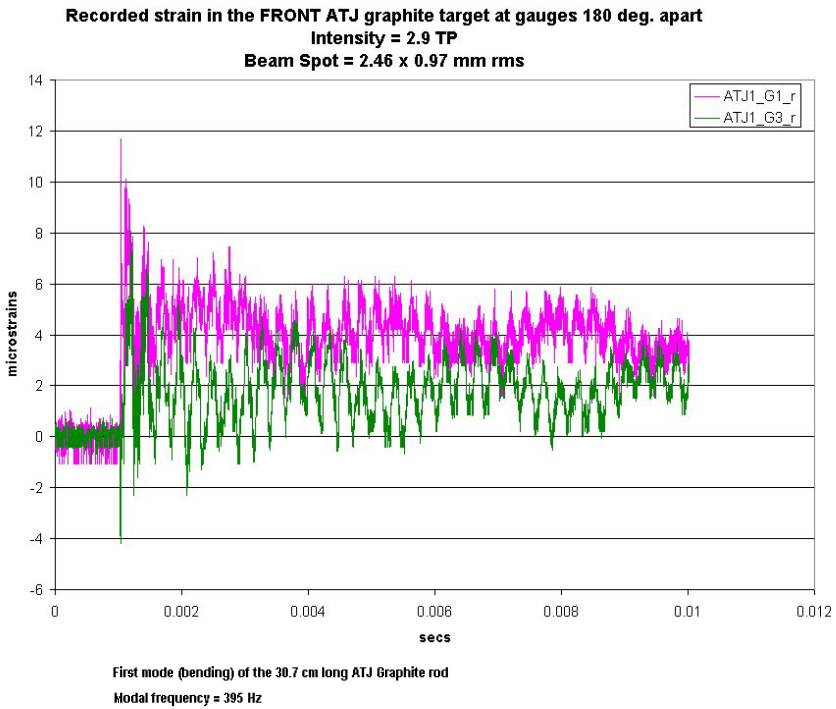
ATJ Graphite Energy Depositions (old beam spots assumed to have been achieved during the two runs)





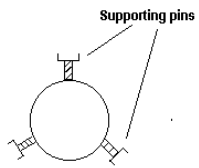
ATJ Graphite Strain Data

Verification of fundamental modes of target response



First mode (bending) of the 30.7 cm long ATJ Graphite rod

Modal frequency = 395 Hz



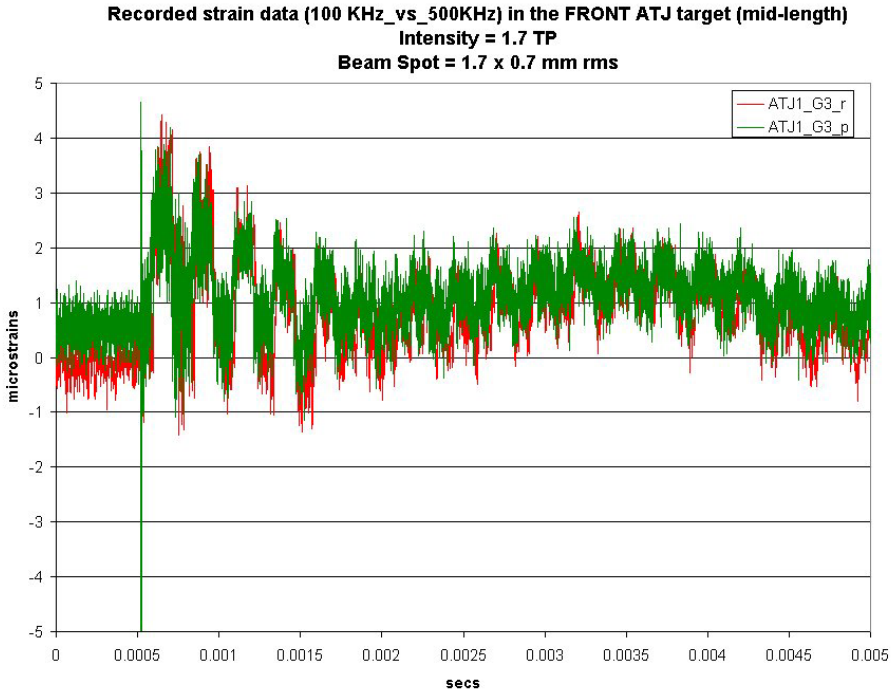
Record of strains in the middle of the graphite rod (left) shows a bending frequency between 380-390 Hz

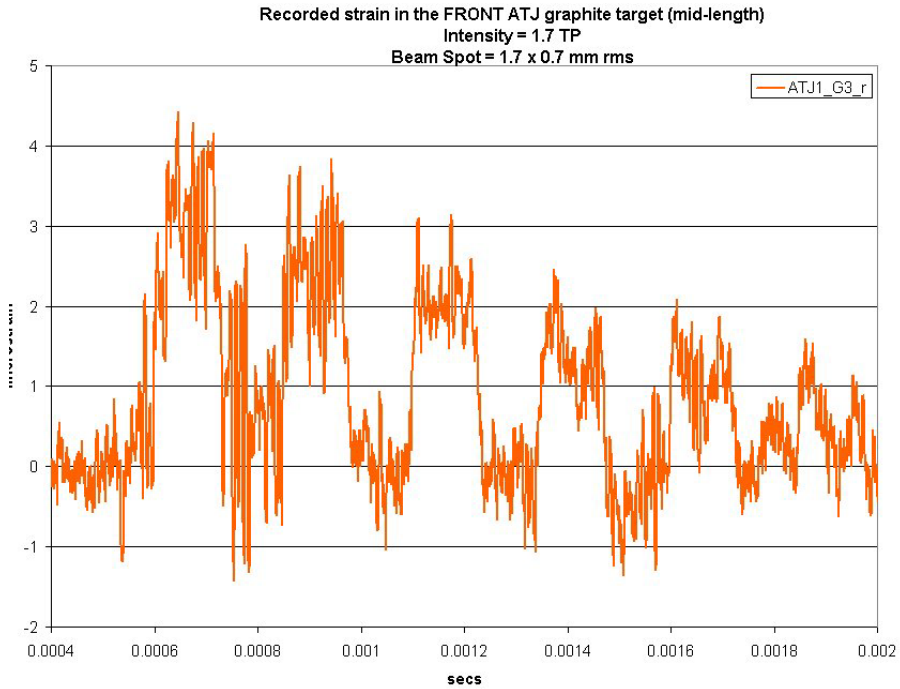
The prediction of the detailed model that implements the supporting/holding fixtures of the target as close to the real setting as possible, predicts a bending frequency of 395 Hz

