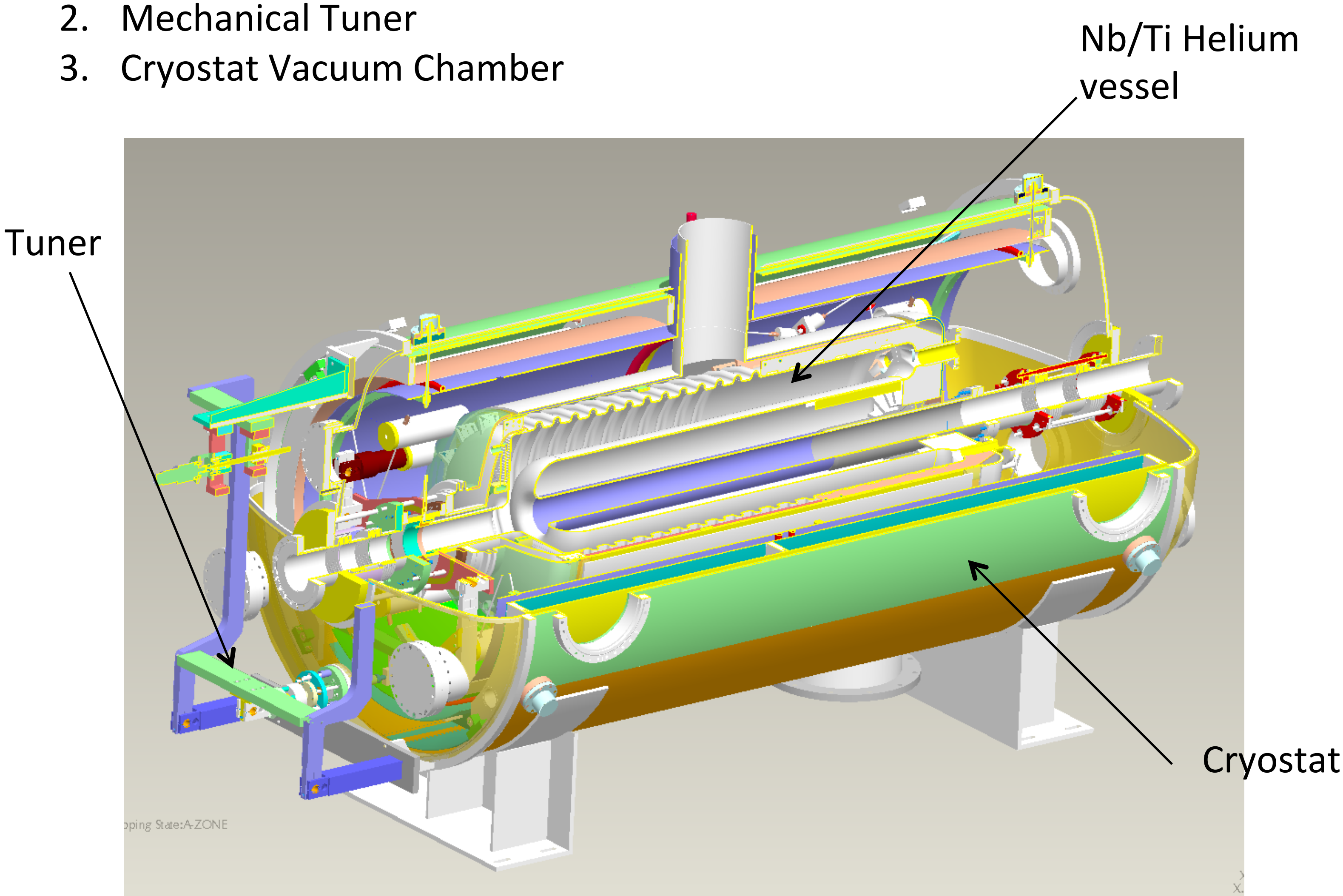
56 MHz SRF Cavity and Helium vessel Design

C. Pai

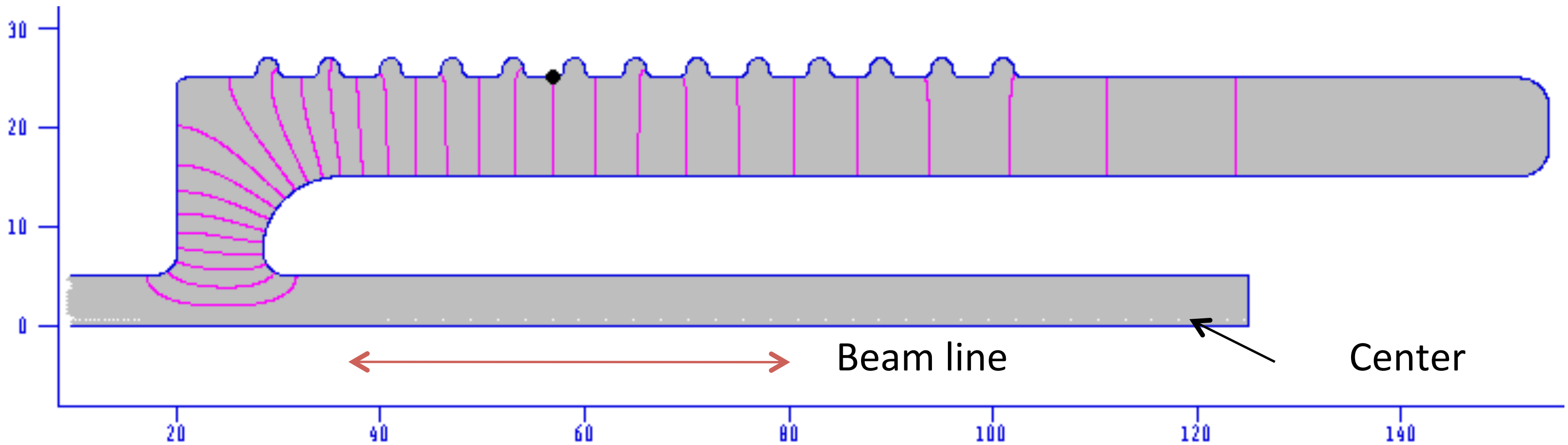
3-08-2011

Major Components in the 56 MHz SRF cavity and Cryostat

1. Nb Cavity/Ti Helium Vessel
2. Mechanical Tuner
3. Cryostat Vacuum Chamber



56 MHz RF Cavity Geometry and Design Requirements (Axisymmetric)

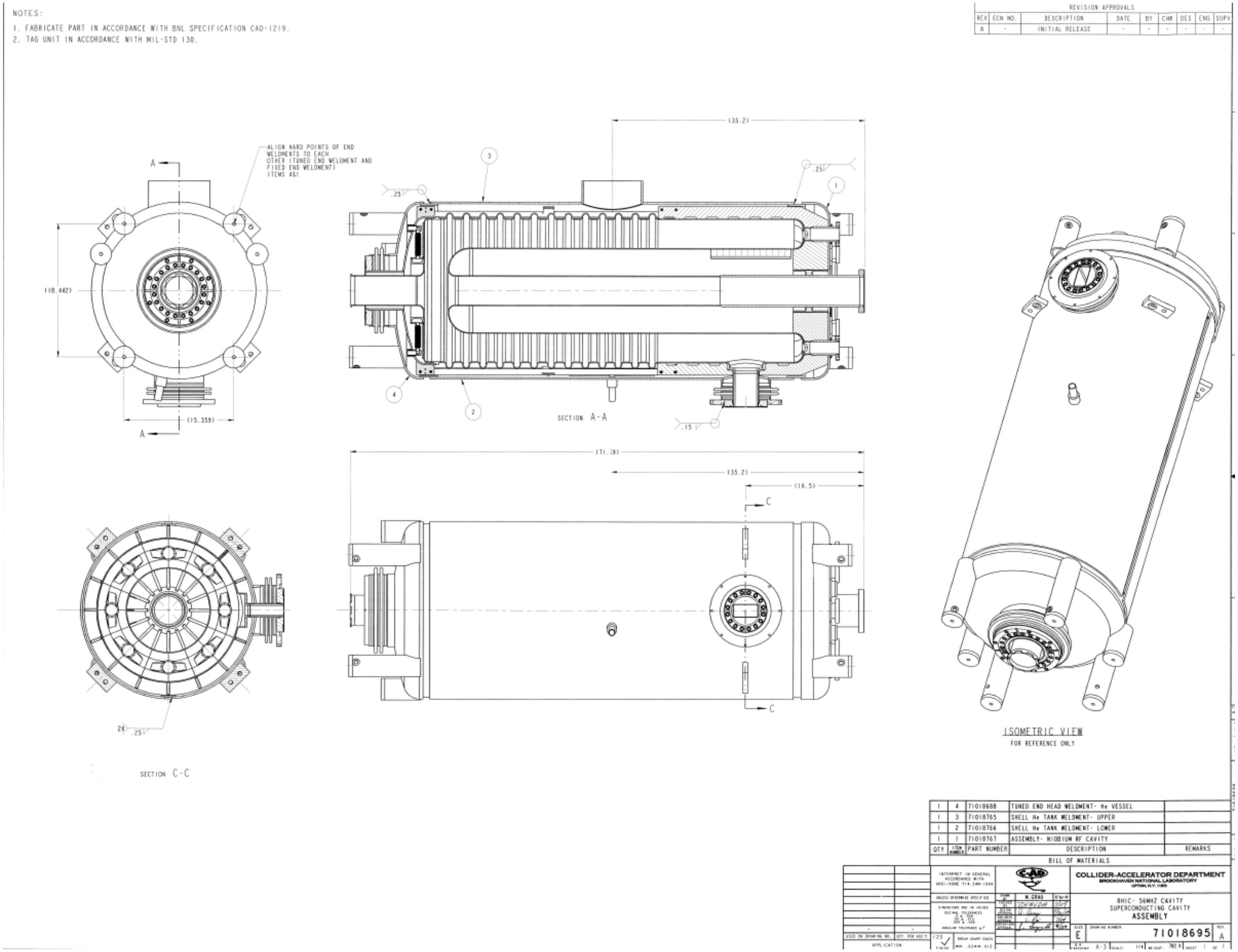


Cavity geometry: Inside surface
Date: 11/5/08 from X. Chang.
Dimension in Room temperature

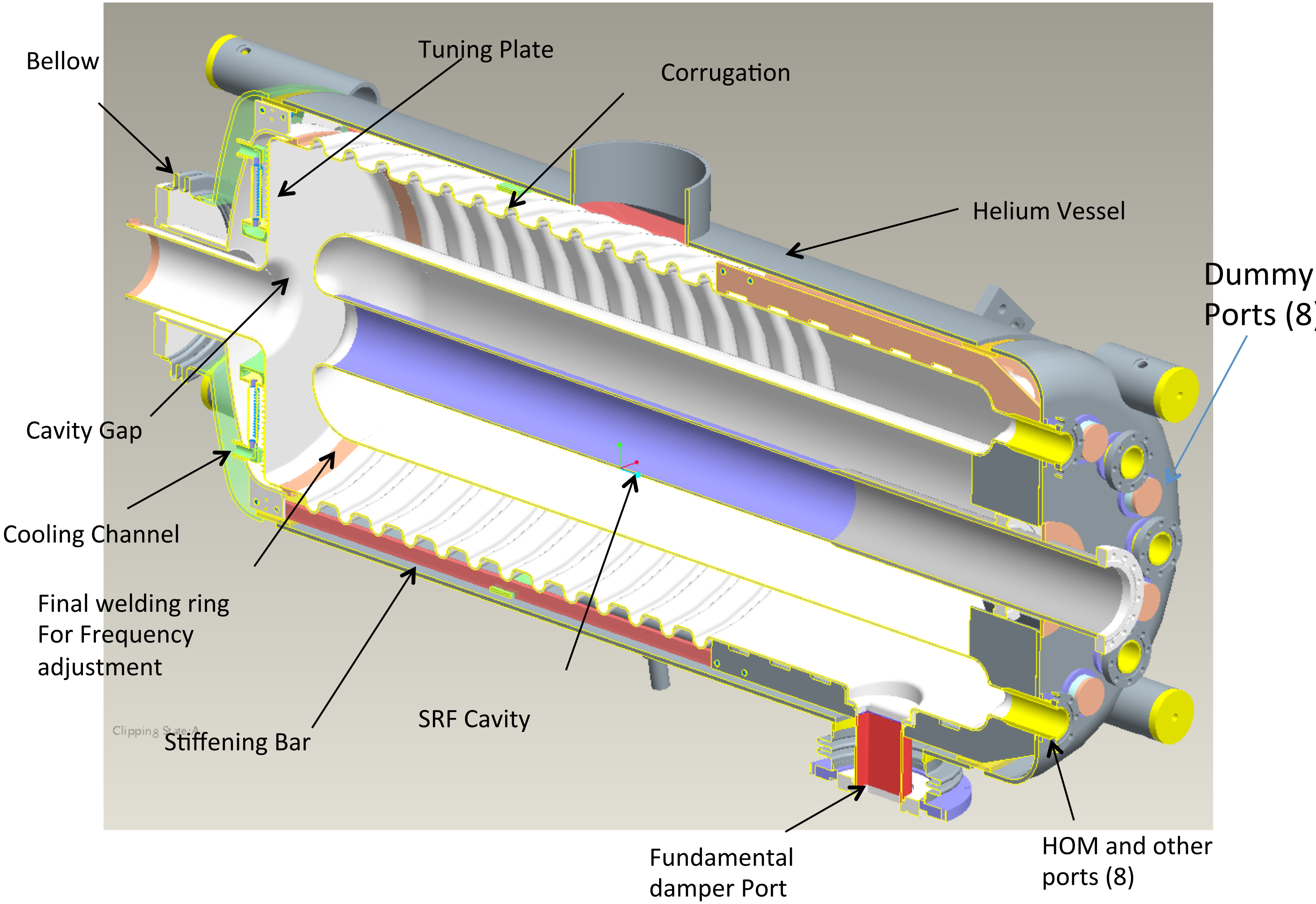
Four Design Requirements

1. Prevent Multipacting
2. Minimize Pressure Sensitivity
3. Meet ASME pressure vessel code
4. Provide mechanical frequency Tuning

56 MHz Cavity Drawing, # 71018695

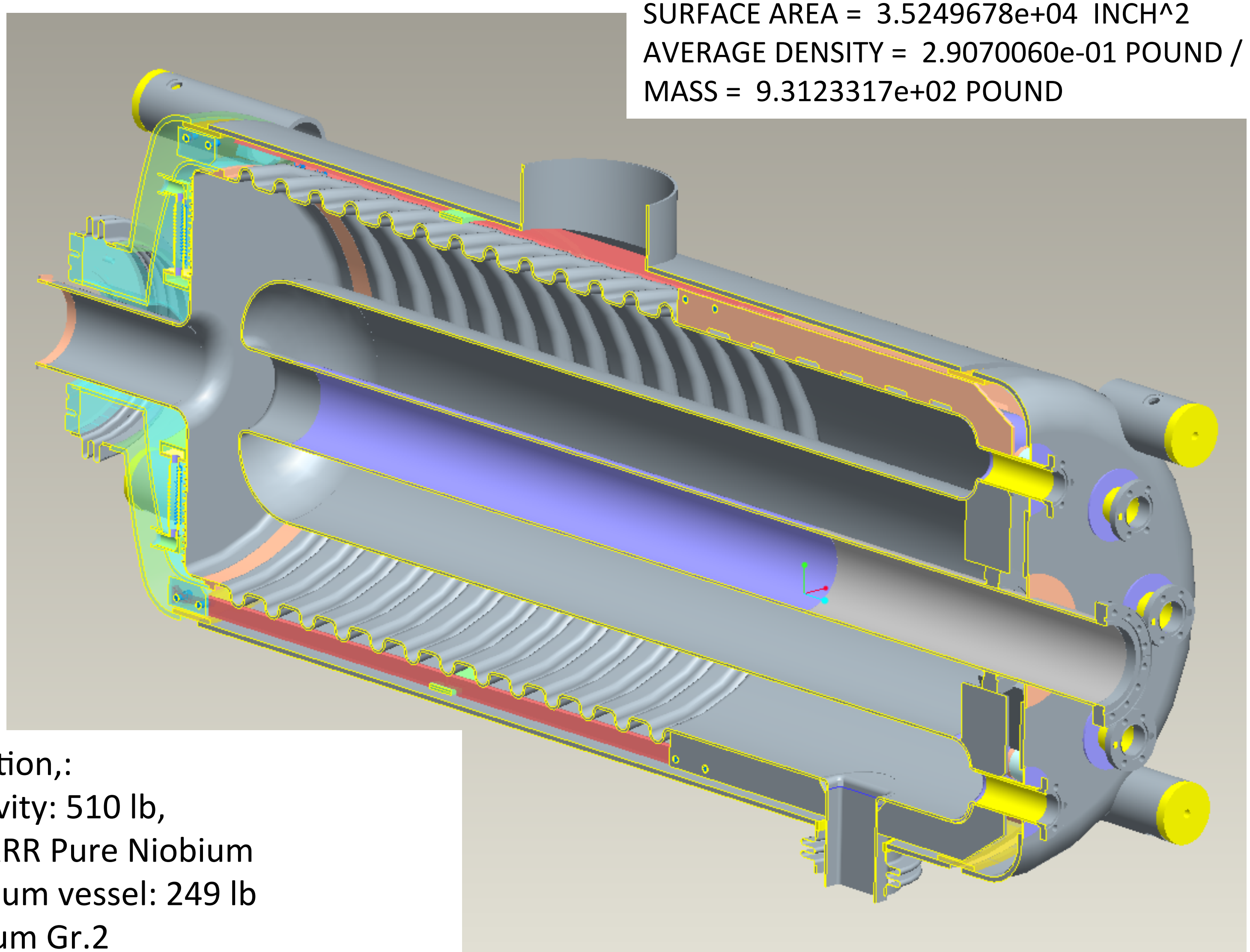


Cross Section View of Nb/Ti Cavity Helium Vessel



Weight of Full Cavity with helium vessel

PRO-E model
VOLUME = 3.2034099e+03 INCH^3
SURFACE AREA = 3.5249678e+04 INCH^2
AVERAGE DENSITY = 2.9070060e-01 POUND / INCH^3
MASS = 9.3123317e+02 POUND



By calculation,:

1. Nb cavity: 510 lb,
   High RRR Pure Niobium
2. Ti Helium vessel: 249 lb
   Titanium Gr.2

Total weight : 759 lb

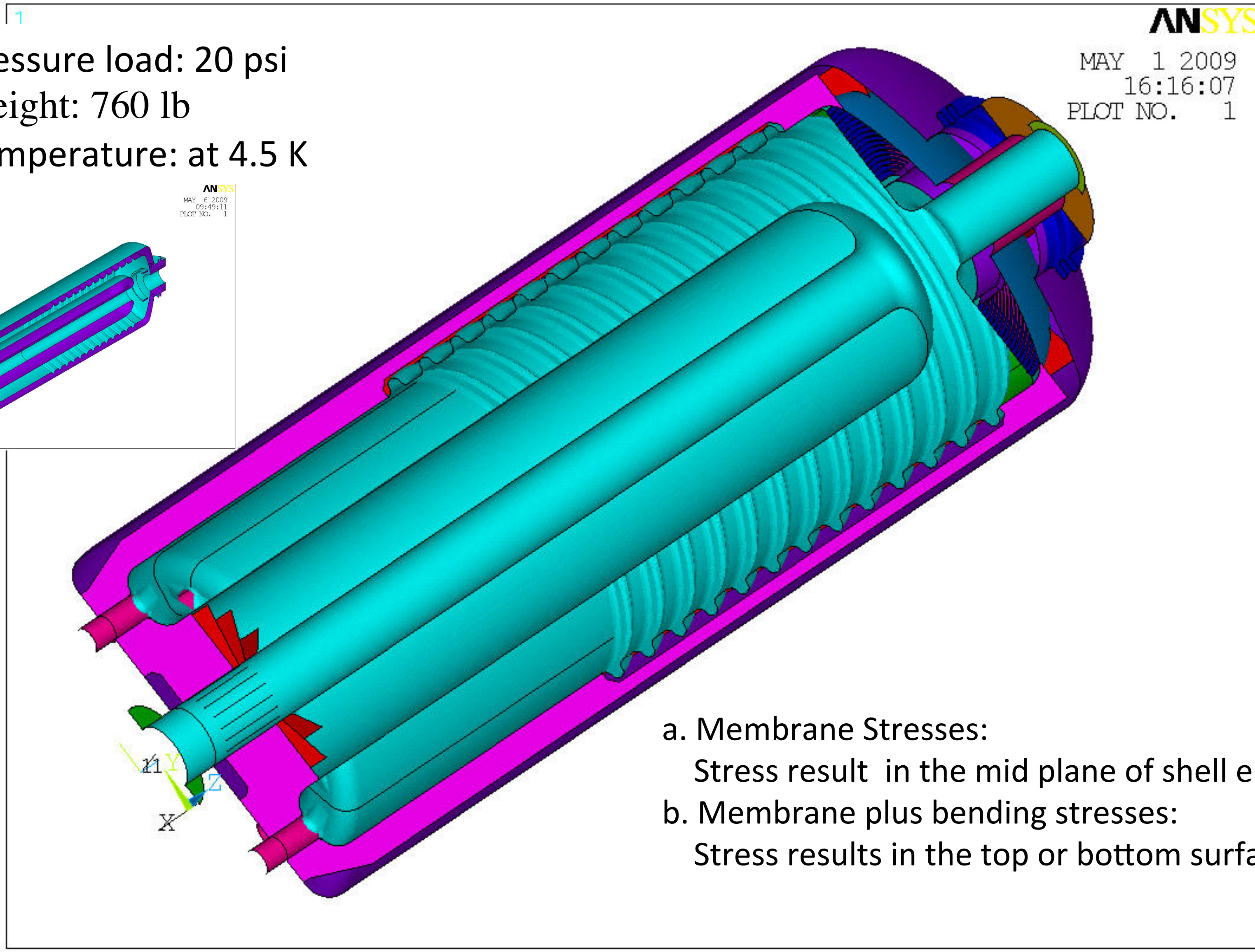
ASME Pressure vessel Code section VIII, division 2
Design by Analysis

4 failure modes to be checked to meet compliance.

