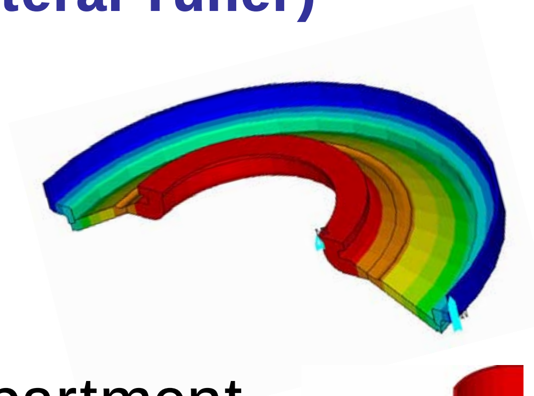
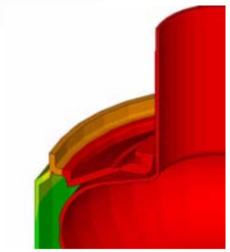
Fermi National Accelerator Laboratory

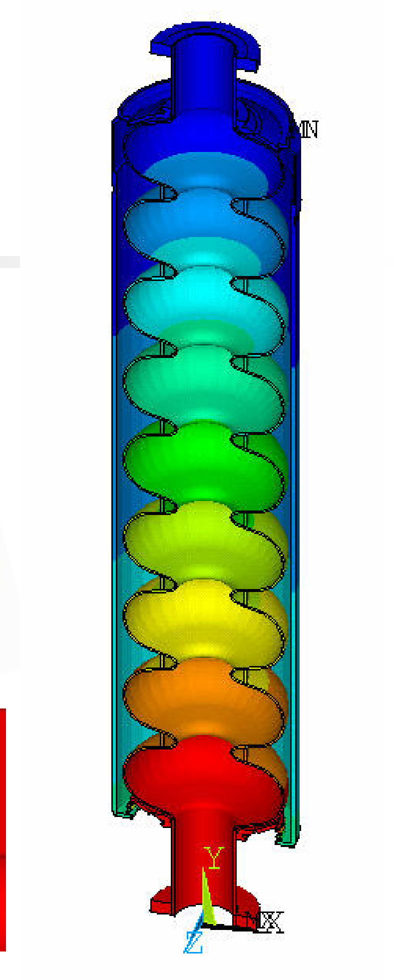
International Linear Collider at Fermilab

1.3GHz Cavity/Cryostat Stiffness Model
&
Tuning Sensitivity

(with emphasis on the Lateral Tuner)







Salman Tariq

Accelerator Division

Mechanical Support Department

SRF Engineering Meeting- TDHQ- February 15, 2006

A Summary of this work (& Talk):

- Identify different stiffness components in the cryostat assembly (such as cavity, bellows, conical end plate, etc.)
- Define a spring-system stiffness model of the cryostat (for both lateral & axial tuner configurations)
- Use FEA to solve for these individual component stiffness
- Simulate cavity cool-down and tuning operation to determine force loads, particularly forces on the tuner to understand Piezo (initial) preload issues + evaluate fast tuning parameters
- Also study the effects of cryo loads (i.e. tuning sensitivity due to He pressure fluctuations) & required tuning compensation

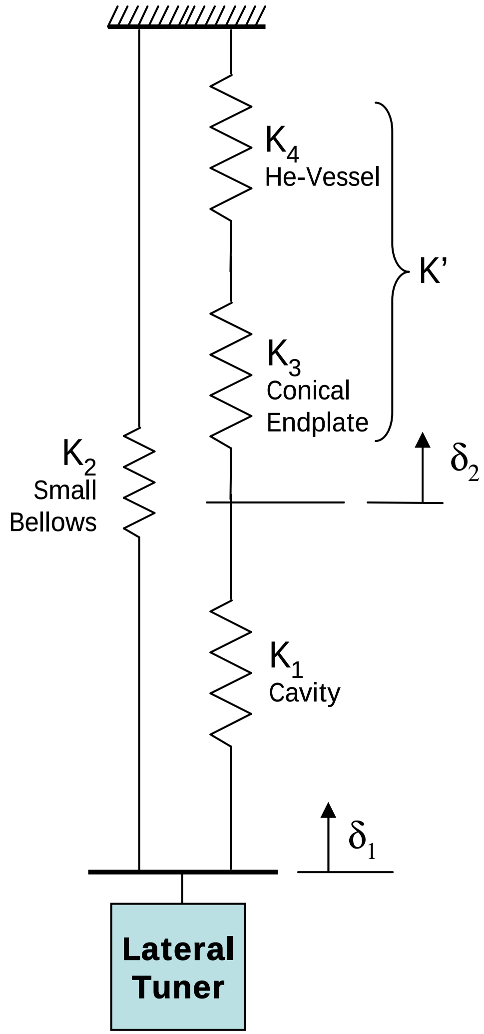
CC2 Fast Tuner:

- Update on ongoing fast tuner work using CC2
- Evaluate *Single Pulse* vs. *Resonant* method for fast tuning

  (Investigate resonant tuning characteristics of cavity using vibration studies- *Future Work*)

Cryostat Assembly Spring System

Using Saclay Lateral Tuner



$$K' = \frac{K_3 K_4}{K_3 + K_4}$$

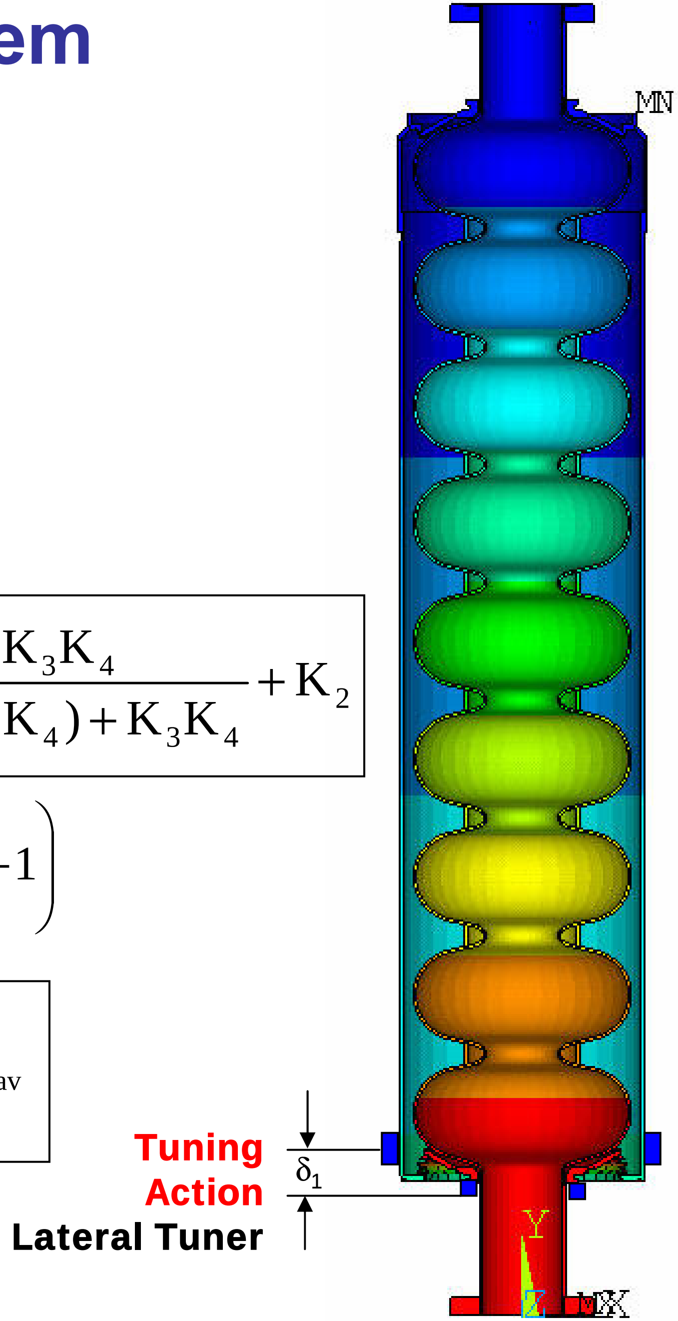
$$K'' = \frac{K_1 K'}{K_1 + K'}$$

Equivalent stiffness:

