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To: J. R. Haines
Subject: Neutrino Factory R&D Milestone: Stresses in ATJ Graphite Rod from AGS Beam
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John,

Experiments planned at the AGS facility in support of Neutrino Factory R&D include hitting an ATJ graphite rod with an intense, narrow proton beam pulse. I performed a simulation to estimate the mechanical response with these beam parameters: Gaussian distribution with $\sigma = 1$ mm, 25 GeV $1.5\text{x}10^{13}$ protons deposited in 40 ns. Phil Ferguson provided energy deposition data I used in the simulation.

The estimated maximum stress is below 10 MPa. At room temperature the tensile strength of ATJ graphite is more than 15 MPa. In the limited time allowed only the axisymmetric condition was considered (perfectly centered, aligned beam). However, I point out that simulations done for a similar rod with the LANSCE-WNR beam gave an axisymmetric estimate of maximum stress to be about 30% higher than a 3D estimate with an offset beam.

Maximum stress with a broader beam, $\sigma = 3$ mm, is less than 2.5 MPa.

What follows is a summary of the simulations for the AGS beam.

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Thermal Shock Simulation of Graphite Rod from AGS Beam Pulse

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Experiments planned in support of neutron factory target R&D include hitting ATJ graphite rod with the AGS proton beam. The target rod is to be instrumented with fiber optic strain gages. Simulations of the mechanical response to the rapidly deposited energy were carried out to give rough estimates of maximum stress expected. Beam parameters are summarized in table I.

Table I AGS Beam Parameters

	Case 1	Case 2
Beam Size (1 σ, mm)	1	3
Proton Energy (GeV)	25	25
No. of protons	1.5×10^{13}	1.5×10^{13}
Pulse length (ns)	40	40

The simulations were conducted using the finite element code ABAQUS/Explicit (v5.8-18). Given the time constraints for the task, only an axisymmetric condition was examined. A further simplification was the use of isotropic elastic properties (graphite has mild anisotropy). The properties used were based on room temperature values and are summarized in table II.

Table II ATJ Graphite Properties

Elastic Modulus, E (GPa)	9.6
Poisson's ratio, ν	0.13
Linear coefficient of thermal expansion, α (1/°C)	2.46×10^{-6}
Density, ρ (gm/cc)	1.73
Specific Heat, C_v (J/kg-°C)	690

The rod dimensions are length of 12.1 inch (30.7 cm) and diameter of 5/8 inch (15.9 mm). The model region was uniformly meshed with 30 radial and 100 axial elements.

Using the beam parameters in table I, Phil Ferguson performed neutronics calculations that provided the spatial description of the deposited energy. Figure 1 shows the energy deposited for the 1 mm beam on the finite element model. The maximum energy density is 350 J/cc, located approximately 5.5 cm from the beam incident end. Energy density as a function of axial position and radius (at Z=5.5 cm) are shown in figures 2 and 3. Energy deposited over complete radial sections is shown in figure 4; this reaches a maximum further back from the beam incident end at about Z=20 cm.

The simulation is begun by linearly increasing temperature over 40 ns . The applied temperature change is simply energy density divided by mass density and specific heat; the maximum temperature rise is 293°C for $\sigma = 1$ mm and 61°C for for $\sigma = 3$ mm. In this temperature range properties stay close to those at room temperature. Analysis time step was fixed at 5 ns due to the short pulse length; the default step based on stability limits is approximately 75 ns. Total simulation length was 4 ms.

Output was created at fine intervals (0.5 μs) for select locations and coarse intervals (4 μs) for the entire model. Reviewing all output indicated maximum VonMises stress under 10 MPa for $\sigma = 1$ mm under 2.5 MPa for $\sigma = 3$ mm. One location of high stress is near the location of maximum energy density; the history of stress at this location is shown in figure 5 ($\sigma = 1$). The figure shows evidence of radial and axial wave propagation frequencies.

Frequency of axial wave propagation is clearer in figure 6, which shows axial displacement of 5 model nodes equally spaced on the surface of the rod. All indicate about 3800 hz motion. The longitudinal wave speed in graphite (uniform bar) is given by $c_L=(E/\rho)^{1/2} = 2356$ m/s. The time for a wave to traverse the rod length is (0.3073 m)/(2356 m/s) = 130 μs, or 7666 hz. For the wave to reflect and traverse the length again, the frequency is 3833 hz.