1. Protection Against Plastic Collapse
   Check Membrane and bending stress in whole structure.
   Loading includes maximum pressure (External and Internal) and Weight of the Vessel
2. Protection Against Local Failure
   Check principle stresses, $\sigma1 + \sigma2 + \sigma3 < 4 S$ Where $\sigma1, \sigma2, \sigma3$ are the principle stresses at any point. S is the allowable stress of material.
   Loading includes: Mechanical Load (Primary) and Thermal load)
   For Niobium S=4,666 psi, (2/3 of yield :7000 psi)
3. Protection Against Collapse From Buckling
4. Protection Against Failure From Cyclic Loading (Fatigue), including Ratcheting assessment.

Integral RF cavity/Helium Vessel Finite Element Model

1. Pressure load: 20 psi
2. Weight: 760 lb
3. Temperature: at 4.5 K

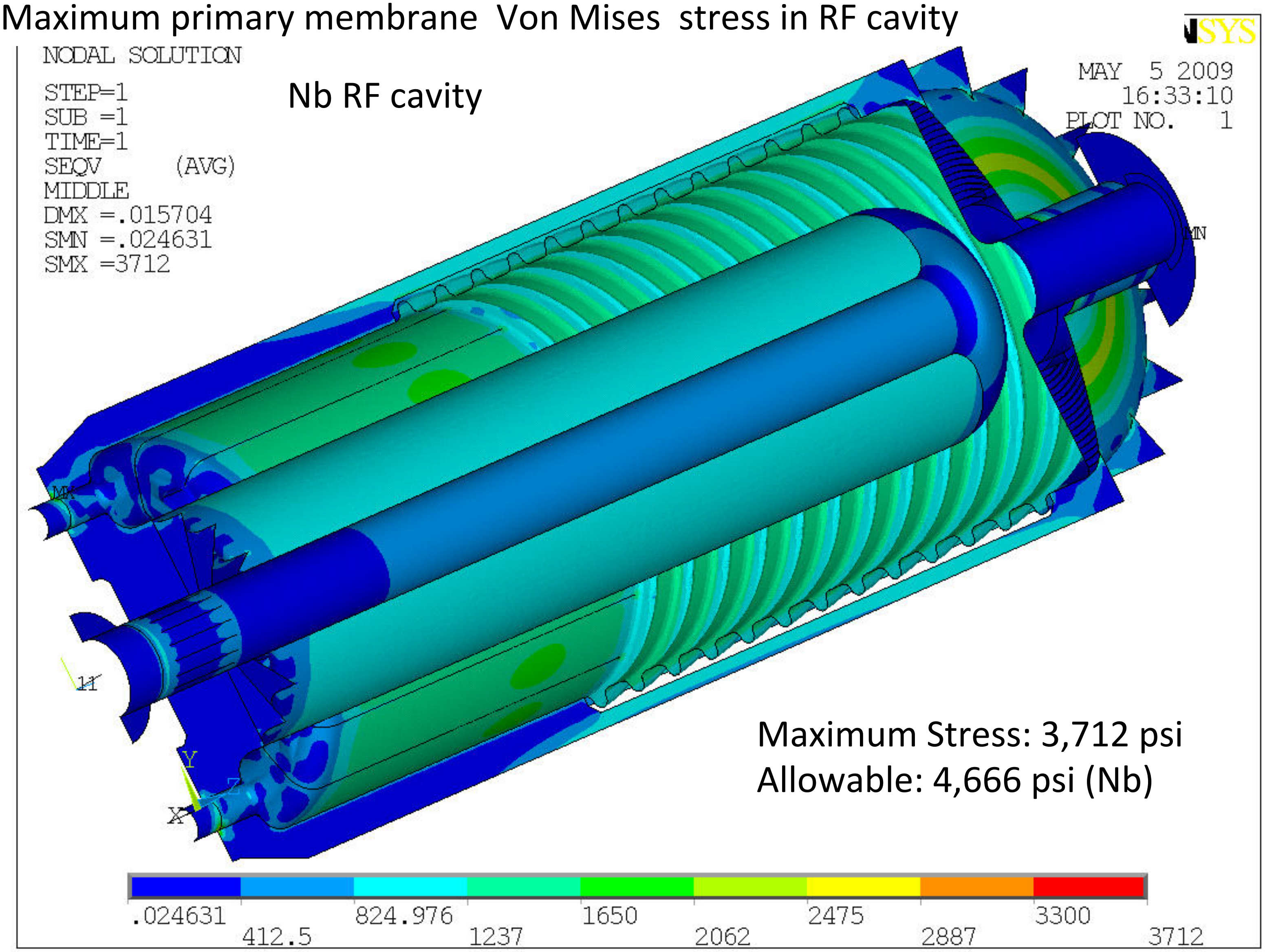


a. Membrane Stresses:
   Stress result in the mid plane of shell element

b. Membrane plus bending stresses:
   Stress results in the top or bottom surface

Integral Pressure Vessel, Under Weight + Pressure

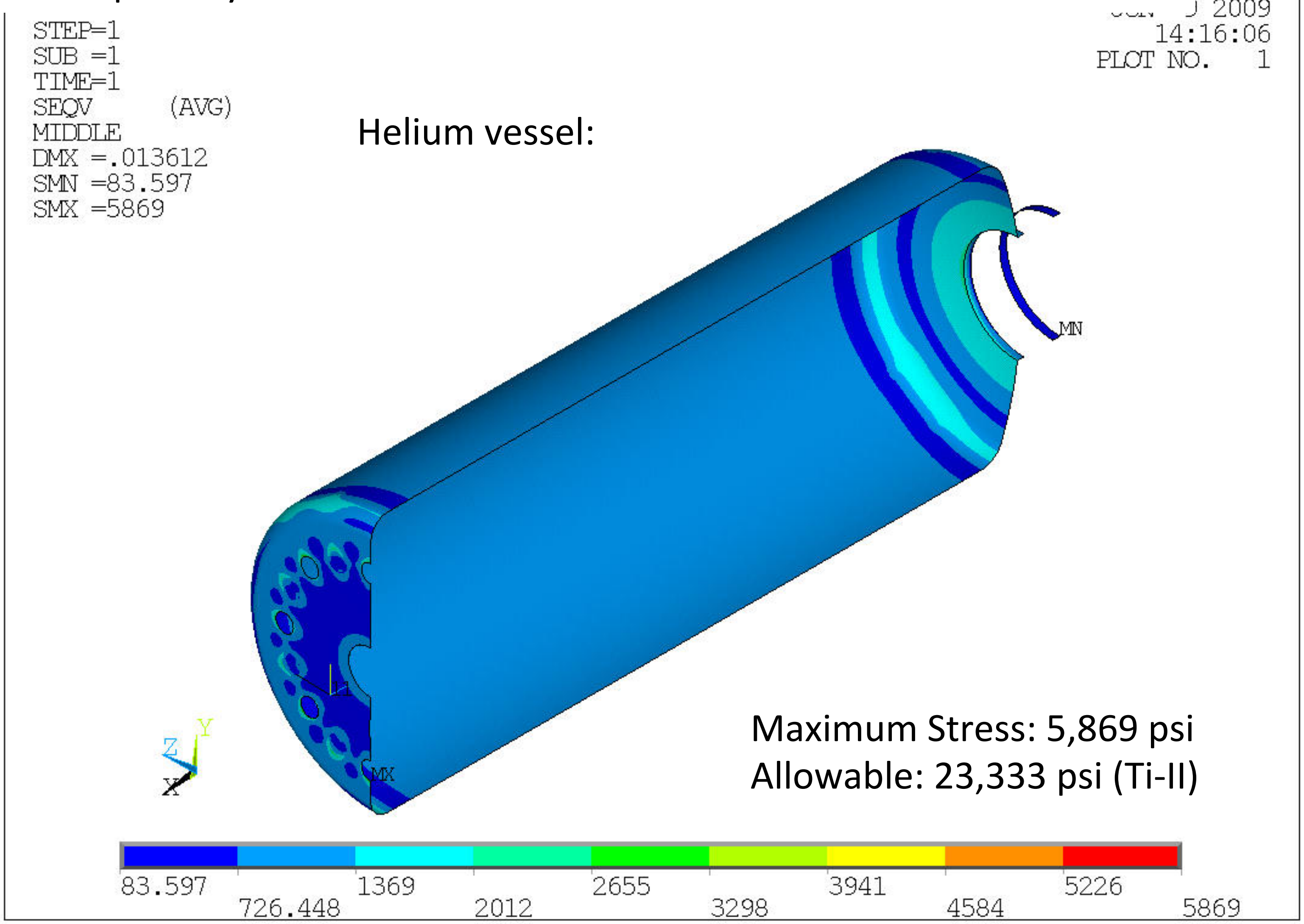
Maximum primary membrane Von Mises stress in RF cavity



(psi)

Integral Pressure Vessel, Under Weight + Pressure

Maximum primary membrane von Mises stress in Helium vessel:



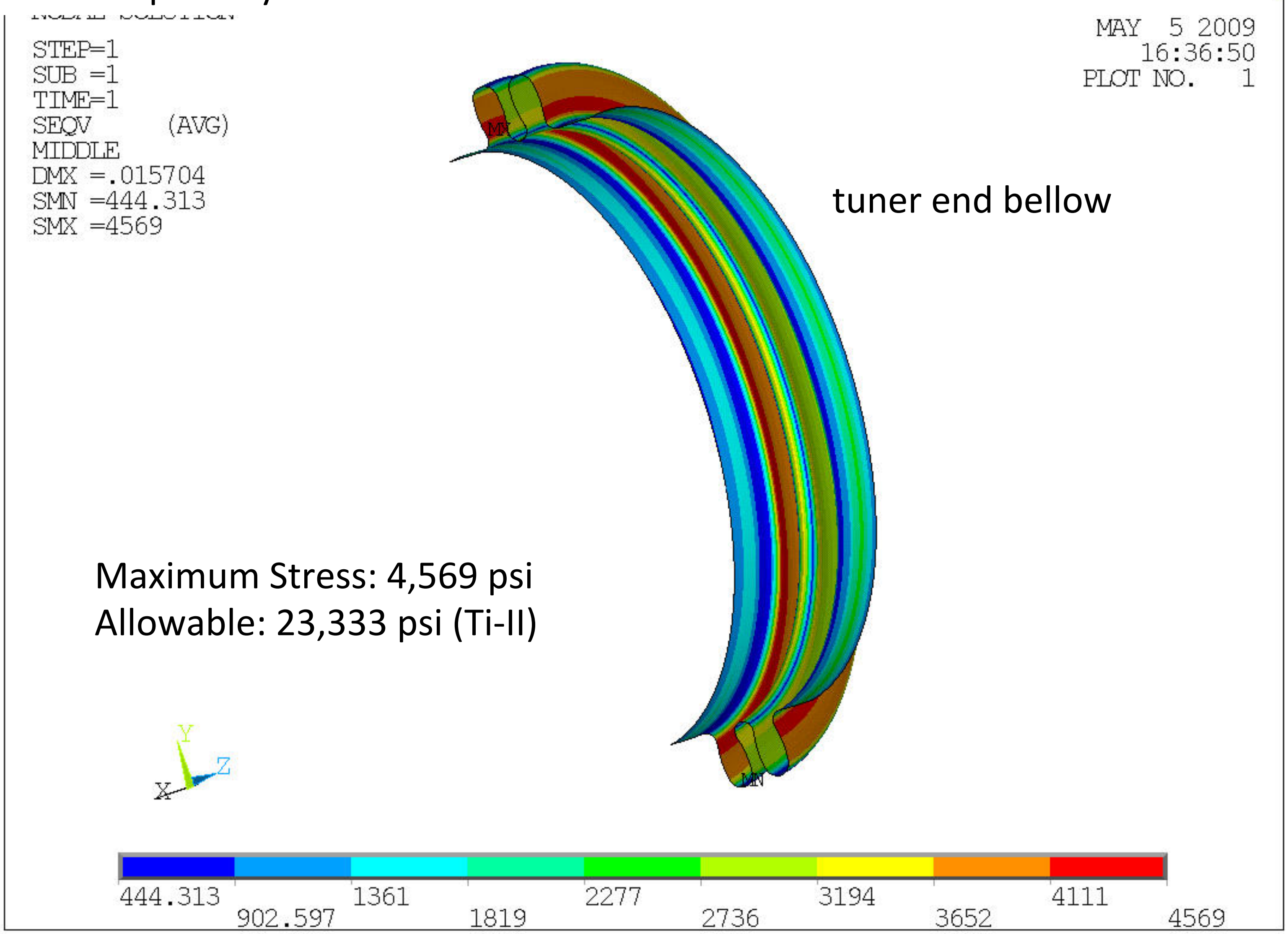
Helium vessel:

Maximum Stress: 5,869 psi
Allowable: 23,333 psi (Ti-II)

psi

Integral Pressure Vessel, Under Weight + Pressure

Maximum primary membrane stress in the tuner end bellow:

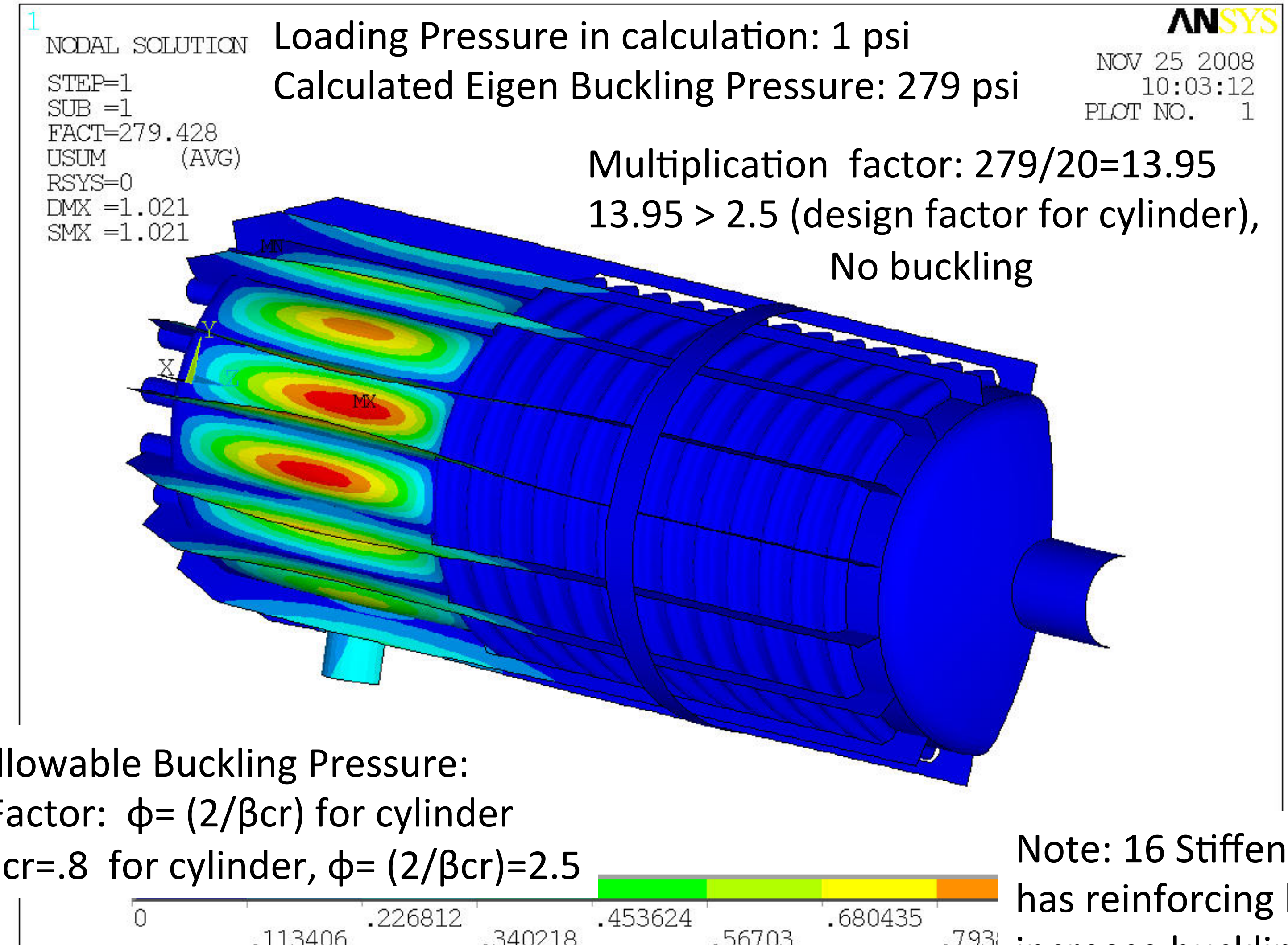


tuner end bellow

Maximum Stress: 4,569 psi
Allowable: 23,333 psi (Ti-II)

(psi)