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

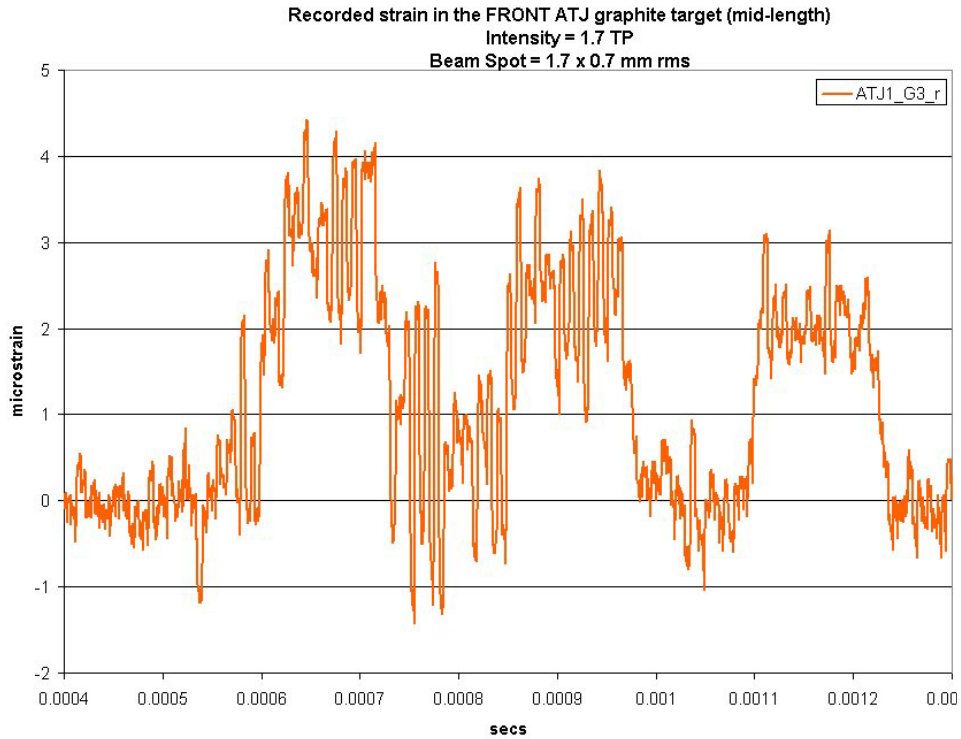
ATJ Graphite Strain Data

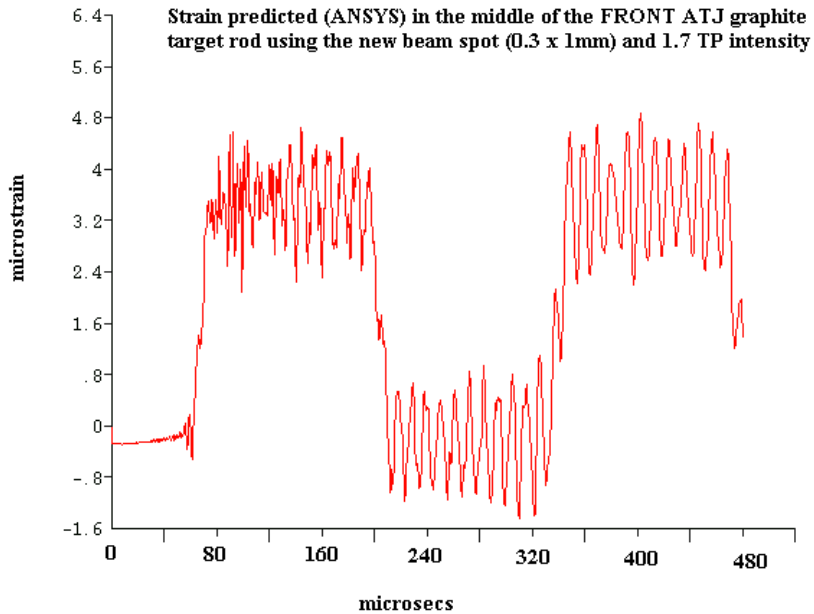




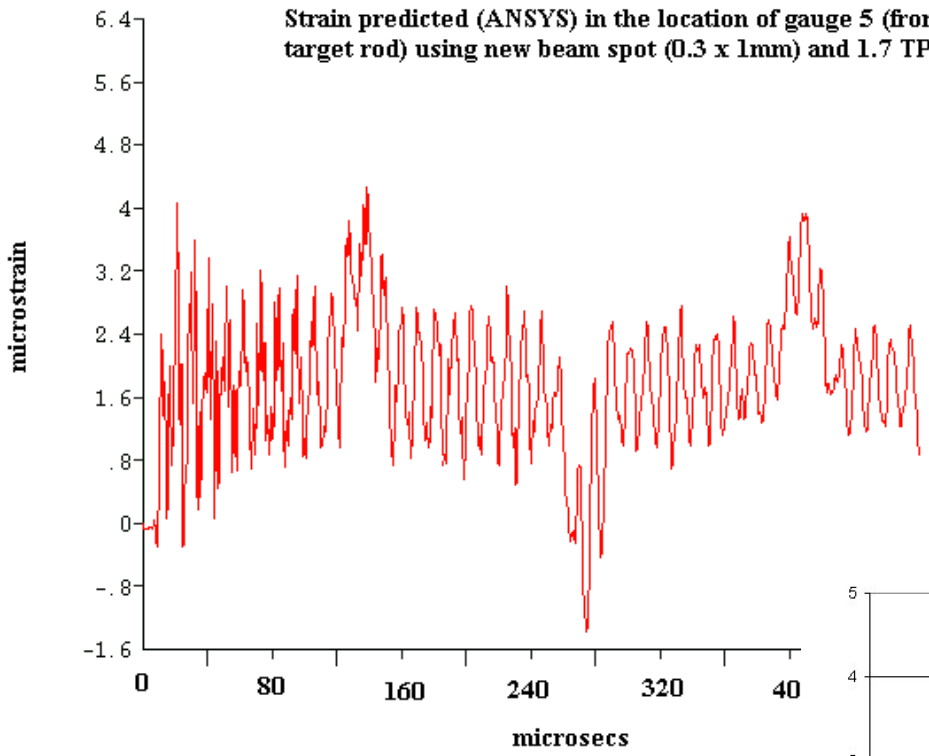
ATJ Graphite Strain Comparison

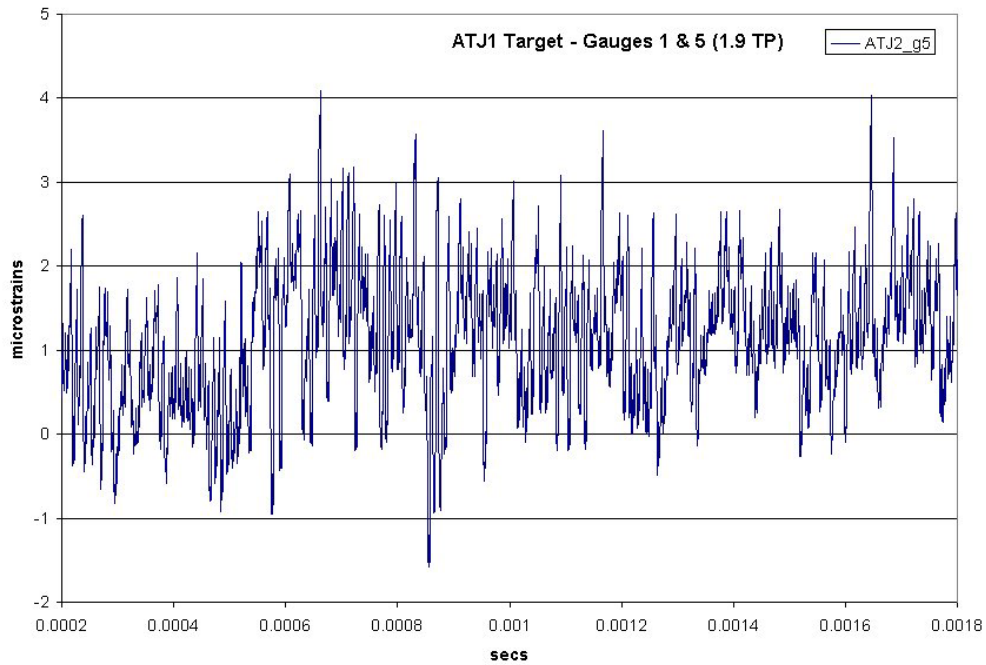
Prediction model has not implemented damping from supports or material



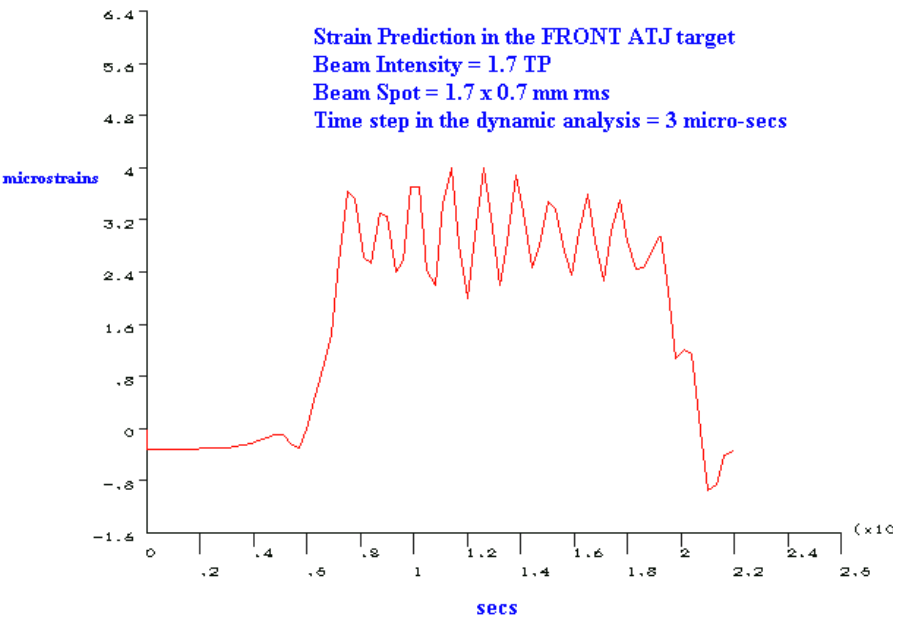


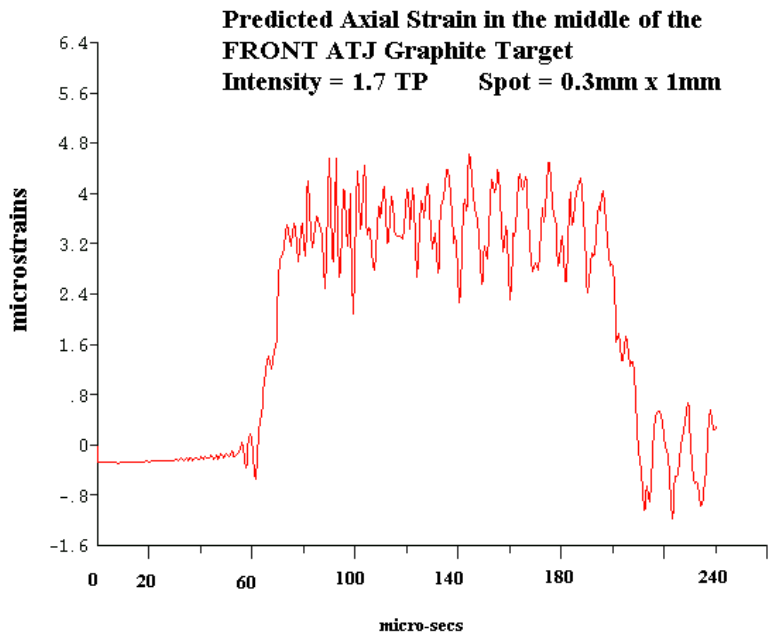
ATJ Graphite Strain Data - Predictions



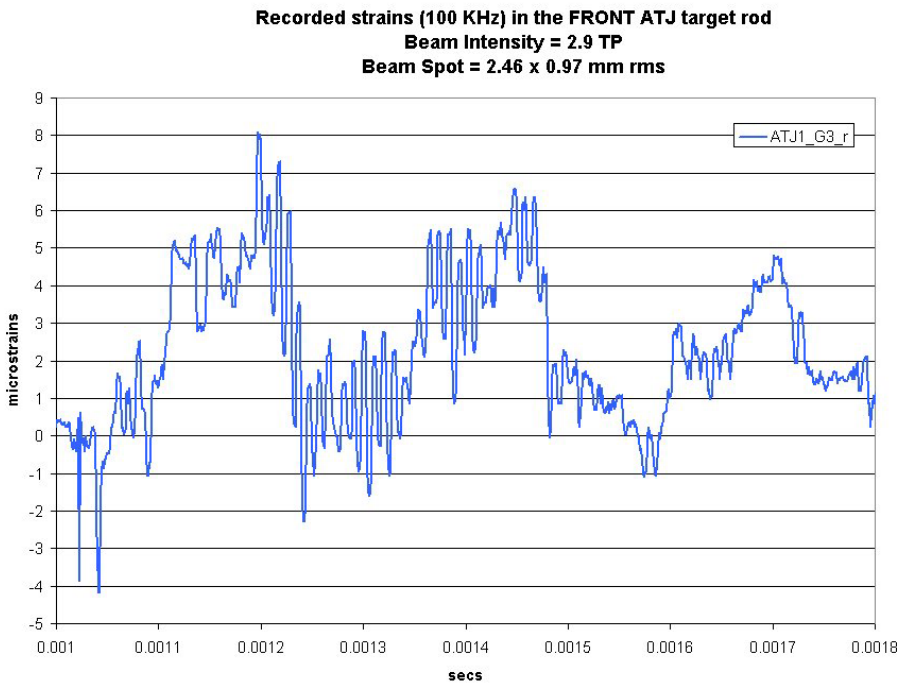


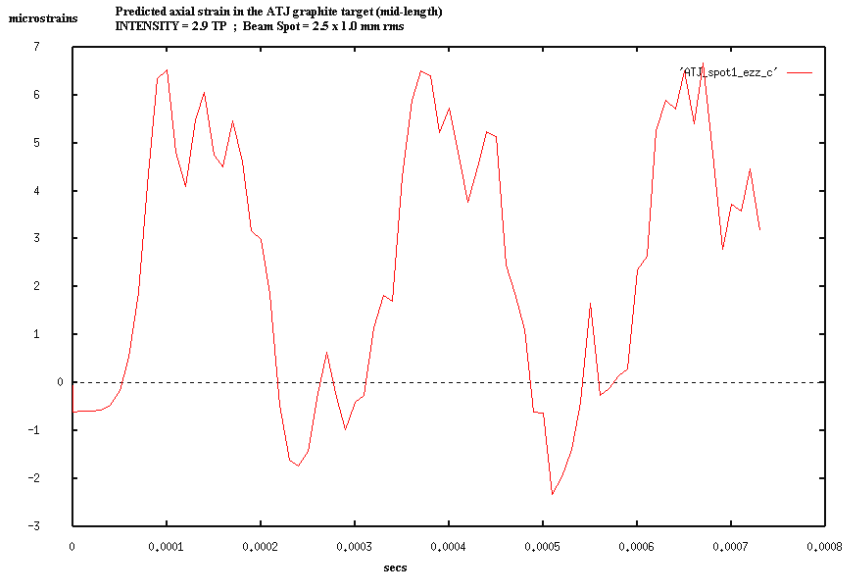
ATJ Graphite Strain Data - Prediction comparison between beam spots