$$K_{eqv} = K'' + K_2 = \frac{K_1 K_3 K_4}{K_1 (K_3 + K_4) + K_3 K_4} + K_2$$

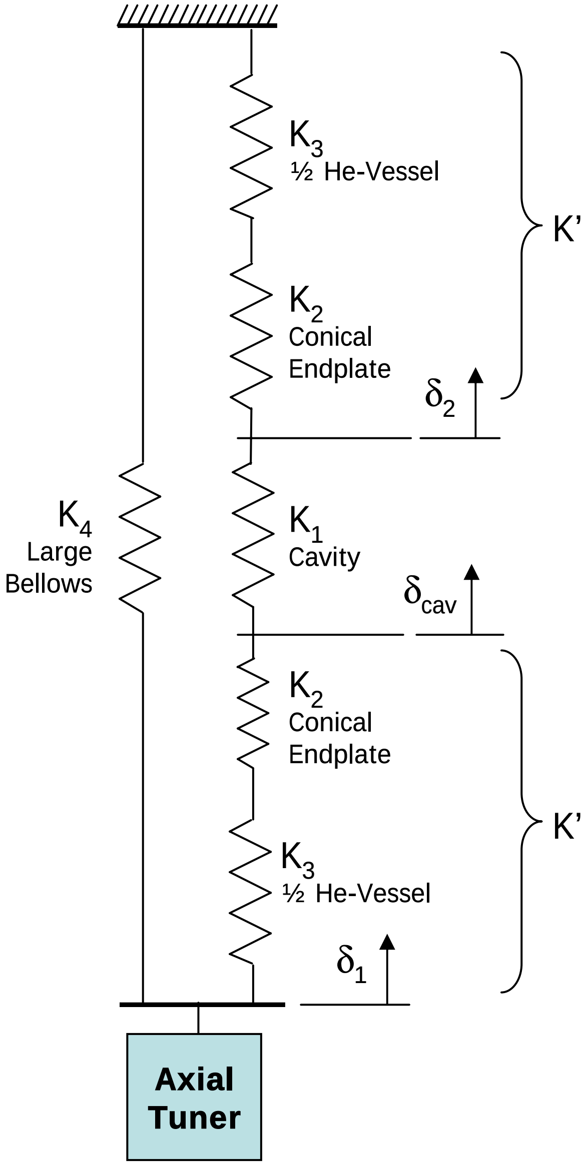
$$\delta_1 = (\delta_{cav} + \delta_2) = \delta_2 \left(\frac{K'}{K_1} + 1 \right)$$

$$\delta_2 = \frac{K_1}{K'} (\delta_1 - \delta_2) = \frac{K_1}{K'} \delta_{cav}$$



Cryostat Assembly Spring System

Using INFN Axial Blade Tuner



$$K' = \frac{K_2 K_3}{(K_2 + K_3)}$$

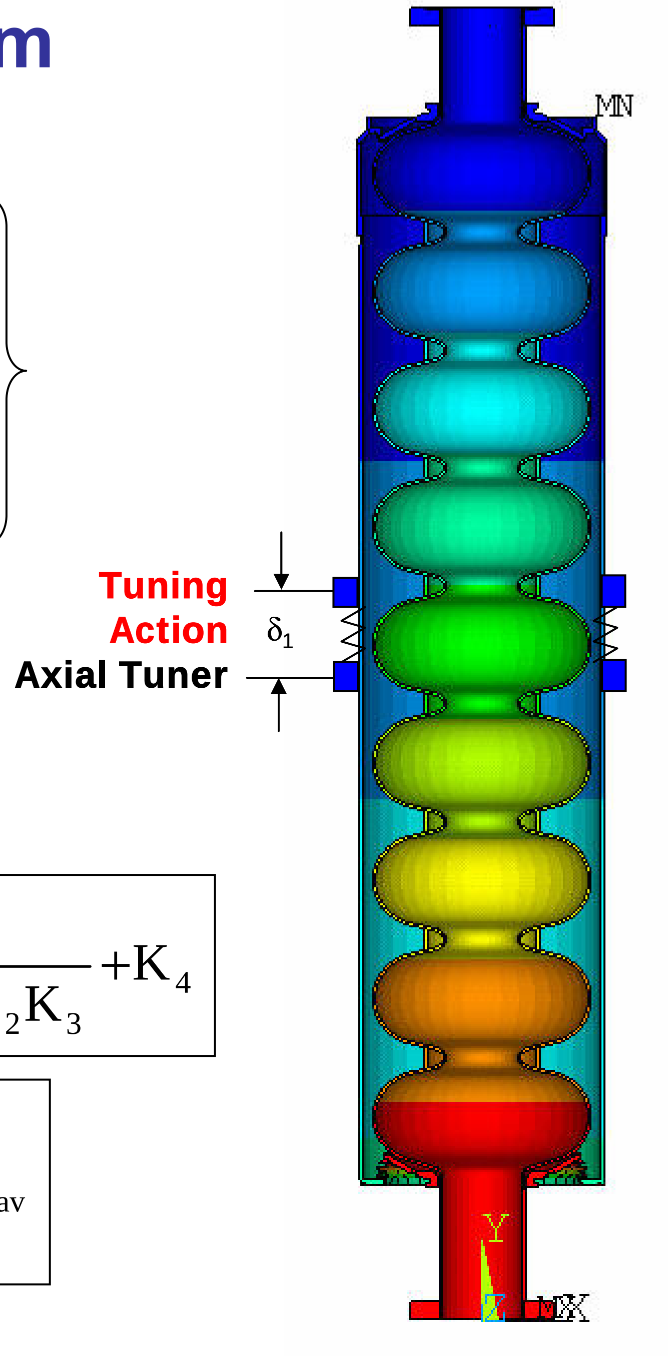
$$K'' = 2K' = \frac{2K_2 K_3}{K_2 + K_3}$$

Equivalent stiffness:

$$K_{eqv} = \frac{K_1 K''}{K_1 + K''} + K_4$$

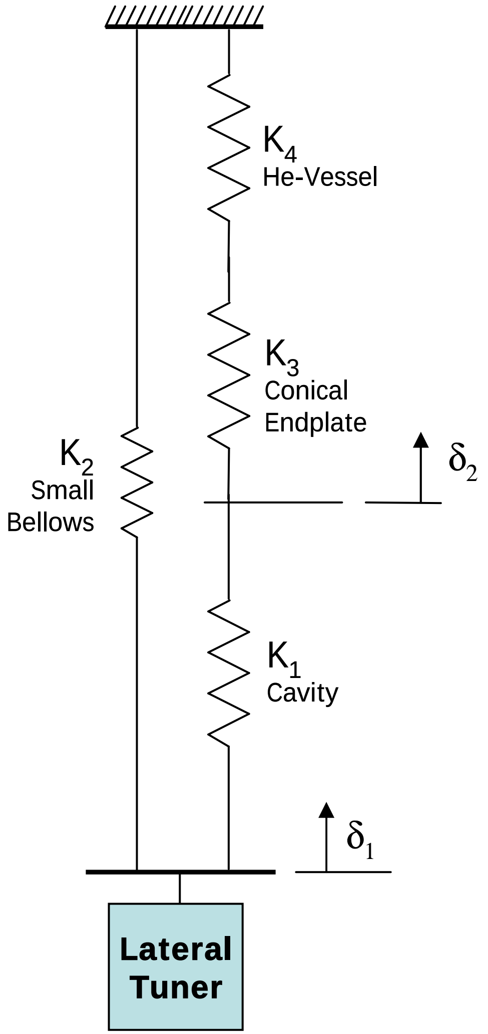
$$K_{eqv} = \frac{2K_1 K_2 K_3}{K_1(K_2 + K_3) + 2K_2 K_3} + K_4$$

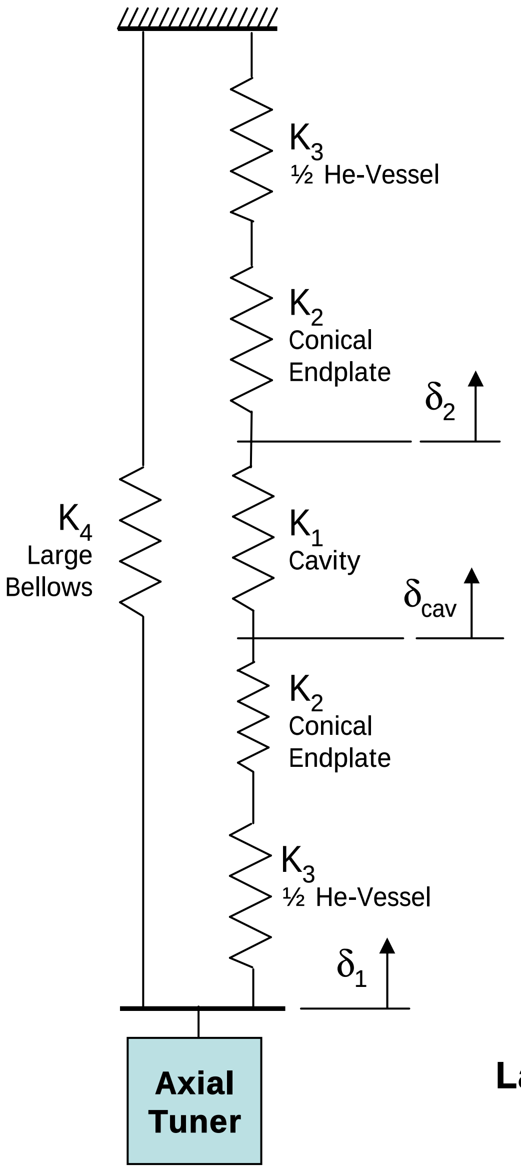
$$\delta_2 = \frac{1}{2}(\delta_1 - \delta_{cav}) = \frac{K_1}{K'}\delta_{cav}$$