Buckling Analysis, First Mode Shape of Eigen Buckling



Loading Pressure in calculation: 1 psi

Calculated Eigen Buckling Pressure: 279 psi

Multiplication factor: 279/20=13.95

13.95 > 2.5 (design factor for cylinder),

No buckling

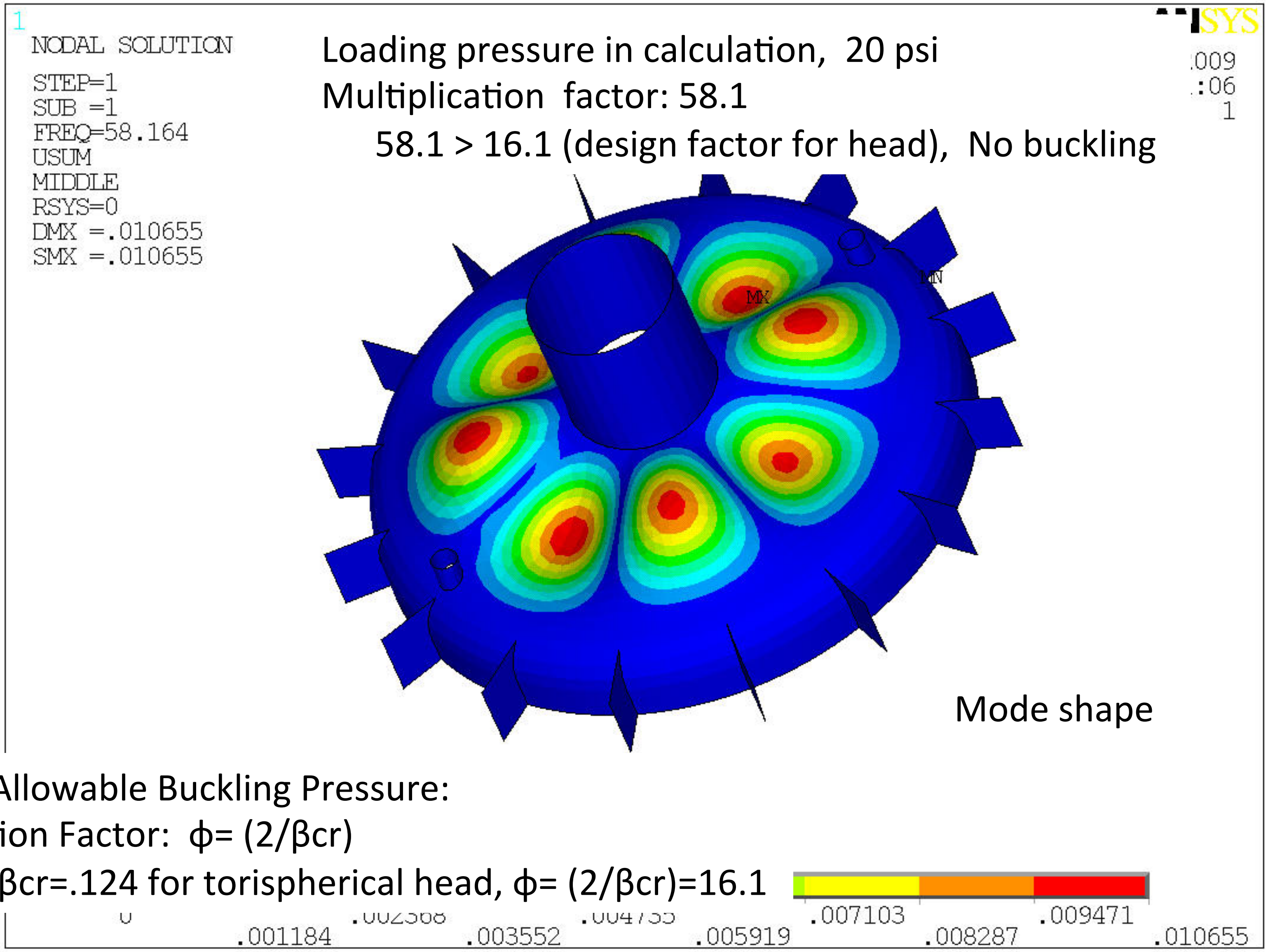
ASME Allowable Buckling Pressure:

Design Factor: ϕ= (2/βcr) for cylinder

where βcr=.8 for cylinder, ϕ= (2/βcr)=2.5

Note: 16 Stiffener bars has reinforcing band to increase buckling load

Buckling (Eigen value) of RF cavity Head



Loading pressure in calculation, 20 psi

Multiplication factor: 58.1

58.1 > 16.1 (design factor for head), No buckling

Mode shape

ASME Allowable Buckling Pressure:

Reduction Factor: $\phi = (2/\beta cr)$

where $\beta cr = .124$ for torispherical head, $\phi = (2/\beta cr) = 16.1$

Fatigue analysis is not required:

Base on screen criteria: (Depends on total operational cycles in life time)
The 56 MHz RF cavity Satisfy provisions of paragraph 5.5.2.3, Method A

1. Condition A: Minimum tensile stress is not exceeding 80,000 psi.
2. Total expected number of cycles of type (a) plus type (b) plus type (c) plus type (d) does not exceed 1000.

Type (a): the expected number of full range pressure cycles including start up and shut down. (4x 20 years)

Type (b): the expected number of operating pressure cycles in which the range of pressure variation exceeds 20% of design pressure. (0)

Type (c): the effective number of change in metal temperature between any two adjacent joints. (same as start up, 4x 20 years)

Type (d): the number of temperature cycles for component involving welds between material having different coefficient of expansion is that which causes the value of (alpha1-alpha2) x del T to exceed .00034. (same as start up, 4 x 20 years)

Total cycle number=(a)+(b)+(c)+(d)= 240. The projected cycle number of 56 MHz RF cavity operation won't exceed 1000. Fatigue analysis is not required. Also, the stresses are all in elastic range there is no ratcheting concern.

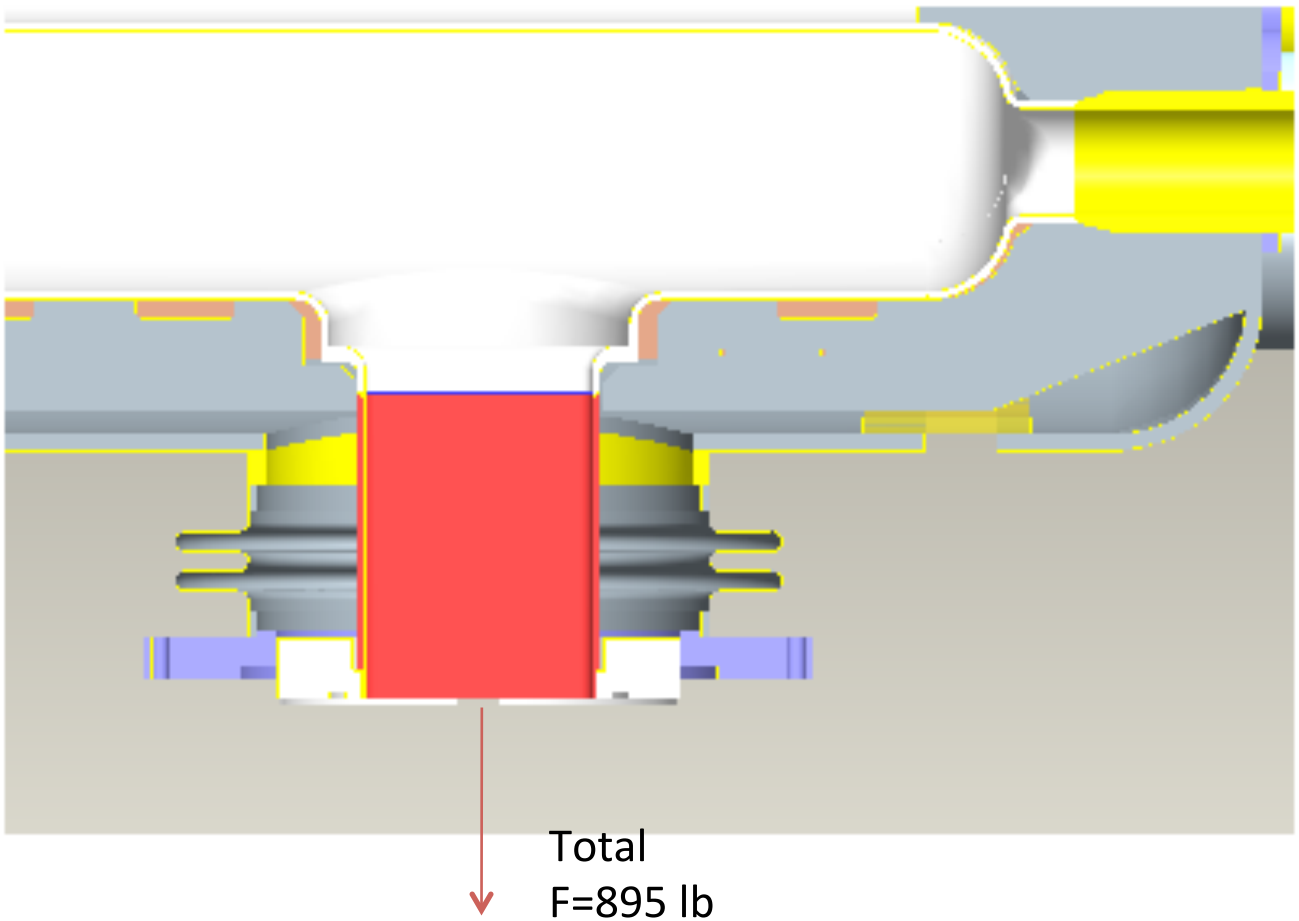
Various Local features Stress analyses

Local Features of Pressure Vessel

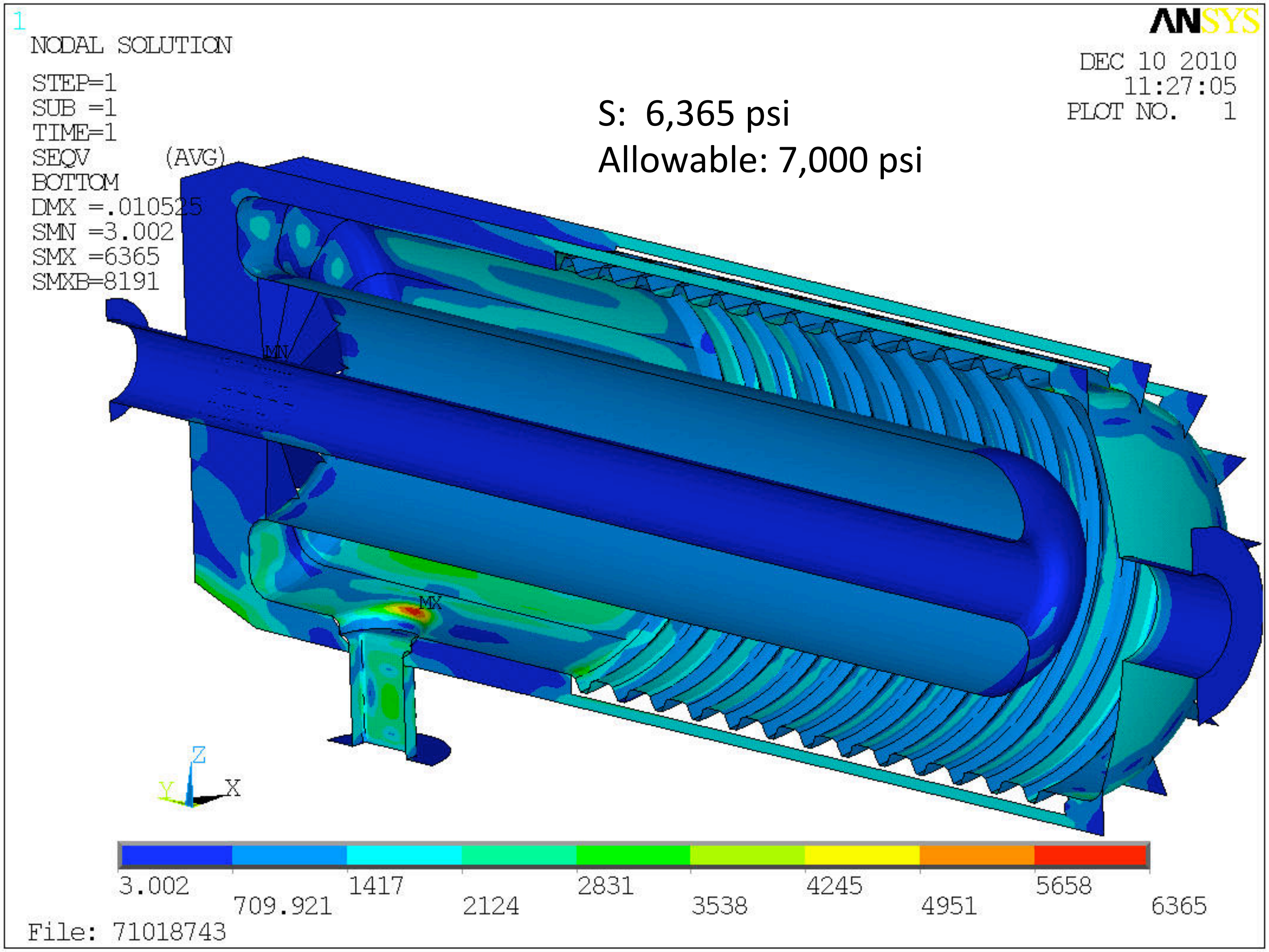
1. Fundamental Damper Port
2. Nb Crown Head
3. Tuning Plate
4. Cooing Channel Bellow
5. Cavity Support Lug

Force in the Fundamental damper port

1. Internal Helium Pressure: 20 psi
2. Expanding force in the bellow: 340 lb
3. End flange pushing force: 555 lb
4. Total Force in the End flange and port: 895 lb