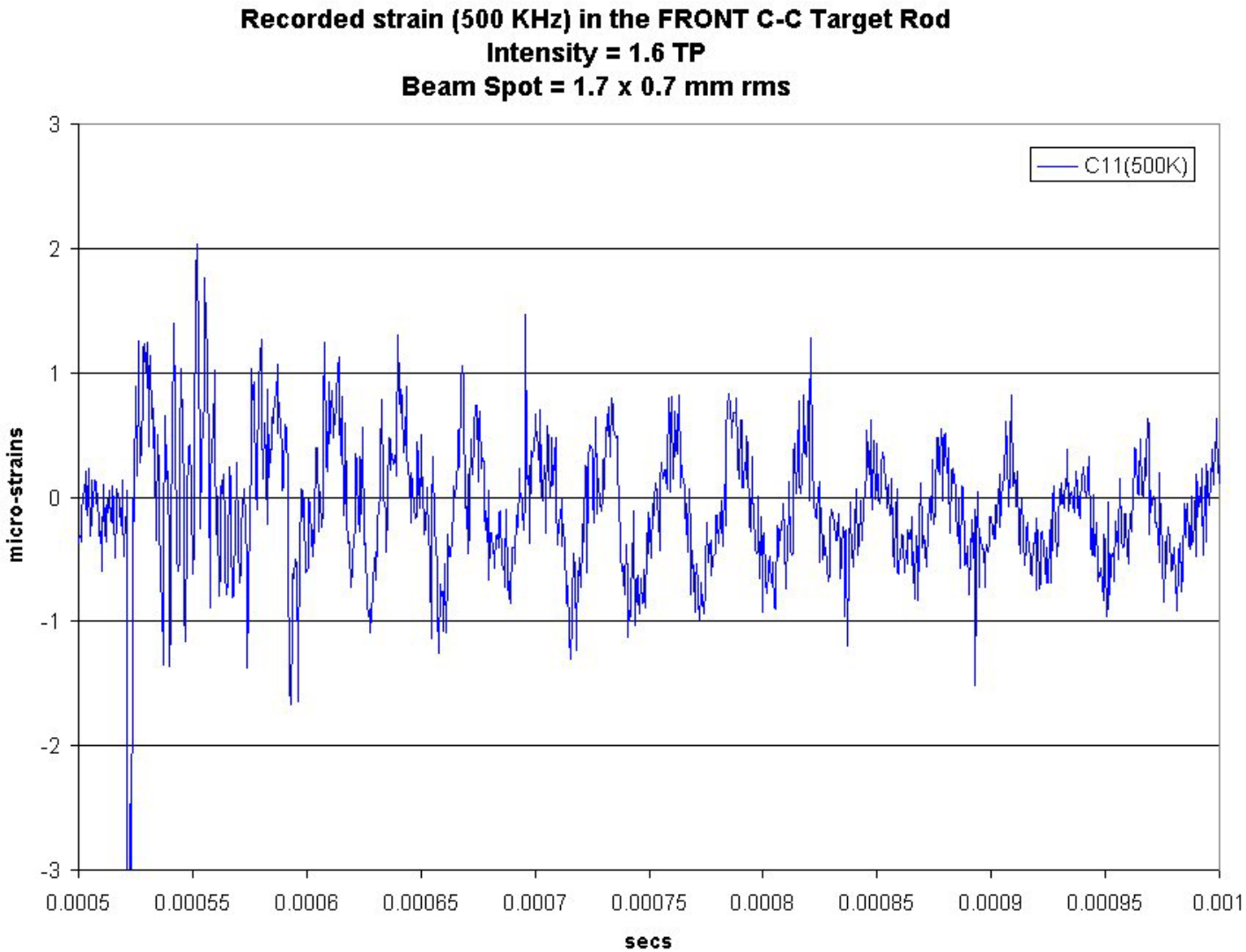


ATJ Graphite Strain Data - Predictions



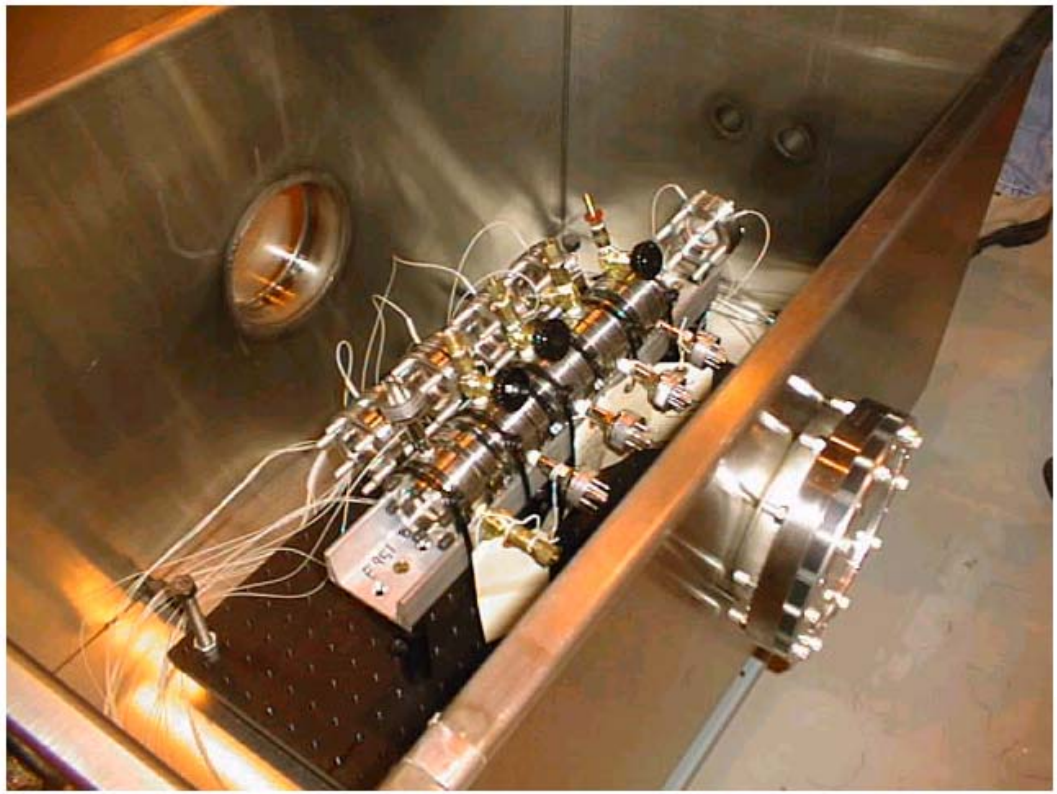


Carbon-Carbon Strain Data

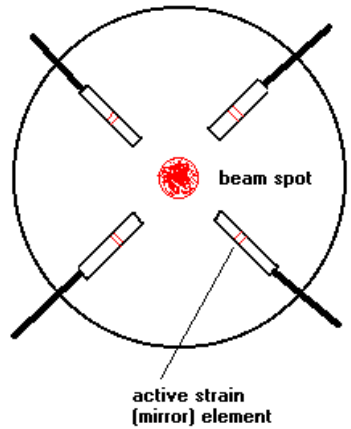


E951 WINDOW TEST Station Set-Up

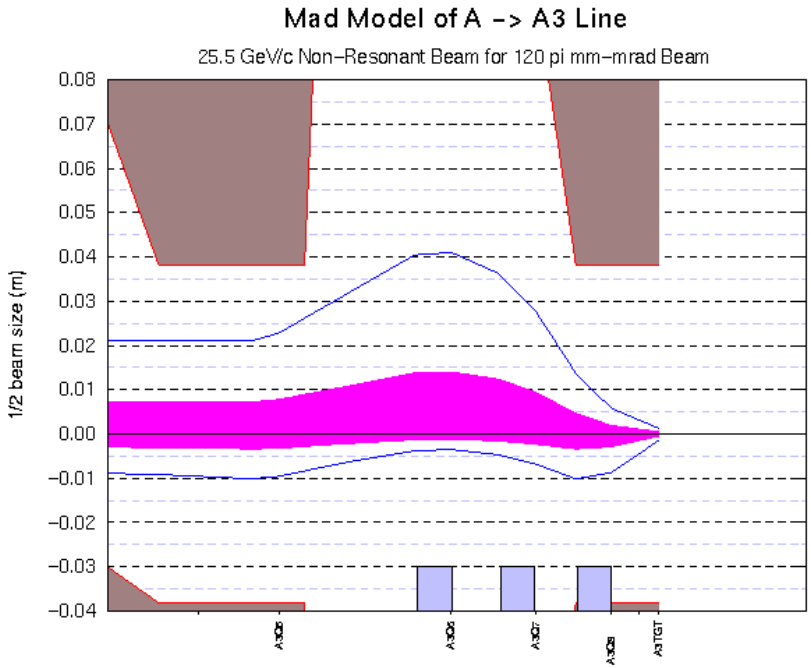
Fiber-optic Strain Gauges & Double window vacuum monitoring