Radial frequency is observed as approximately 94 kHz (no figure shown). The acoustic wave speed is given by $c_0=(K/\rho)^{1/2}$, where K is the bulk modulus and is related to E by $K=E/(3(1-2\nu))$. For these properties the acoustic wave speed is 1581 m/s; radial sound frequency would then be $c_0/2R$ or 99.6 kHz, slightly higher than the simulation value.

On the other hand, dilatational wave speed is given by:

$$c_1 = \sqrt{\frac{E(1-\nu)}{\rho\,(1+\nu)(1-2\nu)}} = 2403 \quad m/s$$

The frequency given by $c_1/2R$ is 151 kHz, higher still than the simulation value. The difference is probably due to axial effects not giving true dilatation motion.

Finally, figure 7 shows a typical deformed shape plot from the axisymmetric simulation. Note that shape has been magnified more in the radial direction than the axial. This figure illustrates that the radial motion is not uniform along the length of the rod.

Given that the tensile strength of ATJ graphite is greater than 15 MPa at room temperature, the maximum stress estimated here gives reasonable assurance that the rod will survive single proton pulses of this type. Although three-dimensional analysis was not done, past analyses with this rod type and size with the LANSCE-WNR proton beam pulse give some relief. For that 3D case, the centered beam gave the same result as the axisymmetric model; further, an offset beam gave stresses about 30% lower than the centered beam condition. The 3D simulation agreed well with measurements taken at the WNR. Axisymmetric analysis is conservative.

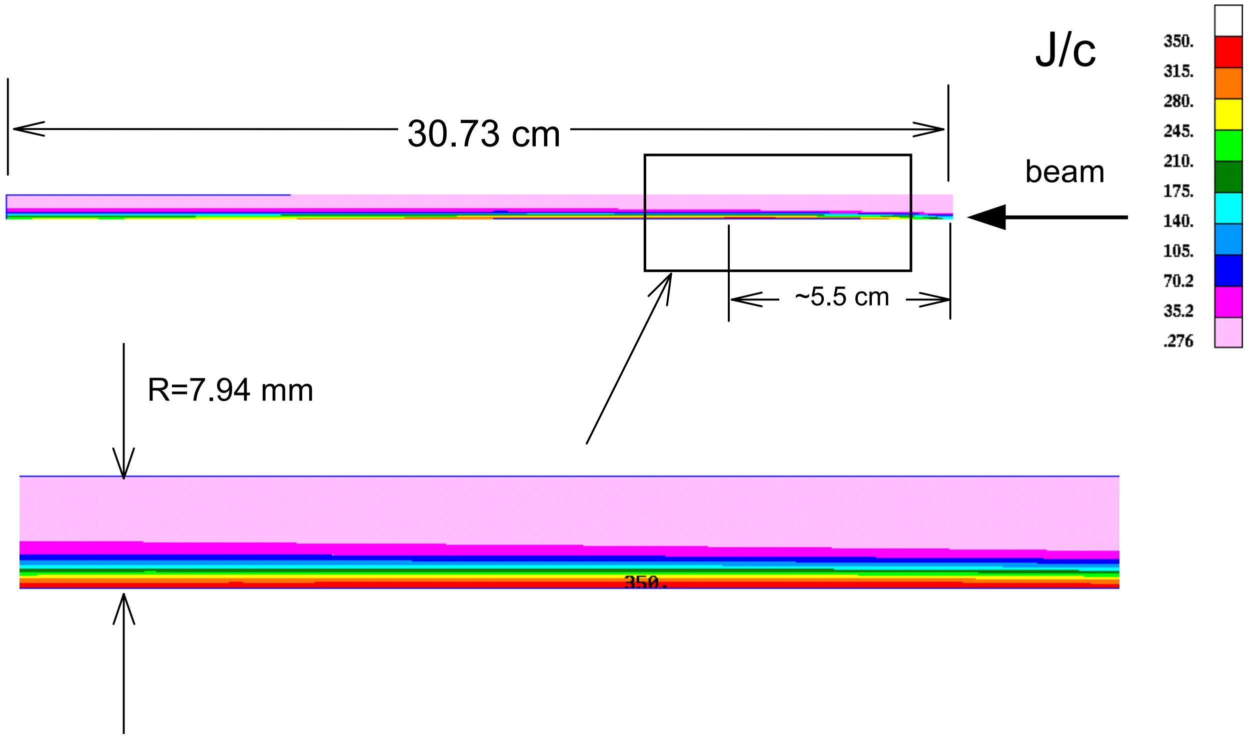


Figure 1 Maximum Energy Deposition in ATJ Graphite Rod
$1.5e^{13}$ 25 GeV Protons, $\sigma = 1$ mm