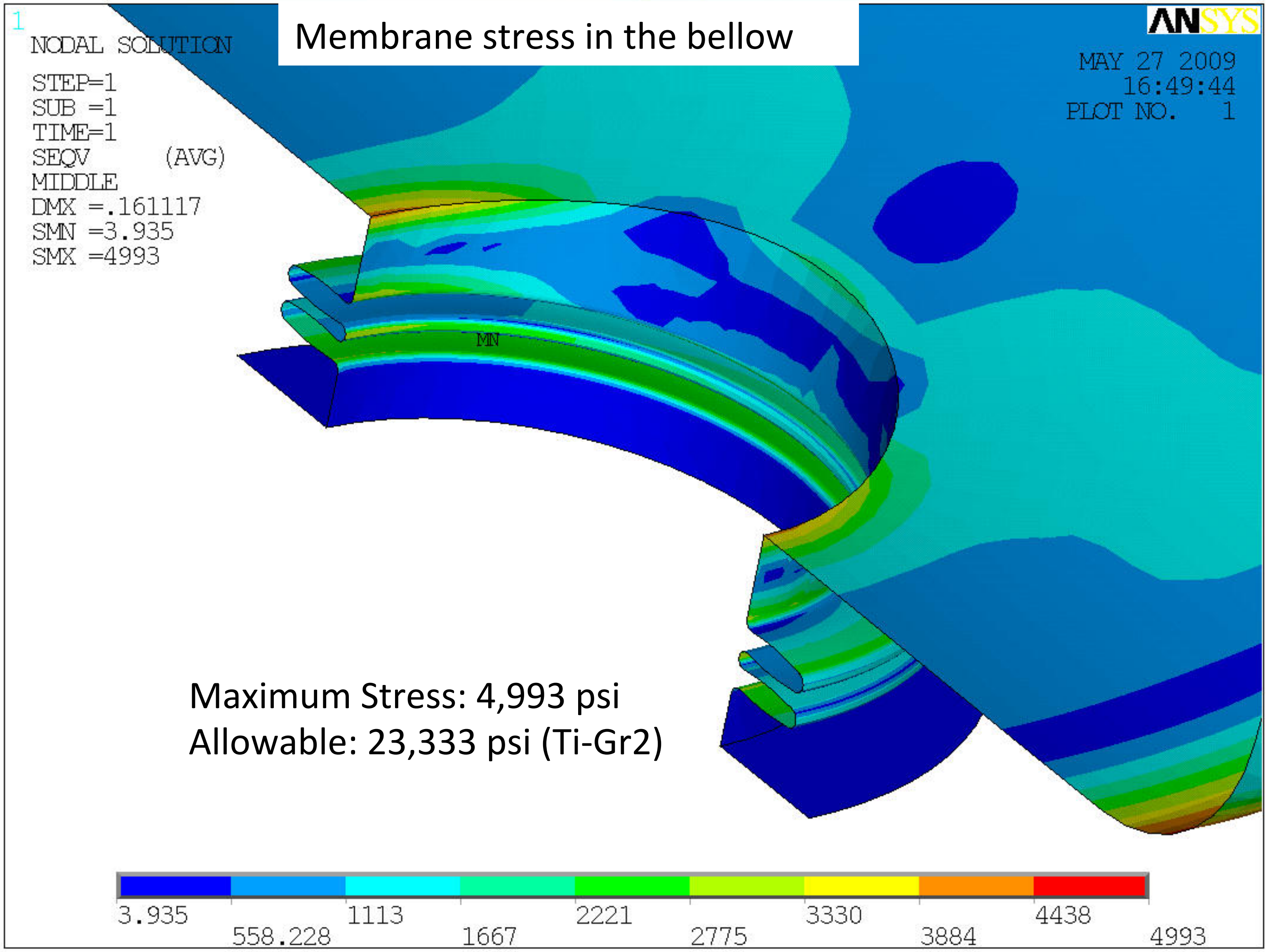


Fundamental port (Nb cavity) Bending stress at bottom surface



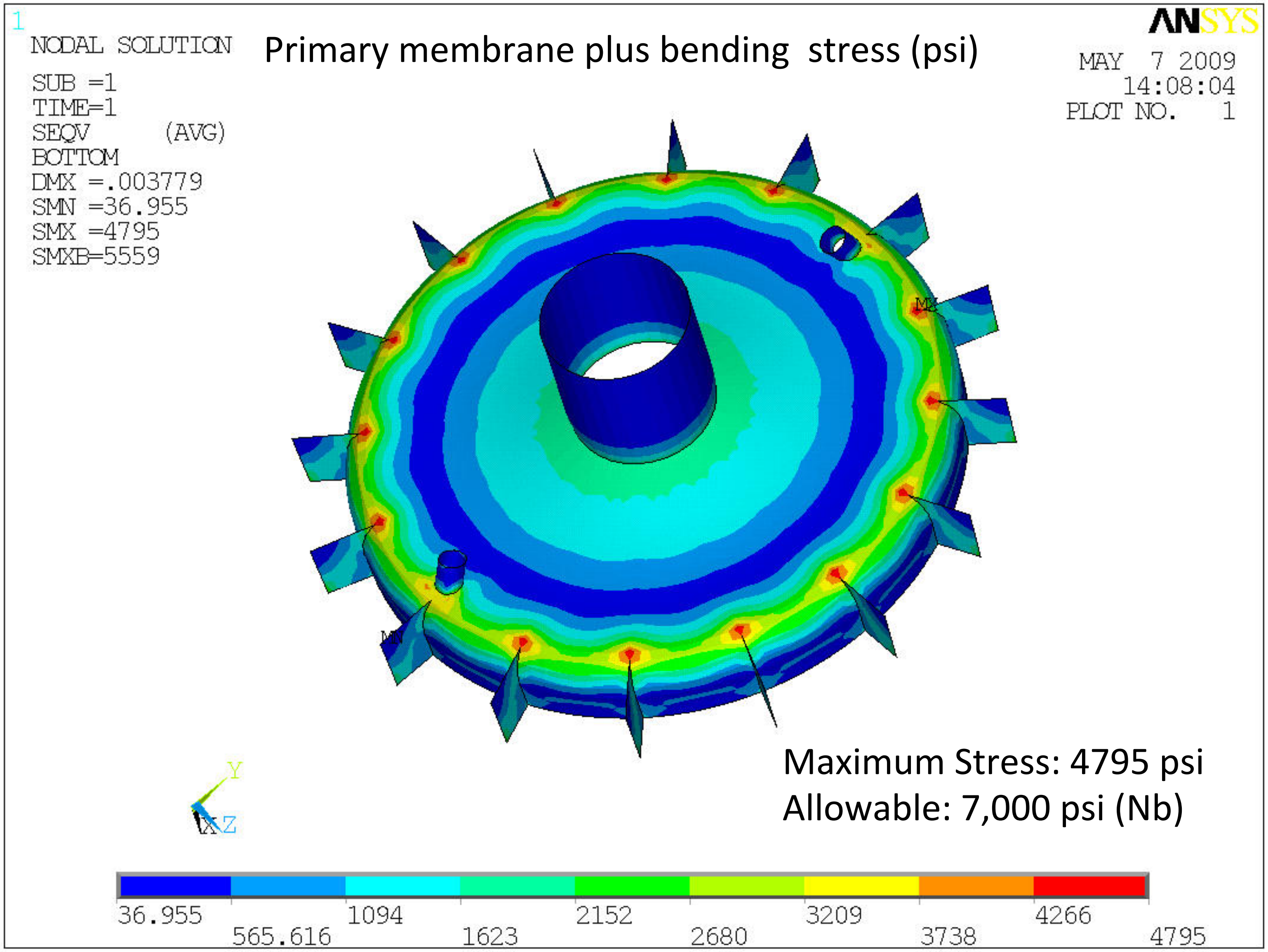
psi

Fundamental Damper port (Helium vessel), Under Weight + Pressure



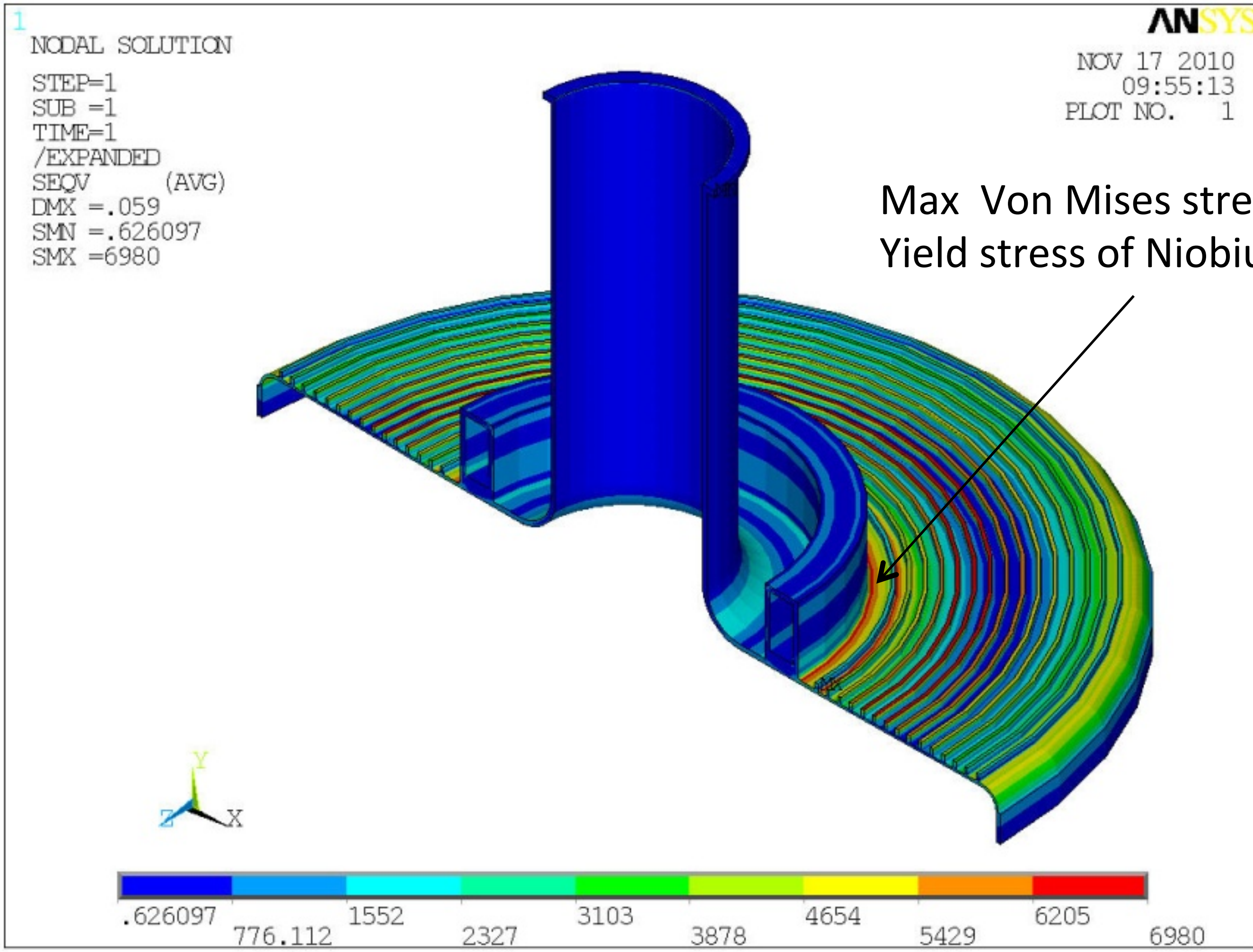
psi

Crown Head Under Pressure Load



psi

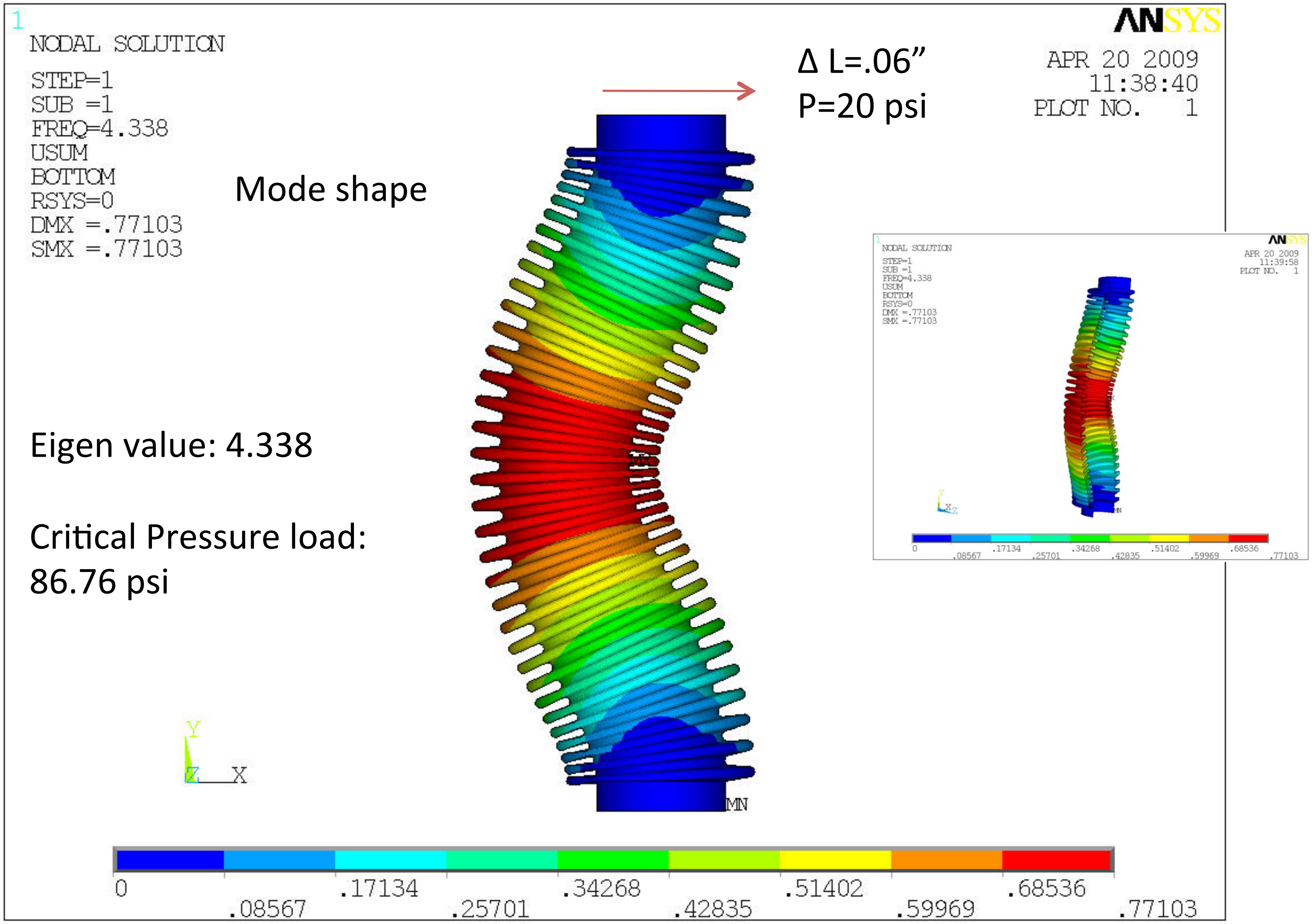
Tuning Plate, Von Mises Stress (push down 1.5 mm + 20 psi in channel)
For Elastic tuning



Max Von Mises stress: 6,980psi
Yield stress of Niobium : 7,000 psi

psi

Buckling mode shape (Squirm), 1.5mm tune + 20 psi



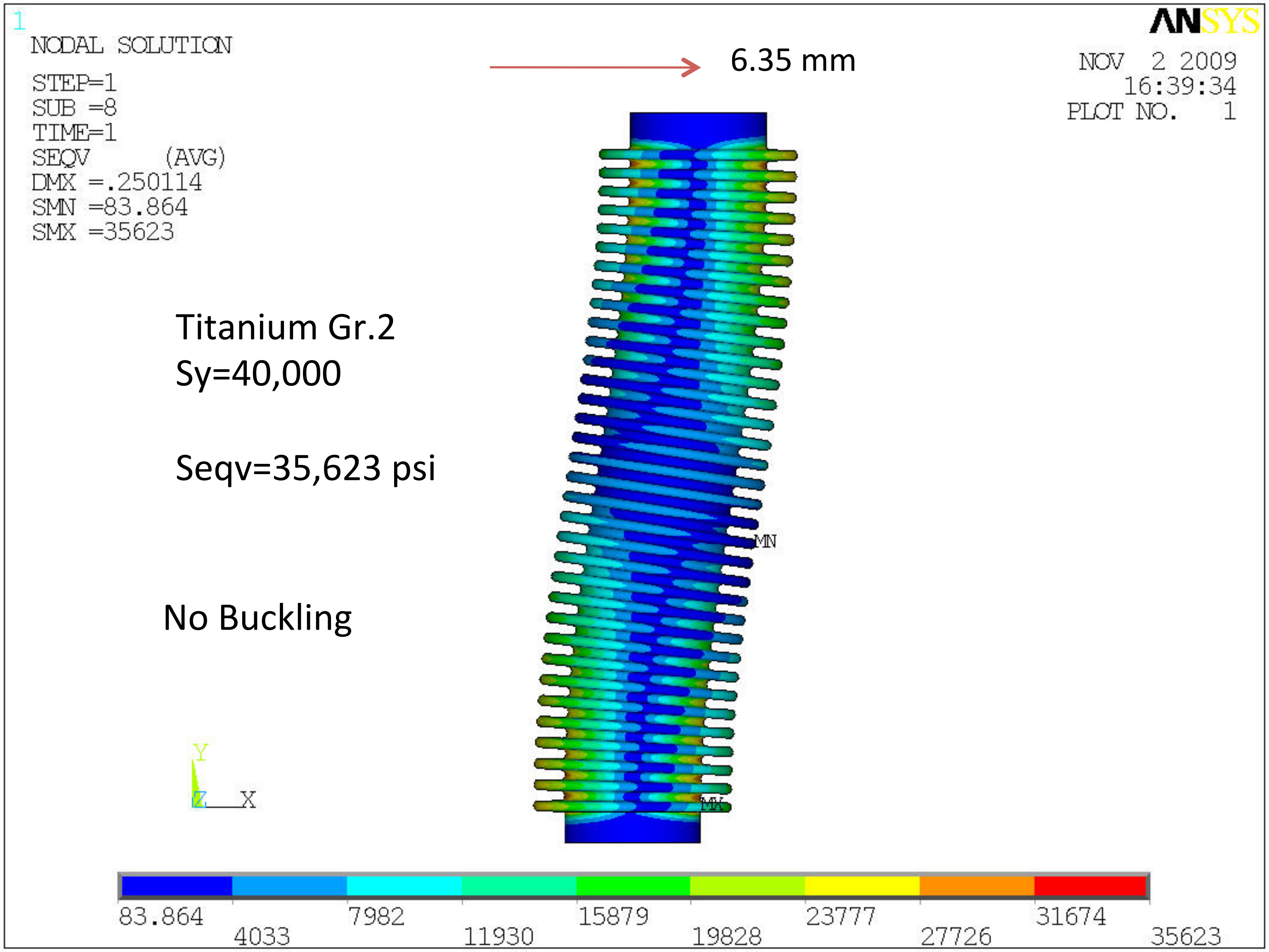
Δ L=.06”
P=20 psi

Mode shape

Eigen value: 4.338

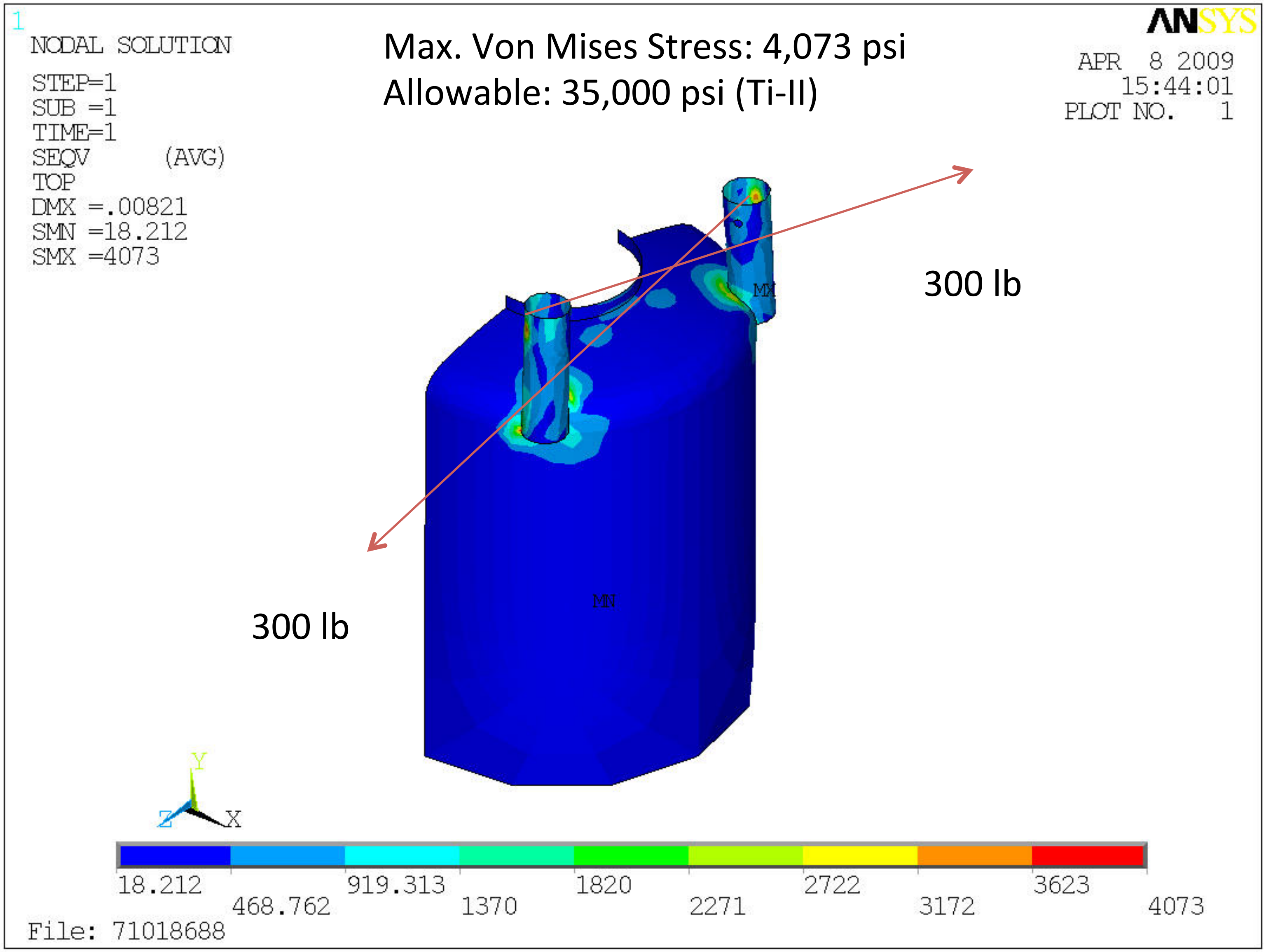
Critical Pressure load:
86.76 psi

Extreme case in bellow: Large deflection, 20 psi, .25” (6.35mm) sideway



Vessel Support structure Under hanging weight

Von Mises Stress, Membrane plus bending stress



psi

Frequency Sensitivity And Port Shape effect of SRF Cavity

C. Pai

3-08-2011

RF Frequency Sensitivity to Helium Pressure Fluctuation

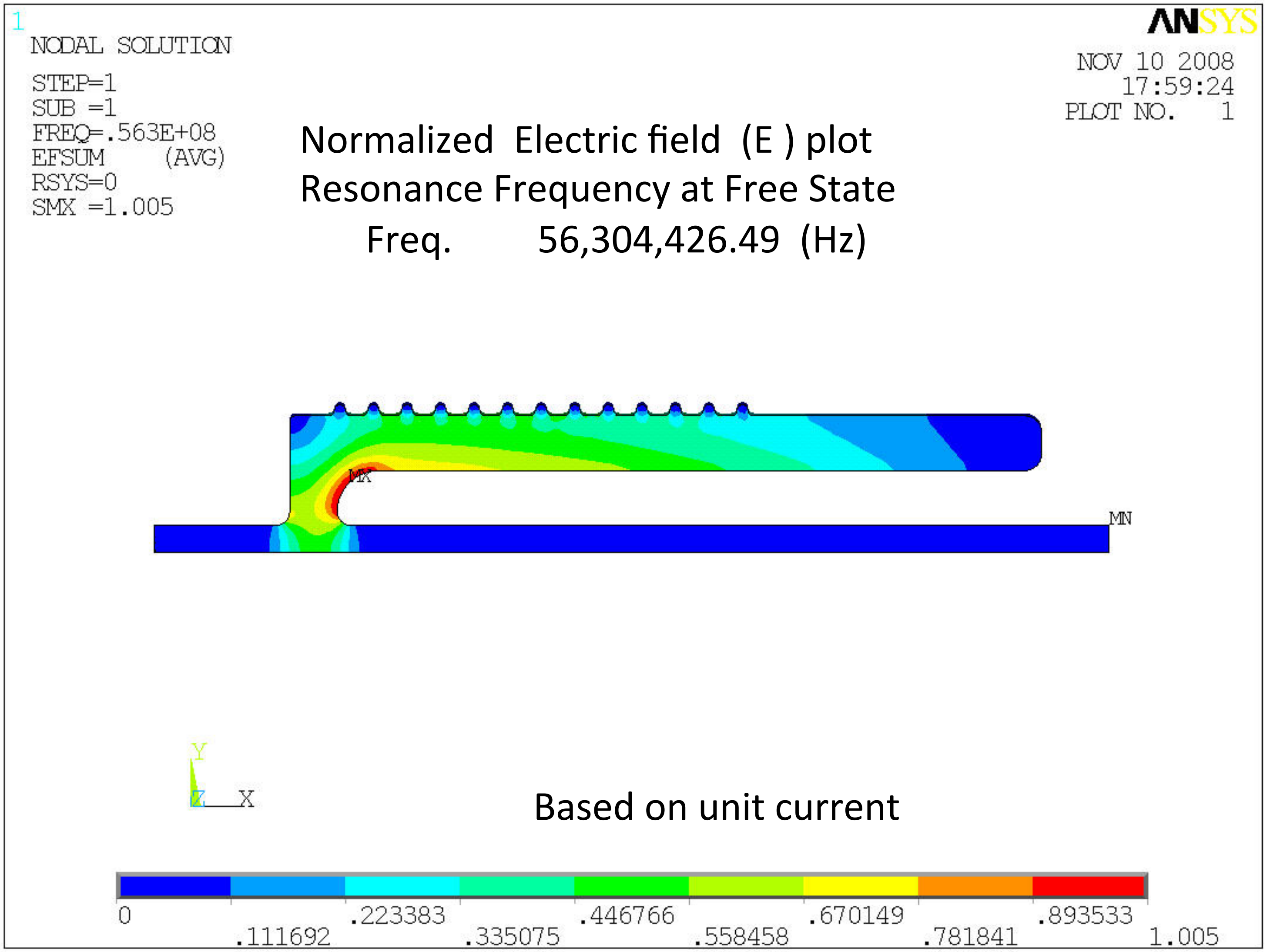
Cavity is cooled by 20 psi L1quid helium. Fluctuation of helium pressure will change the shape of the RF cavity vessel. When the shape of the cavity changes the resonance frequency will change too.