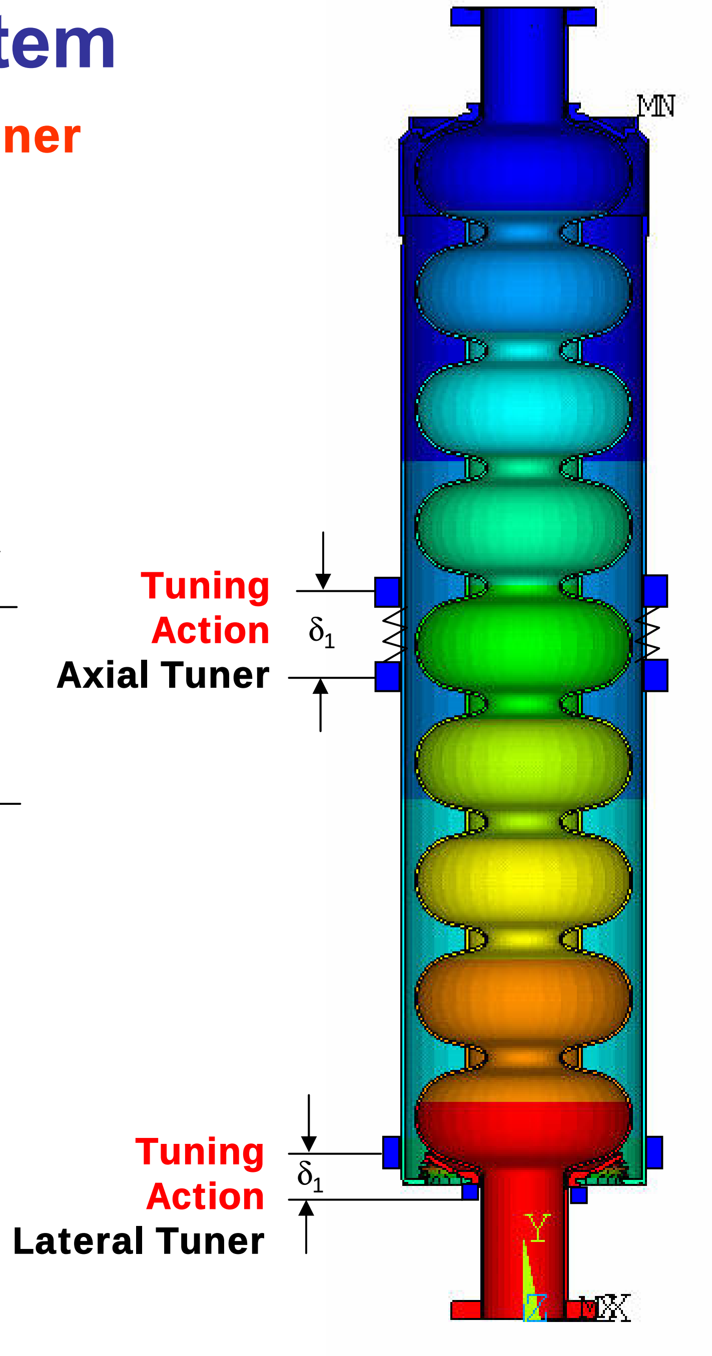


Cryostat Assembly Spring System

Saclay Lateral Tuner *vs.* INFN Axial Blade Tuner

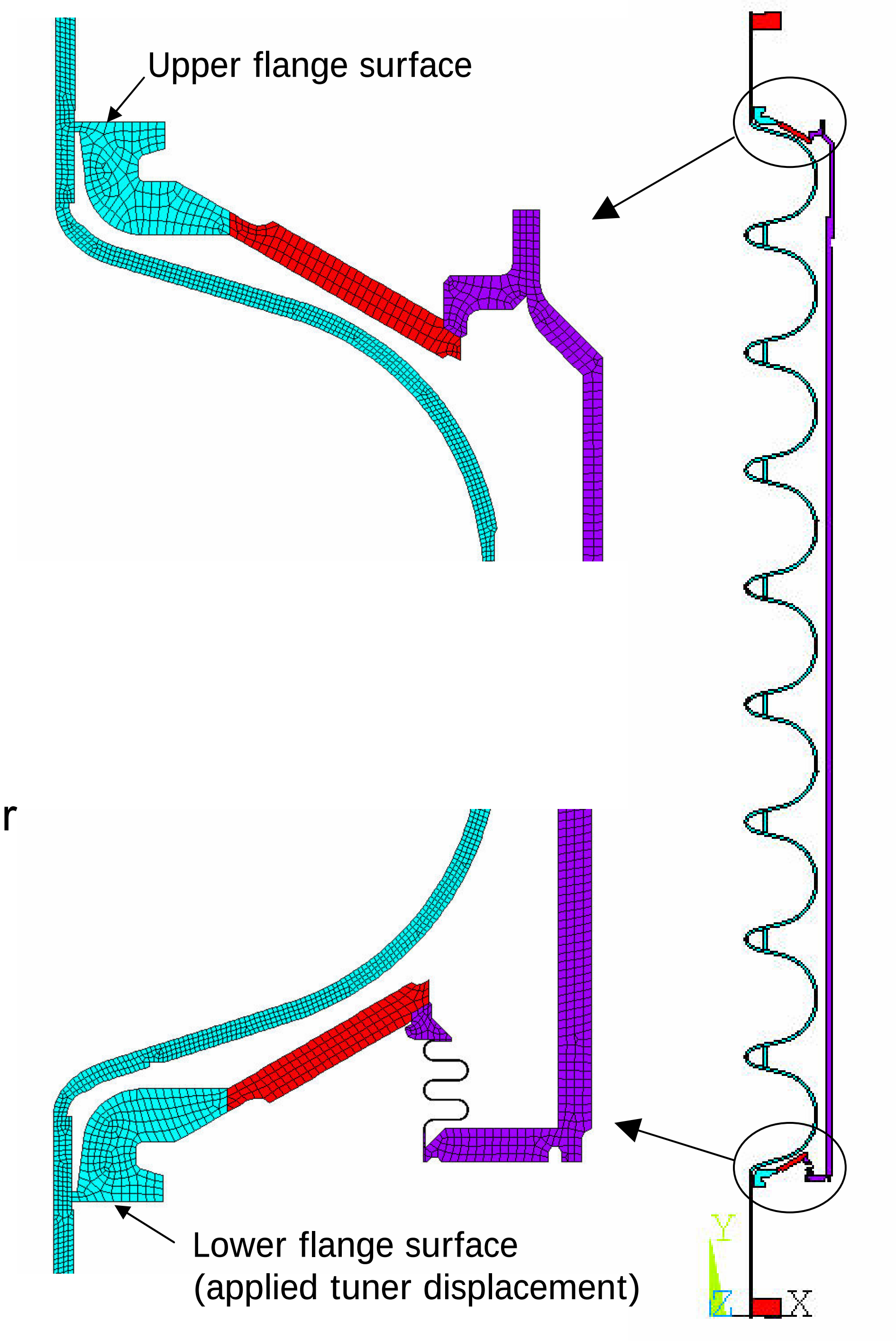






ANSYS FEA MODEL

- 2-d axisymmetric model
  - -PLANE183 higher order, 2D 8-node elements
  - -Average element size = 0.75mm
- Stiffness determined by applying axial displacement and reading corresponding reaction force
- Vacuum/cryo pressure loads applied as nodal pressures on surfaces
- Tuner is assumed to be infinitely rigid (translated into model by coupling lower flange surface to mounting surface on helium vessel)
- Tuner implied displacements are applied directly to lower flange surface
- End effects due to interconnect/bellows, etc. are ignored



Material Properties- E, υ

- Cavity stiffness directly related to E
  - Nb: E reported anywhere between 100–120GPa @ RT
  - Myneni reports: E =110±3 GPa
  - (used **110GPa** for this analysis)

