Towards a High Gradient Lithium Collection Lens for the Fermilab Anti-proton Source

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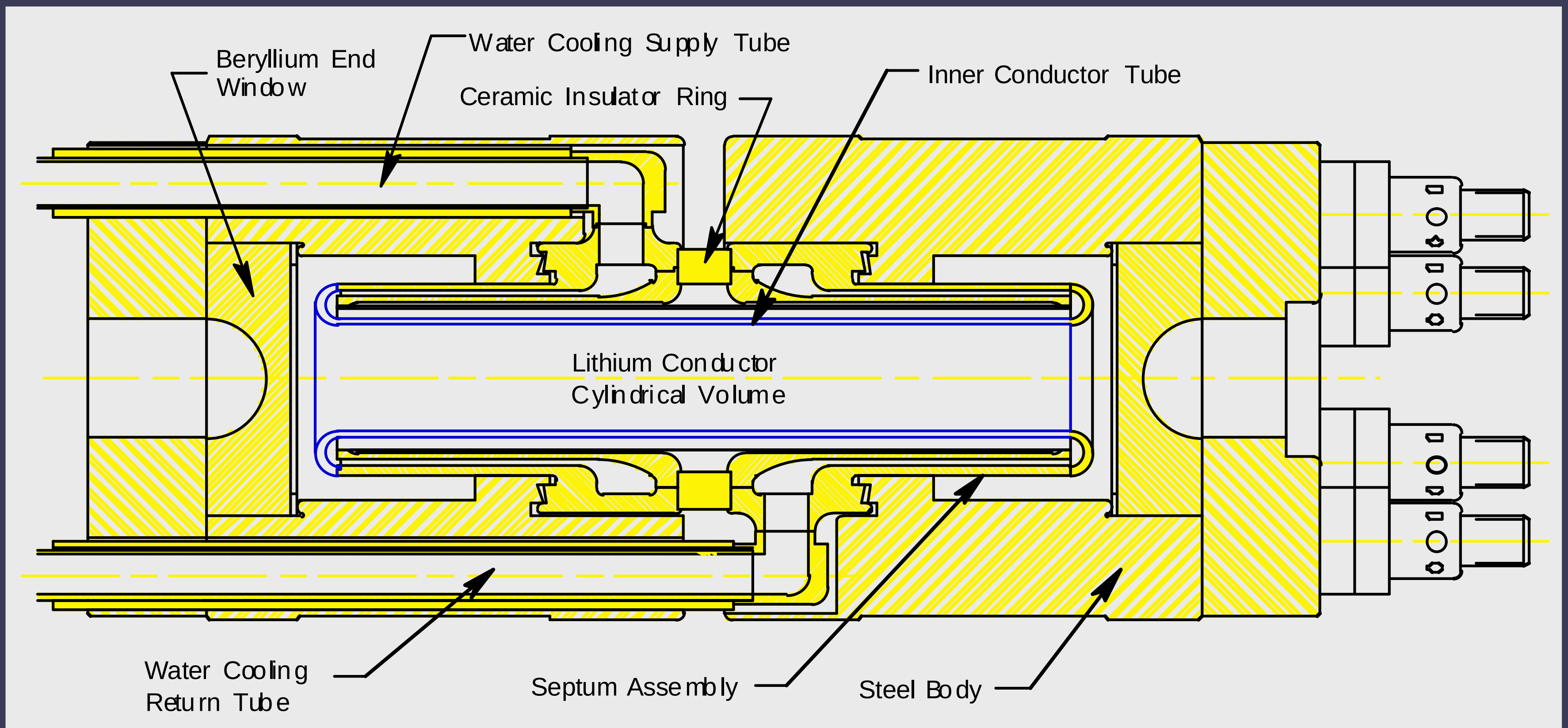
High Power Targetry Workshop 2003

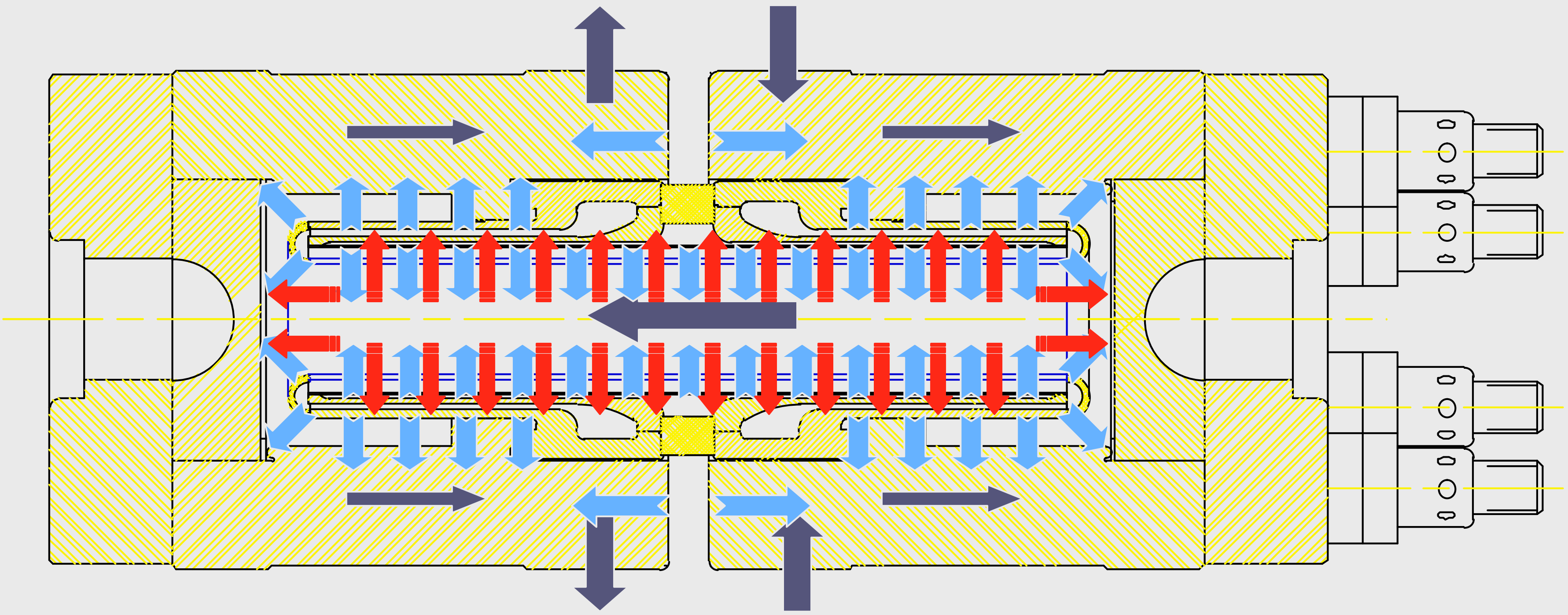
Presentation Overview

- ✓ Introduction to Lens
- ✓ Identified Problems and Issues
- ✓ Possible Solutions
- ✓ Conclusion and Future Work

Introduction - **Anatomy of a Lens**



Introduction - **Anatomy of a Lens**



Introduction - **Operating vs Design Parameters**

- ✓ Original Design Parameters (1000 T/m)
  - 670 kA, 350 µs half-sine pulse
  - 5E12 ppp on target every 2 seconds
- ✓ Current Operating Parameters (745 T/m)
  - 500 kA, 370 µs half-sine pulse
  - 5.2E12 ppp on target every 2.4 seconds

Introduction - **Fatality**

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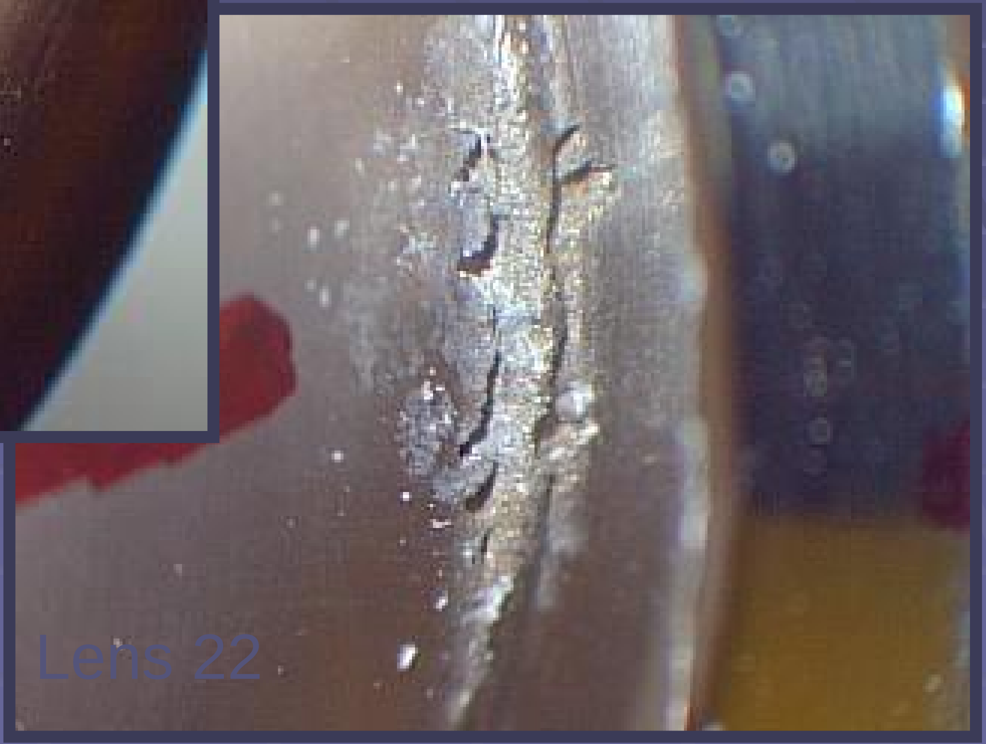
Introduction - **Fatality**

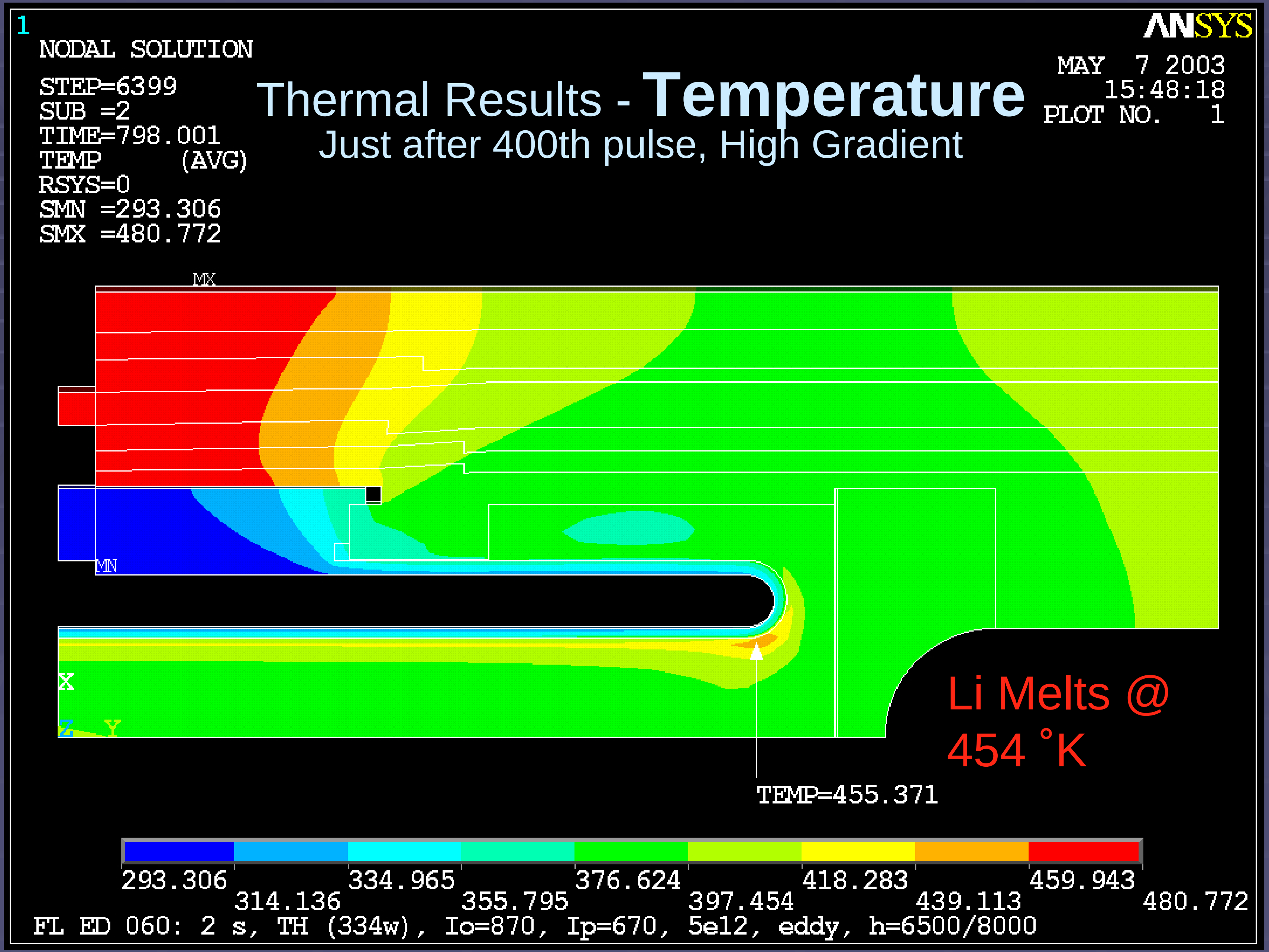


Introduction - **Fatality**

- ✓ Subsequent analyses (FEA) have shown that these failures are not consistent with predicted loads.
- ✓ This indicates:
  - Material degradation
  - Actual loads more severe than predicted by analyses