This cavity is reinforced by 16 stiffener bars. These stiffeners reduce its sensitivity to helium pressure fluctuation.

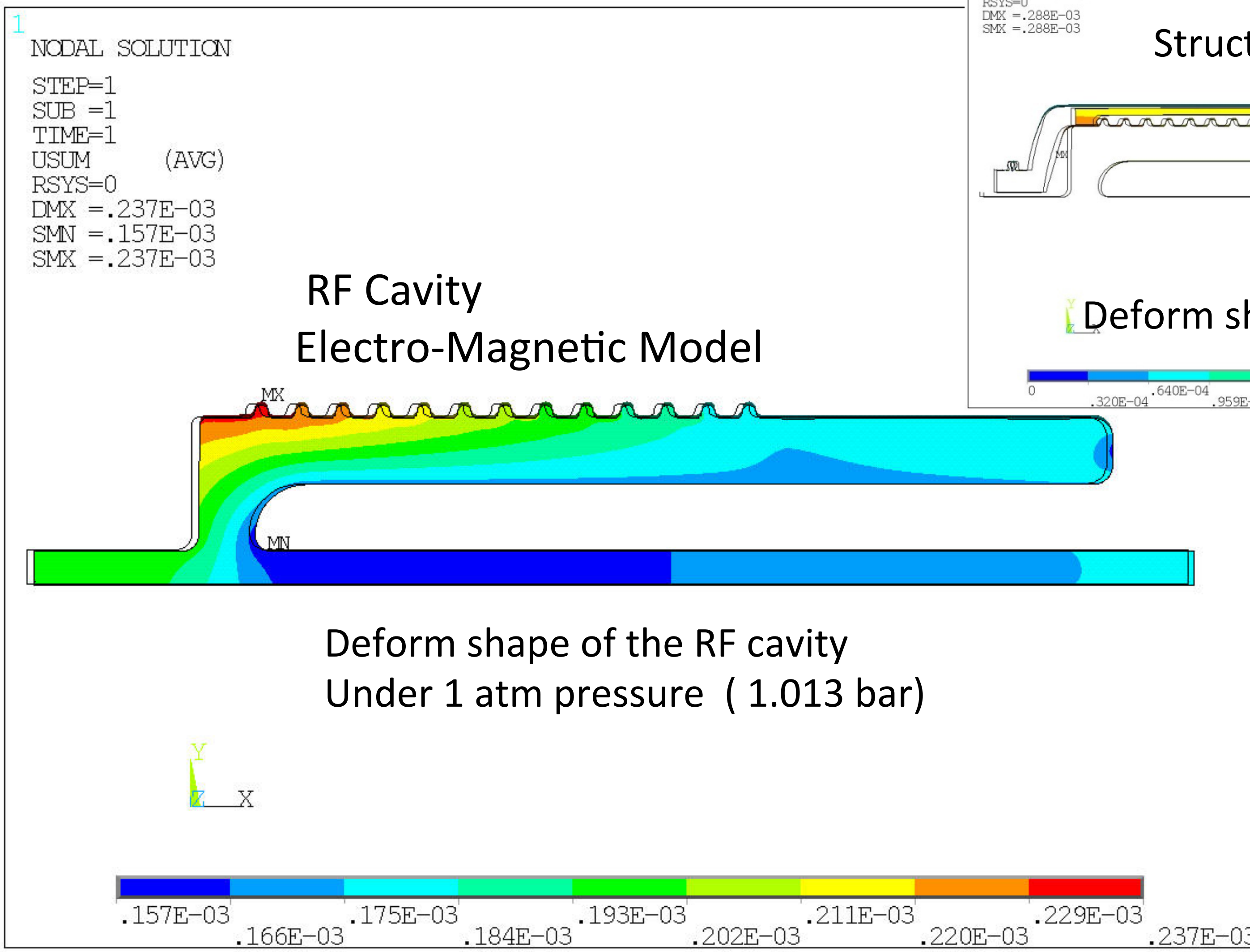
Parameters used in calculation (by ANSYS FE Code)

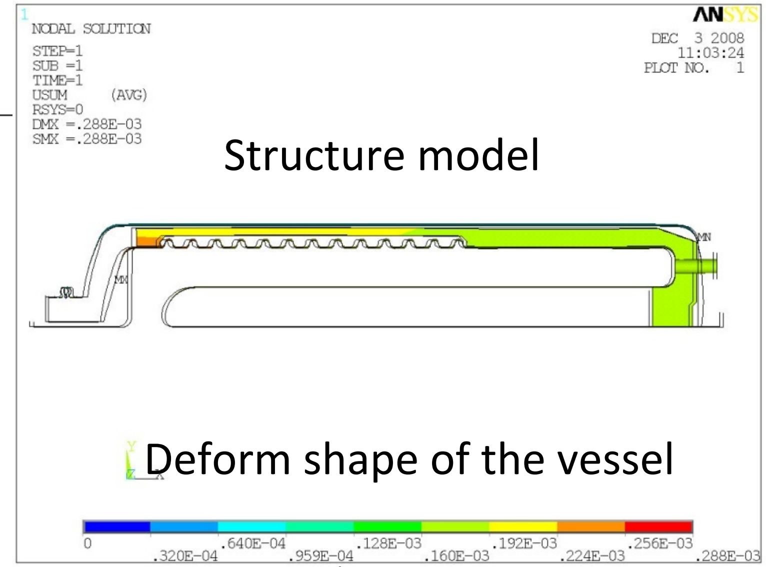
Resonance frequency at Free state:
56,304,426.49 Hz
Applied Helium Pressure: 1 atm (1.013 bar)
Helium stability: +/- 1 mbar

Electric Field (E) and Free State RF Resonance Frequency



Deform Shape of RF Cavity Due to Helium Pressure (1 atm)

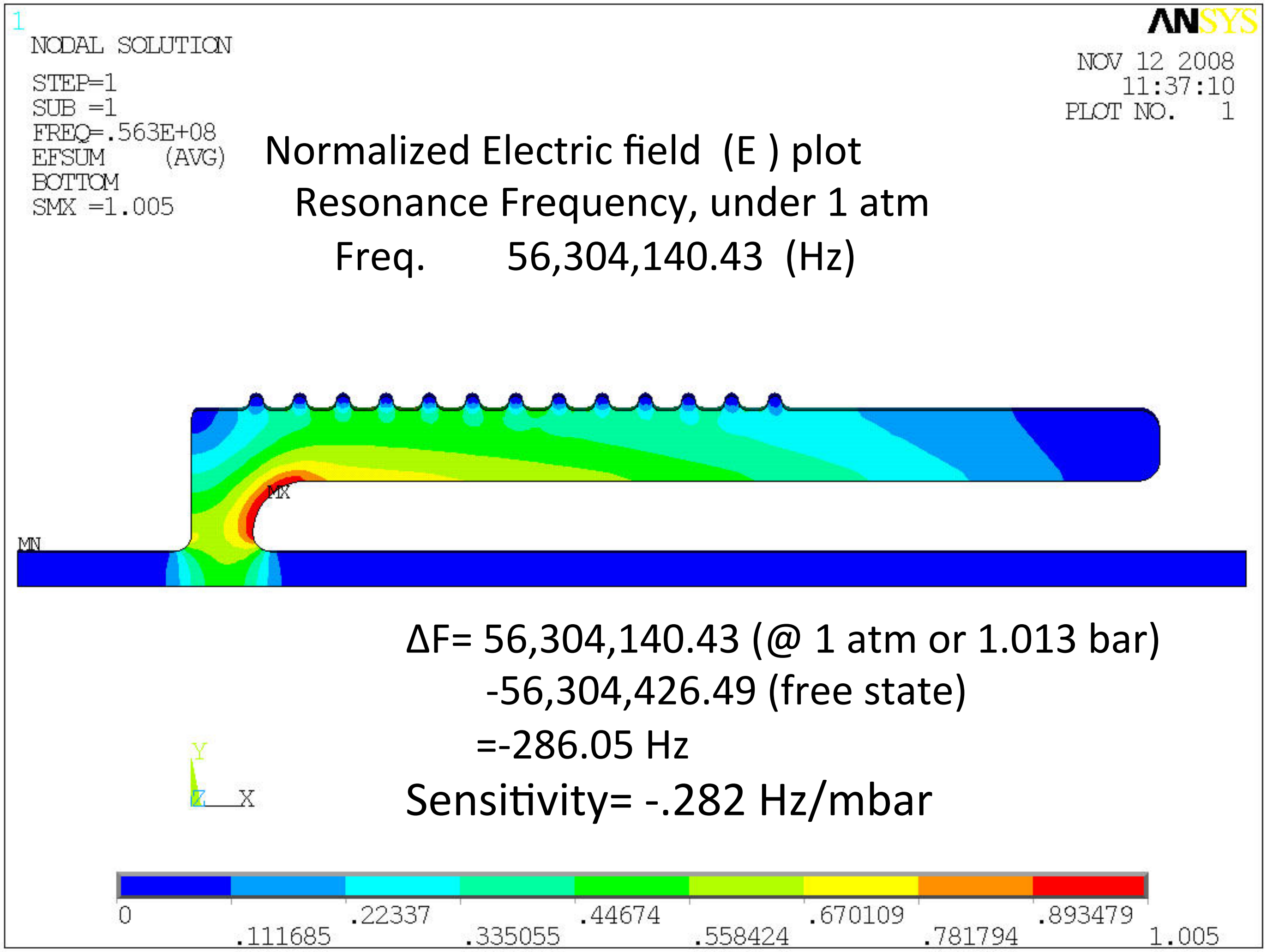




Unit in meter

Unit in meter

RF Sensitivity Due To Helium Pressure Fluctuation



RF Frequency Change Due To Lorentz Detuning

Lorentz Pressure:

During operation, magnetic field and electric field will produce pressure in the RF cavity wall.

Pressure from Magnetic field:

$P = \frac{1}{4} \mu_o H^2$, μ_o is permeability of vacuum

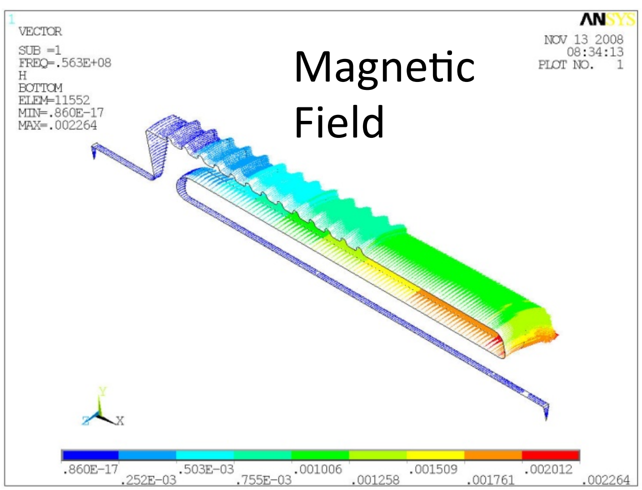
Direction: push out the RF cavity wall.

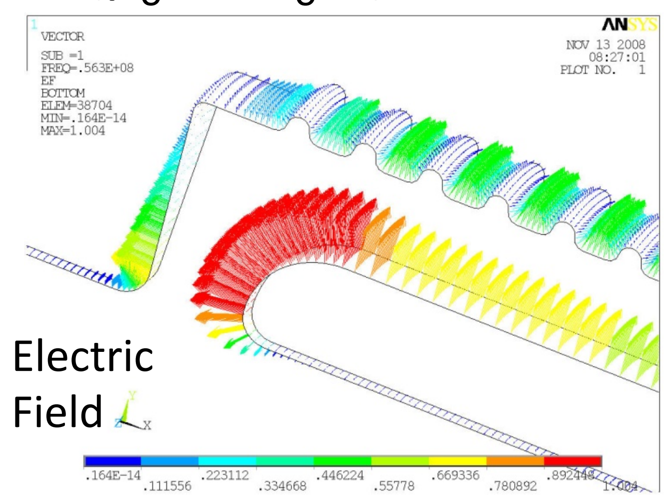
Pressure from Electrical field:

$P = \frac{1}{4} \varepsilon_o E^2$, ε_o is permittivity of vacuum

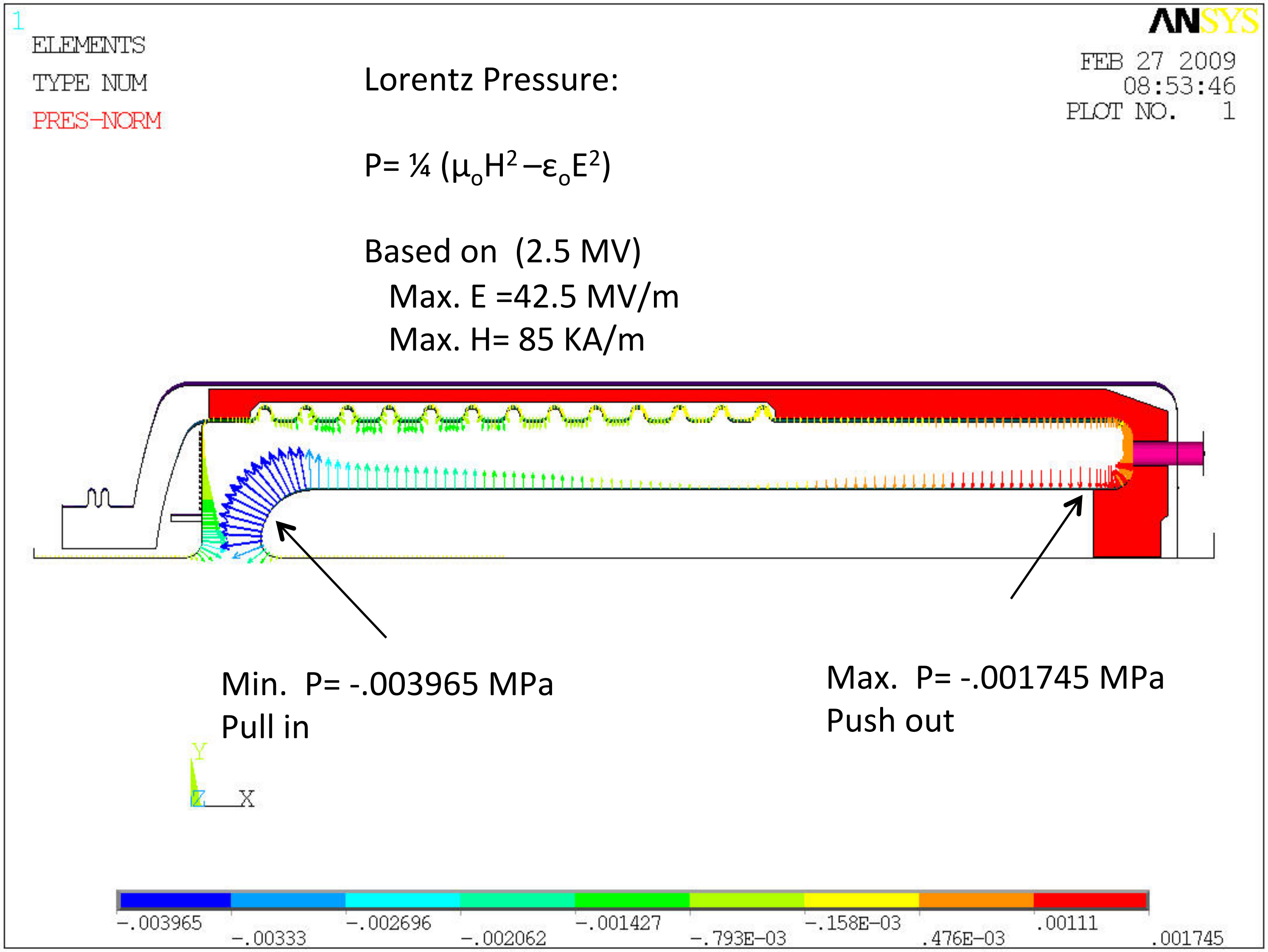
Direction: Pull in the RF cavity wall.