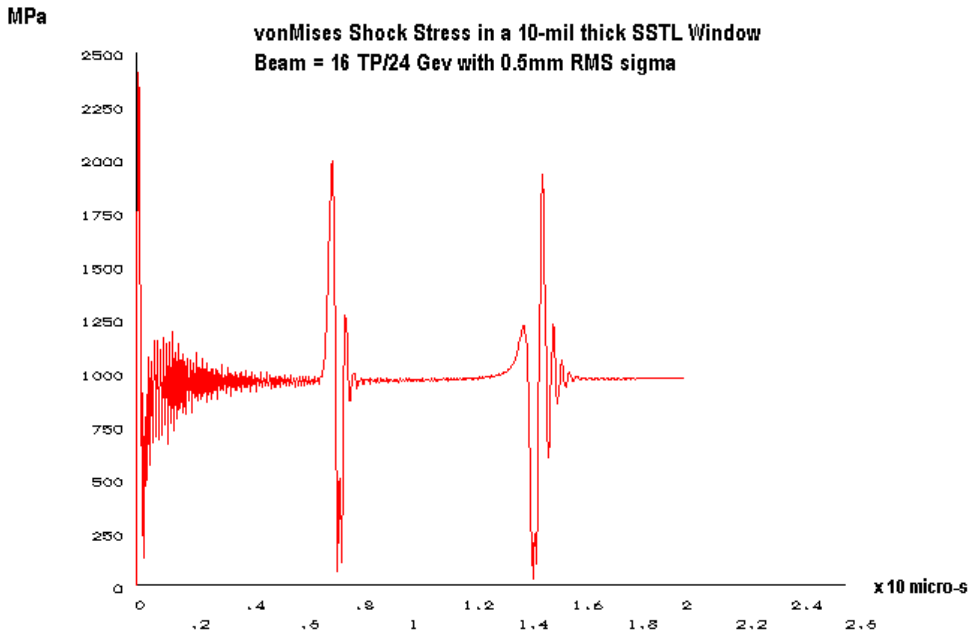


Fiberoptic Strain Gauge Arrangement in the 2" diam. Beam Window



What Triggered the Window Experimental Effort





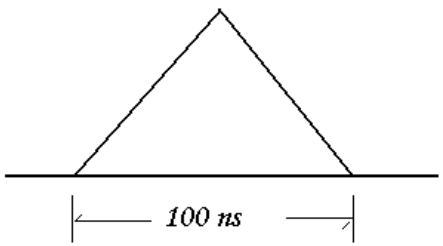
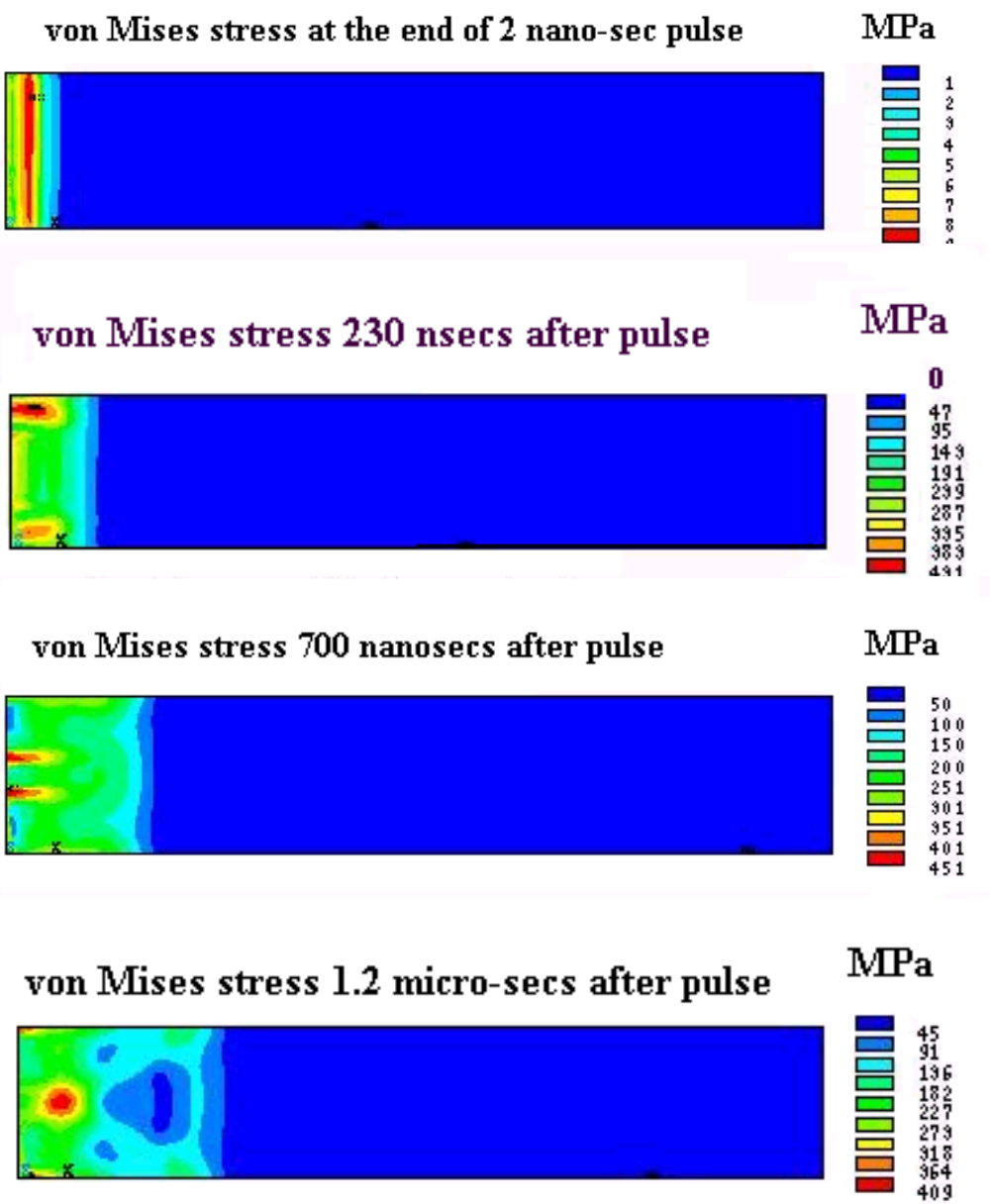


Figure above depicts the tight beam spot requirement (0.5 x 0.5 mm rms) for target experiment at AGS

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

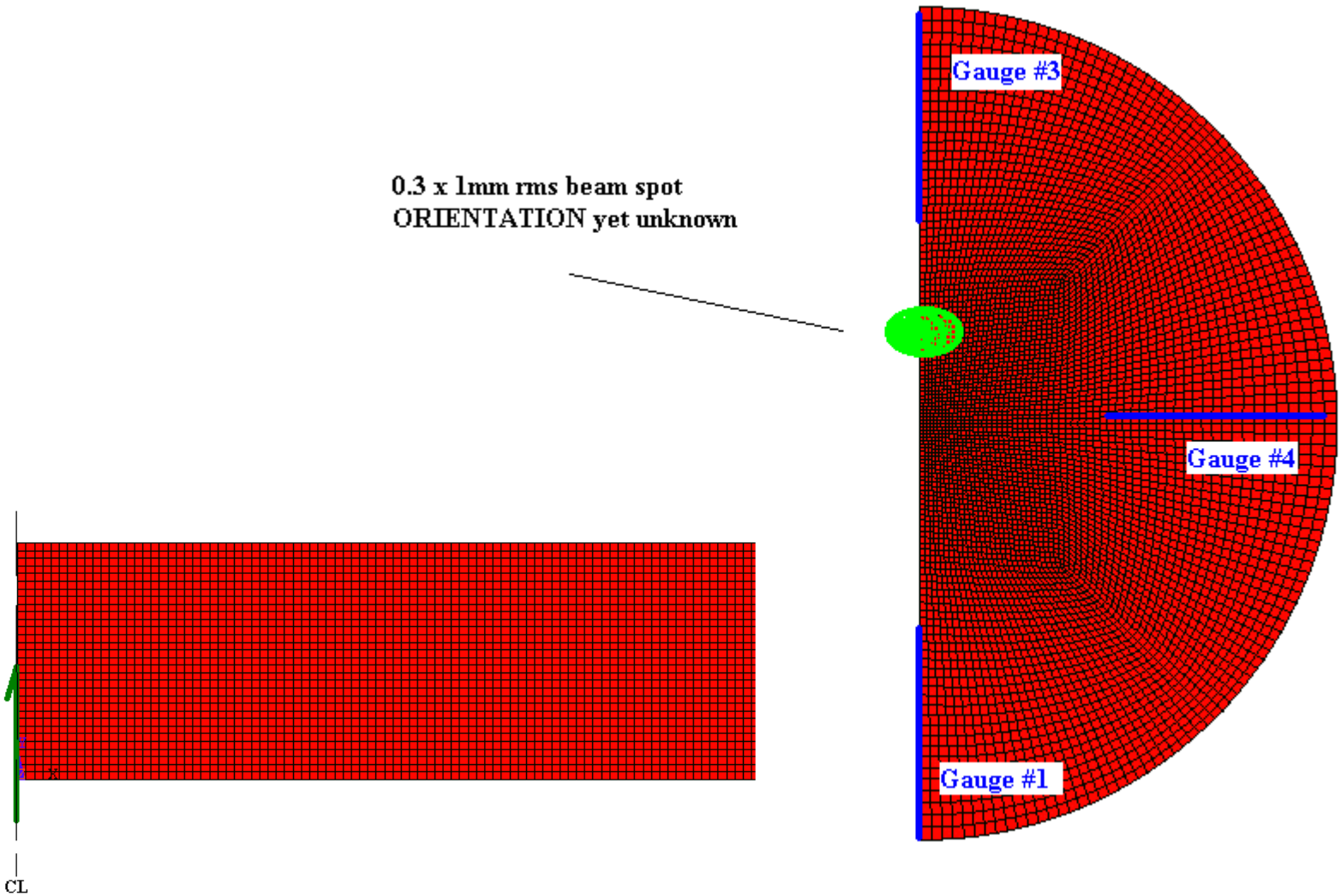


- No matter how thin the window is, the reverberation of stress between surfaces is the key issue
- vonMises stress amplitude depends on the spot size (initial compressive load amplitude), thickness of window, speed of sound and pulse shape
- the measurement of strain on the surface is to be used as 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

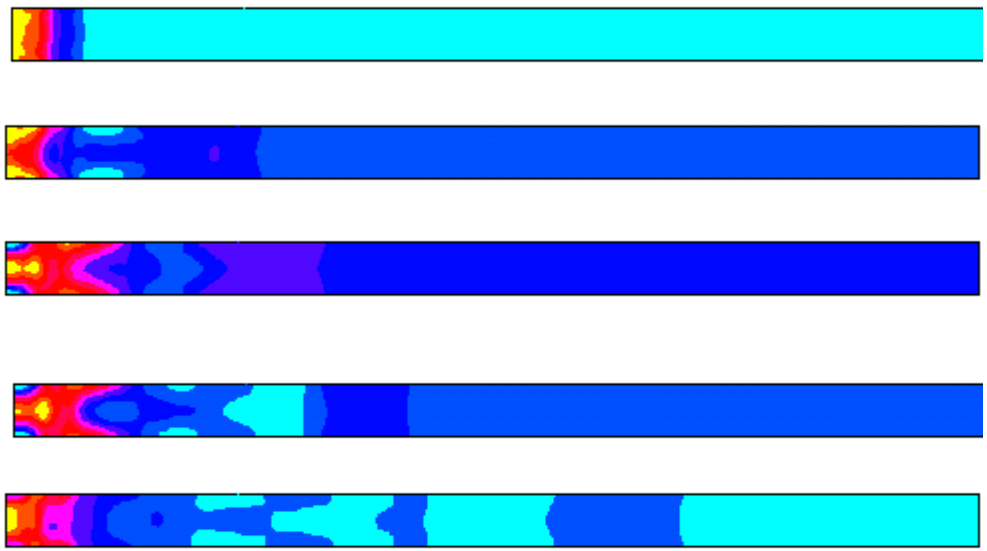
Issues and Material Matrix selection

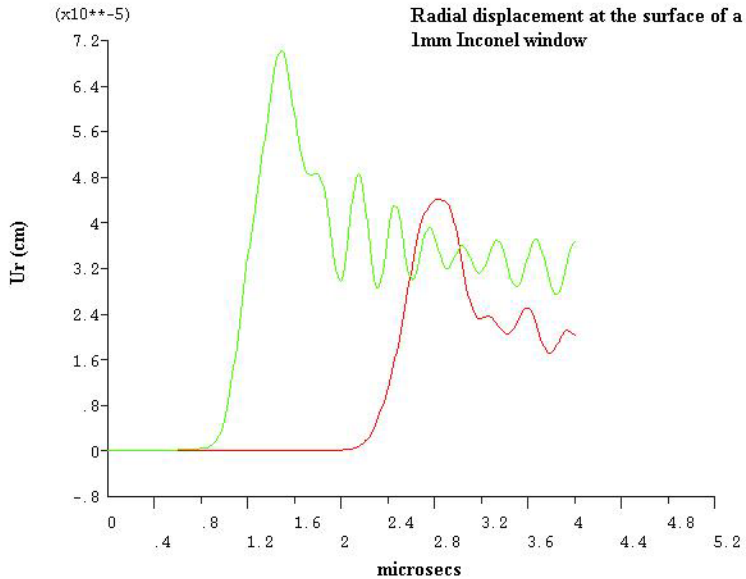
- FAST proton beam interacting with window and depositing energy in small spot inducing shock waves
- Based on a 24 GeV/16 TP/0.5 mm rms beam MOST materials could fail with a single pulse
- Though thin, failure in window governed by through-thickness response
- **Sound speed**, **material thickness** 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)

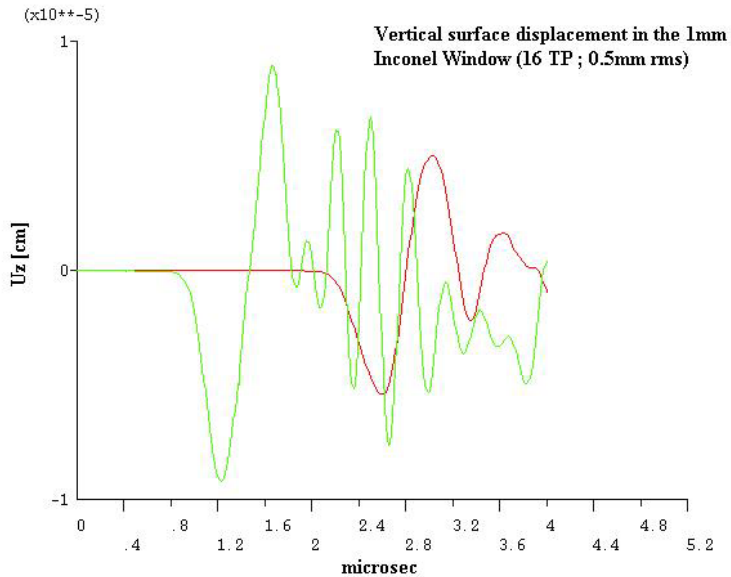
Finite Element Models to Capture the Dynamic Response of Windows
2D axisymmetric vs. Shell model