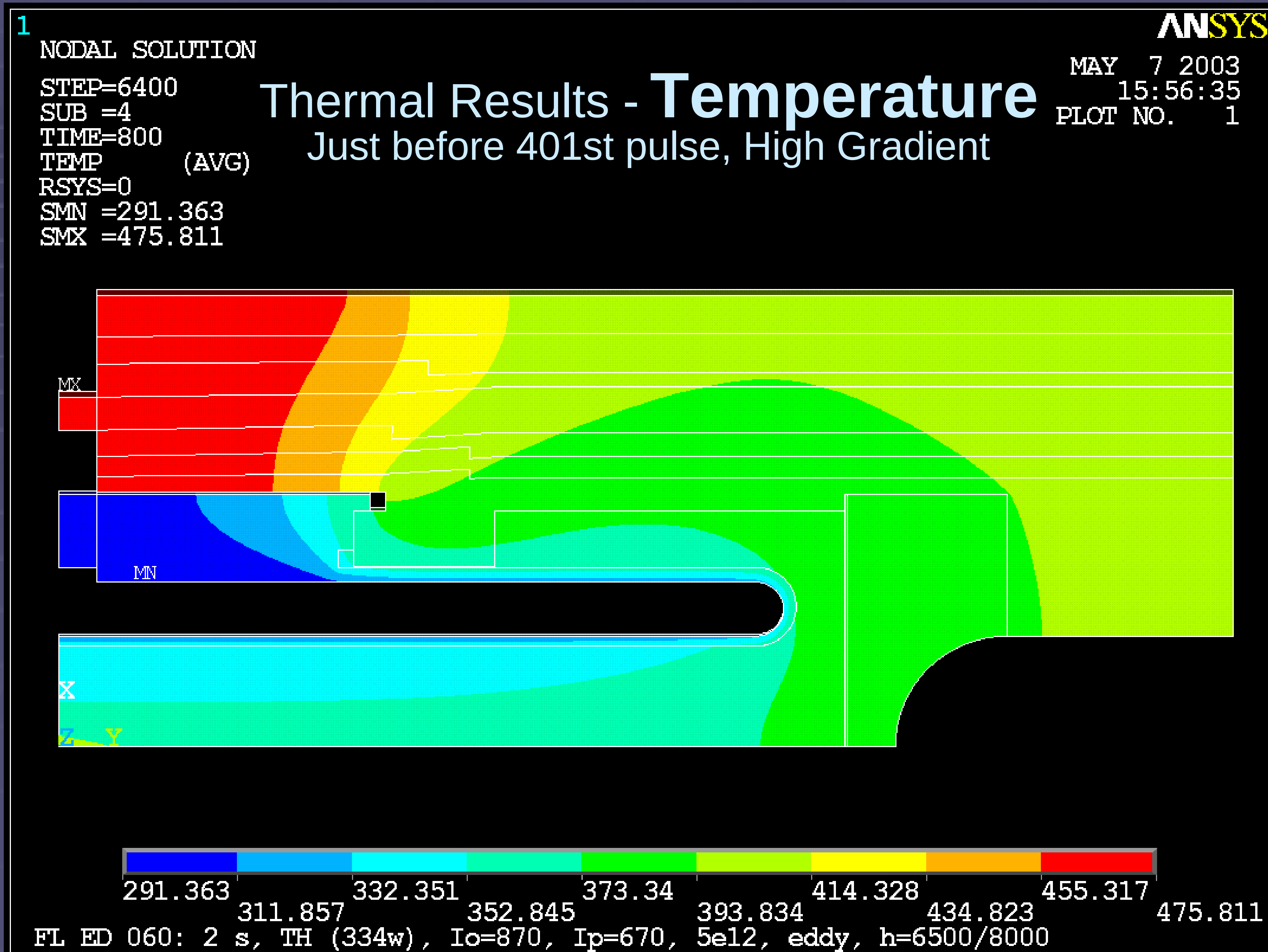
Identified Problems & Issues - **Overview**

- ✓ Ongoing analyses and investigations have revealed the following issues with the current lens design:
  - Overheating (melting lithium)
  - Material Degradation (embrittling titanium)
  - Li/Ti Separation (moving lithium)
  - Fatigue (cracking titanium)
  - Fabrication & Assembly Difficulties


1
ANSYS
NODAL SOLUTION
STEP=6399
SUB =2
TIME=798.001
TEMP (AVG)
RSYS=0
SMN =293.306
SMX =480.772
MAY 7 2003
15:48:18
PLOT NO. 1
Thermal Results - Temperature
Just after 400th pulse, High Gradient
MX
MN
X
Z Y
Li Melts @ 454 °K
TEMP=455.371
293.306
314.136
334.965
355.795
376.624
397.454
418.283
439.113
459.943
480.772
FL ED 060: 2 s, TH (334w), Io=870, Ip=670, 5e12, eddy, h=6500/8000