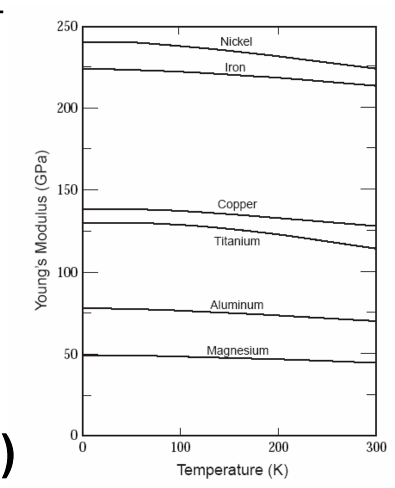
Myneni (JLab) SRF 2003:

-High purity Nb mechanical properties vary from batch to batch & are very sensitive to various treatments & handling

-Elastic behavior of high purity Nb is normal & is unaffected by heat treatments

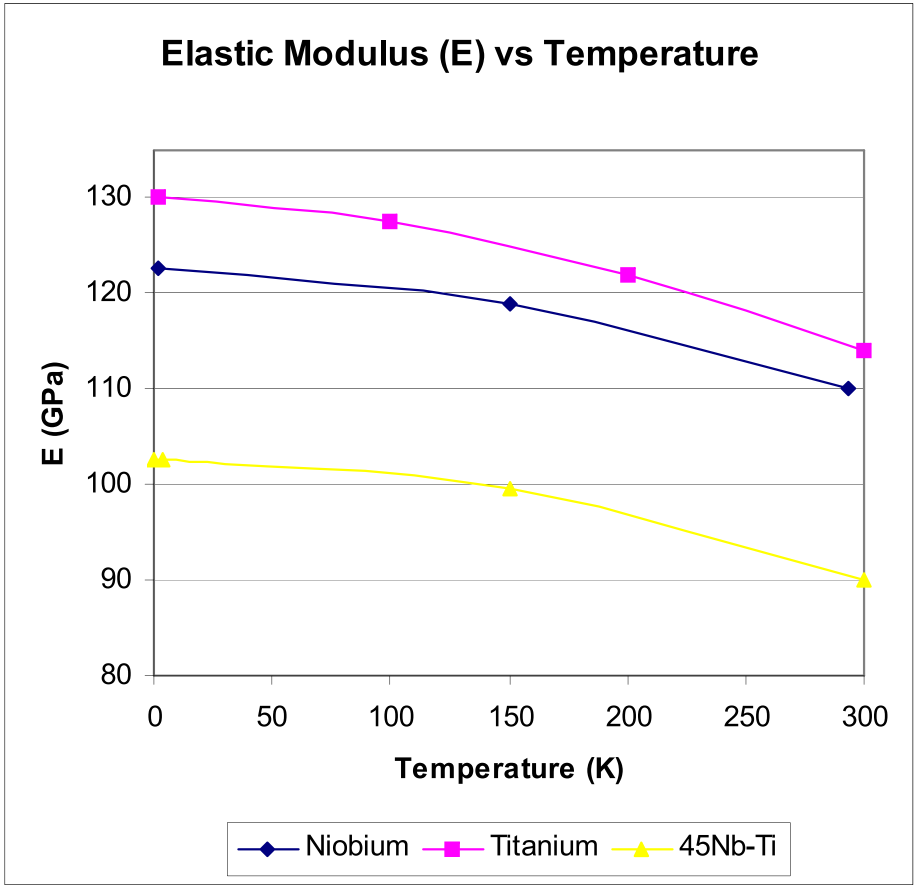
- Assume 10-12% increase in E going down to 2K (typical for most metals)

Plot Courtesy of: Jack Ekin, NIST (Cryogenic Measurements, Oxford U. press)

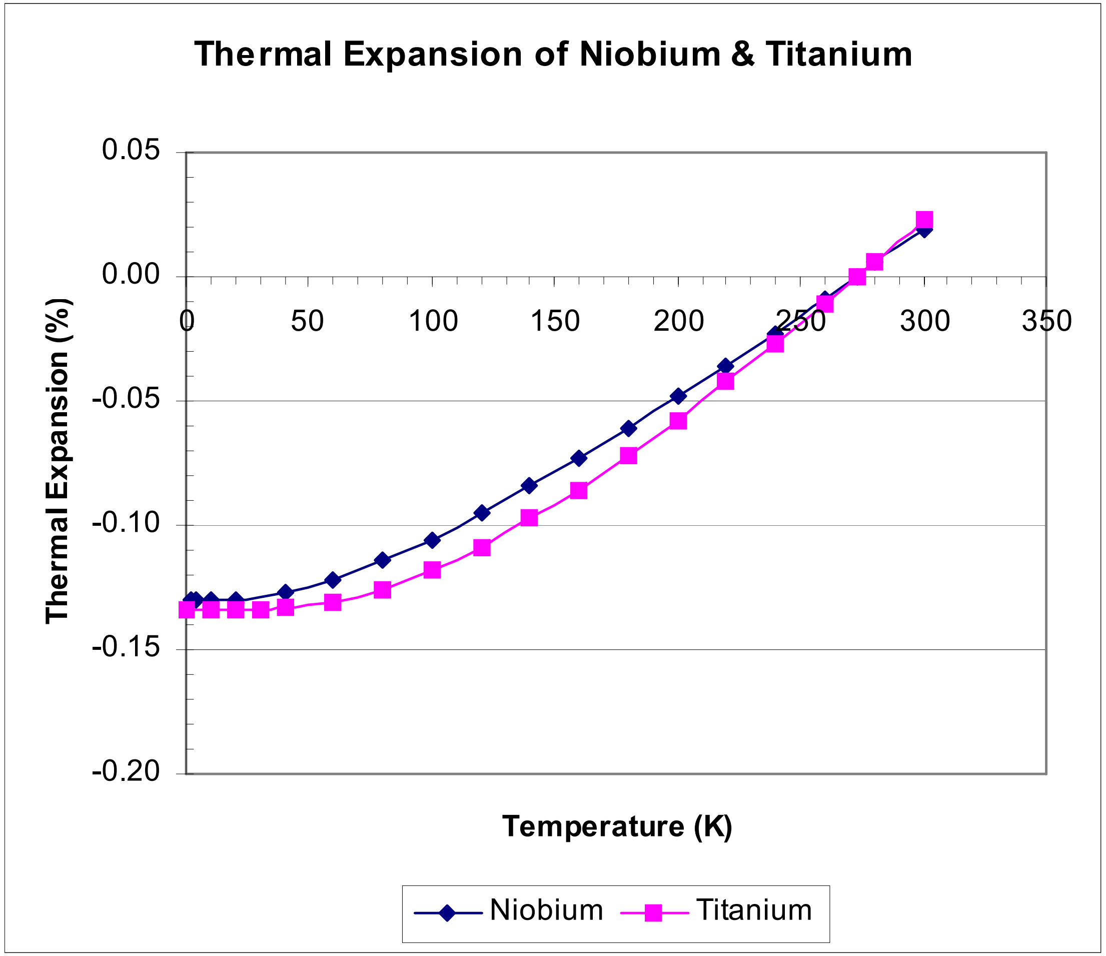


- Poisson's ratio υ:
  - **Nb: 0.38**
  - **Ti: 0.37**
  - **(Nb-Ti: 0.375 est.)**

Assumed υ to be constant over temperature



Material Properties contd- α



Source:
Handbook on Materials for Superconducting Machinery
MCIC-HB-04
November 1974