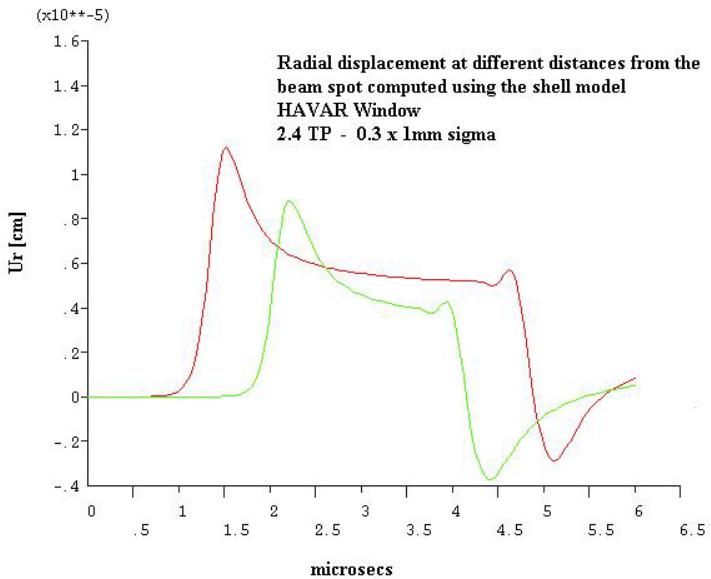


2D axisymmetric vs. Shell model
Strain wave in a 1mm Inconel window - Rayleigh Waves



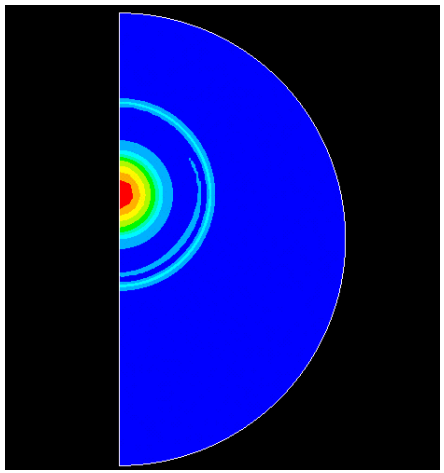


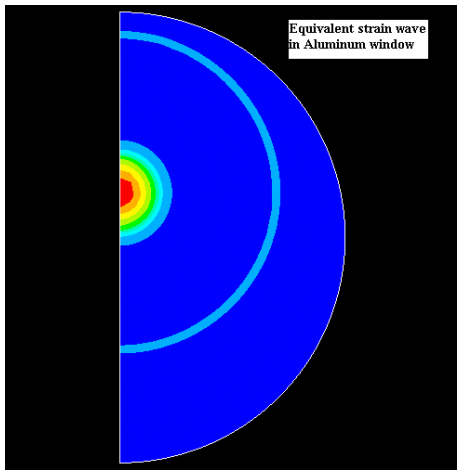


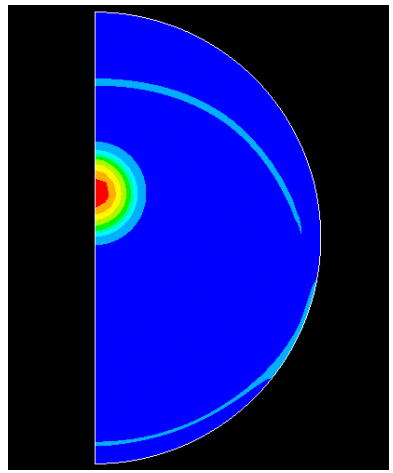


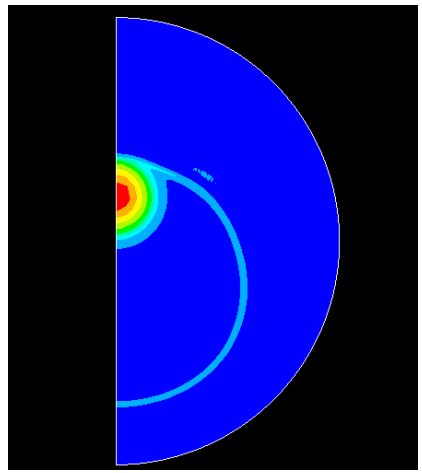
Aluminum Window Strain Data - Shell model

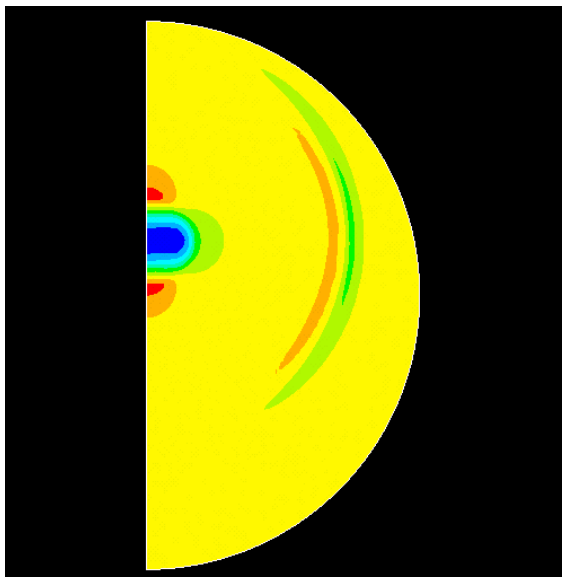
Experimental data vs. prediction using the new beam spot (0.3 x 1mm)