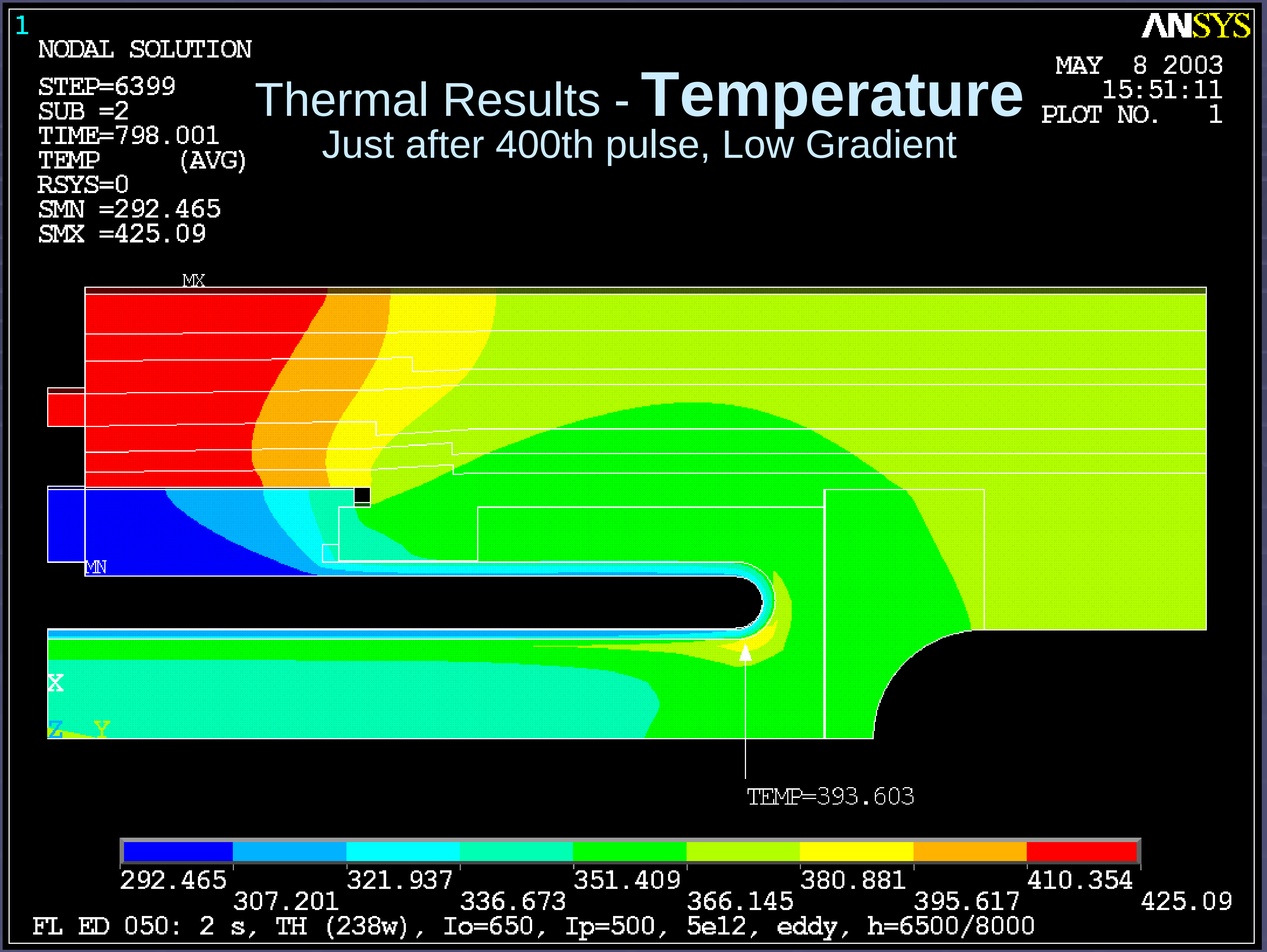
Thermal Results - **Temperature**

Just before 401st pulse, High Gradient



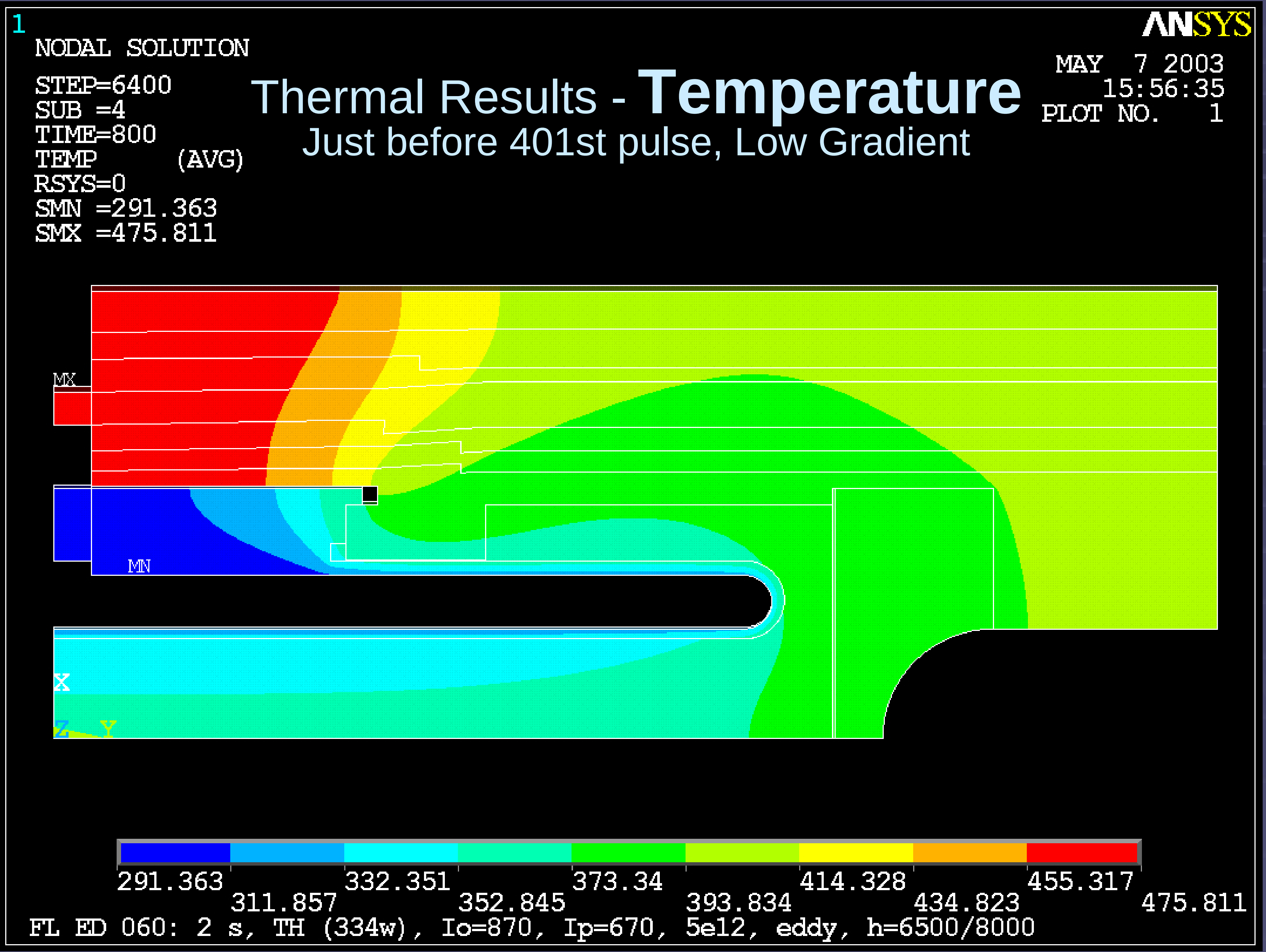
Thermal Results - **Temperature**

Just after 400th pulse, Low Gradient



Thermal Results - **Temperature**

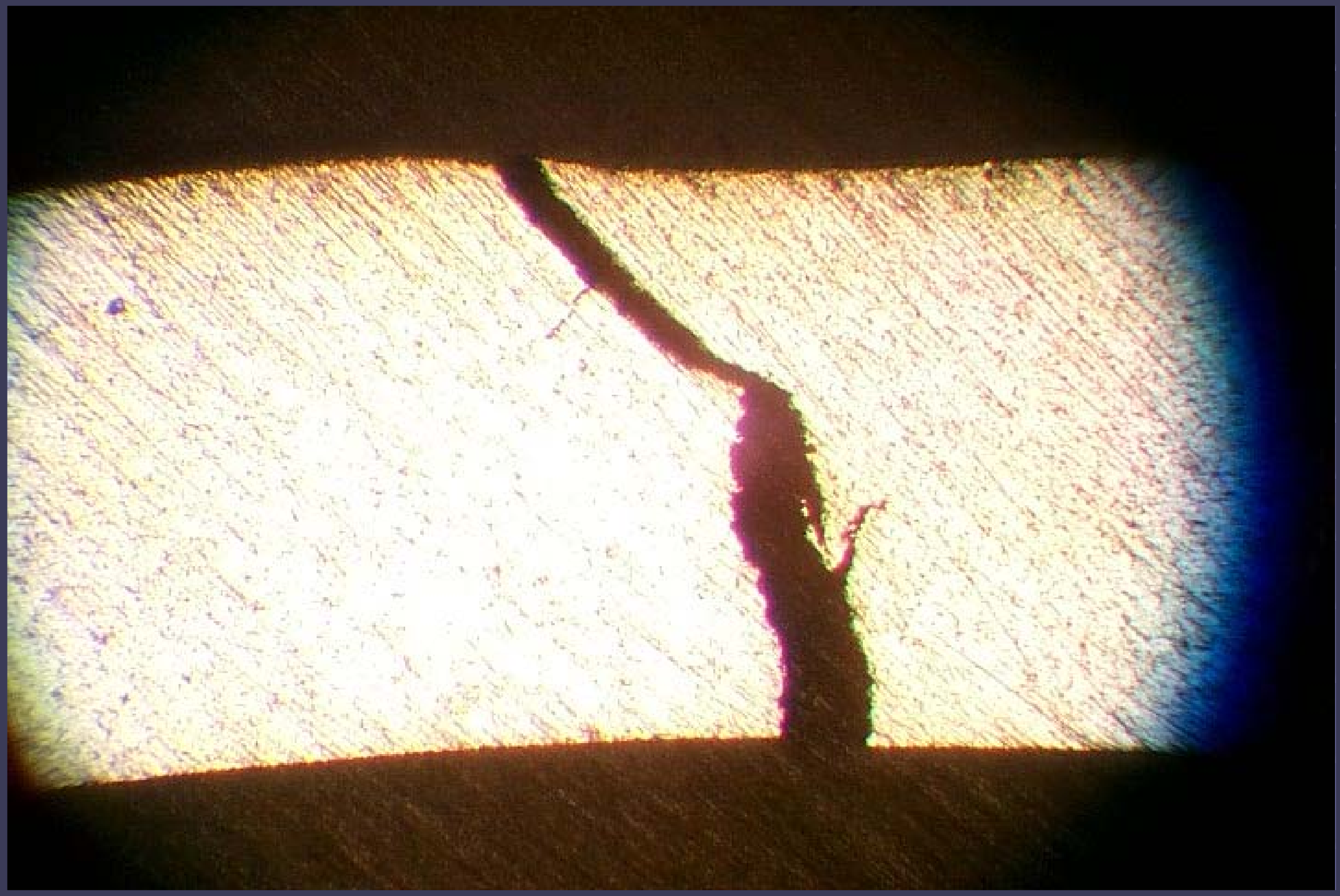
Just before 401st pulse, Low Gradient



Identified Problems & Issues - **Overheating**

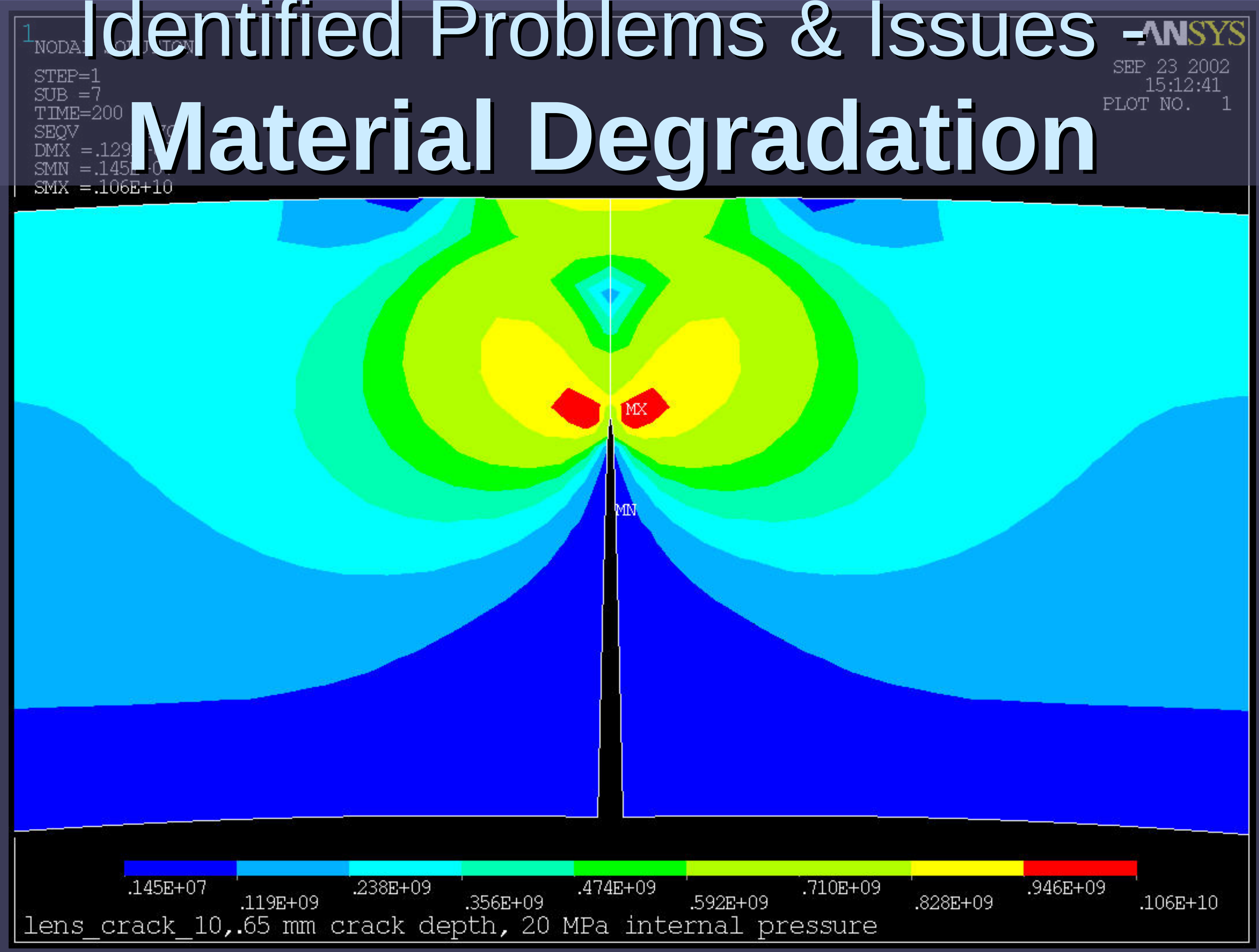
- ✓ High Gradient pulse appears to create local melting
- ✓ Low Gradient pulse does not appear to create local melting
- ✓ Structural portion of FEA analysis does not currently model phase transition effects

Identified Problems & Issues - **Material Degradation**



- ✓ Crack profiles exhibit brittle and ductile fracture regions consistent with fatigue

Identified Problems & Issues – Material Degradation



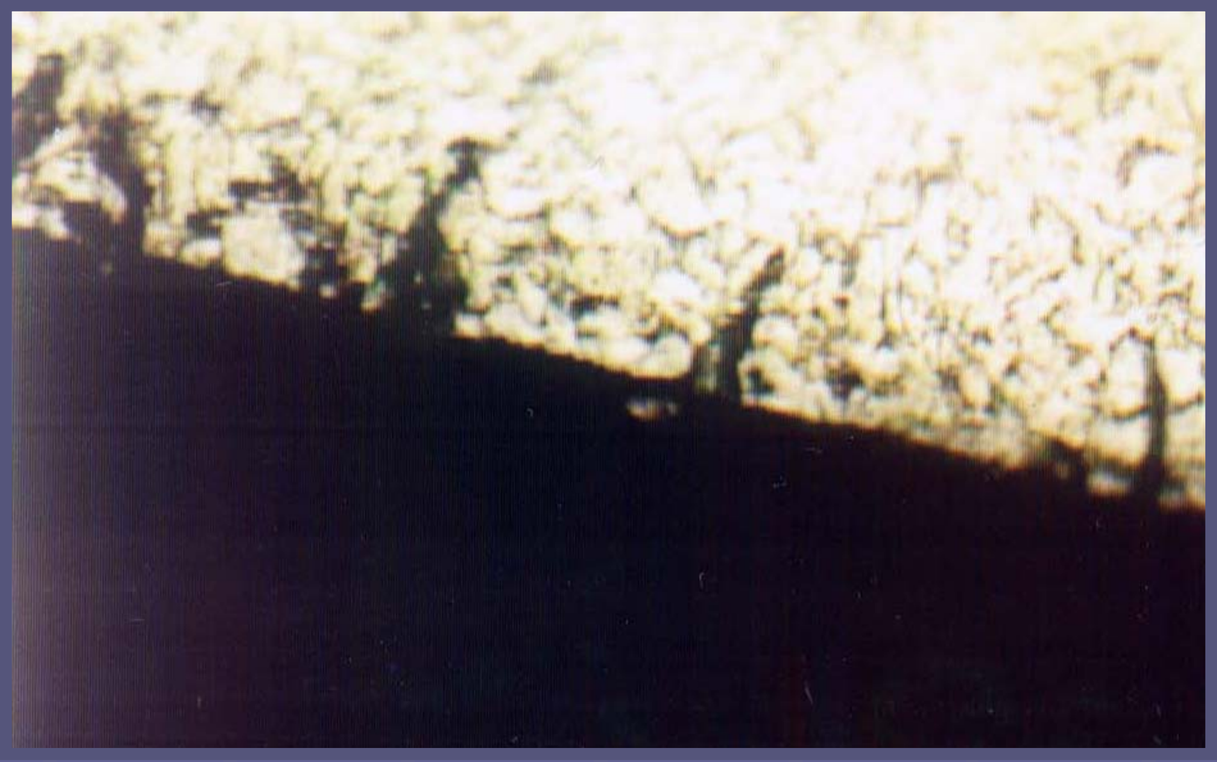
- ✓ Load at final fracture was estimated from crack depth and is consistent with models