Total Lorentz Pressure: $P = \frac{1}{4} (\mu_o H^2 - \varepsilon_o E^2)$





Lorentz Pressure



Lorentz Pressure:

$P = \frac{1}{4}(\mu_o H^2 - \varepsilon_o E^2)$

Based on (2.5 MV)

Max. E =42.5 MV/m

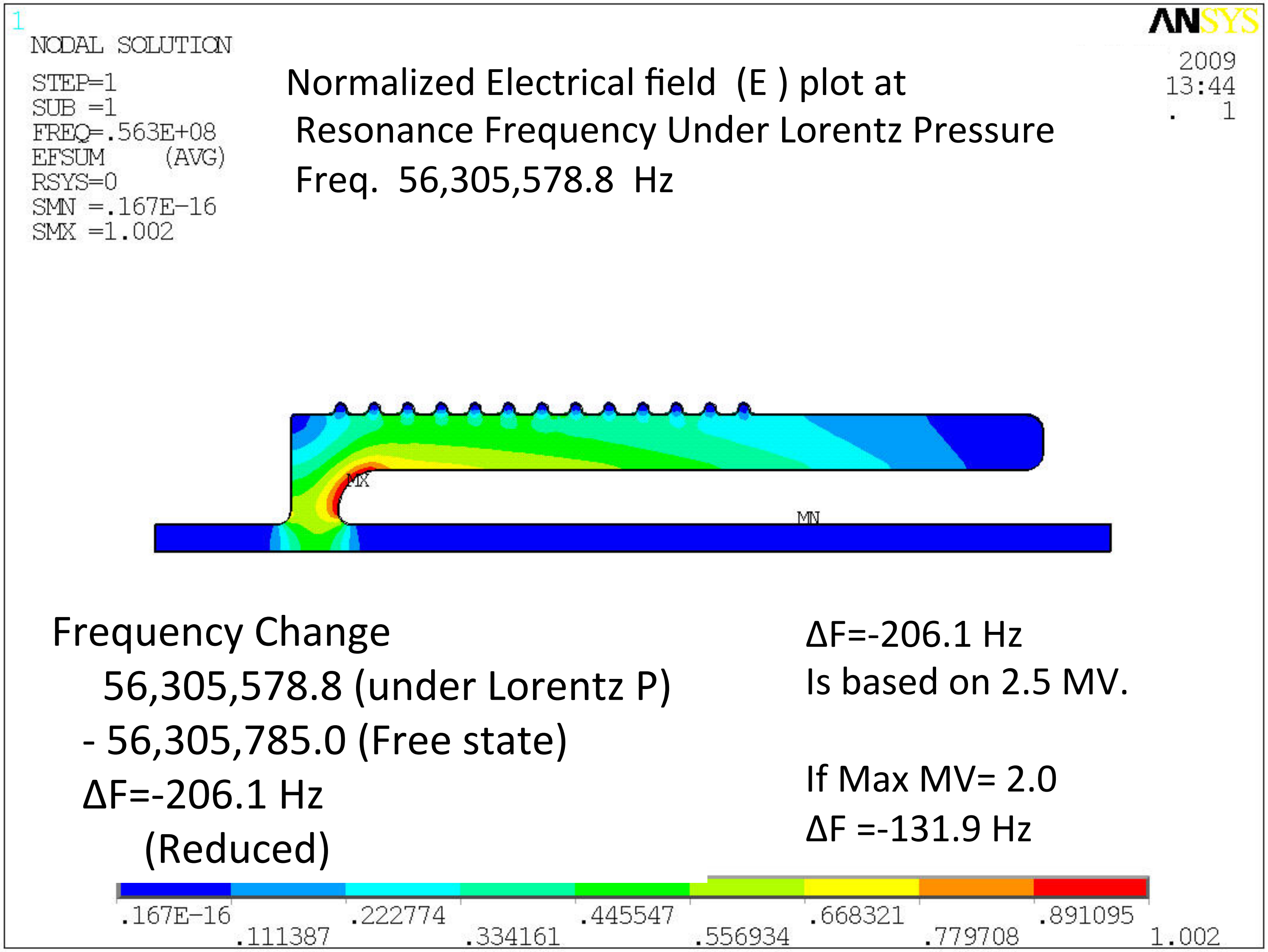
Max. H= 85 KA/m

Min. P= -.003965 MPa
Pull in

Max. P= -.001745 MPa
Push out

Pressure unit: MPa

RF Frequency Change Due To Lorentz Detuning



Normalized Electrical field (E) plot at
Resonance Frequency Under Lorentz Pressure
Freq. 56,305,578.8 Hz

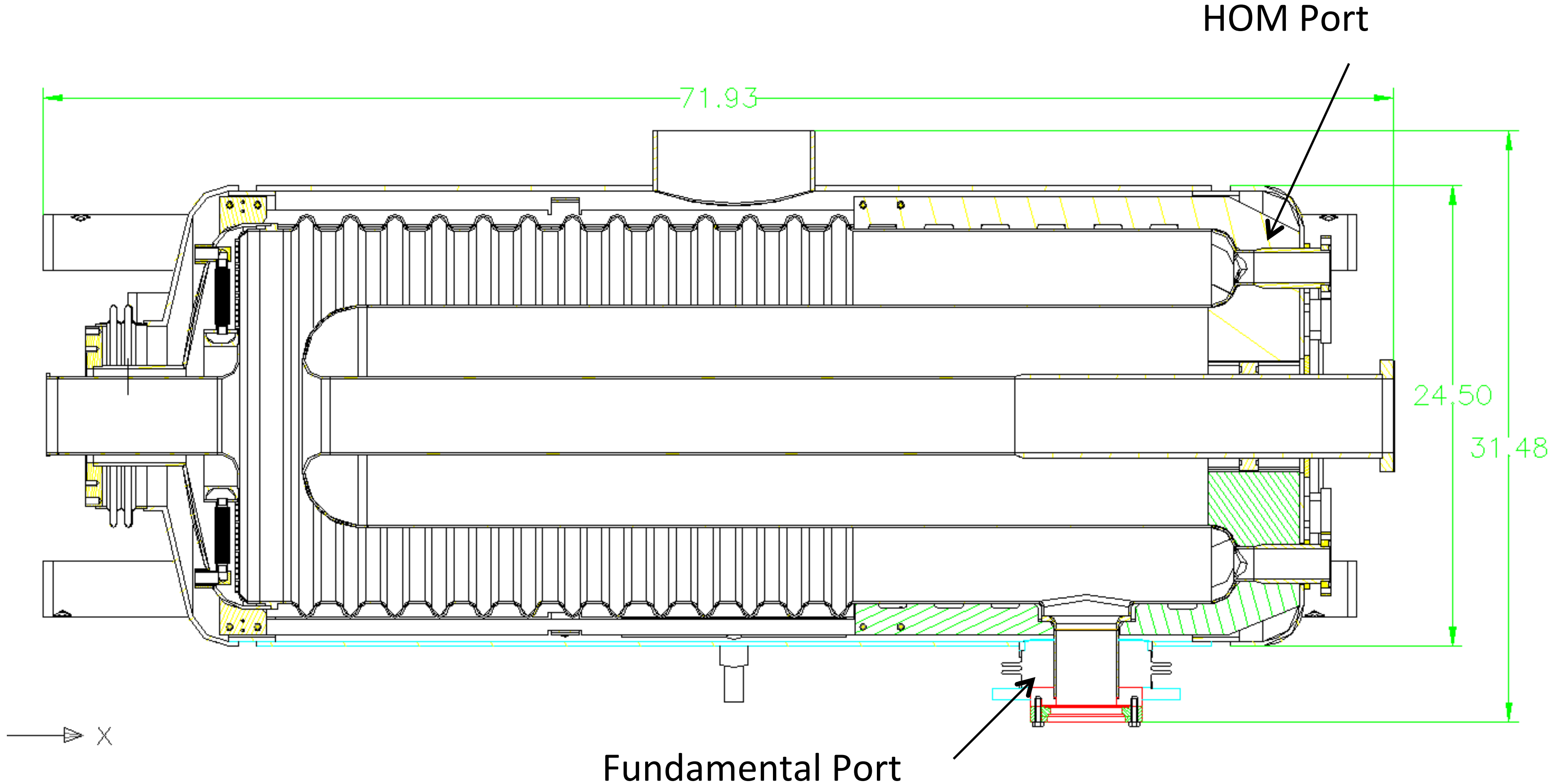
Frequency Change
56,305,578.8 (under Lorentz P)
- 56,305,785.0 (Free state)
ΔF=-206.1 Hz
(Reduced)

ΔF=-206.1 Hz
Is based on 2.5 MV.

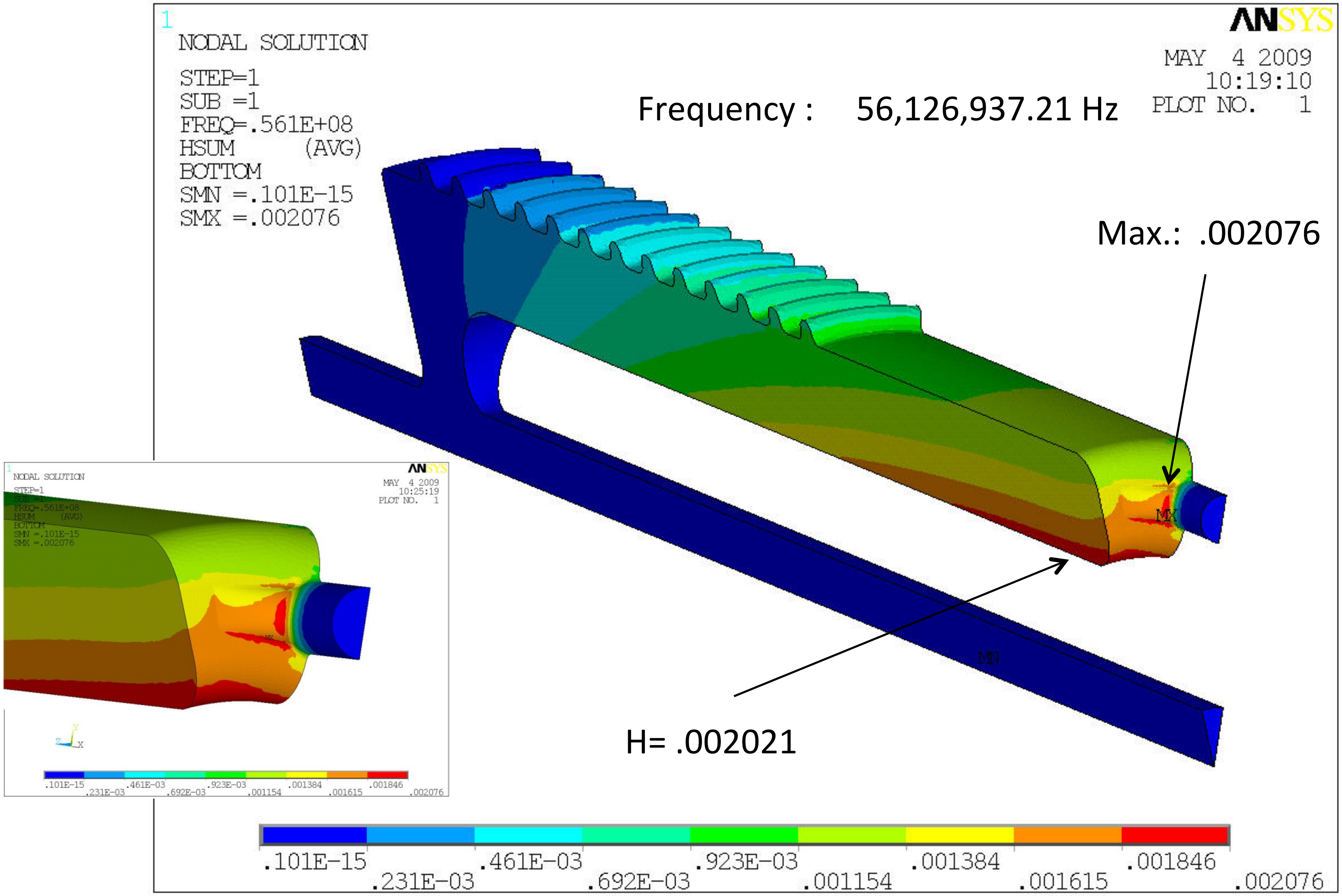
If Max MV= 2.0
ΔF =-131.9 Hz

Cavity Port shape effect

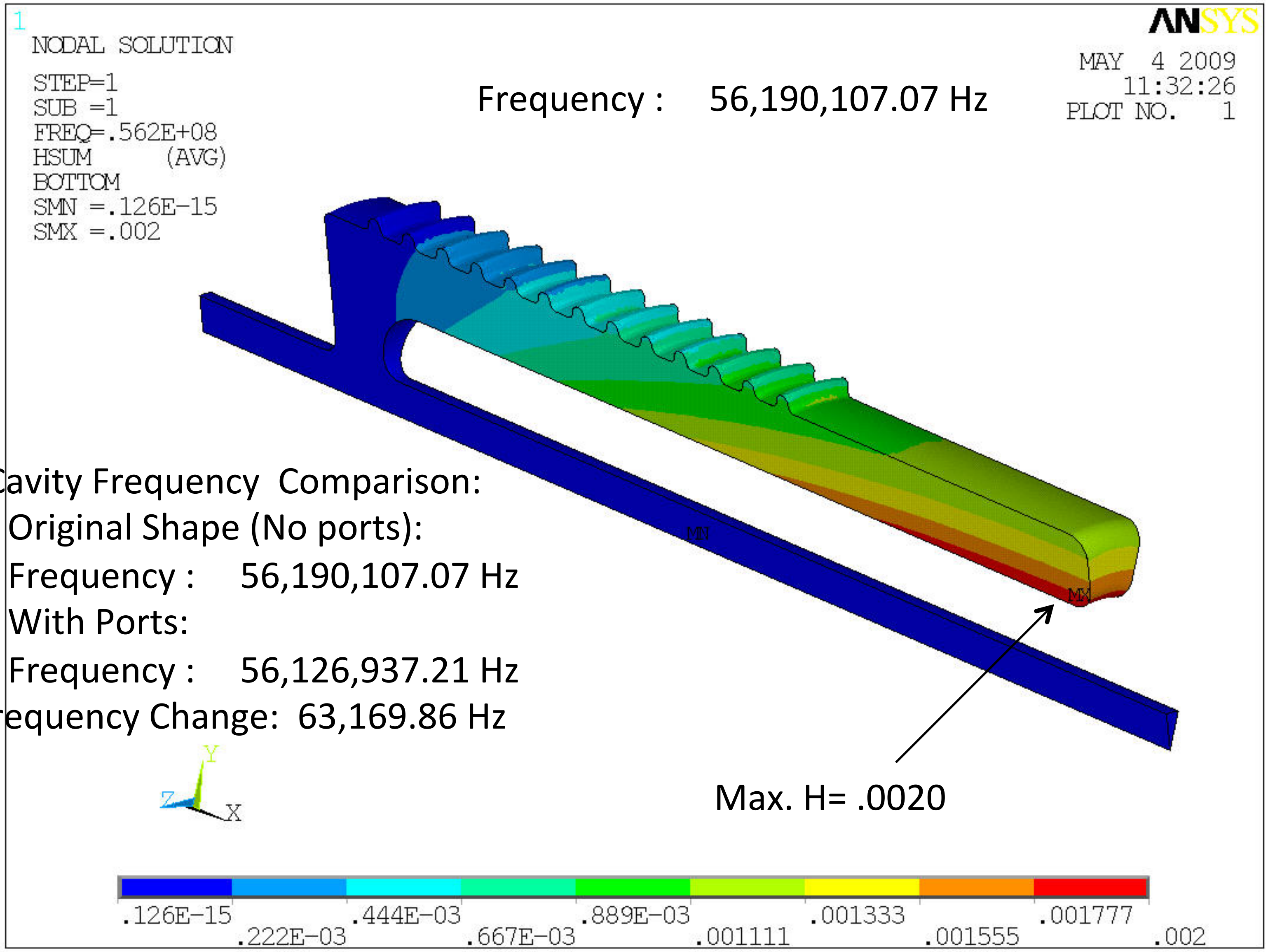
1. HOM port (8)
2. Fundamental Port (1)



Free State, Magnetic Field with end ports, based on normalized electric field



Original shape- Free State, Magnetic Field, without ports



RF Cavity Frequency Comparison:

Original Shape (No ports):

Frequency : 56,190,107.07 Hz

With Ports:

Frequency : 56,126,937.21 Hz

Frequency Change: 63,169.86 Hz

Frequency change due to 8 end ports

RF Cavity Frequency Comparison:

Original Shape (No ports):

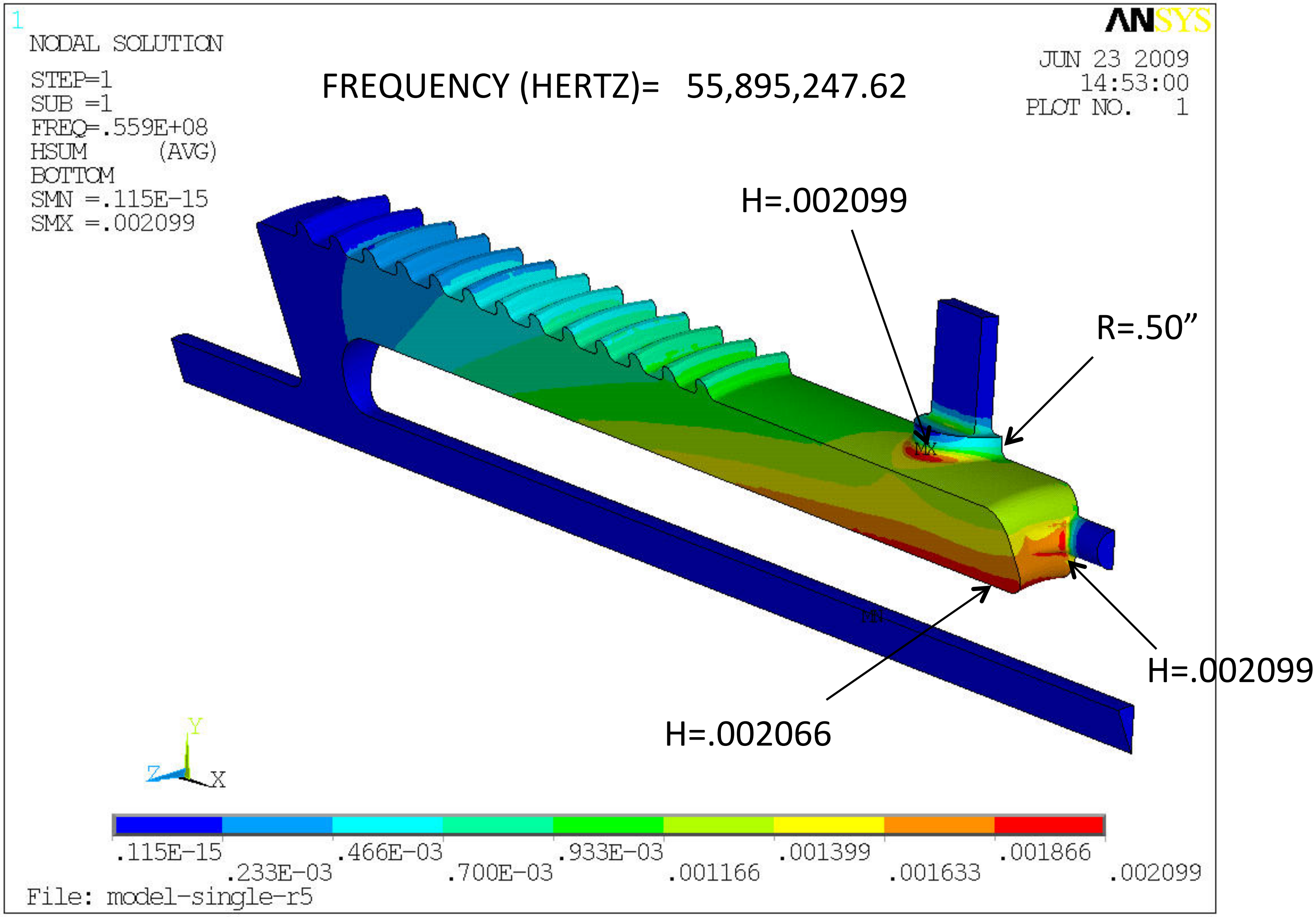
Frequency : 56,190,107.07 Hz

With 8 end Ports:

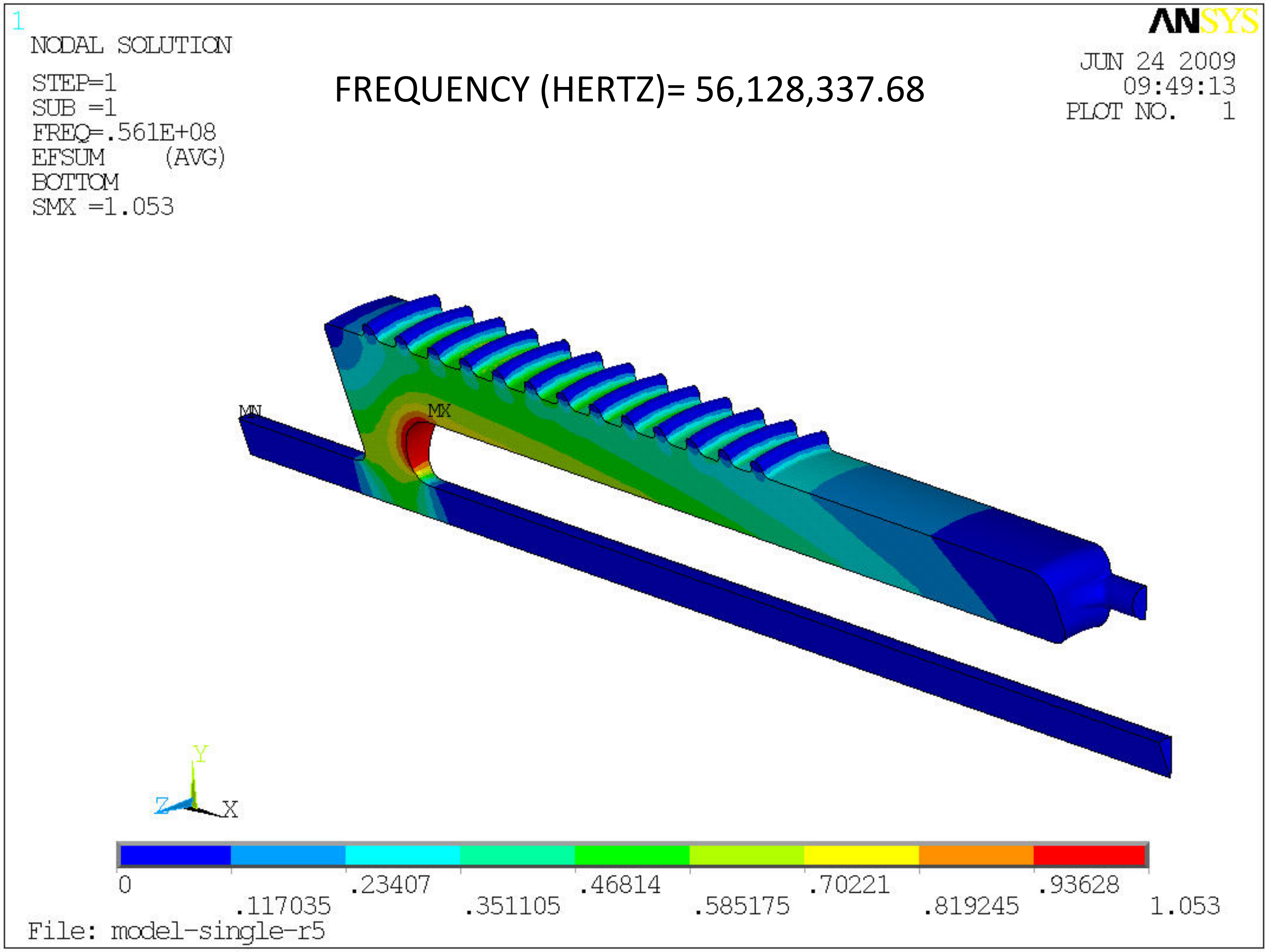
Frequency : 56,126,937.21 Hz

Frequency Change: ΔF= 63,169.86 Hz

H Field, 1/16 model, (simulate ½ x 16= 8 ports), damper port edge radius: .50”