- **Assumed α for 45Nb-55Ti (End Plates) to be the same as Ti**

FEA Results

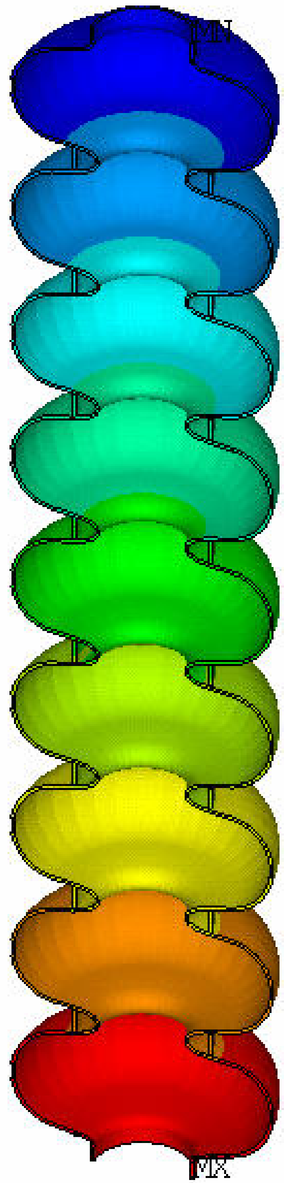
Cavity & Bellows Stiffness

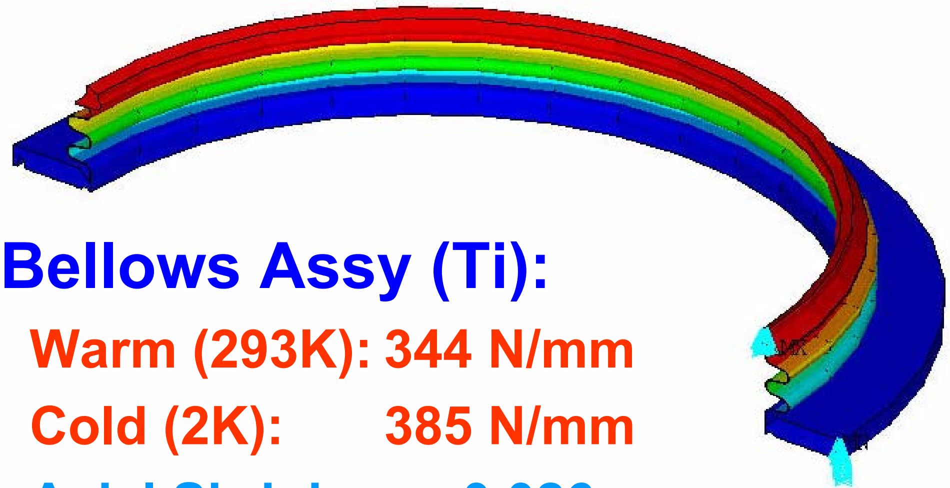
Cavity (Nb):

Warm (293K): 3,473 N/mm

Cold (2K): 3,872 N/mm

Axial Shrinkage: 1.534mm





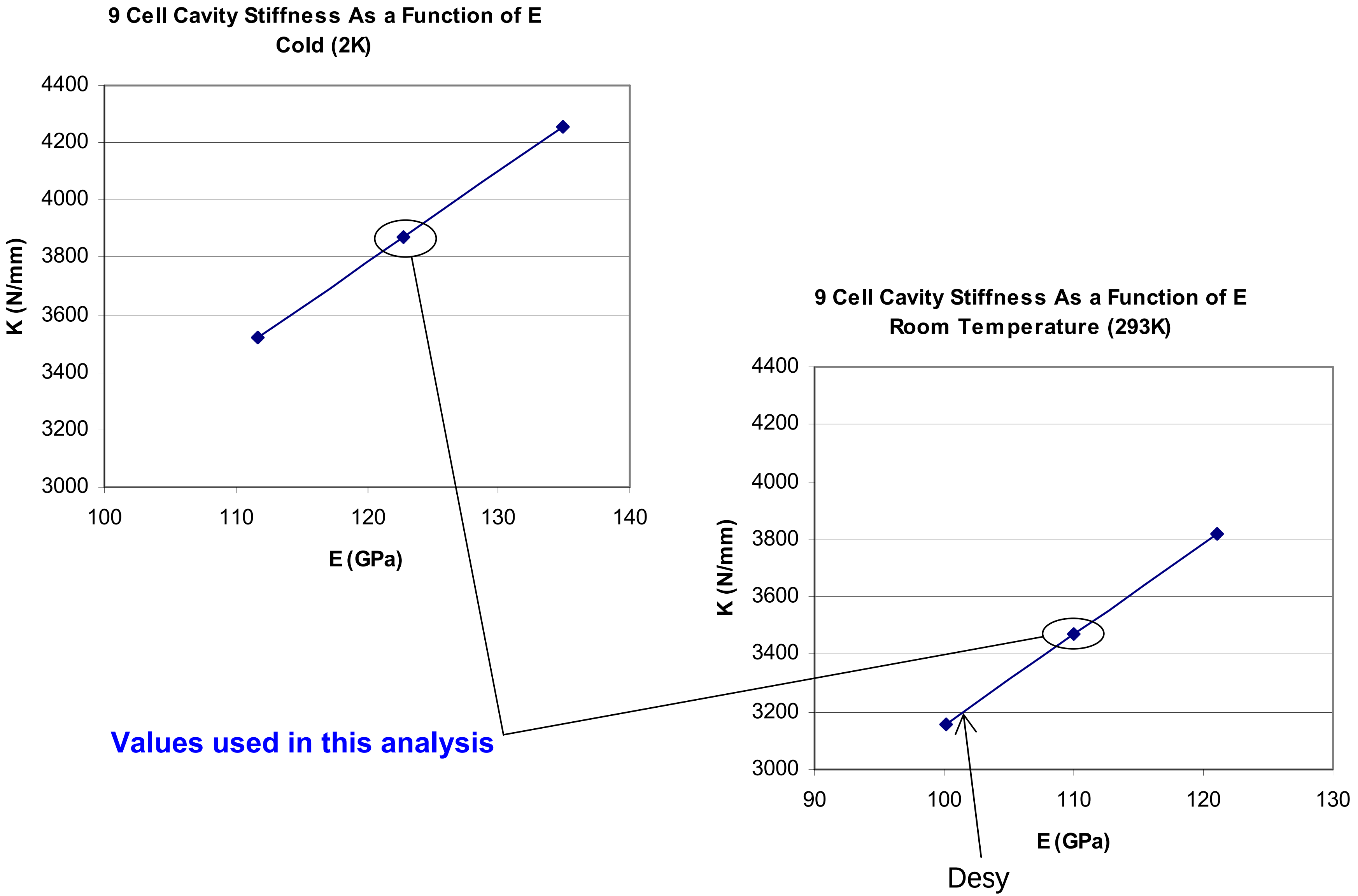
Bellows Assy (Ti):

Warm (293K): 344 N/mm

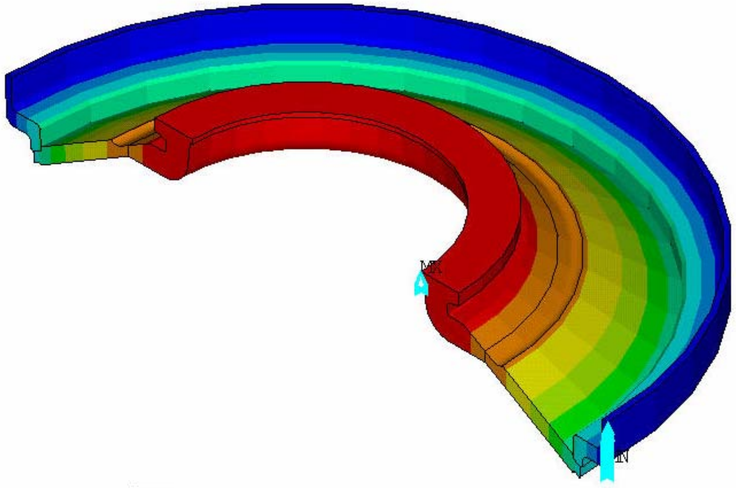
Cold (2K): 385 N/mm

Axial Shrinkage: 0.026mm

Cavity Stiffness as a Function of E



Conical End Plate Stiffness



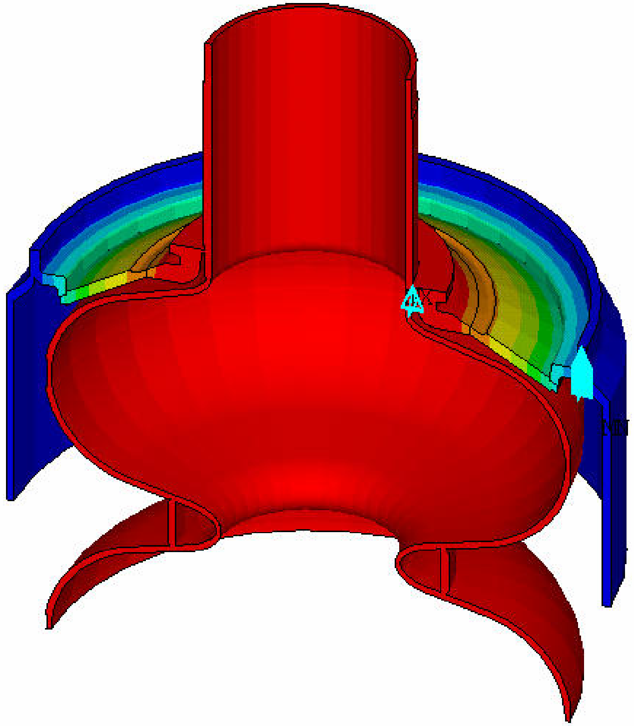
1. End Plate (Nb, Nb-Ti, Ti):

(Free, unstiffened end condition)

Warm (293K): 44,332 N/mm

Cold (2K): 50,095 N/mm

Axial Shrinkage: 0.0068mm



2. End Plate (Nb, Nb-Ti, Ti):

(Stiffened end condition)