Identified Problems & Issues - Material Degradation

	12.4 MPa int pressure			20.0 MPa int pressure			28.6 MPa int pressure		
Crack depth(micron)	Stress Intensity Factor, K1 (MPa-m$^{-1/2}$)	FCP (micron/cycle)	Number of cycles	Stress Intensity Factor, K1 (MPa-m$^{-1/2}$)	FCP (micron/cycle)	Number of cycles	Stress Intensity Factor, K1 (MPa-m$^{-1/2}$)	FCP (micron/cycle)	Number of cycles
50	1.8	0.00E+00	inf	2.9	0.00E+00	inf	4.1	0.00E+00	inf
100	2.6	0.00E+00	inf	4.2	0.00E+00	inf	6.2	0.00E+00	inf
200	4.2	0.00E+00	inf	6.9	0.00E+00	inf	10.2	7.00E-06	1.43E+07
300	6.2	0.00E+00	inf	10.3	7.00E-06	1.43E+07	15.8	6.00E-05	1.67E+06
400	8.9	2.50E-06	4.00E+07	15.3	6.00E-05	1.67E+06	25	2.50E-04	4.00E+05
500	12.8	3.00E-05	3.33E+06	22.9	2.00E-04	5.00E+05	40.3	1.00E-02	1.00E+04
600	19.3	6.00E-04	8.33E+04	38.6	1.00E-02	5.00E+03	81	OL	0.00E+00
650	26.6	3.50E-04	1.00E+06	64.5	OL	0.00E+00	--	--	--
1000	--	--	--	--	--	--	--	--	--

- ✓ However at those low loads a crack would have to be at least 200 microns deep initially before propagating

Identified Problems & Issues - **Material Degradation**



- ✓ In addition, inner tube wall shows micro-cracks (25 microns deep).

Identified Problems & Issues - **Material Degradation**

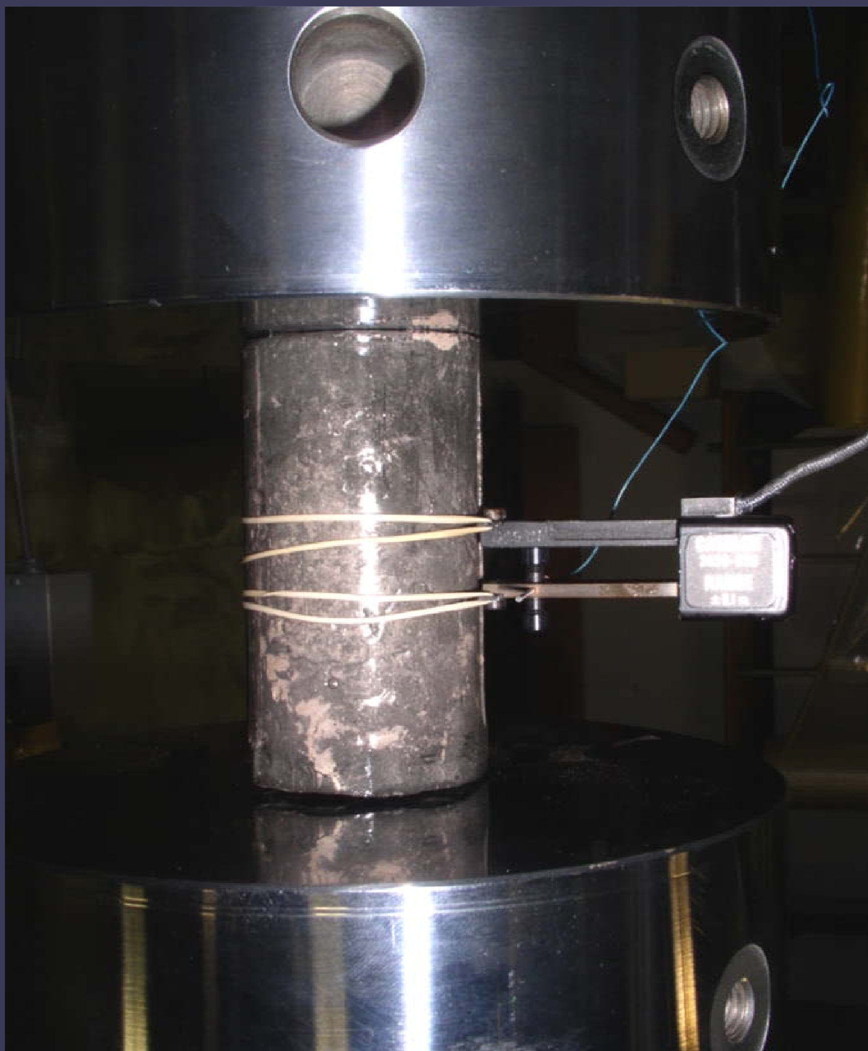
- ✓ Hydrogen Embrittlement?
- ✓ Liquid Metal Embrittlement?
- ✓ Other Contamination?
- ✓ Radiation Damage?

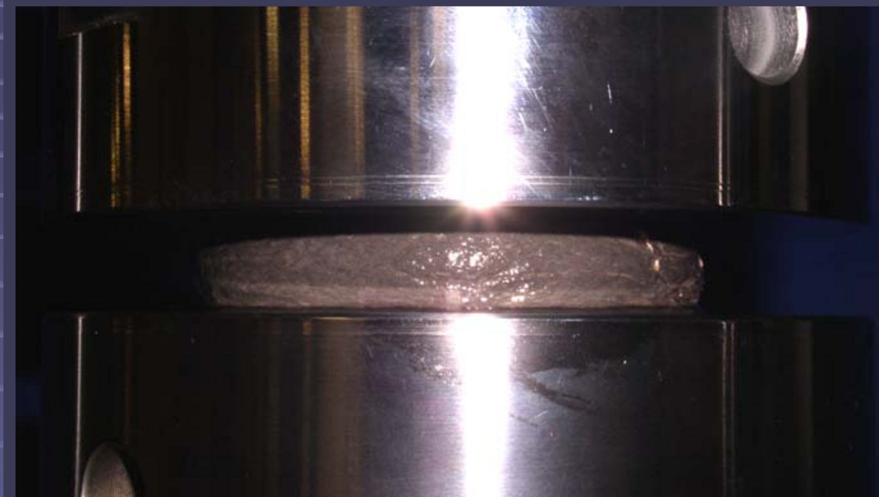
Identified Problems & Issues -
Li/Ti Separation

- ✓ Magnetic pinch effect pulls lithium inward away from septum conductor tube.
- ✓ If lithium motion is large and pre-load is insufficient, voids instantly form and close.
- ✓ This may cause detrimental arcing and/or shock effects along the septum conductor tube wall.