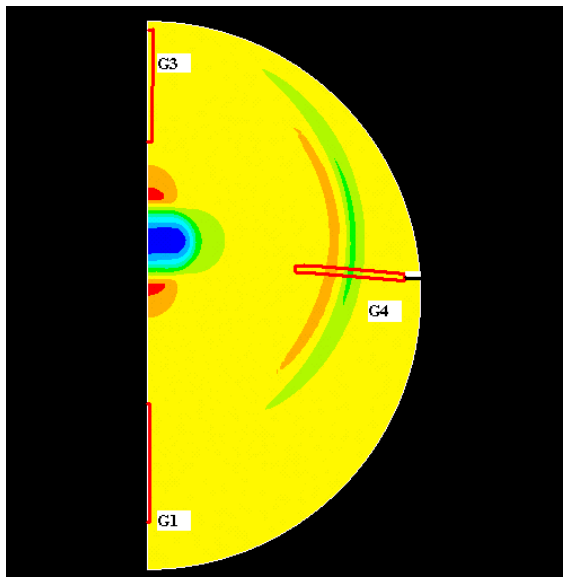


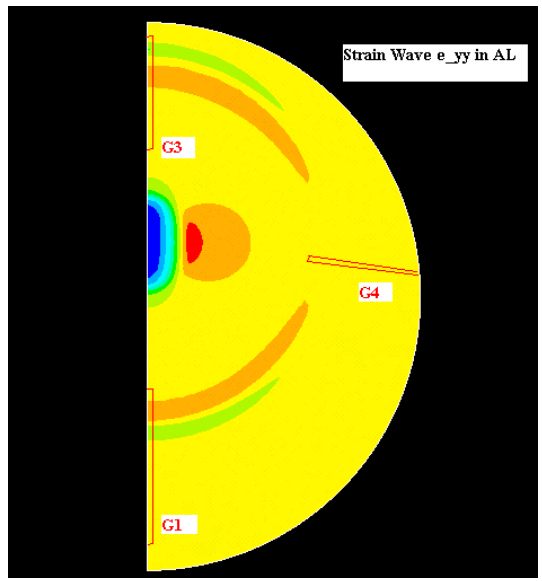






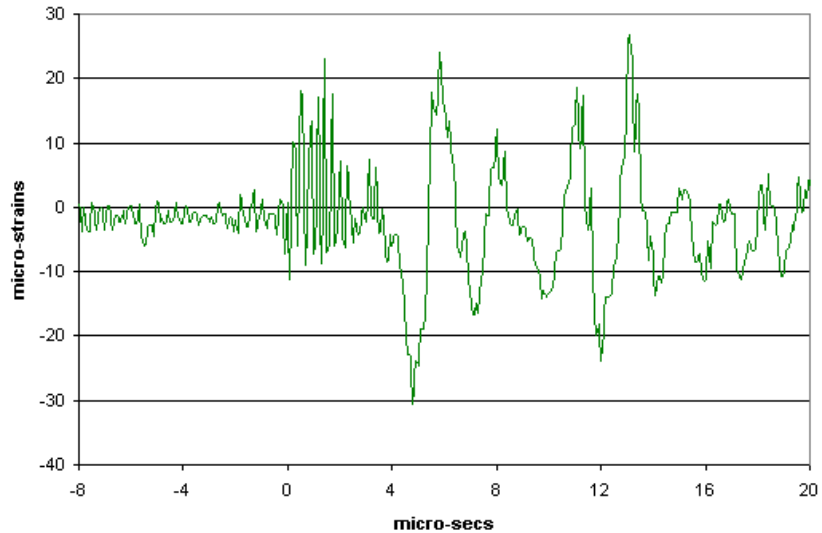


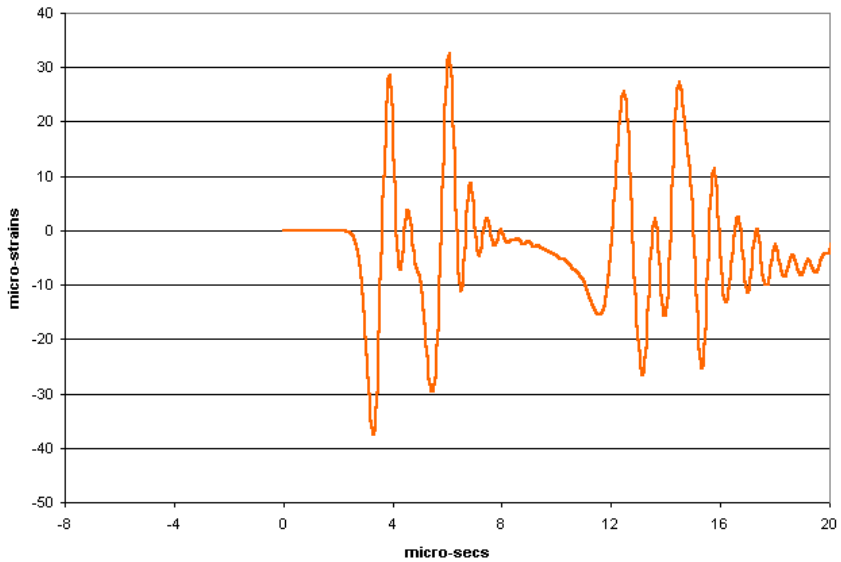


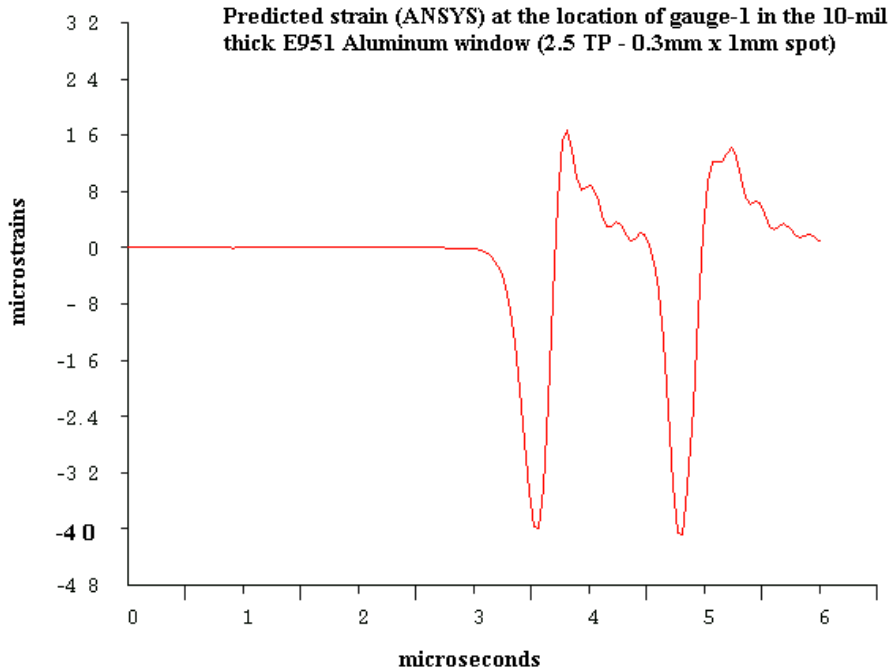


Aluminum Window Strain Data

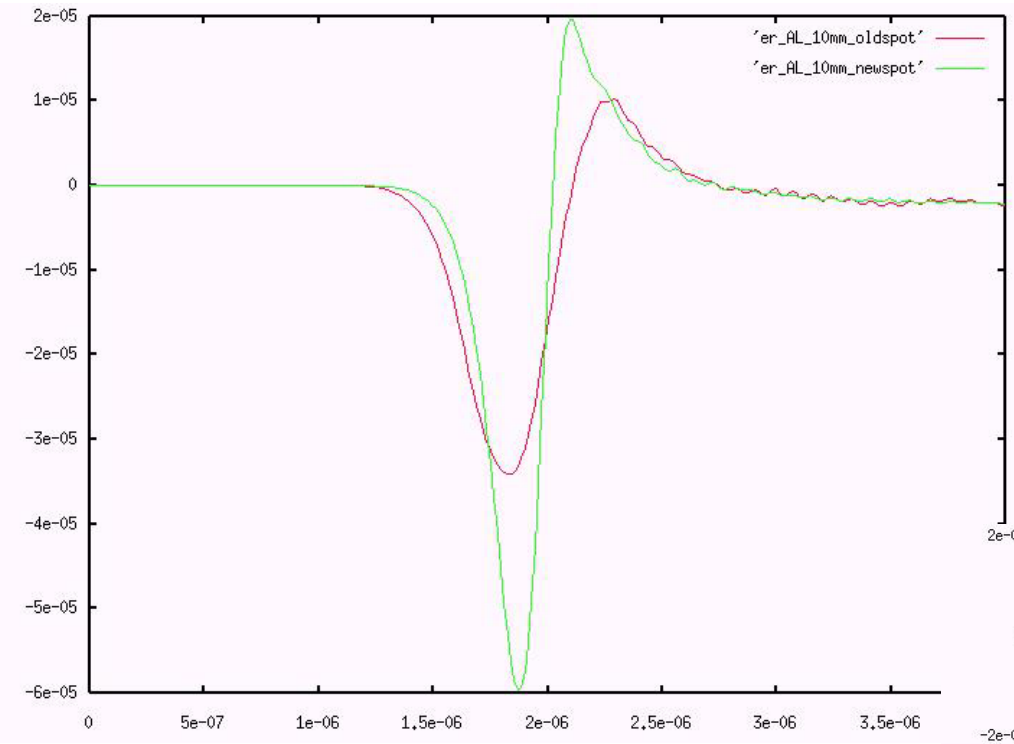
Experimental data vs. prediction using the new beam spot (0.3 x 1mm)

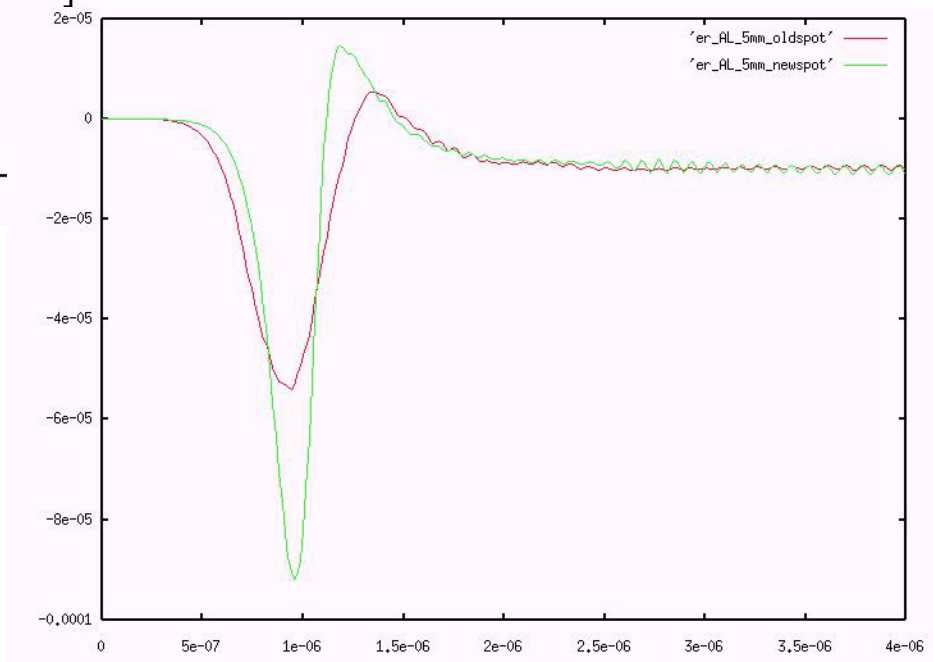






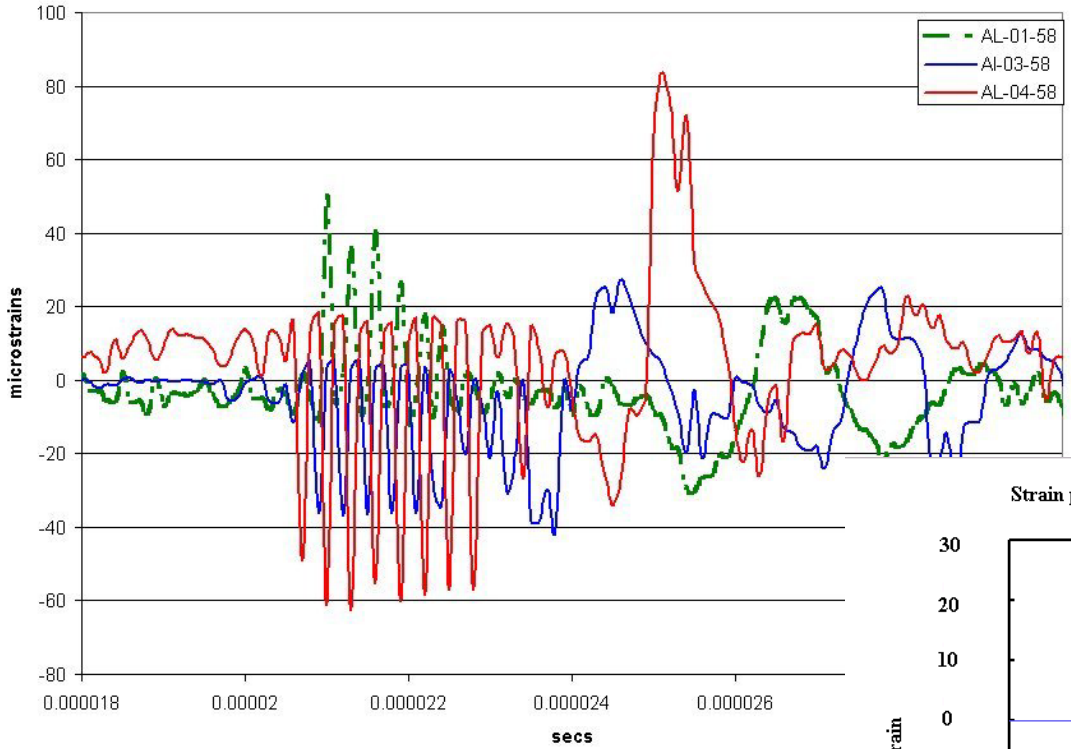
First strain wave arrival comparison between old and new spots



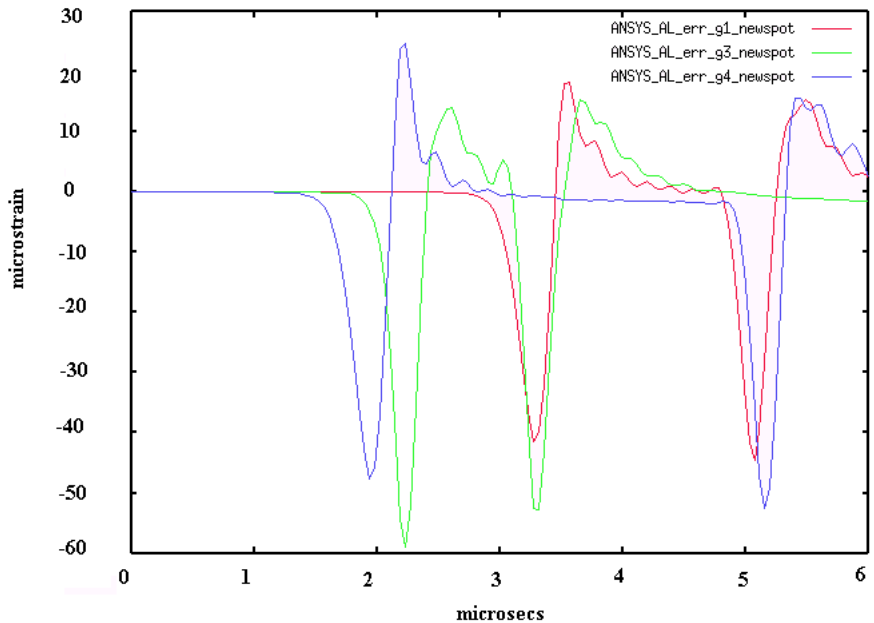


Recorded Aluminum Window Strain Data

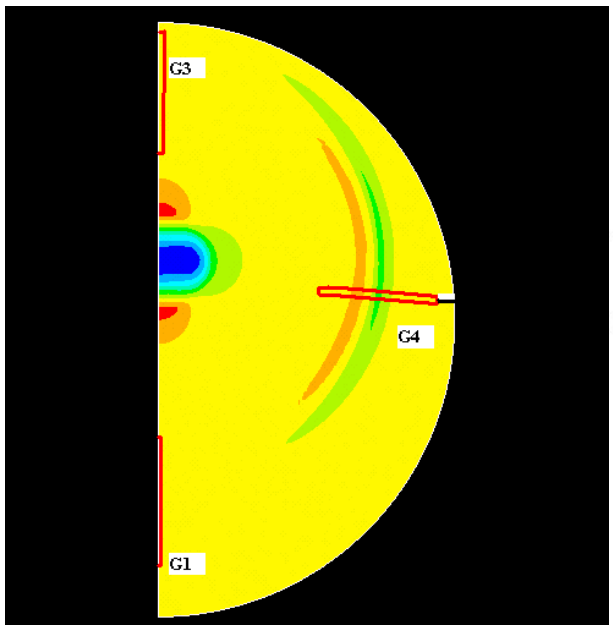
500 KHz Strain Data in Aluminum Window - Shot 58 (2.5 TP) - Gauges 1 - 3 - 4