E Field, 1/16 model, no Damper Port (but with end ports)



Frequency change due to Fundamental Damper Port (estimate based on a result of 8 damper ports)

RF Cavity Frequency Comparison:

No fundamental damper ports but with 8 end ports:
Frequency : 56,128,337.68 Hz

8 fundamental damper ports and 8 end ports:
Frequency : 55,895,247.62 Hz

Frequency Change: ΔF = 233,090.06 Hz (per 8 port)

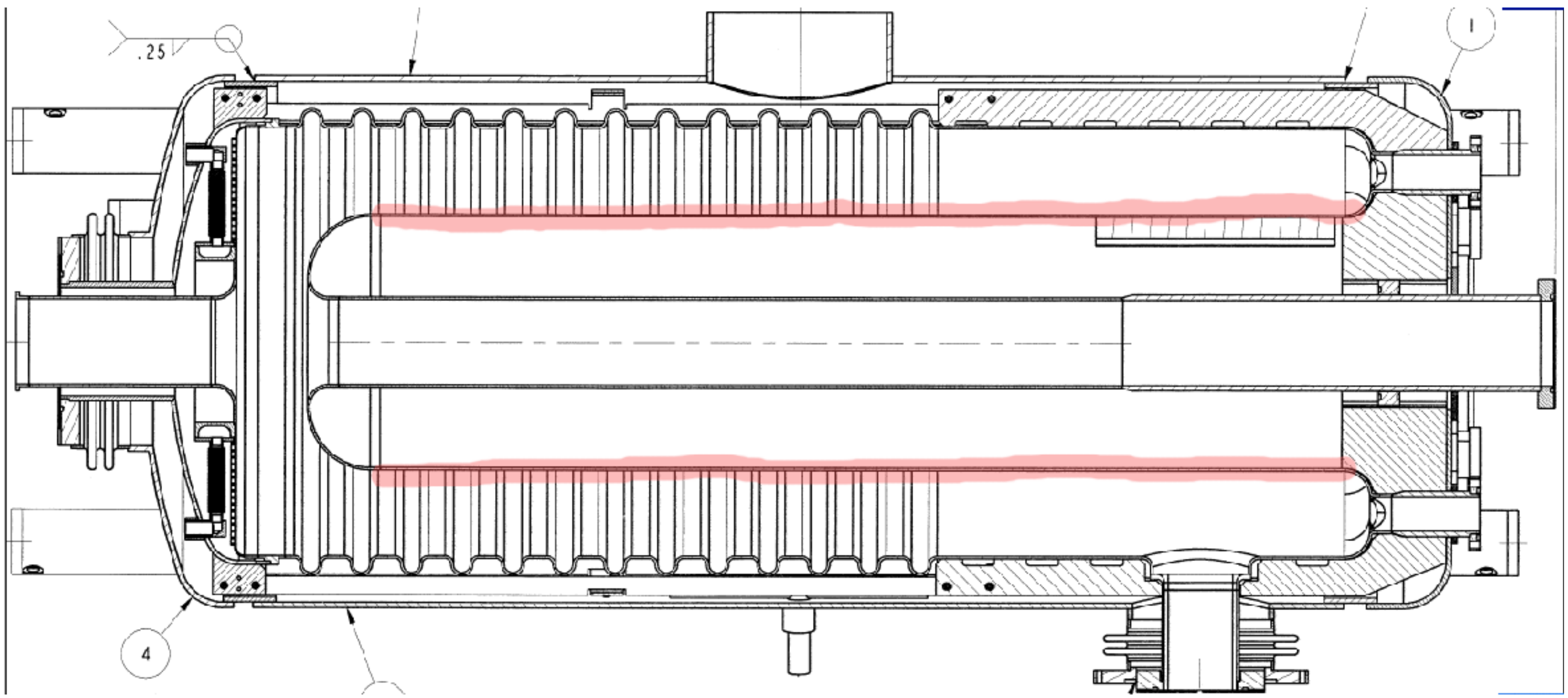
Estimate Frequency change by a single damper port:
ΔF=29,136 Hz

56 MHz Cavity Fabrication Status

Material Taken from Niowave Biweekly Status Reports

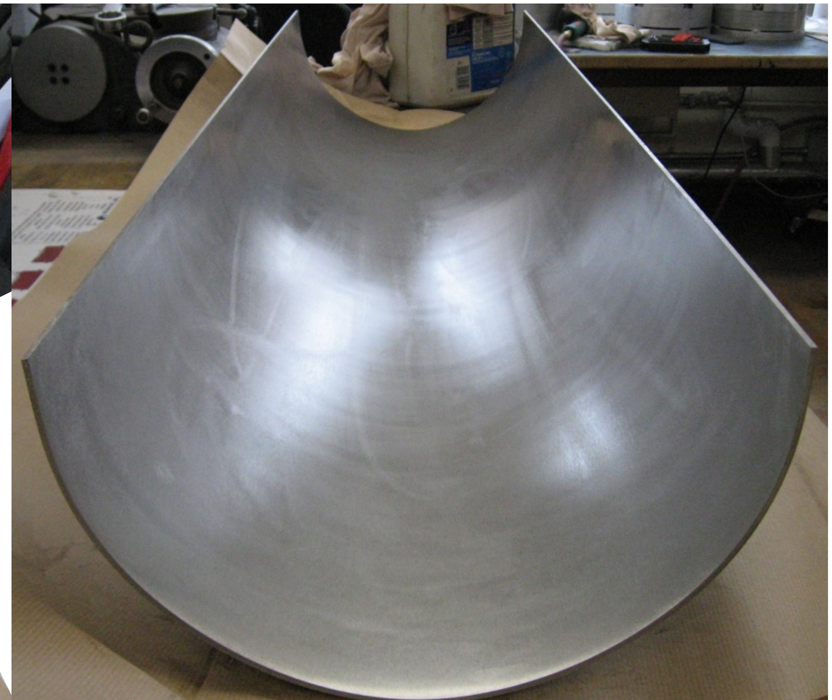
Components Supplied by Niowave

Availability of highlighted section lead to schedule delay

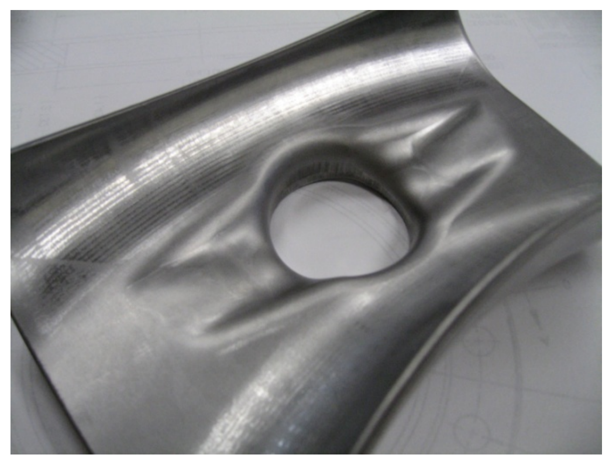


Nb Fabrication – Inner Conductor

- Forming Complete, machining weld prep edges soon



- Part formed, machining preparations to perform 8 pullthroughs



Drawn End Plate Prototype

Nb Fabrication –
Drawn End Plate Prototype

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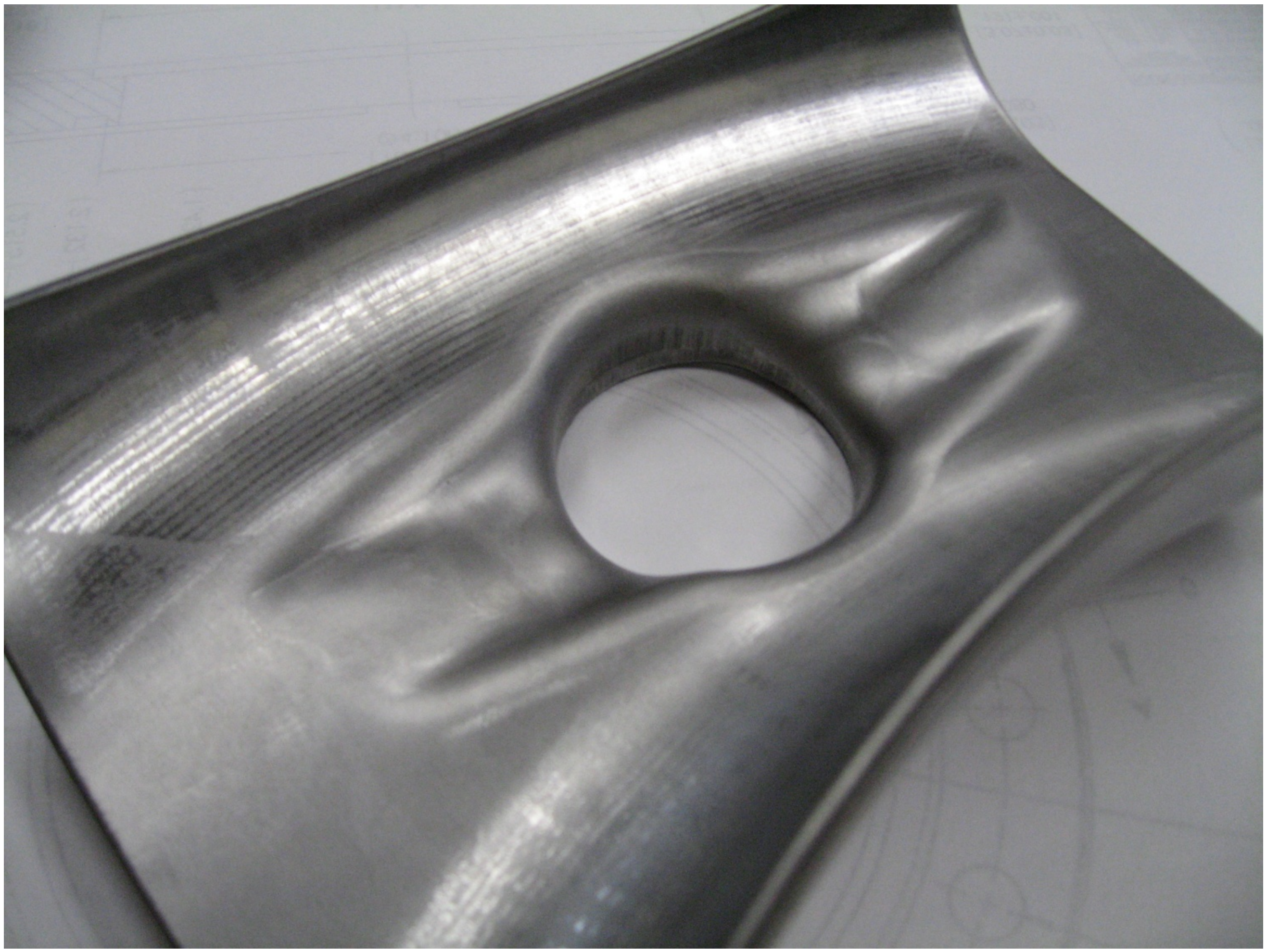
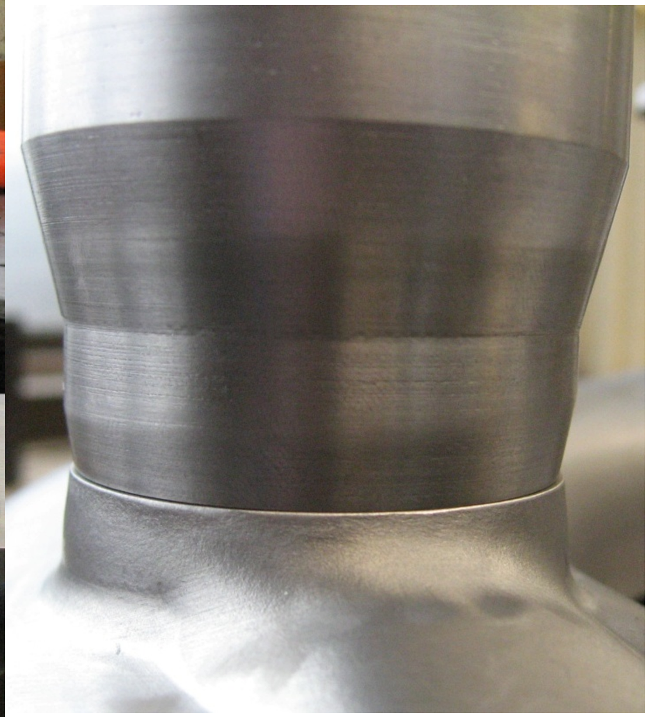


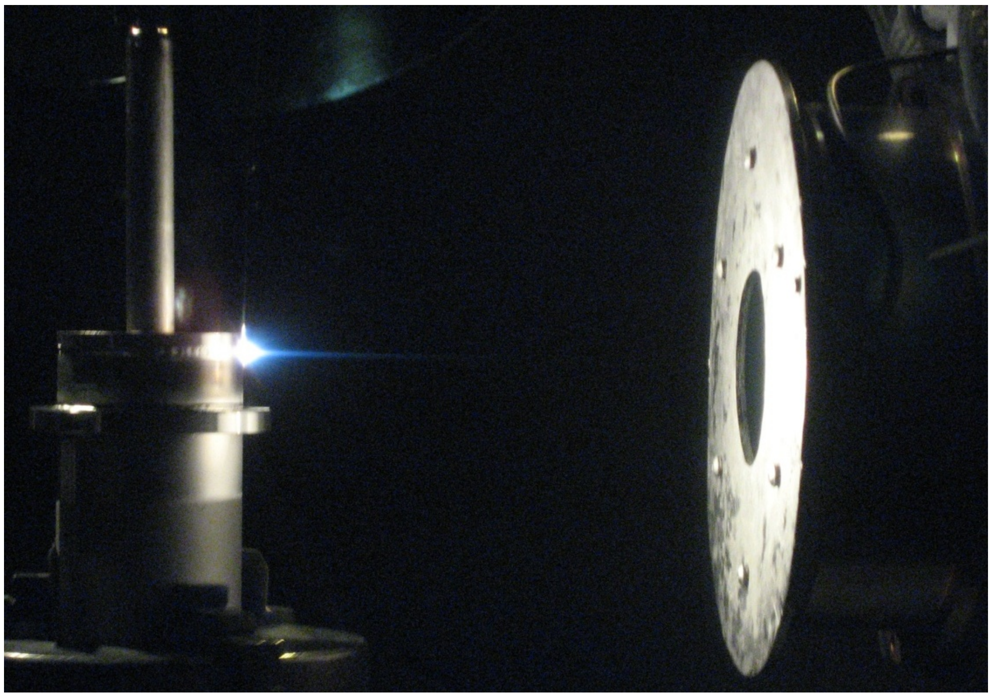
Nb Fabrication – Drawn End Plate

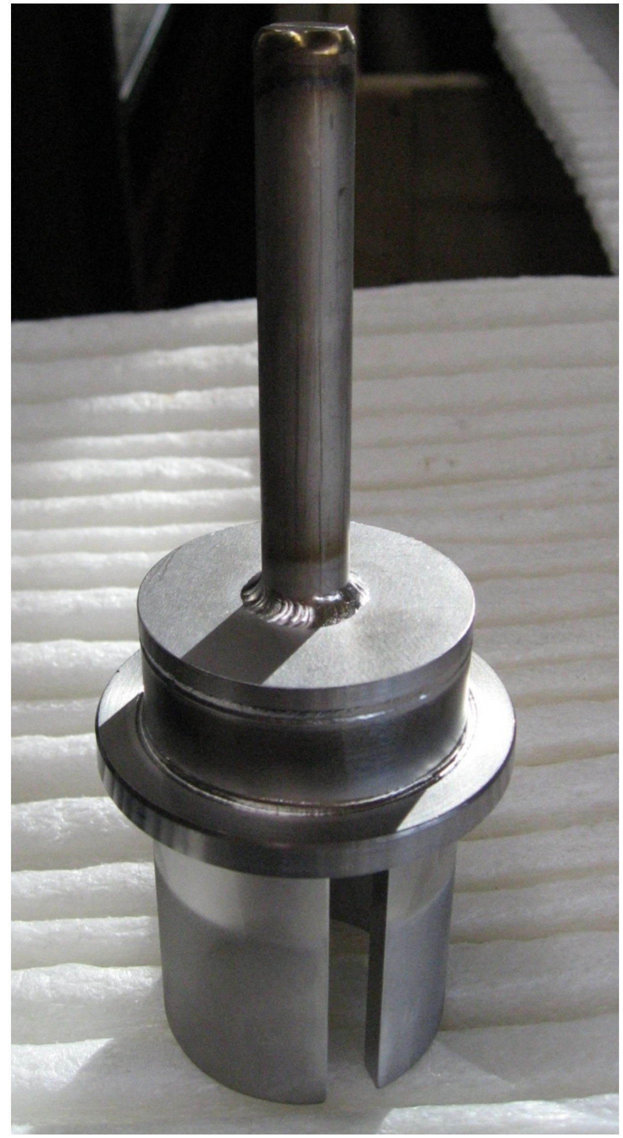
- Subassembly Test Fit Successful
    - Parts going through cleaning process to EB weld soon