Identified Problems & Issues -

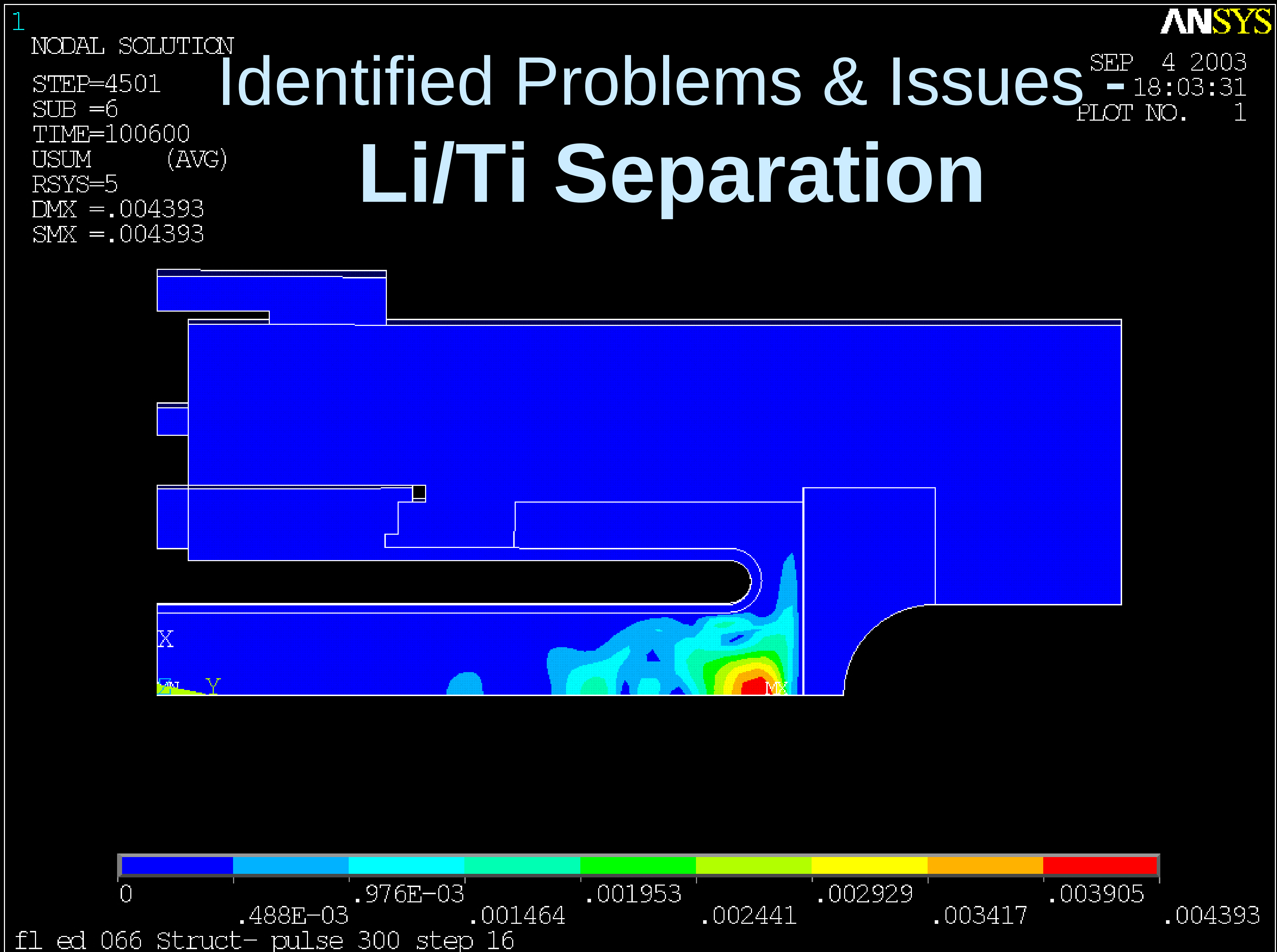
Li/Ti Separation

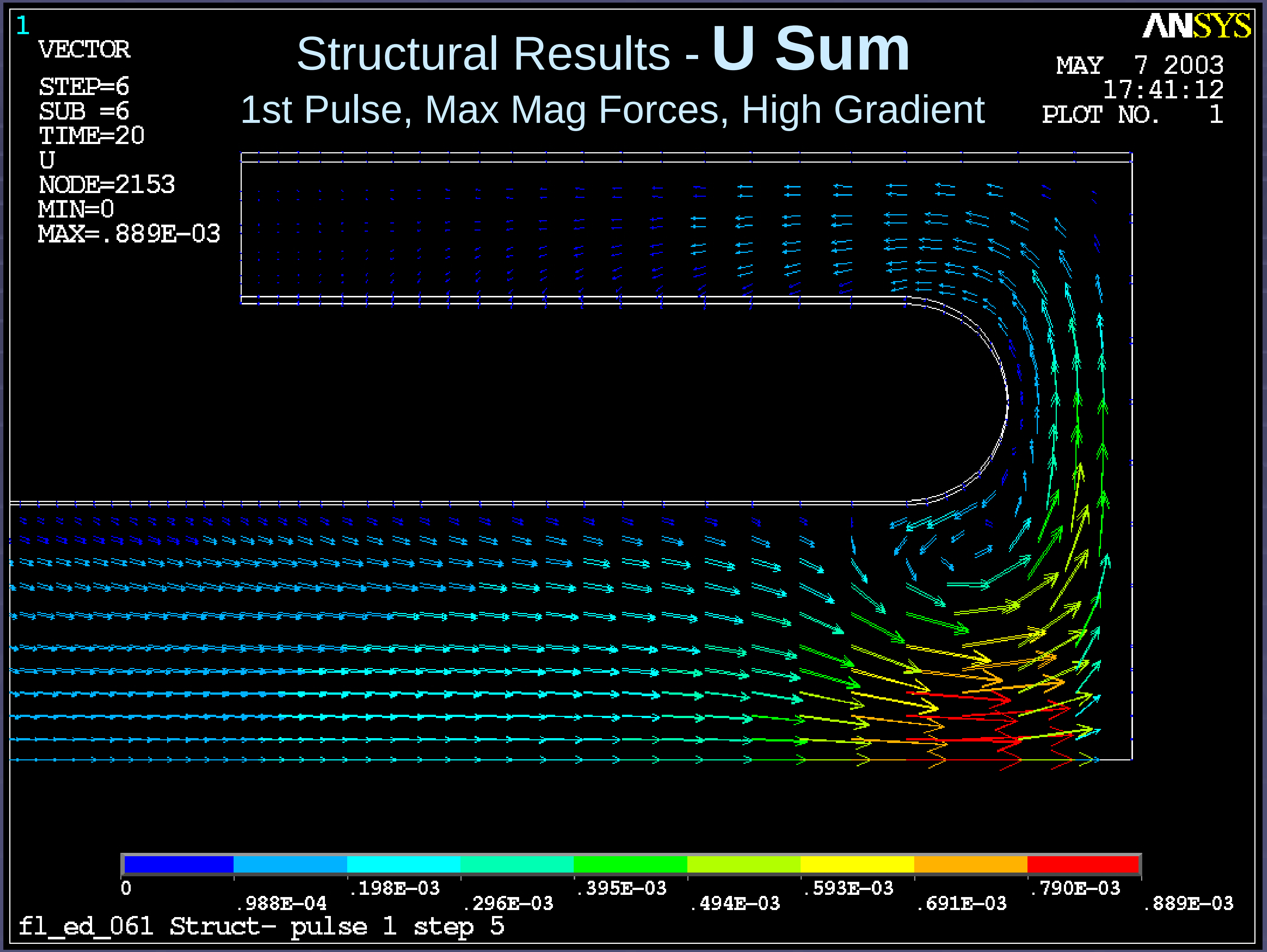




Identified Problems & Issues -

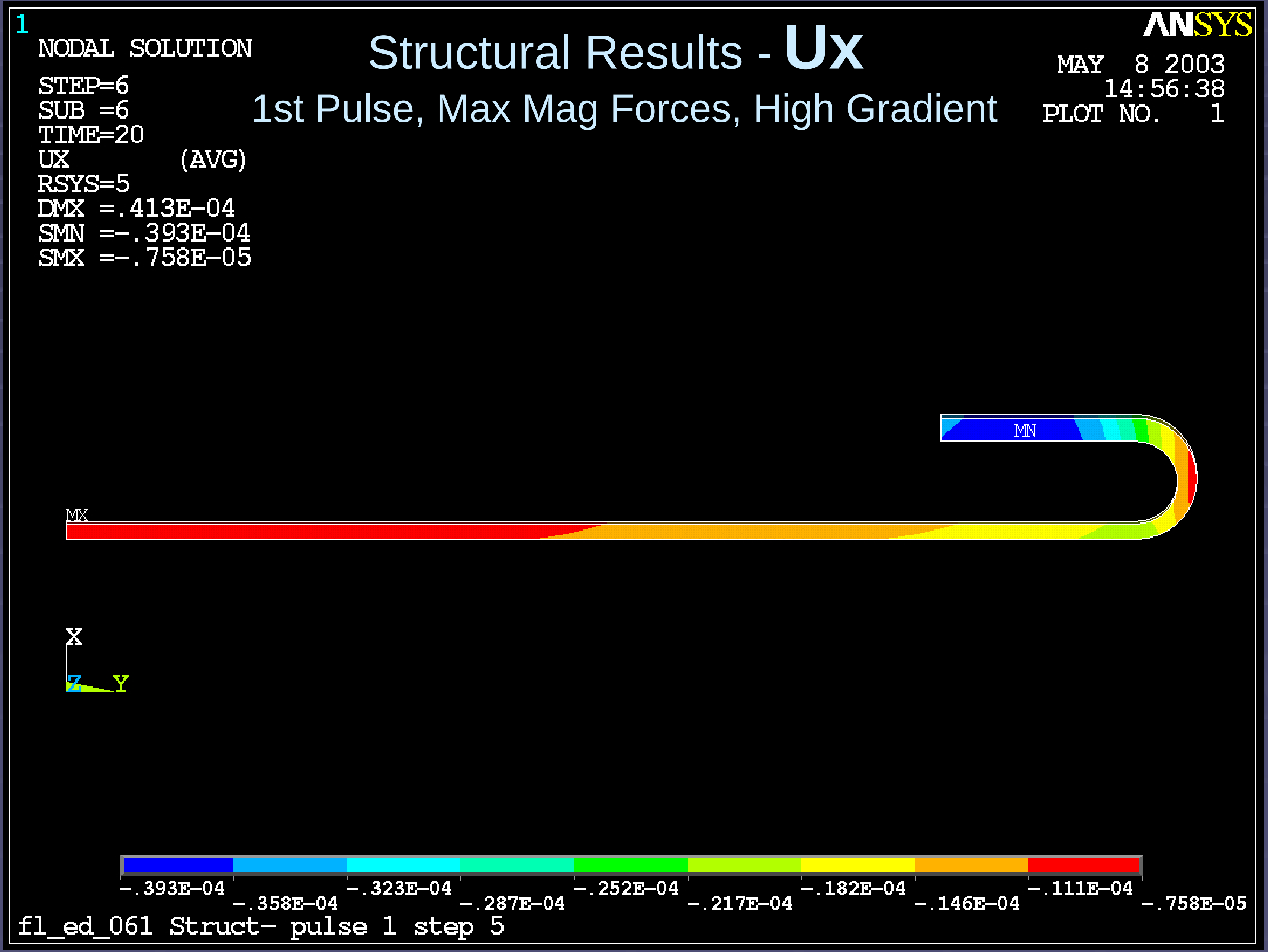
Li/Ti Separation



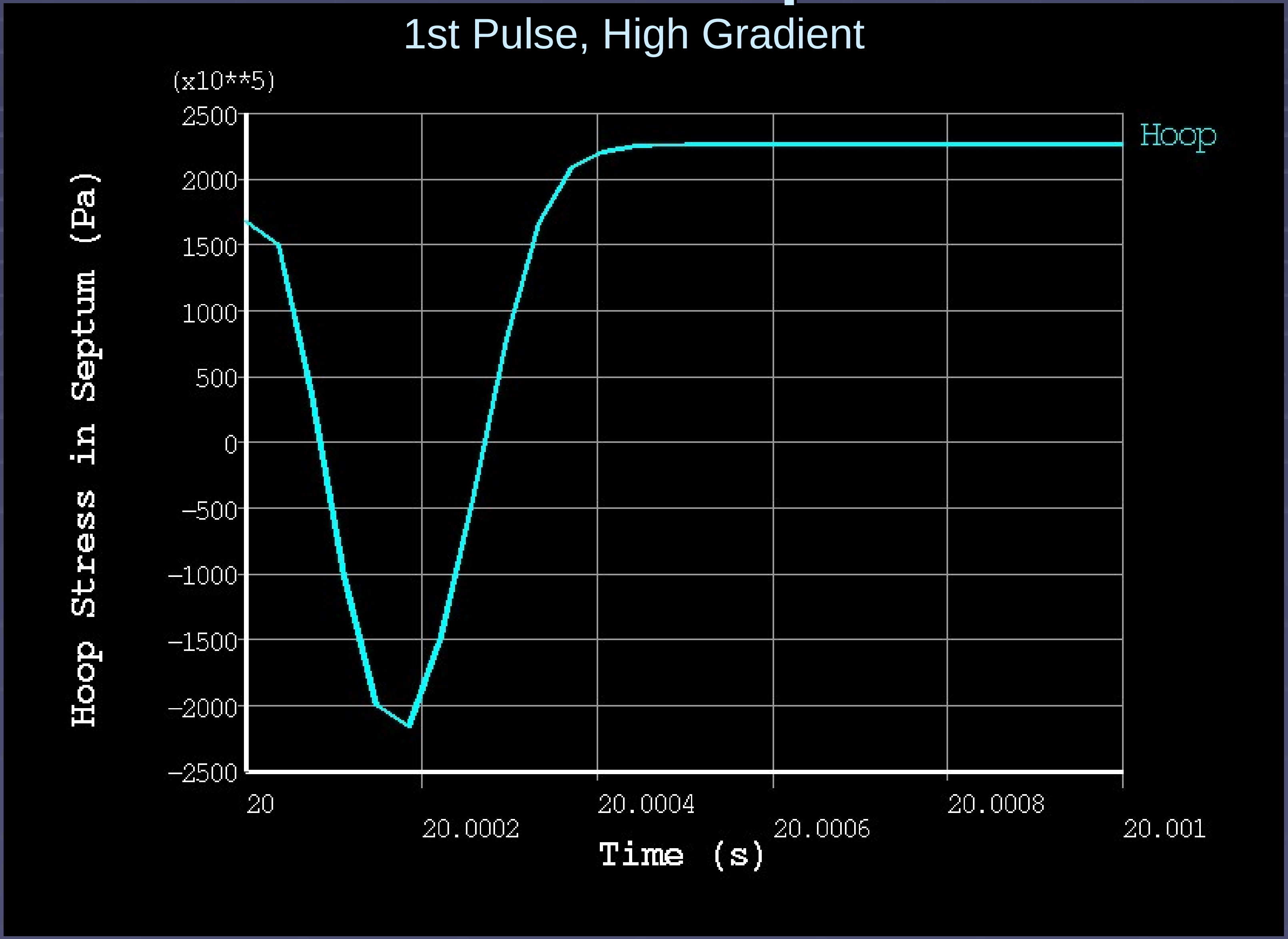

Structural Results - U Sum
1st Pulse, Max Mag Forces, High Gradient
1
VECTOR
STEP=6
SUB =6
TIME=20
U
NODE=2153
MIN=0
MAX=.889E-03
ANSYS
MAY 7 2003
17:41:12
PLOT NO. 1
0
.988E-04
.198E-03
.296E-03
.395E-03
.494E-03
.593E-03
.691E-03
.790E-03
.889E-03
fl_ed_061 Struct- pulse 1 step 5