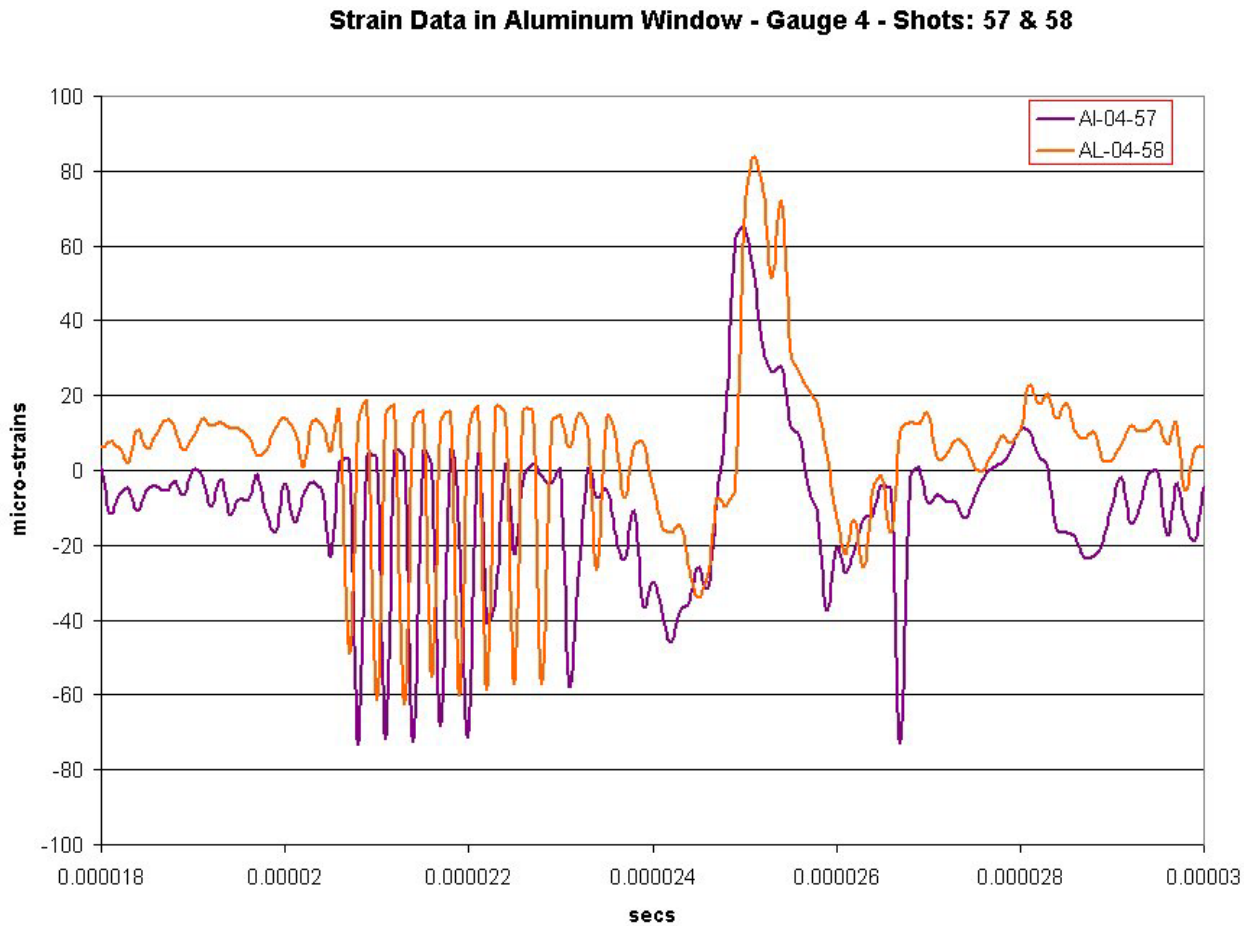


Strain predictions in the Aluminum window based on the new beam spot (0.3 x 1mm)

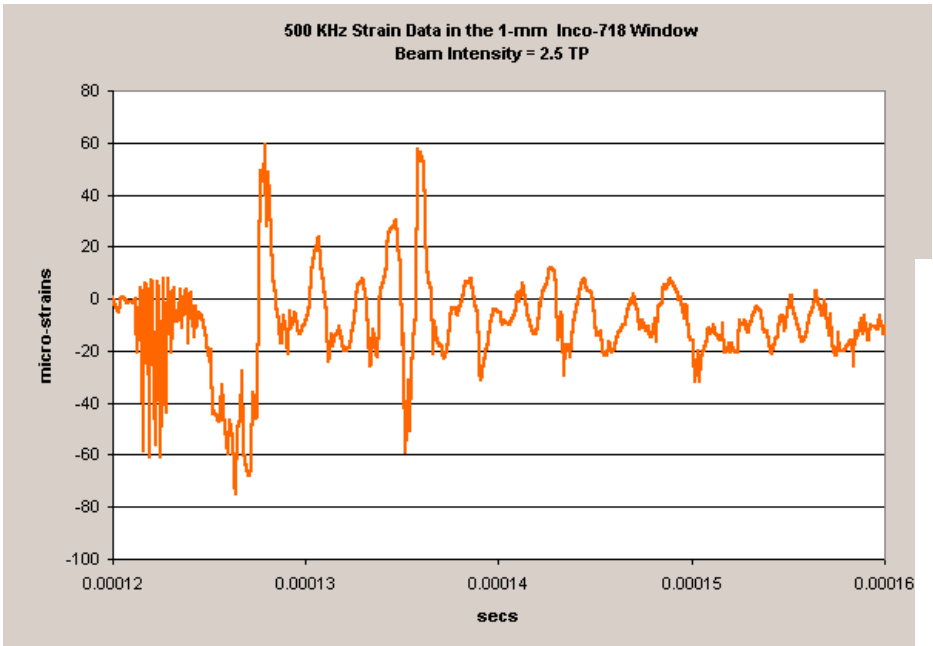


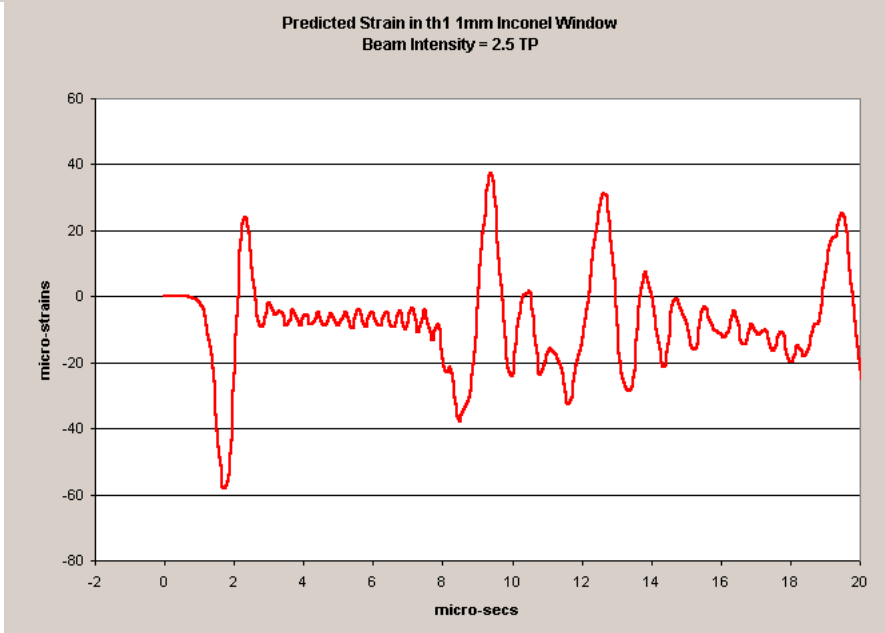
Recorded Aluminum Window Strain Data in back-to-back pulses

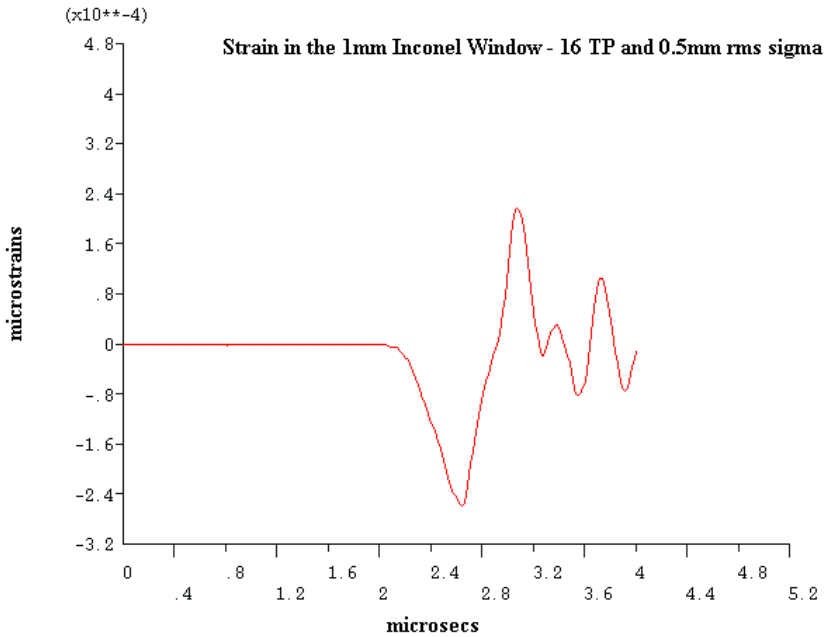




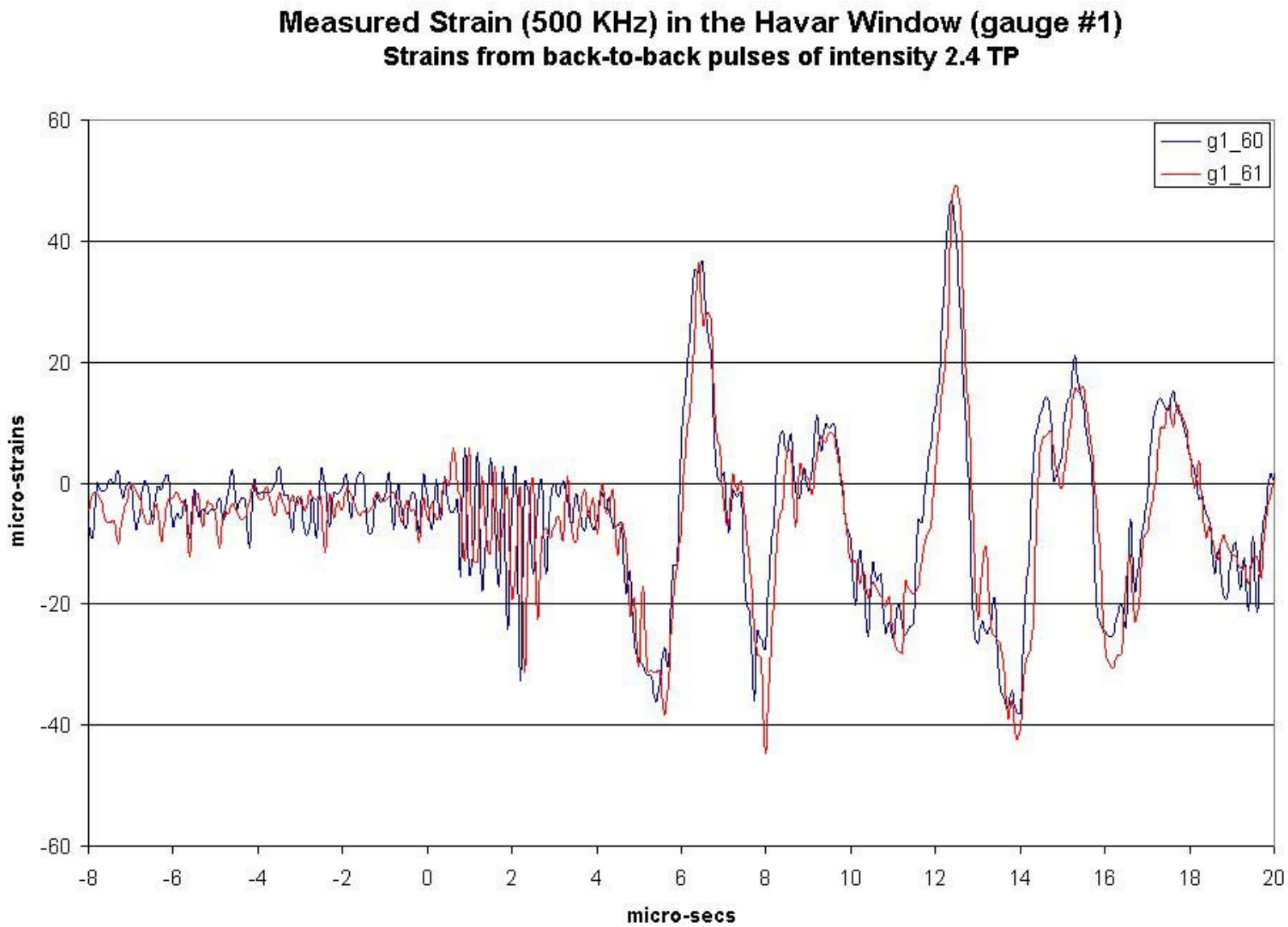
Measured and predicted strains in the 1mm thick Inconel