Nb Fabrication – Helium Fill Ports

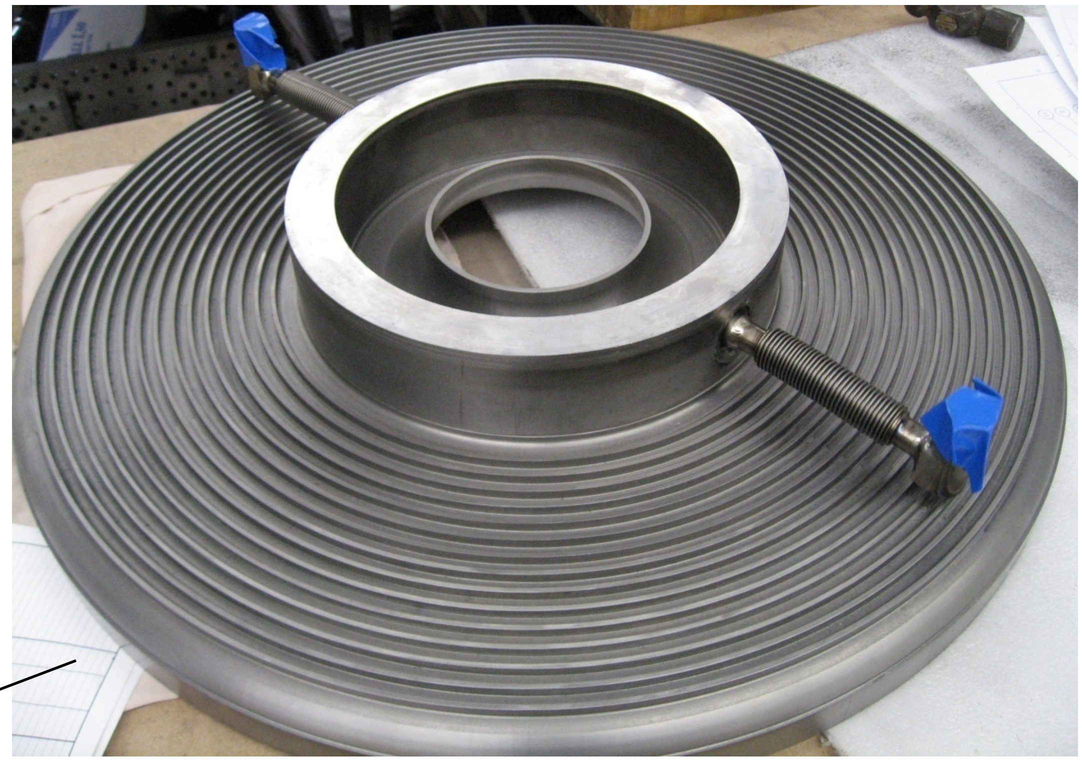
- Subassemblies complete

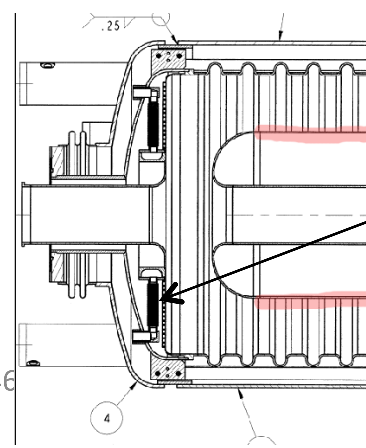




Niobium Fabrication –
Nb Tuning Plate Subassembly

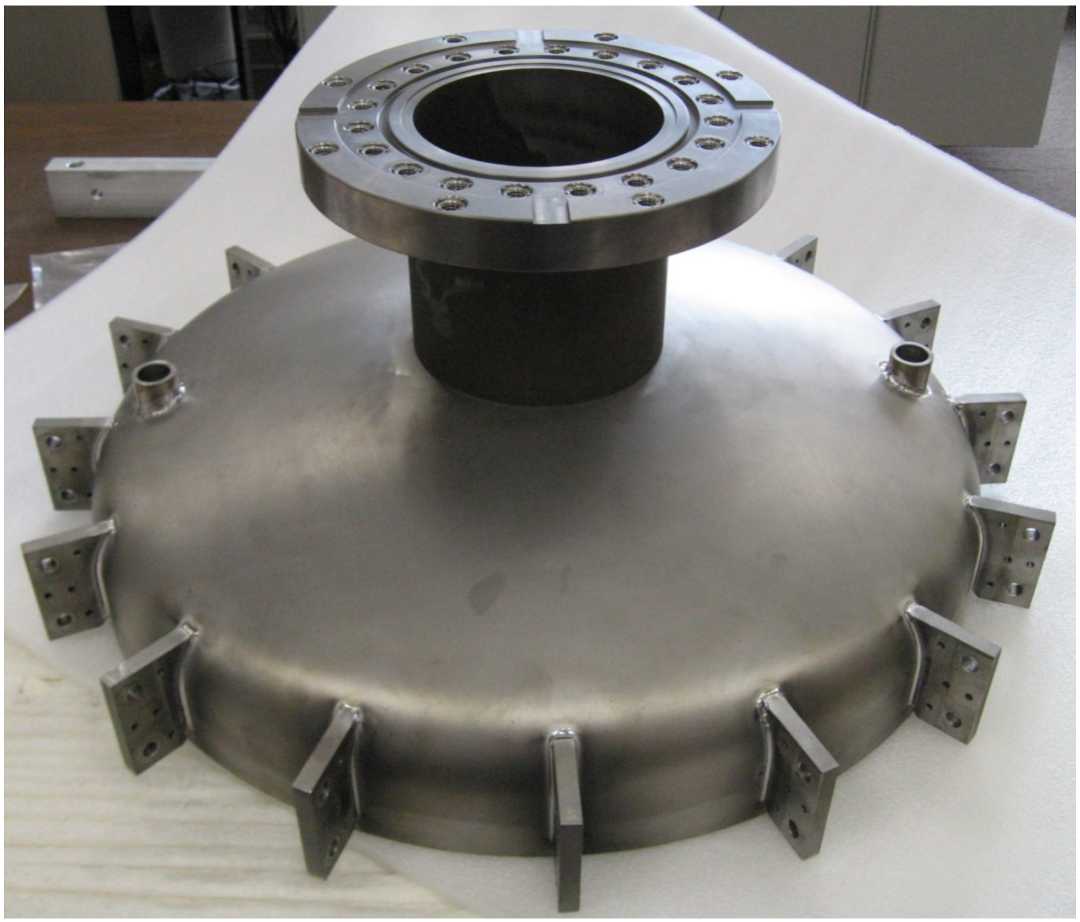
- Parts going through cleaning process
    - EB welding subassembly next week

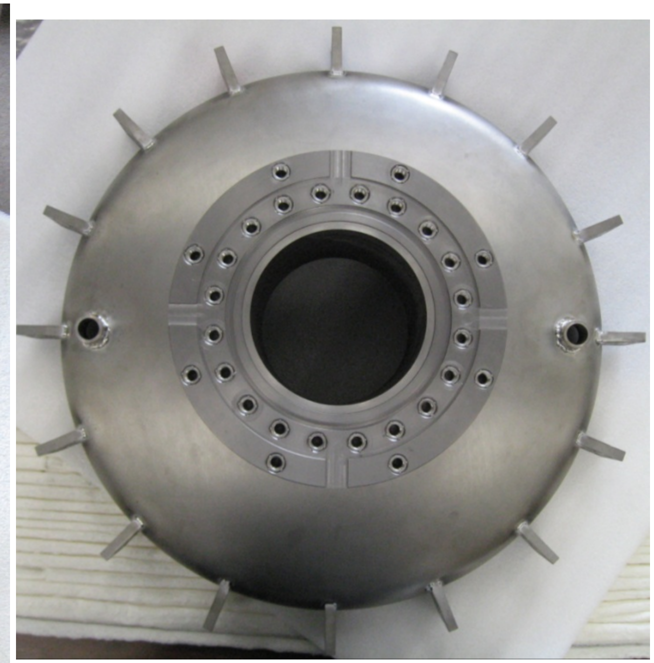




Niobium Fabrication –
Nb Head Subassembly

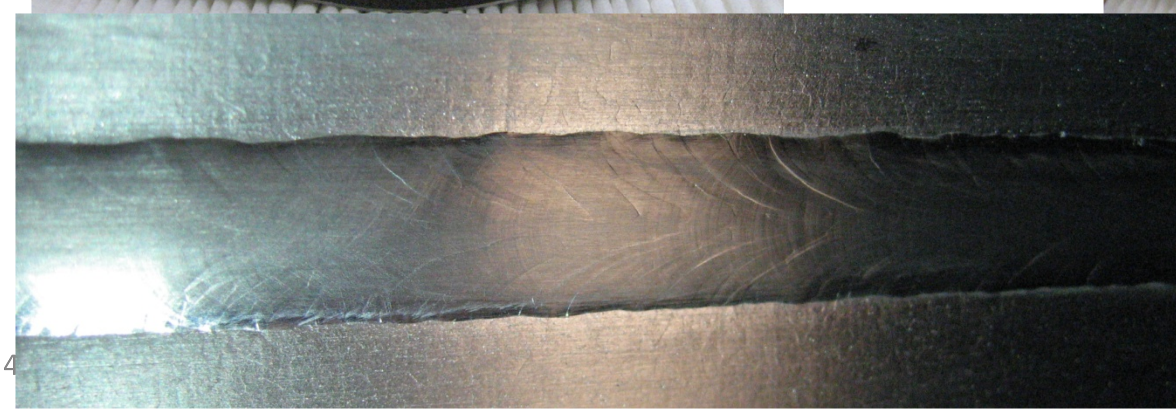
- Weld fixture test fit. Cleaning process started on head, tube, and flange





Niobium Fabrication – OC Tube

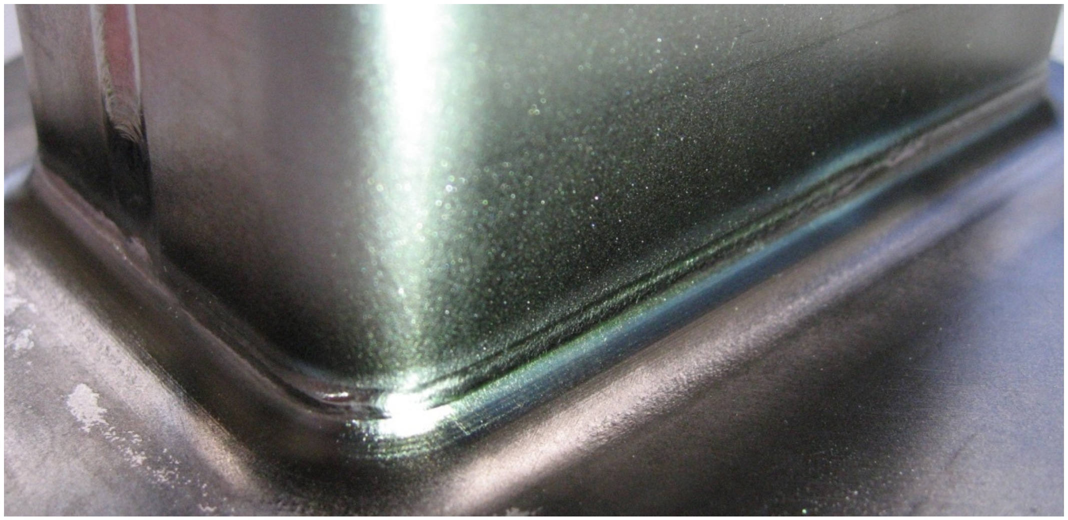
• OC tube being corrugated

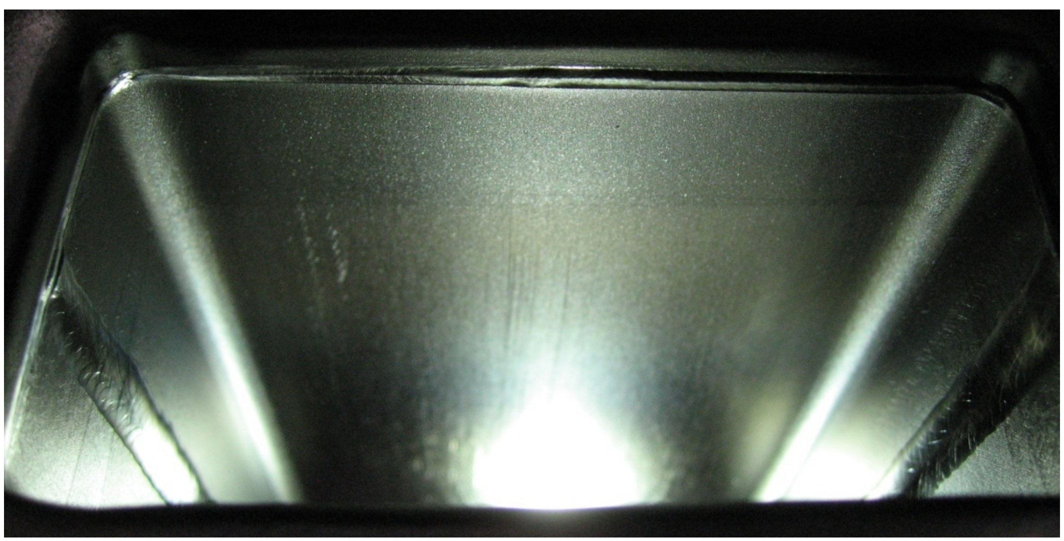


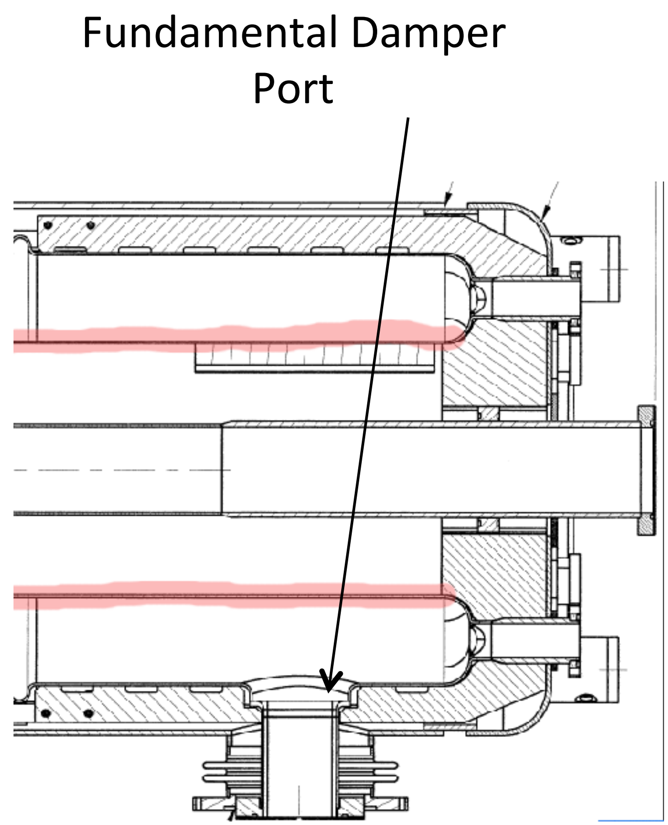
Smooth full Penetration Back Bead

Niobium Fabrication –
Nb Corrugation Prototype

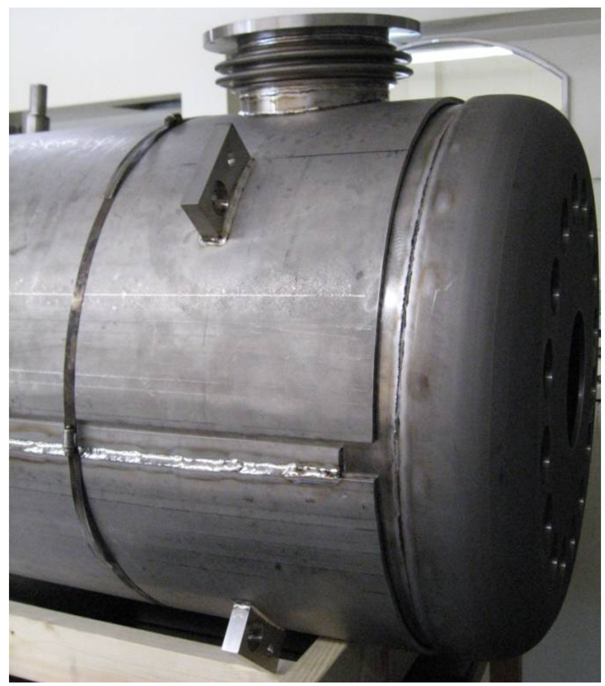
Nb Saddle and Box-tube EB welding successful



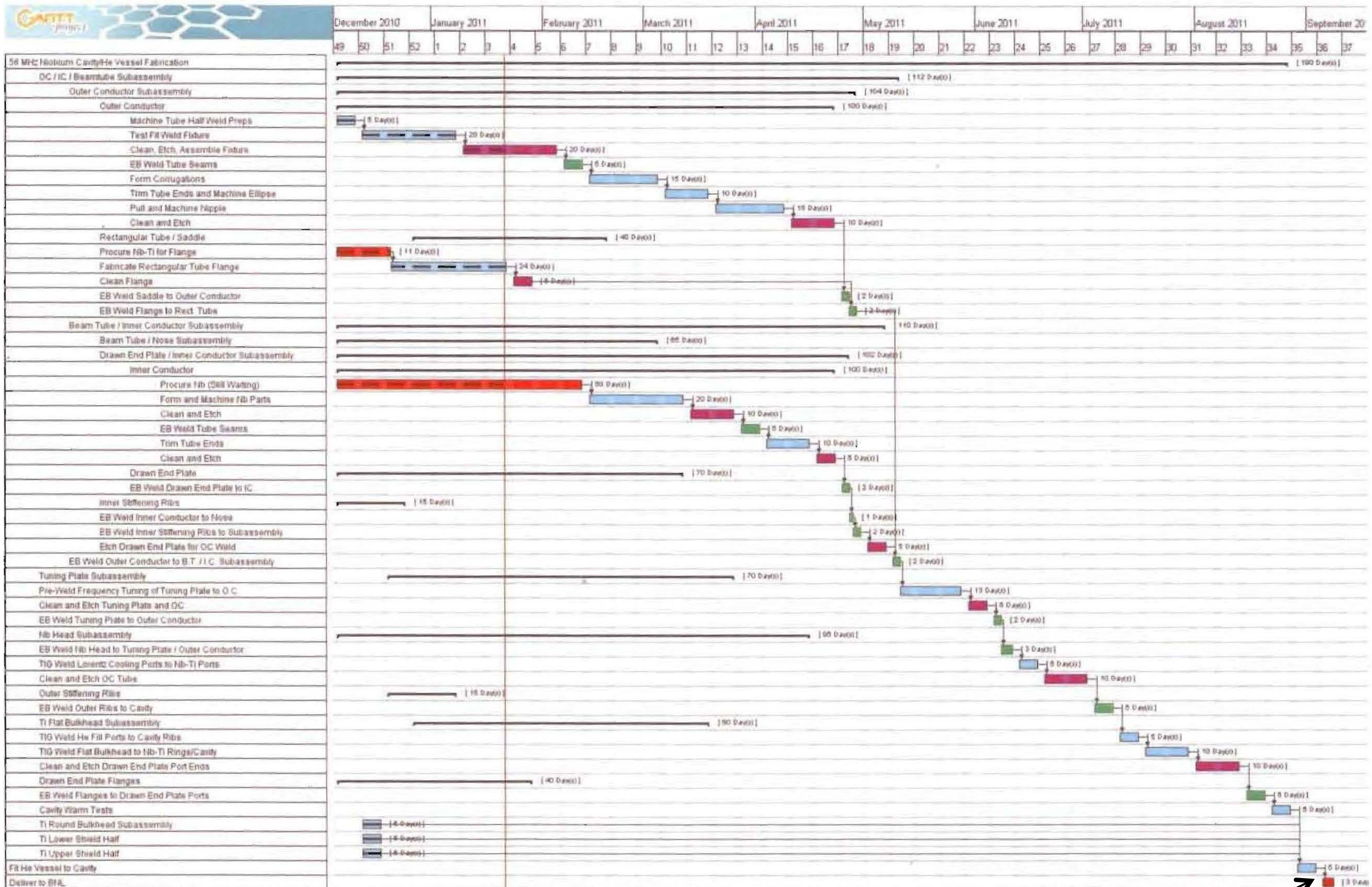




Titanium Test Fit Successful



Niowave Schedule as of 01/21/11



x shows cavity delivery 09/01/11 – BNL schedule based on this date

RHIC 56 MHz Cryomodule

External Review 03/08/11

- <u>Cavity and Helium Vessel</u>

• Design Complete	03/09/10
• Contract Awarded	05/10/10
• Fabrication Complete	09/01/11
• Processing Complete (including VTF)	02/14/11
• String Assembly Complete	04/25/11
• Cryomodule Complete	08/24/13
• Cryomodule Cold Testing Complete	06/24/13
• RHIC IP4 Installation Complete	08/25/13