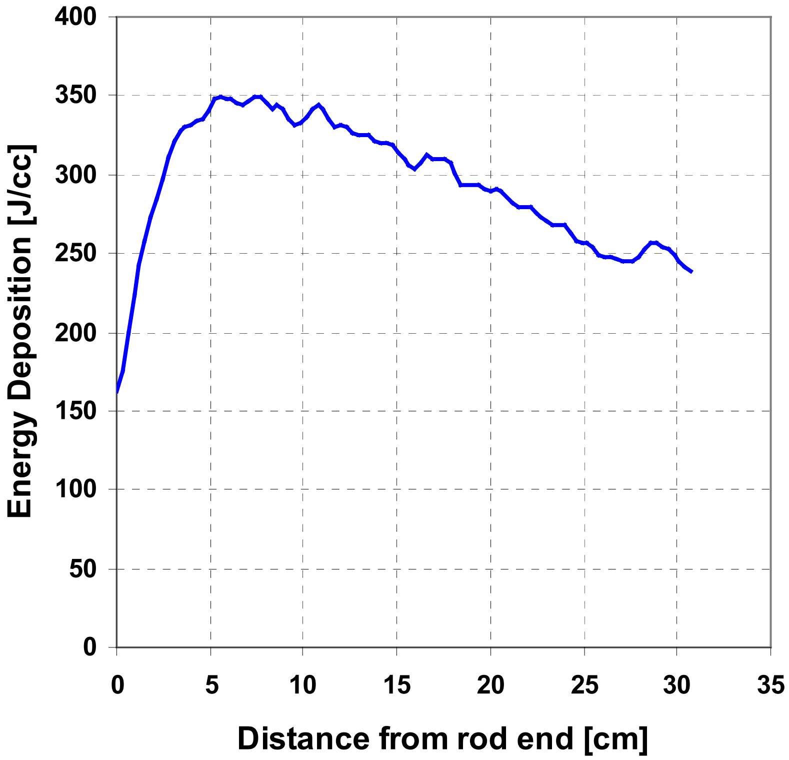


Figure 2 Energy deposition vs. length along rod axis, σ=1 mm

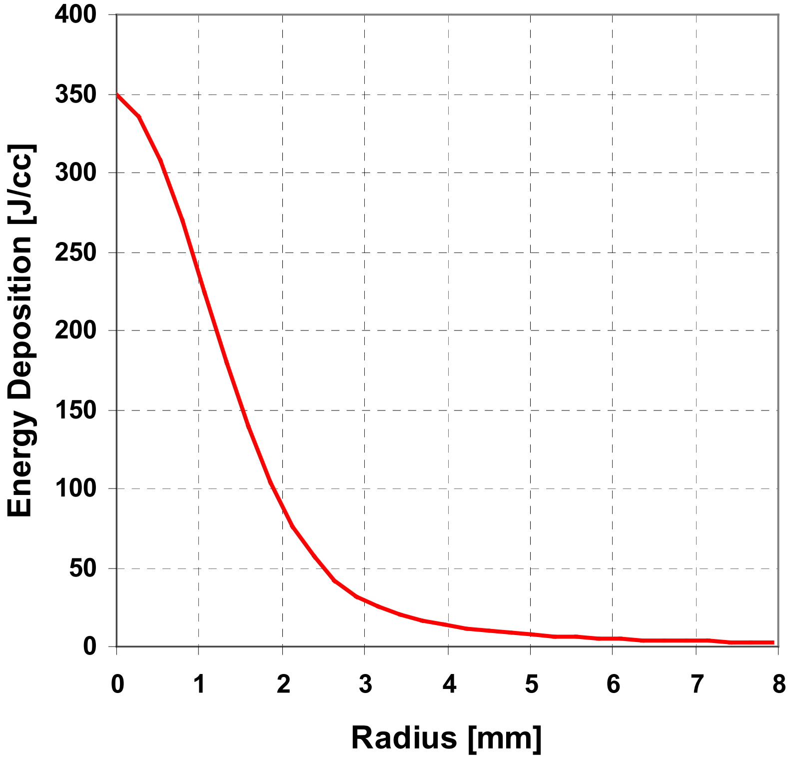


Figure 3 Energy deposition vs. radius at Z=5.5 cm, σ=1 mm

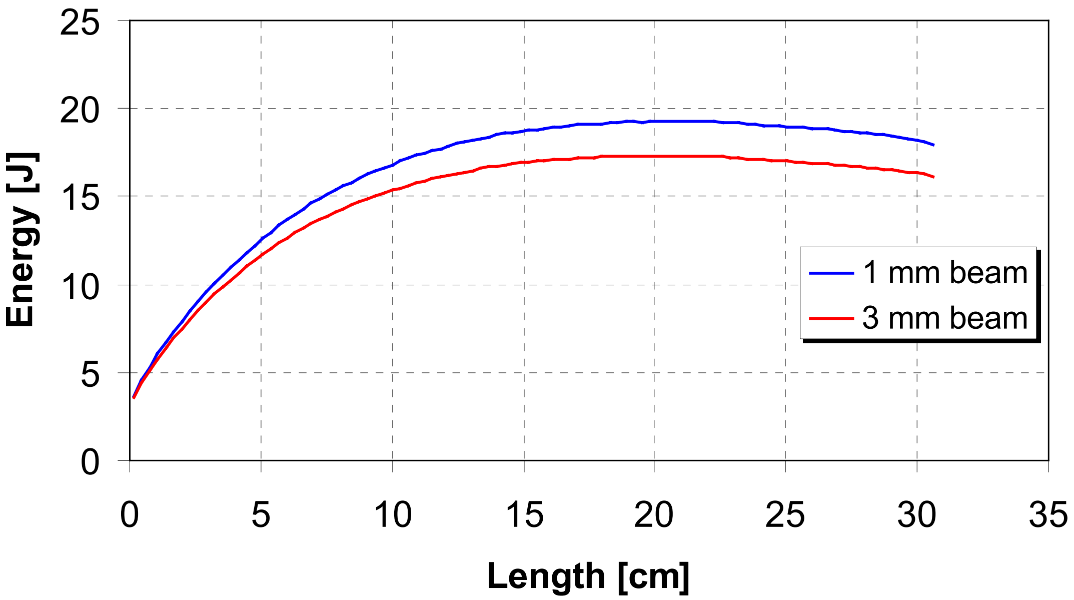


Figure 4 AGS Beam Deposited Energy in ATJ Graphite Rod, summed over radial sections of 0.307 cm axial length.