Structural Results - Ux

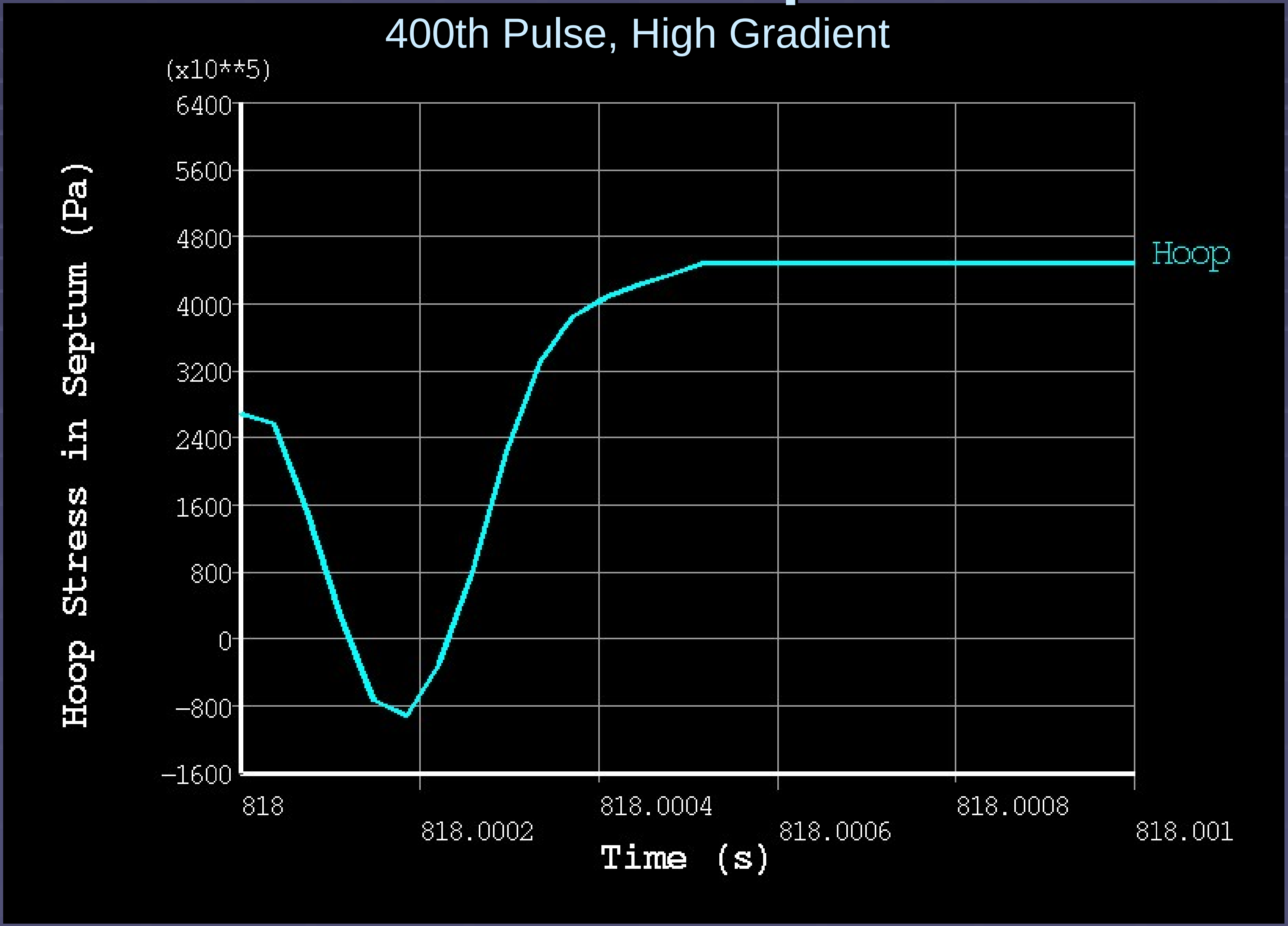
1st Pulse, Max Mag Forces, High Gradient