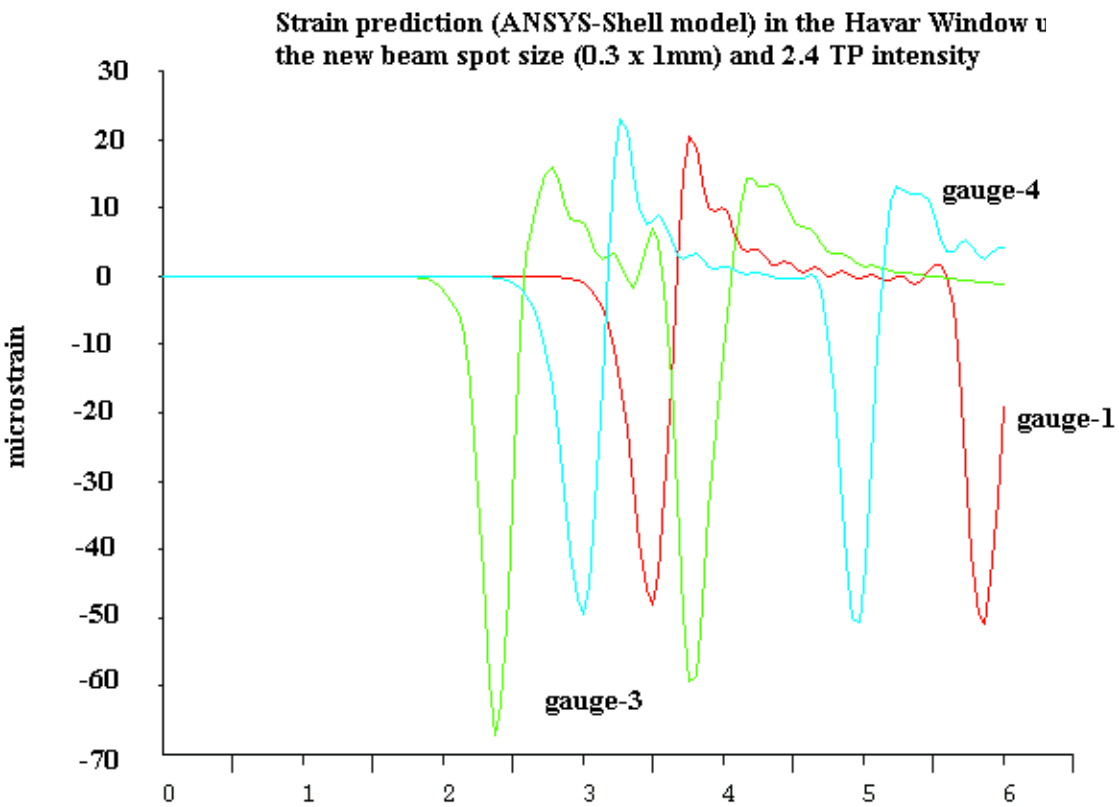


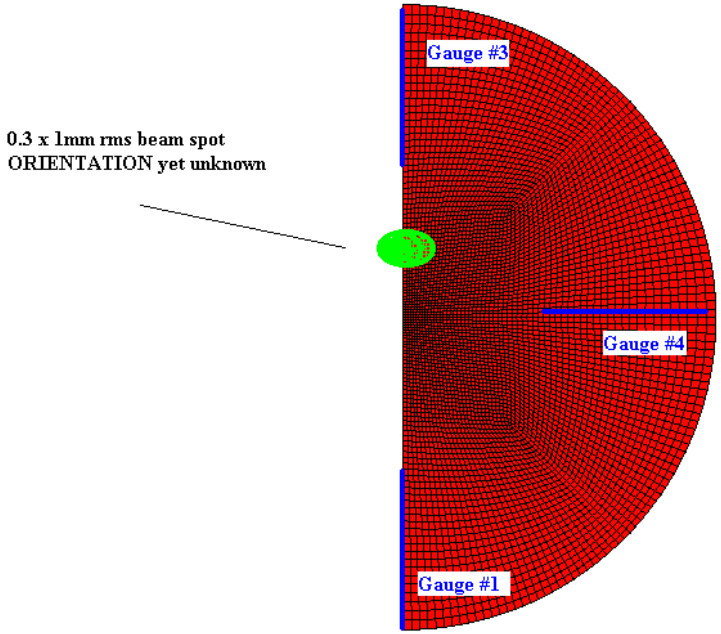


RECORDED strains in the Havar Window (back-to-back pulses)

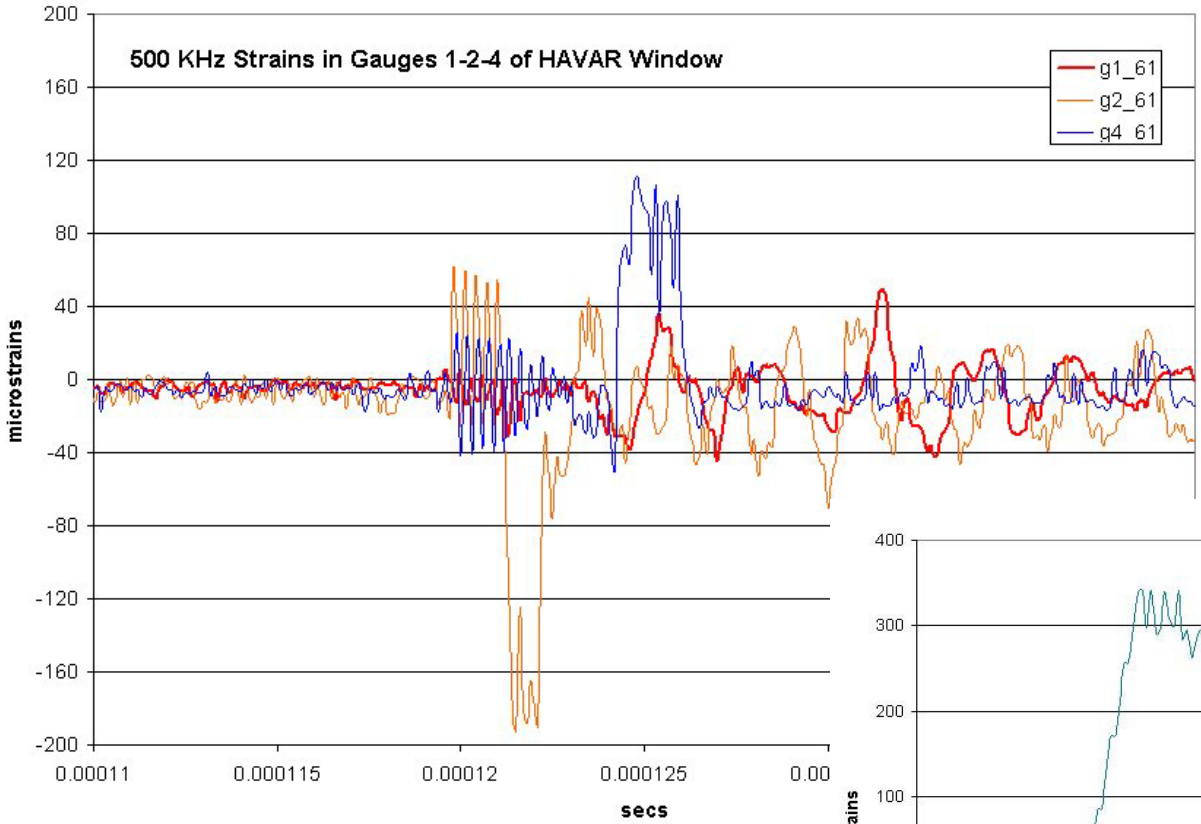


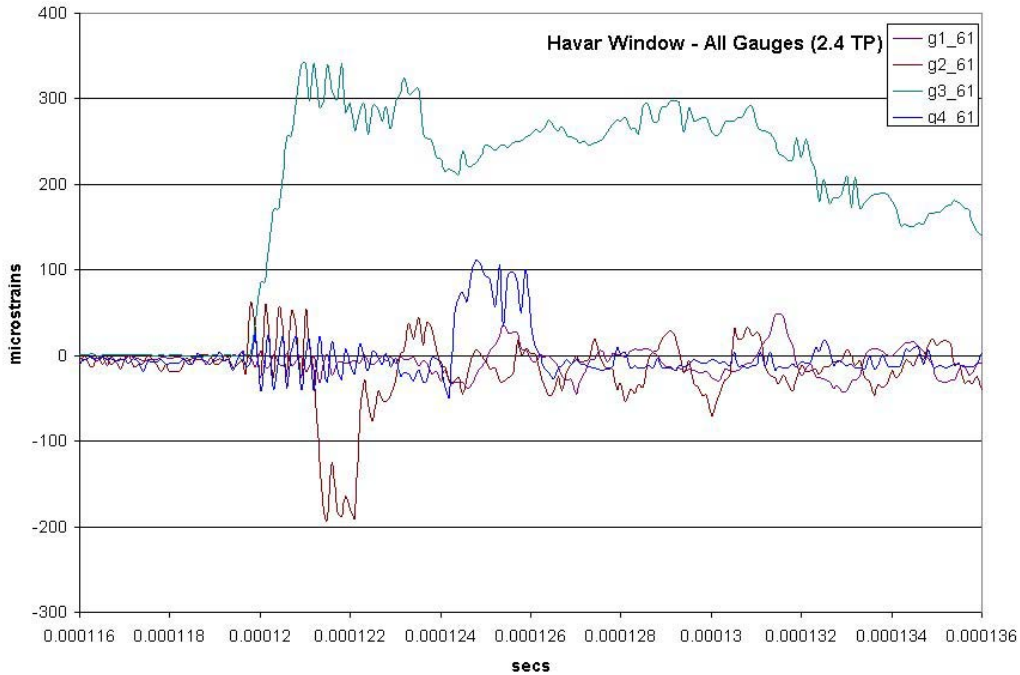
Predicted trains in the 11-mil thick Havar Window – Shell model





Measured strains in the Havar Window





SUMMARY

- Based on close examination of activation in the E951 windows (P.Thieberger) it is very likely that the beam spot size was smaller than originally estimated
- The new study, given the offset of the beam, utilized a 3-D model (rather than an axisymmetric one). This meant much greater computational cost.
- Shell theory was used to capture strain propagation in the "thin" windows - Drawbacks
- As expected, the strain predictions changed but not considerably. Still in general agreement with the recorded strains
- The smaller beam spot means that a reduced dynamic effect is already built-in (pulse relaxes in the radial direction based on the ratio of pulse length to time of travel over the heated zone). That compensates for the increased effect due to higher temperatures and compressive initial loads
- Detailed analyses in the vicinity of the heated area revealed that the stresses generated in all windows were far lower than their respective yield

Remaining Tasks

- OBTAIN the orientation of the elliptical spot relative to the strain gauges
- Calculate the energy deposition in elliptical concentric rings
- Perform final analysis on the thin windows
- Continue the on-going evaluation of the thick windows that require a full 3-D model
- Filter out the noise in the recorded strains
- Make final comparison and assessments with the recorded strains