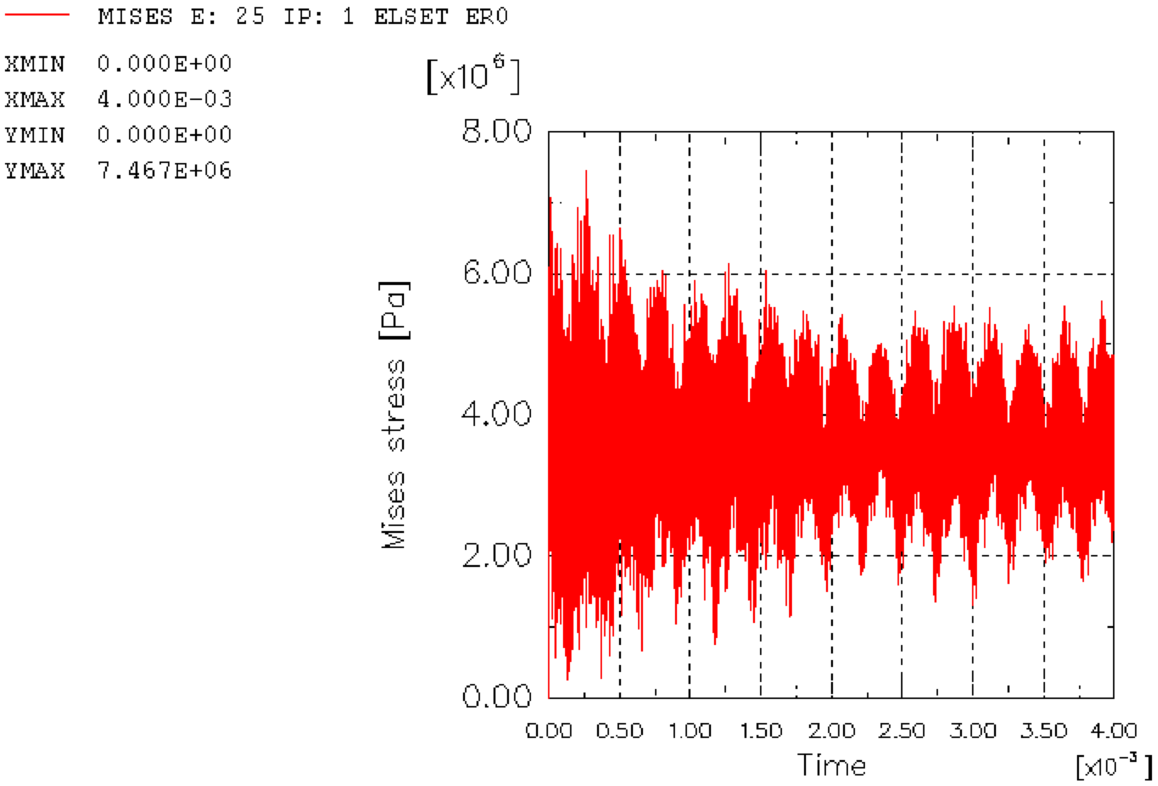


Figure 5 Von Mises Stress at Element Near Location of Maximum Energy Deposition.