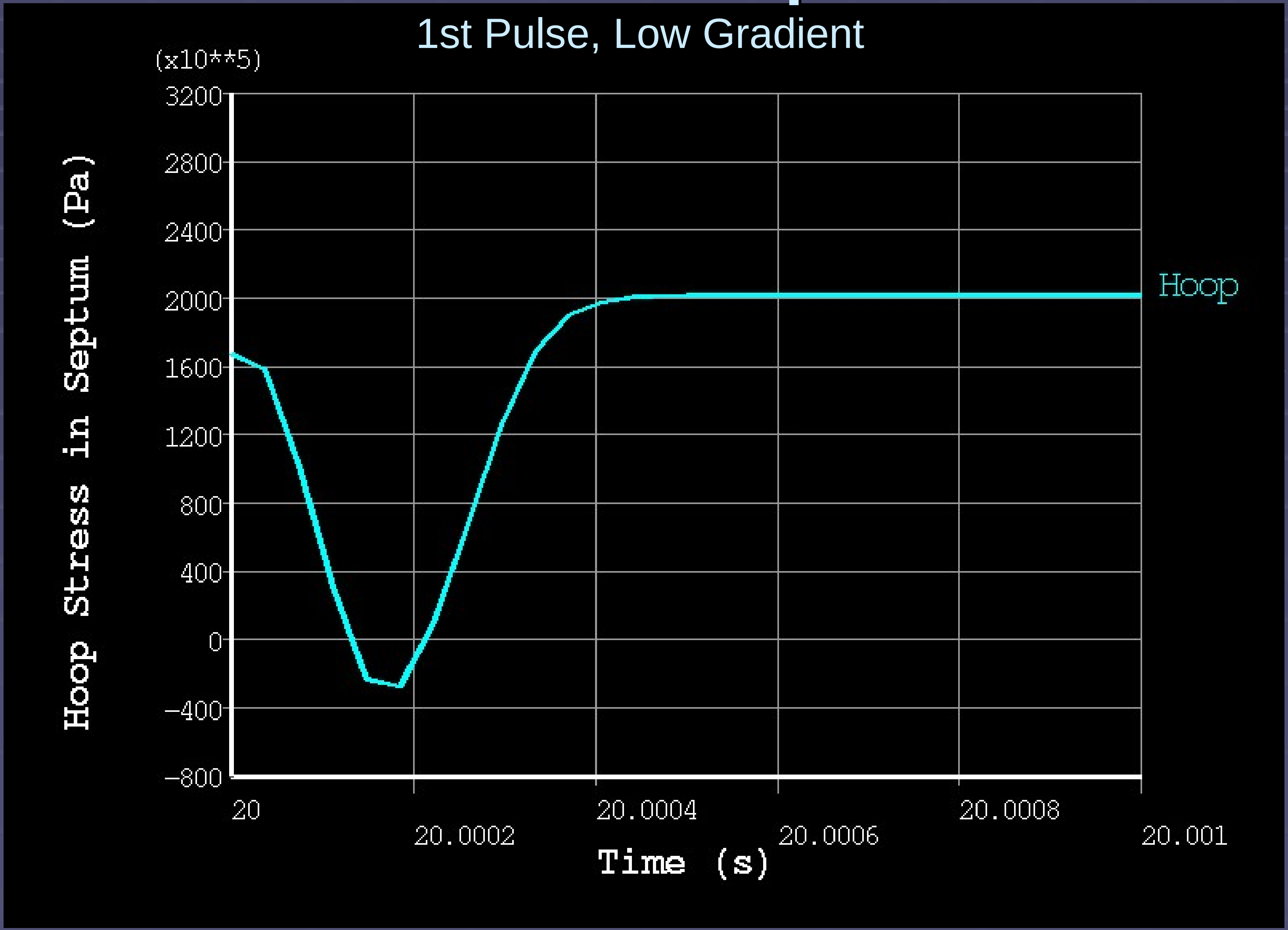
Structural Results - **Hoop Stress**



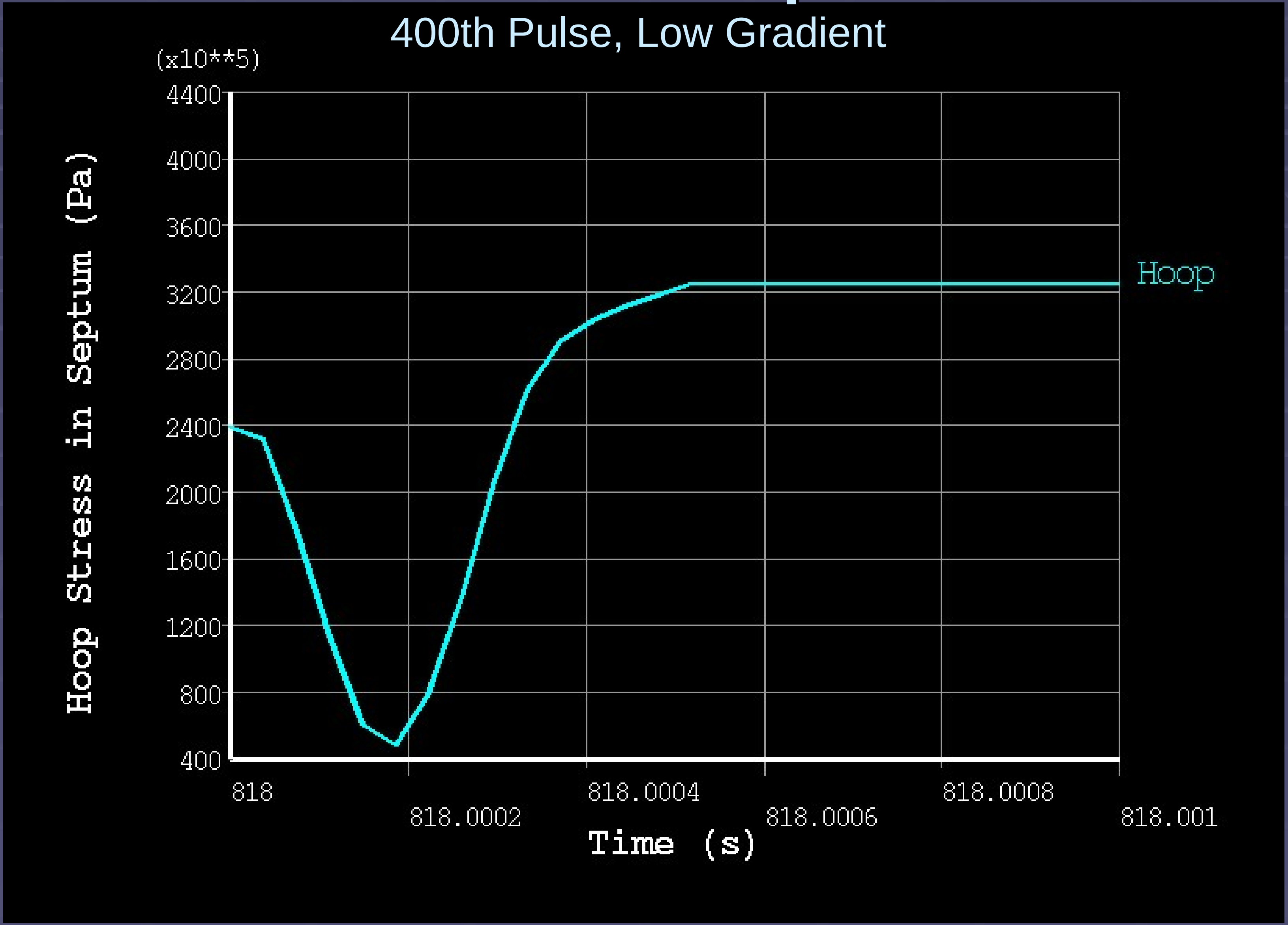
Structural Results - **Hoop Stress**



Structural Results - **Hoop Stress**

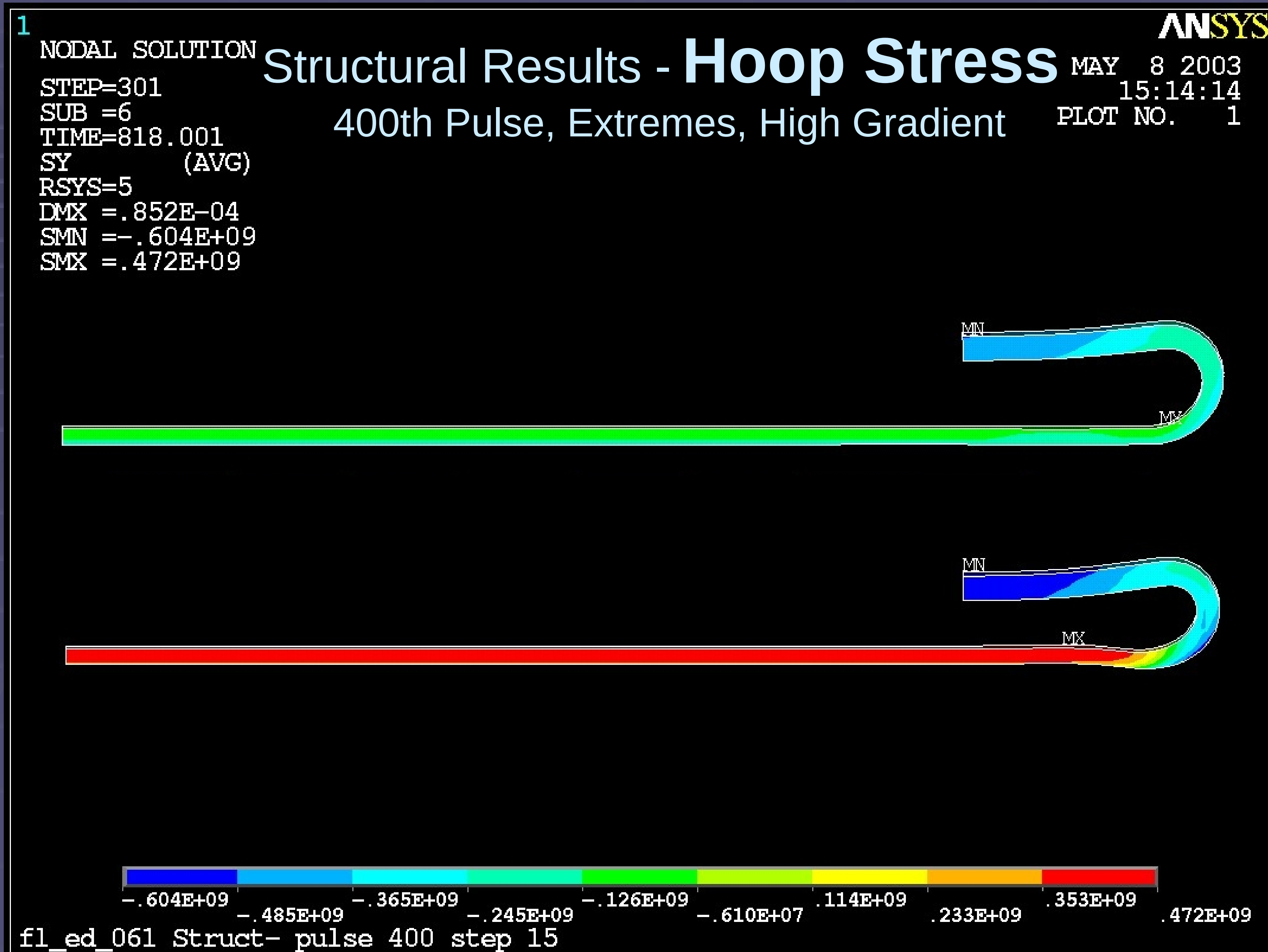


Structural Results - **Hoop Stress**



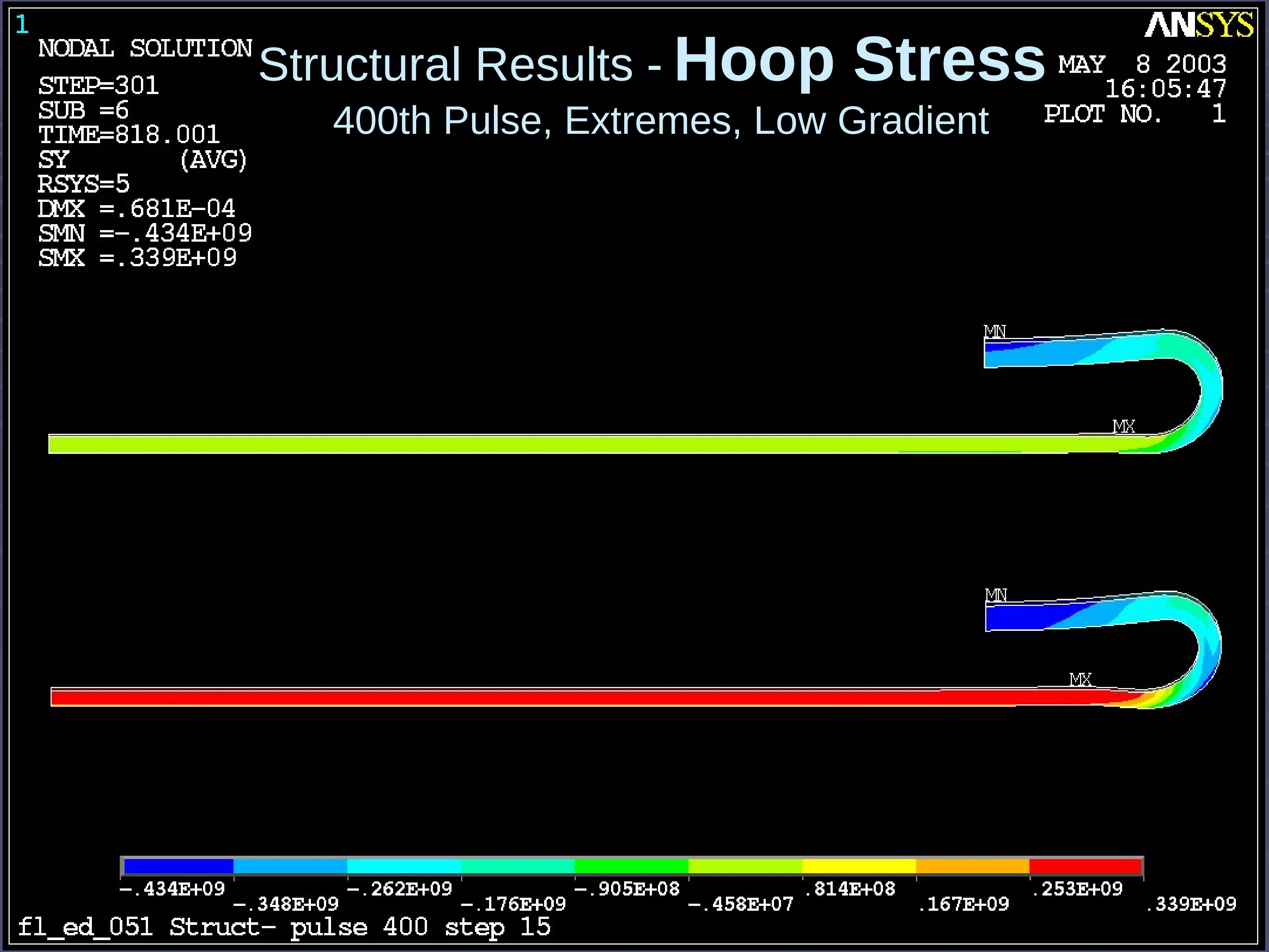
Structural Results - **Hoop Stress**

400th Pulse, Extremes, High Gradient



Structural Results - **Hoop Stress**

400th Pulse, Extremes, Low Gradient

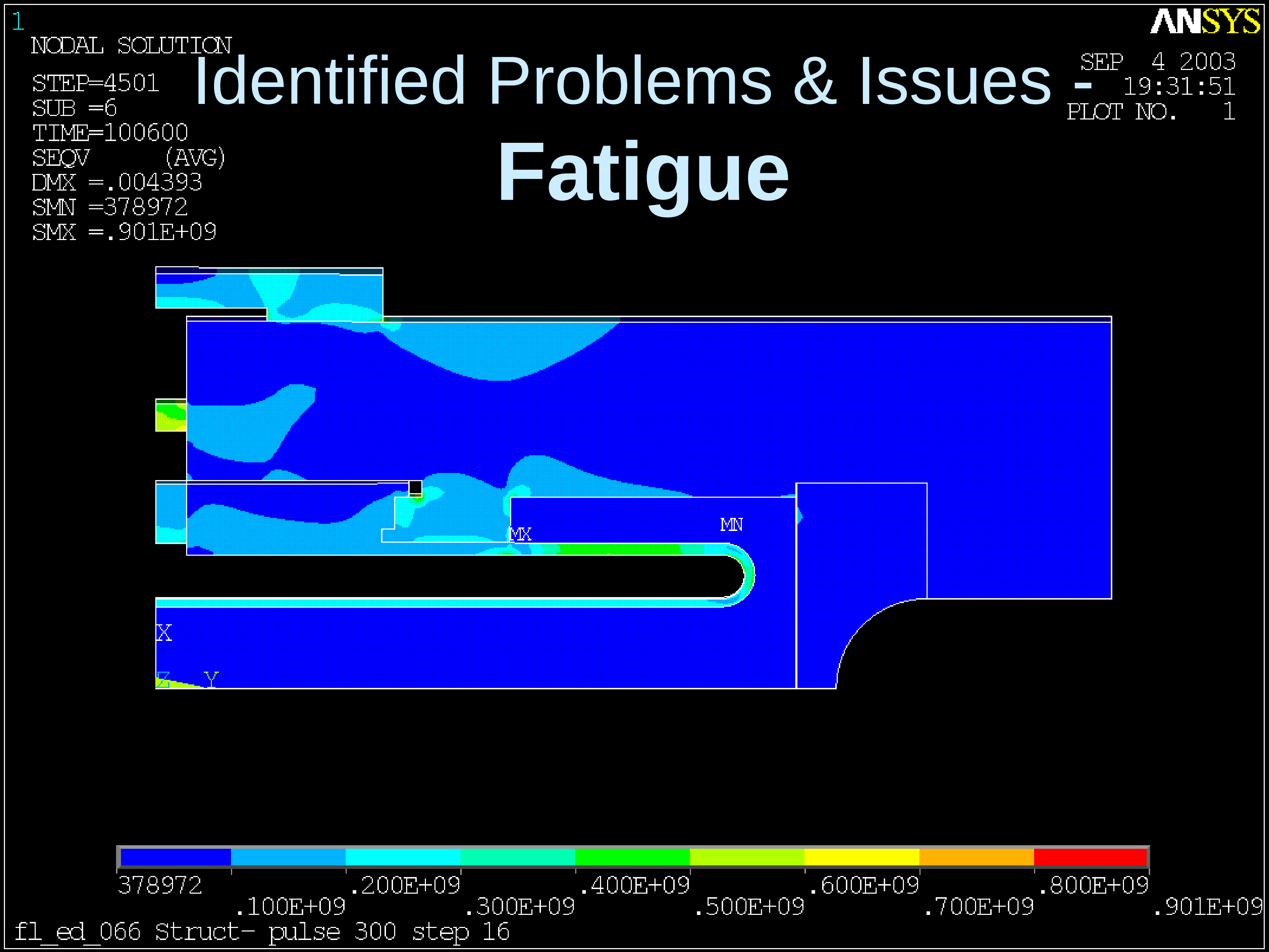


Identified Problems & Issues - **Li/Ti Separation**

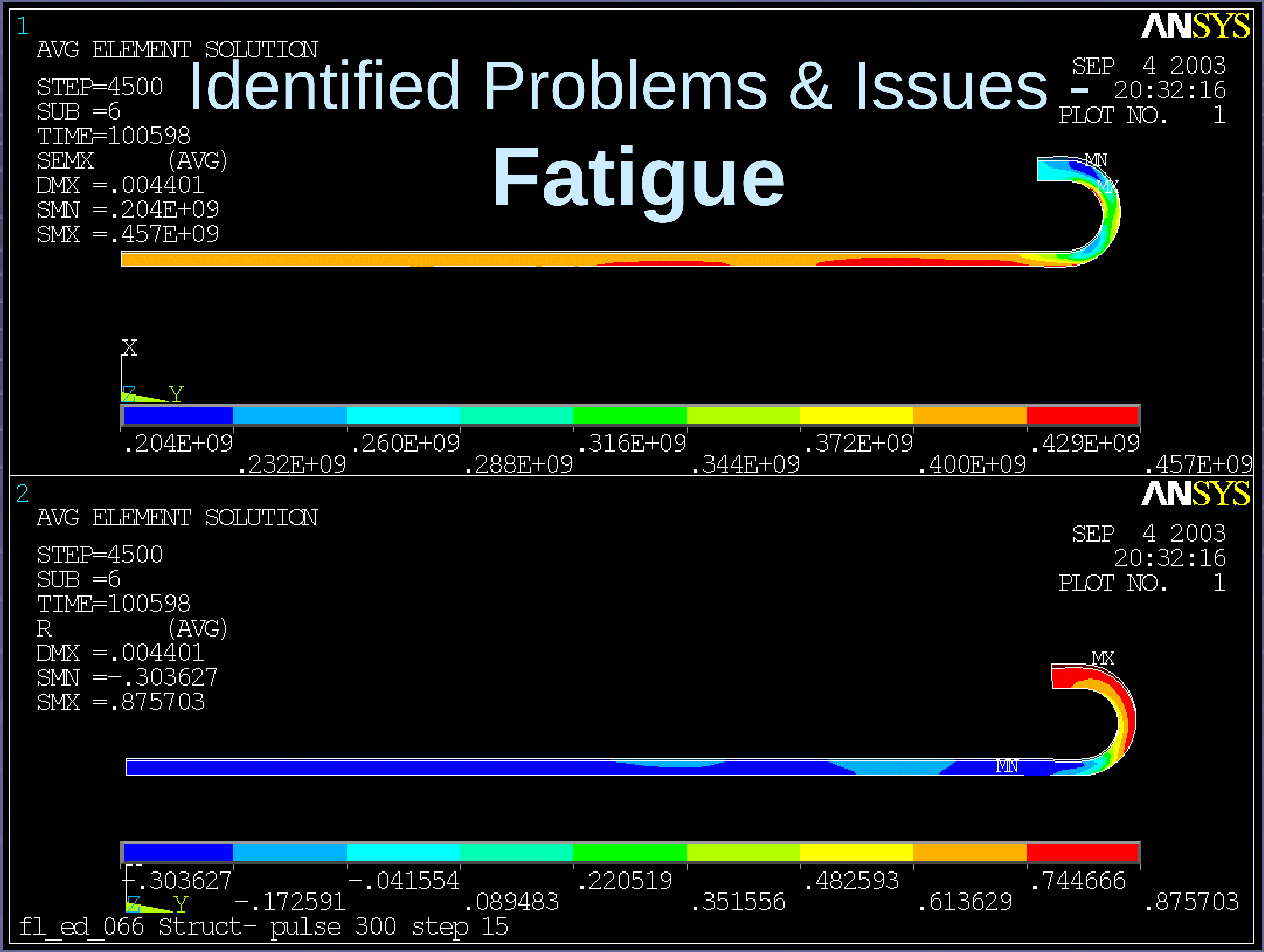
- ✓ FEA model does not simulate lithium failure (void production).
- ✓ FEA model can be used to predict onset of Li/Ti separation.
- ✓ Li/Ti Separation is evident in High Gradient pulse.
- ✓ Li/Ti Separation is not evident in Low Gradient pulse.
- ✓ Insufficient or loss of pre-load aggravates phenomenon

Identified Problems & Issues -

Fatigue



Identified Problems & Issues - Fatigue



Identified Problems & Issues - **Fatigue**

- ✓ FEA model predicts maximum stress of about 68 ksi in areas with R=-.05 (closer to R=0.1 w/o Li/Ti separation).
- ✓ Real world testing of Ti alloy (6 Al-4V) shows endurance limit of 70 to 80 ksi.
- ✓ Environmental and quality control factors could reduce lifetime significantly.