Warm (293K): 69,224 N/mm

Cold (2K): 78,662 N/mm

Axial Shrinkage: 0.0068mm

Helium Vessel Stiffness

He Vessel (Ti):

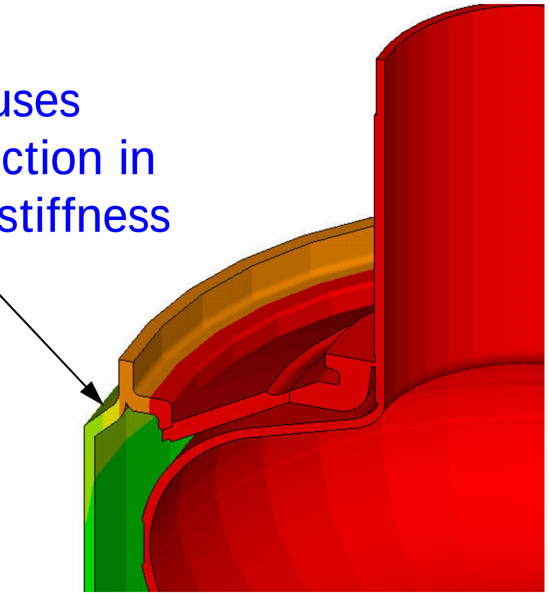
(Stiffened end condition)

Warm (293K): 294,000 N/mm

Cold (2K): 307,000 N/mm

Axial Shrinkage: 1.577mm

Step down causes flexure & reduction in overall vessel stiffness



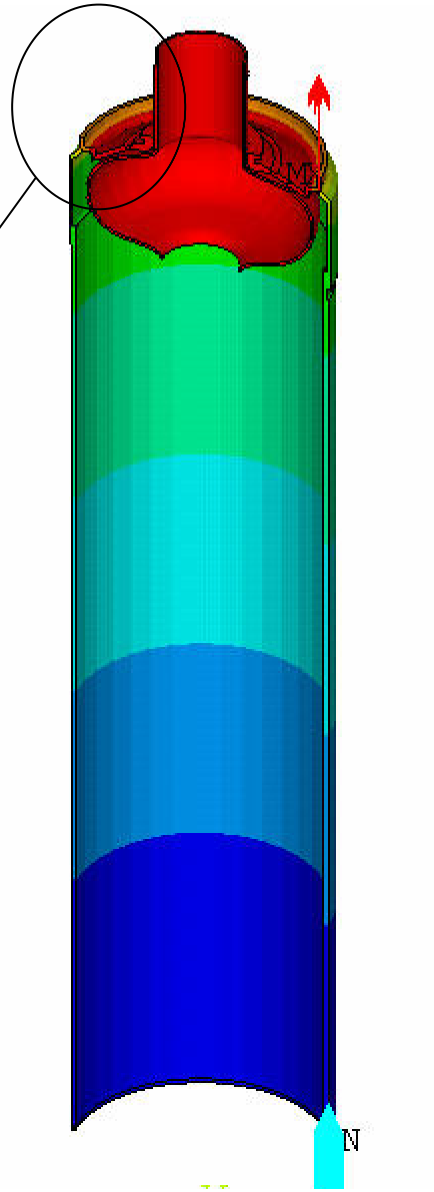
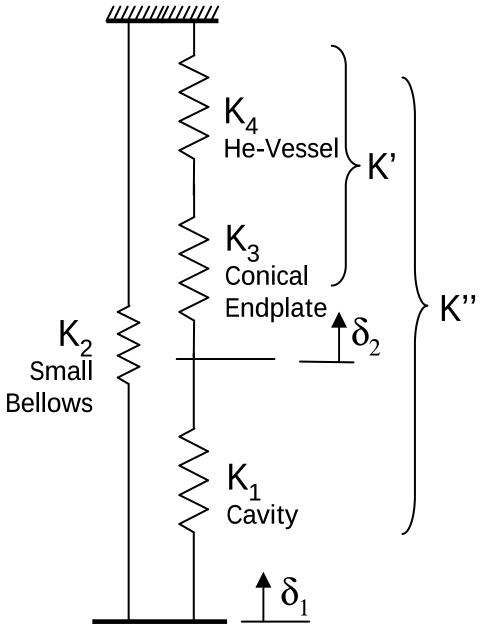


Table of Component Stiffness
Lateral Tuner System

Stiffness in N/mm

	Cavity (K_1)	Small Bellows (K_2)	Conical End Plate (K_3)	Helium Vessel (K_4)	K'	K''	K_{eqv}	
Warm (293K)	3,473	344	69,224	294,000	51,000	3,246	3,590	Ansys
(Desy)	(3,217)		(278,000)	(388,000)	56,031	3,270	3,614	Calculated from eq.
Cold (2K)	3,872	385	78,663	307,000	56,600	3,625	4,010	Ansys
					62,618	3,647	4,032	Calculated from eq.
Shrinkage (mm)	1.534	0.026	0.0068	1.577				



$$\delta_2 = \frac{K_1}{K'}(\delta_1 - \delta_2) = \frac{K_1}{K'}\delta_{cav} = 0.068\,\delta_{cav}$$

$$\text{or}\quad \delta_2 = 0.064\,\delta_1 \quad \& \quad \delta_{cav} = 0.936\,\delta_1$$

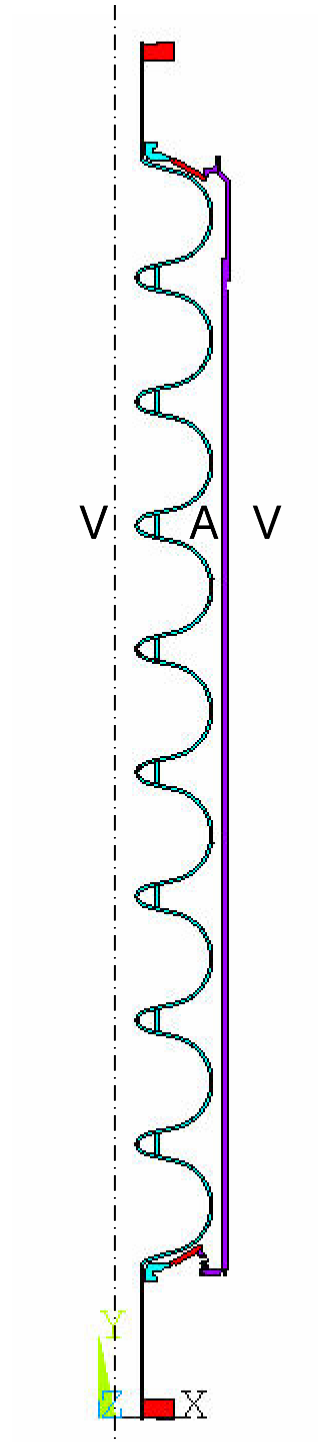
Approximately 6.4% of applied tuning displacement is lost in end plate

93.6% System Efficiency

Vac. State V, A, V:

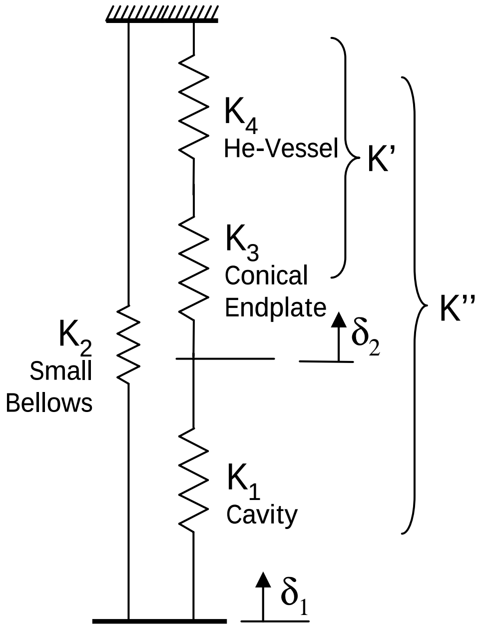
V= vacuum

A= atmosphere



Cavity Cooldown & Frequency Shift- Lateral Tuner

Cavity tuning sensitivity $(\partial F/\partial L) \approx 400$ KHz/mm (from Desy TTF_CDR- measured)



		Warm	Cold
K'	K1 Cavity	3473	3871
	K2 Small Bellows	344	385
	K3 Conical End plate	69224	78663
	K4 He-vessel	294000	307000
	$K' = K_3K_4/(K_3 + K_4)$	51,000	56,600
	$K'' = K_1K'/(K_1 + K')$	3,246	3,625
	$K_{eqv} = K'' + K2$	**3,590**	**4,010**