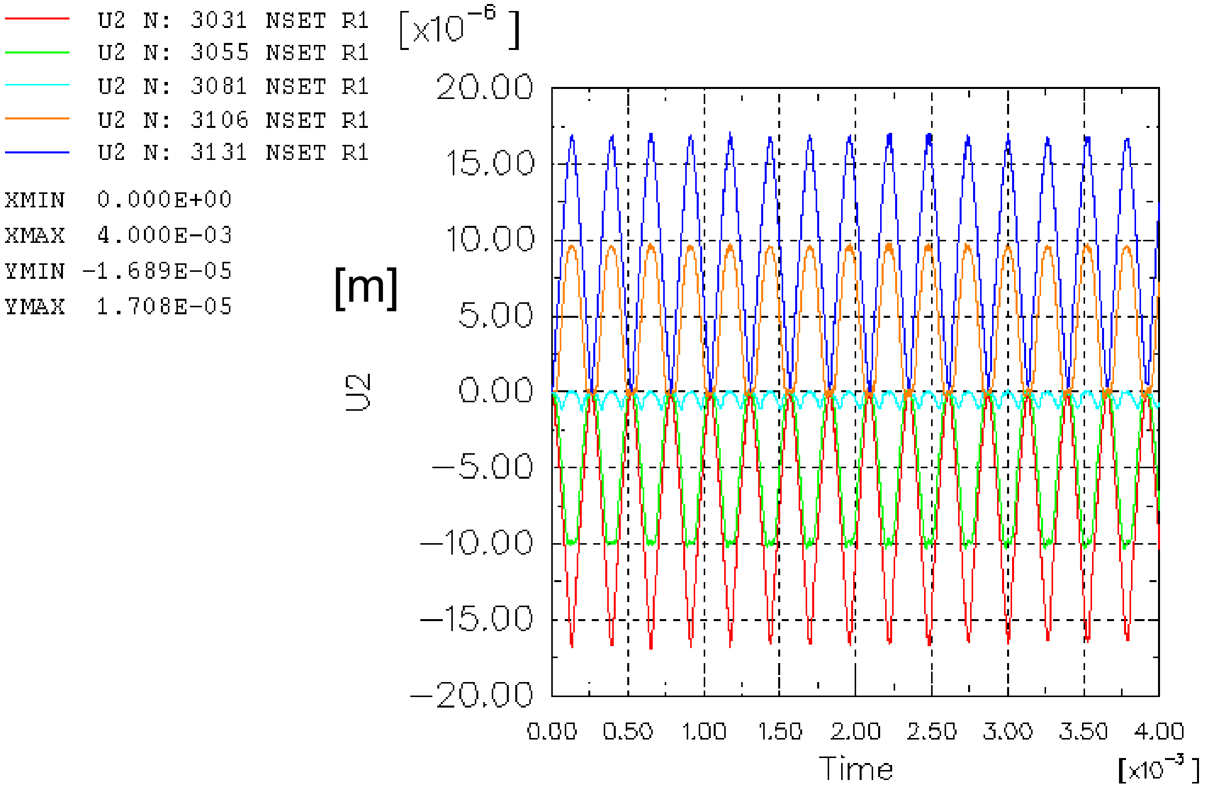
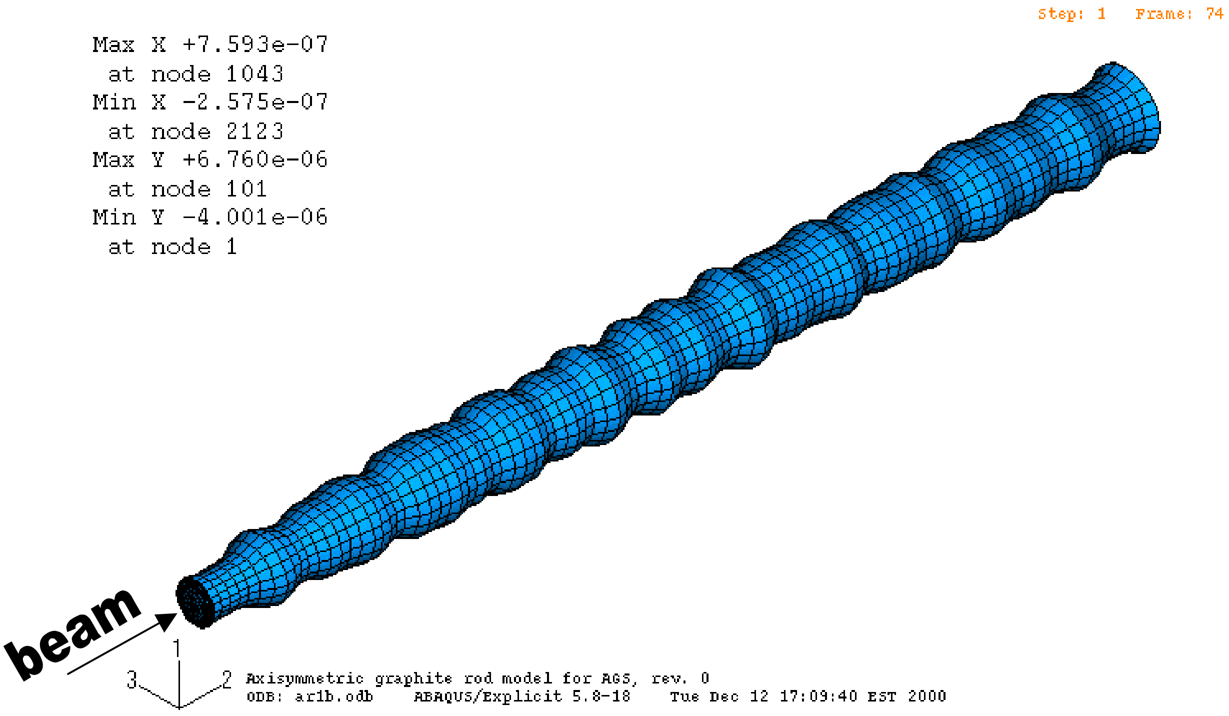


Figure 6 Axial Displacement of 5 Equally Spaced Nodes Along Surface.



```
Max X +7.593e-07
 at node 1043
Min X -2.575e-07
 at node 2123
Max Y +6.760e-06
 at node 101
Min Y -4.001e-06
 at node 1
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Axisymmetric graphite rod model for AGS, rev. 0
ODB: ar1b.odb     ABAQUS/Explicit 5.8-18     Tue Dec 12 17:09:40 EST 2000
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Figure 7 Typical deformed shape, this at 0.296 ms
Non uniform scaling: $dR*10^4$; $dZ*10^3$