Identified Problems & Issues - **Fabrication and Assembly Difficulties**

- ✓ Current design relies on work intensive and high quality electron beam welding of the septum.
- ✓ Multiple etching and machining steps invite quality control errors (hydrogen absorbtion, contamination, weld defects, etc.)
- ✓ Multiple lithium seals are difficult to make and could lead to lithium pre-load loss.
- ✓ Poor instrumentation during lithium filling led to uncertainty in pre-load values (error bars of 50%).
- ✓ Cost and time for construction are relatively high (historically have made new lenses at a rate of 2 per year).

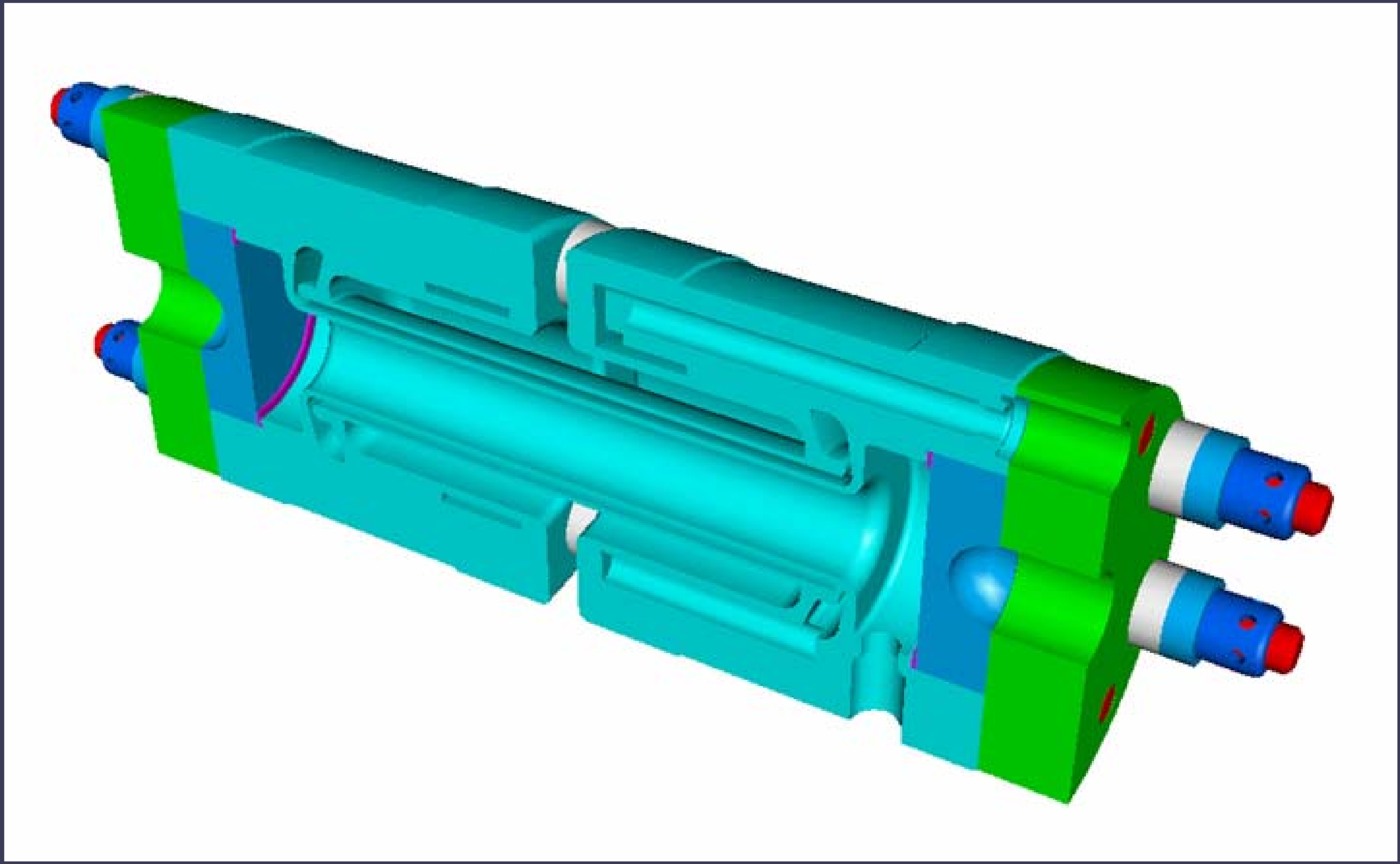
Possible Solutions
Overview

- ✓ Diffusion bonding fabrication technology -(addresses fabrication difficulties, overheating, and loss of pre-load issues)
- ✓ New seal technology & refined Li filling process- (addresses fabrication difficulties and insufficient pre-load issues)
- ✓ New septum alloy (Ti 6Al-4V to Ti 10V-2Fe-3Al) - (addresses fatigue issue)
- ✓ Coating of septum interior surface (anodizing) - (addresses material degradation issue)
- ✓ Re-shaped Li end regions to reduce Li motion - (addresses Li/Ti separation issue)

Possible Solutions
Diffusion Bonding

- ✓ Drastically reduces fabrication difficulties (all joints made at one time, eliminates body/septum seals, reduces number of etches)
- ✓ Easily accommodates body cooling
- ✓ Requires body to be made from Ti alloy

Possible Solutions
Diffusion Bonding



Possible Solutions
Diffusion Bonding

Possible Solutions

Diffusion Bonding

- ✓ Fatigue testing of critical joint show Ti 6Al-4V joint samples endurance limit = 65 ksi, R=0.1 (same as parent material samples)
- ✓ Proof-of-principle prototype complete and in process of lithium filling
- ✓ Fatigue testing of Ti 10V-2Fe-3Al joint samples in process

Possible Solutions

New Septum Material

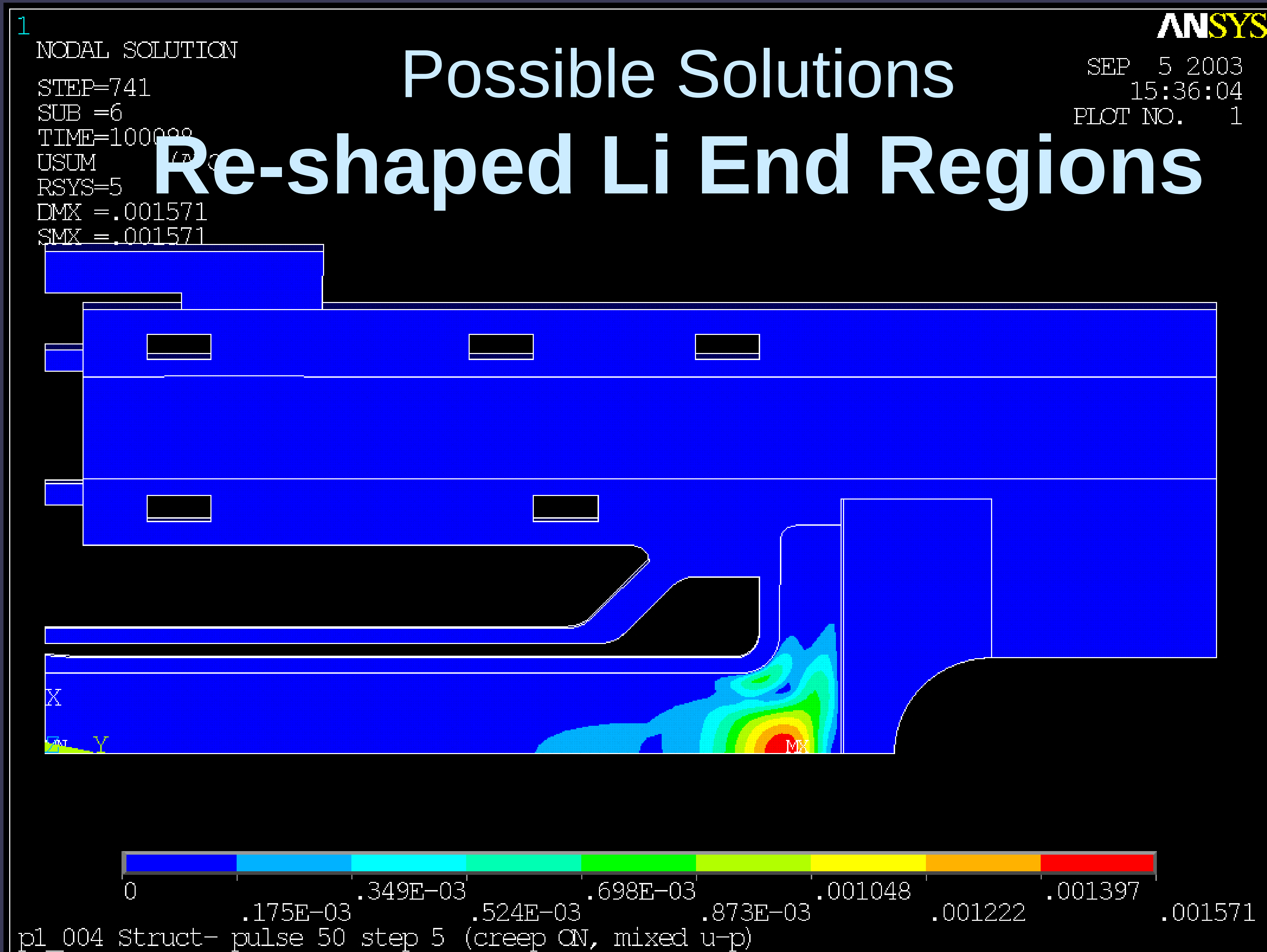
- ✓ Ti 10V-2Fe-3Al exhibits better fatigue and fracture toughness properties than Ti 6Al-4V.
- ✓ Ti 10V-2Fe-3Al is a near Beta alloy that is generally used for forging.
- ✓ Heat treatment can be easily combined with diffusion bonding run to obtain optimum properties (not easily done with Ti 6Al-4V).
- ✓ Fatigue testing of heat treated material show endurance limit of 110 ksi, R=0.1. Fatigue testing of joint samples underway.

Possible Solutions
Re-shaped Li End Regions

- ✓ FEA Model (E-M, Thermal, and Structural) is almost ready to use as design tool
- ✓ Alternate geometries of end regions will be explored to find effect on Li/Ti separation and stresses
- ✓ Also effect of lithium pre-load with various geometries will be explored.

Possible Solutions

Re-shaped Li End Regions



Conclusion & Future Work

- ✓ Many problems and issues have been identified for the current lens design that may be responsible for failures at high gradient.
- ✓ Some possible solutions are being aggressively investigated.
- ✓ The proof-of-principle prototype should be pulsing within 2 months.
- ✓ Final prototype should be completed within 1 year.

Conclusion & Future Work

- ✓ From recent DOE "Lehman" Review findings:

"Lithium lens improvements look promising: good chance of lifetime and/or gradient improvements"

-Fritz Caspers, CERN
-G. Dugan, Cornell
-Flemming Pedersen, CERN