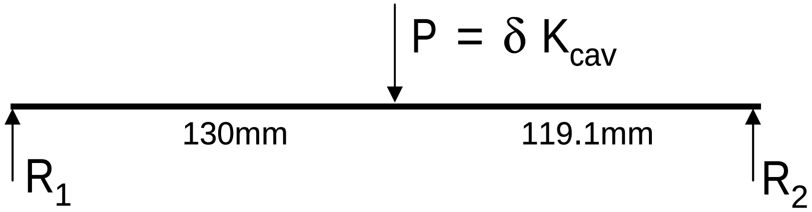
$\delta_2 = K_1/K' \cdot (\delta_1 - \delta_2)$

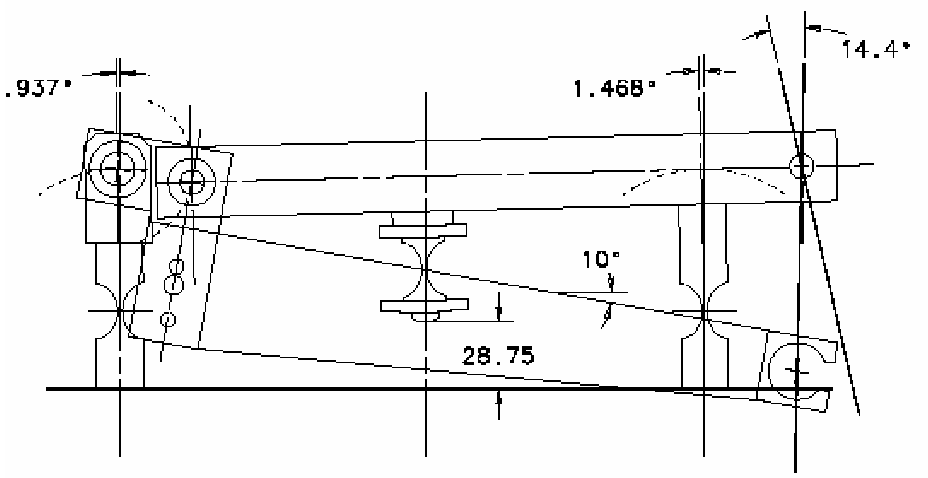
Step	F (lbs)	Piezo F (lbs)
4^{ini}	722	345
4a	1140	545
4b	1424	681
5a	730	349
5b	1550	741

Step	T (K)	Vac State	(Ansys) K_{eqv} (N/mm)	Cavity L (mm)	Cavity ΔL (mm)	End Plate δ_2^{press}	Freq. +ΔF (KHz)	Tuner F (N)	Applied Slow Tuning Parameters: Cavity $\delta_{cav}=\delta_1-\delta_2$	Tuner δ_1 (mm)	End plate δ_2 (mm)	Cavity L' (mm)	Adjusted +ΔF(KHz)	Tuner F (N)
0	293.00	Cavity @ A	3,590	1061.2			914							
1	293.00	V,A,A	3,590	1061.19	-0.0125	-0.0125	909	-622						
2	293.00	V,V,A	3,590	1061.17	-0.033	-0.033	901	-1955						
3	293.00	V,A,V	3,590	1061.22	0.020	0.020	922	1779						
4^{ini}	4.20	V,V,V	4,010	1059.67	-1.535	0	300	0	0.750	0.801	0.0513	1058.92	0	3213
4a	**4.20**	**V,A,V**	**4,010**	**1058.93**	**0.018**	**0.018**	**7.2**	**4990**	**0.018**	**0.019**	**0.0012**	**1058.92**	**0**	**5070**
4b	4.20	V,1.7A,V	4,010	1058.93	0.012	0.012	4.8	6281	0.012	0.013	0.0008	1058.92	0	6335
5a	**1.80**	**V,0.02A,V**	**4,010**	**1058.92**	**0.00035**	**0.00035**	**0.14**	**3247**	**0.00035**	**0.00037**	**0.00002**	**1058.92**	**0**	**3248.2**
5b	1.80	V,2A,V	4,010	1058.95	0.035	0.035	14	6771	0.035	0.037	0.002	1058.92	0	6891

$\partial f/\partial P$ = 7.1 KHz/bar = 7.1 Hz/mbar

Equivalent Stiffness @ Piezo





Equivalent Stiffness @ Piezo location, K_{eq}:

$R_1 = 0.478\ P = 0.478\ \delta\ K_{cav}$

$$K_{eq} = 0.478\ K_{cav}$$

e.g. for 9-cell cavity with K_{cav}=3,473N/mm:

K_{eq} = 1,660 N/mm (373 lb/mm warm)

& K_{eq} = 1,851 N/mm (416 lb/mm cold)

[Desy K_{eq}= 1,530 N/mm = 344 lb/mm warm]

Fast Tuning Implications

From DESY TTF CDR, @ 25 MV/m:

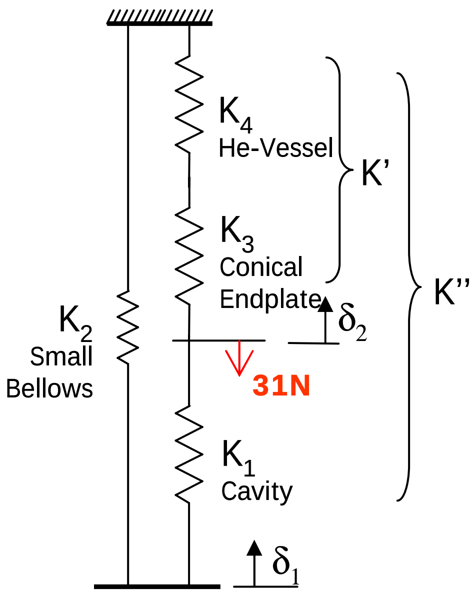
Frequency shift due to Lorentz forces (at constant cell length) $\Delta f_{\text{cell form}} \approx -350$ Hz

Axial constraint needed = -31N (i.e. cavity wants to become shorter)

But cavity is already under compression, thus, if P is new reaction force:

$$P + 31 = K_1 \cdot \delta'_{cav} \qquad P = K' \cdot \delta'_2 \qquad \delta'_{cav} + \delta'_2 = \delta_1$$

$$\delta'_{cav} = \frac{K'\delta_1 + 31}{(K_1 + K')} = \frac{56600\delta_1 + 31}{(3872 + 56600)} = 0.936\delta_1 + 5.126e - 4$$



Net length change:

$$\Delta\delta_{cav} = \delta'_{cav} - \delta_{cav} = 5.126 \times 10^{-4}\,\text{mm}$$

Freq. shift $\Delta f_{\text{cell length}}$ = -5.126e-4mm x 400KHz/mm = -205 Hz

$\Delta f_{\text{Total}} = \Delta f_{\text{cell form}} + \Delta f_{\text{cell length}}$ = -350 – 205 = -555 Hz

(Just a few microns needed from fast tuner to compensate for this)

If cavity was unconstrained, shift in resonant frequency would be:

$\Delta f_{\text{unconst}}$ = -3200 – 350 = <u>3,550 Hz</u>

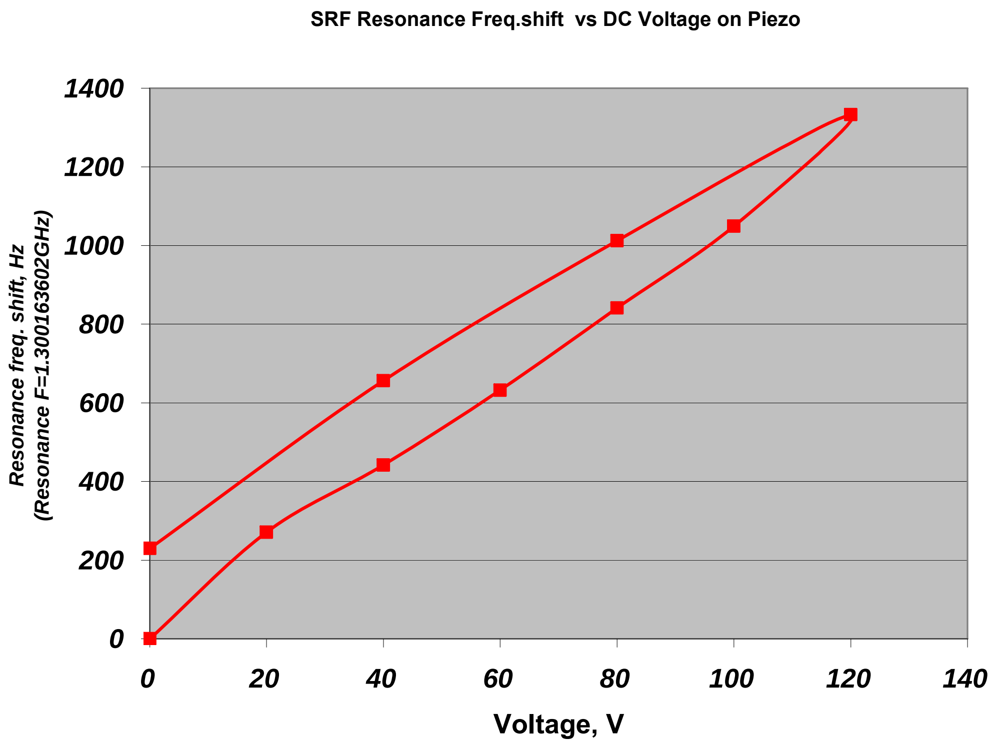
FEA Results Summary

- A stiffness model has been defined which helps in understanding each component stiffness and its contribution to the overall stiffness much better.
- Cavity stiffness values agree well with Desy measurements at RT.

  My estimates for stiffness are ~11% higher when cold- Desy assumes not much change from RT.
- Some discrepancy with Desy numbers on He-vessel & end plate stiffness which needs to be clarified– maybe a misunderstanding on how I'm reading their numbers.
- Cryostat tuning efficiency was found to be ~93.6% (i.e. ignoring tuner system losses by assuming an infinitely stiff mechanism– tuner losses are expected to be very small anyway) *(Future work: estimate the tuner mechanism stiffness)*
- Pressure induced shift in resonant frequency was found to be 7.1 Hz/mbar, close to Desy's measured value of 10.3 Hz/mbar.
- Tuner force results indicate that a relatively high initial preload is required (600 lbs +) for proper Piezo function using the existing Desy bracket design
- A lot of uncertainty: Matl. properties, Cavity-to-cavity differences (due to fabrication, processing, etc), machining/assembly, etc.
- *Finally*, this analysis should be repeated for the axial tuner configuration

CC2 & Fast Tuner update

- Some encouraging results from CC2:



Test Temperature:
20K

Cavity Tuning Sensitivity:
200KHz/mm

Cavity extended 6microns
@ 120V

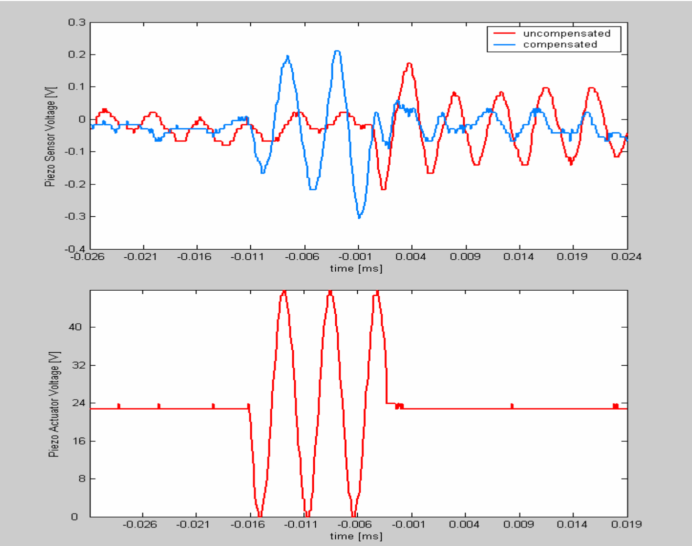
(data from Yuriy P. & Tim K.)

- Plan to compare these & other CC2 measurements to FEA predictions

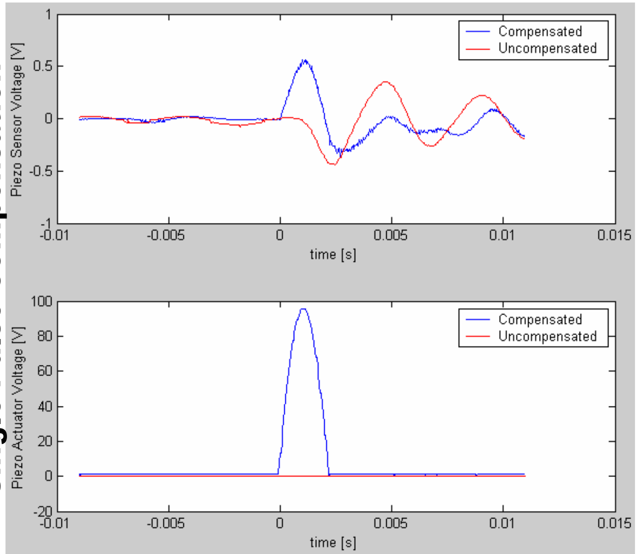
CC2 & Fast Tuner update contd.

• Evaluate *Resonant Excitation* method over *Single Pulse Compensation*

Resonant Excitation



Single Pulse Compensation



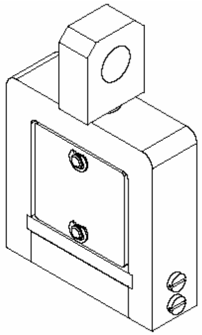
<u>Resonant Method:</u>

By exciting the mechanical resonance of a cavity with a piezo, the cavity can be used as a mechanical amplifier, so that a small stroke of the active element can compensate large detuning.

Desy has shown that with the excitation of three periods of the mechanical resonance frequency, about 1000 Hz could be compensated.

(Ref.: Lutz Lilje-Desy)

New (proposed) Piezo Bracket Design

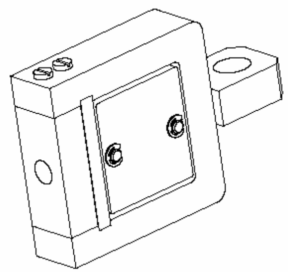


This means we can go ahead with the new Piezo Bracket Design which reverses the loading on the Piezo element 'bracketry'

i.e. tensile force is translated into a compressive load on the Piezo element

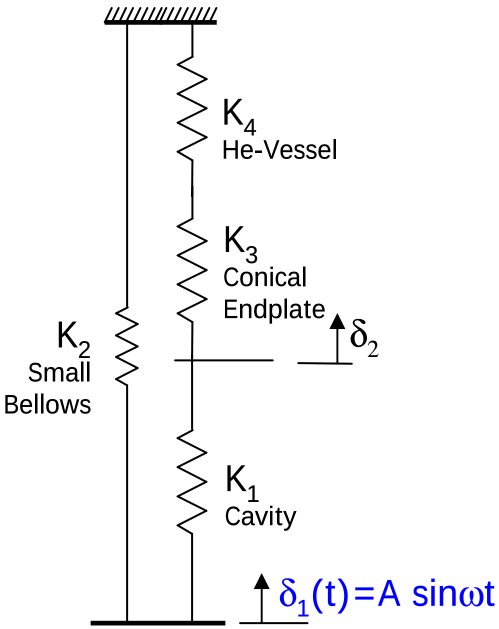
This new design should eliminate existing piezo bracket problems such as:

- Attaining correct *initial* preload &
- Preload loss at cool down
- Transverse loading/bending of bracket
- Dynamic instability

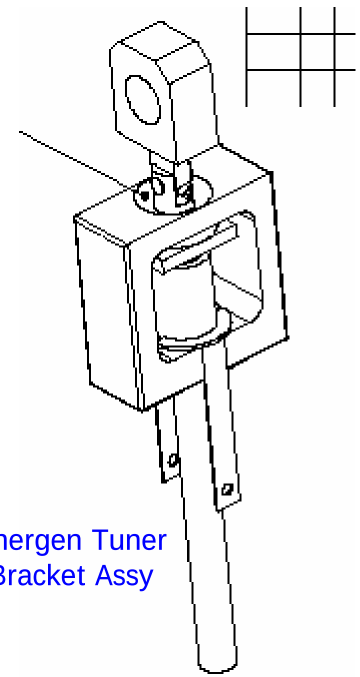


CC2 & Fast Tuner update contd.

- *Resonant Excitation* method requires a vibration study of the cavity/cryostat assembly, an Ansys FEA model will be the first step (Mike McGee)



- Ruben's Group is already looking into the Resonant Method and will be helping with the new Piezo Bracket mechanical design (instrumentation, etc.)
- Plans are also underway to test magnetostrictive actuators using Energen's design (requires modification)
- The new Piezo Bracket design will also be evaluated for magnetostrictive actuator use



Energen Tuner Bracket Assy

Finally, to test all these designs:

- If CC2 time frame doesn't work, possibly use the Horizontal test cryostat for fast tuner R&D work

Other Individuals involved in fast tuner work:

TD: Cosmore Sylvester, Ruben Carcagno, Yuenian Huang, Darrel Orris, Yuriy Pischalnikov, Fred Lewis, Charlie Hess

AD: Mike McGee, Rob Polera (Co-op)

END