TUNING SYSTEMS

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Introduction – "Big Picture" for Tuners

- SRF/RF system should consume RF power efficiently
  - Minimizes klystron size and capital cost
  - Higher $Q_{external}$ (> 10^7) ←→ more efficient ER
  - Reduced Microphonics – actively controlled?
- RF Stability
  - Attained by controlling cavity RF phase (0.05°, RMS) and RF amplitude (2 x 10^{-4},RMS)
- Availability / Reliability / Maintainability
  - Use machine as scheduled
  - Operate machine as desired
  - Repair machine (if required) for use and operation

→ Examine what has been achieved on some existing systems to stimulate discussion

Introduction: Pertinent Cavity Info

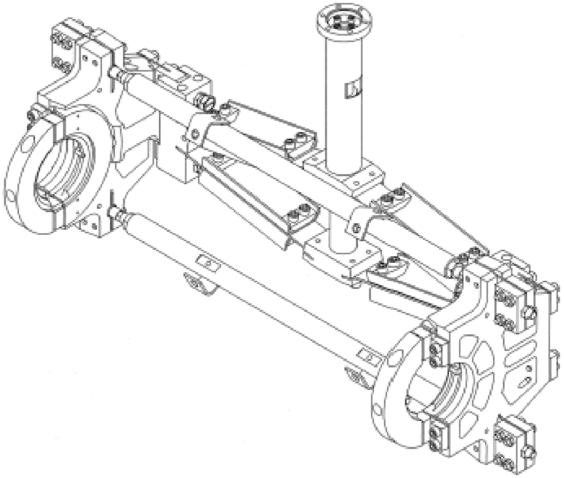
	CEBAF	CEBAF Upgrade (SL21,FEL03)	CEBAF Upgrade (Renascence)	RIA, =0.47	SNS, =0.61	SNS, =0.81	TESLA 500
Frequency (MHz)	**1497**	**1497**	**1497**	805	805	805	**1300**
Gradient (MV/m)	**5**	**12.5**	18	**10**	**10.3**	**12.1**	23.4
Operating Mode	CW	CW	CW	CW	**Pulsed, 60 Hz, 7%**	**Pulsed, 60 Hz, 7%**	**Pulsed, 60 Hz, 1%**
Bandwidth (Hz) $Q_{external}$	**220** **6.6 x 10^6**	75 2.0 x 10^7	75 2.0 x 10^7	40 2.0 x 10^7	**1100** **7.0 x 10^5**	**1100** **7.0 x 10^5**	**520** **3.0 x 10^6**
Lorentz Detuning (Hz)	**75**	**312**	**324**	**1600**	**470**	**1200**	**434**
Microphonics (Hz, 6)	**-**	±10	±10	±10	**±100**	**±100**	**NA**
Stiffness (lb/in)	**26,000 (calc'd)**	**37,000 (calc'd)**	**20,000-40,000 (calc'd)**	**< 10,000**	**8,000 (meas'd)**	**17,000 (meas'd)**	**31,000 (est'd)**
Sensitivity (Hz/ m)	**373**	**267**	**~300 (calc)**	**> 100**	**290**	**230**	**315**

Tuner Requirements & Specifications

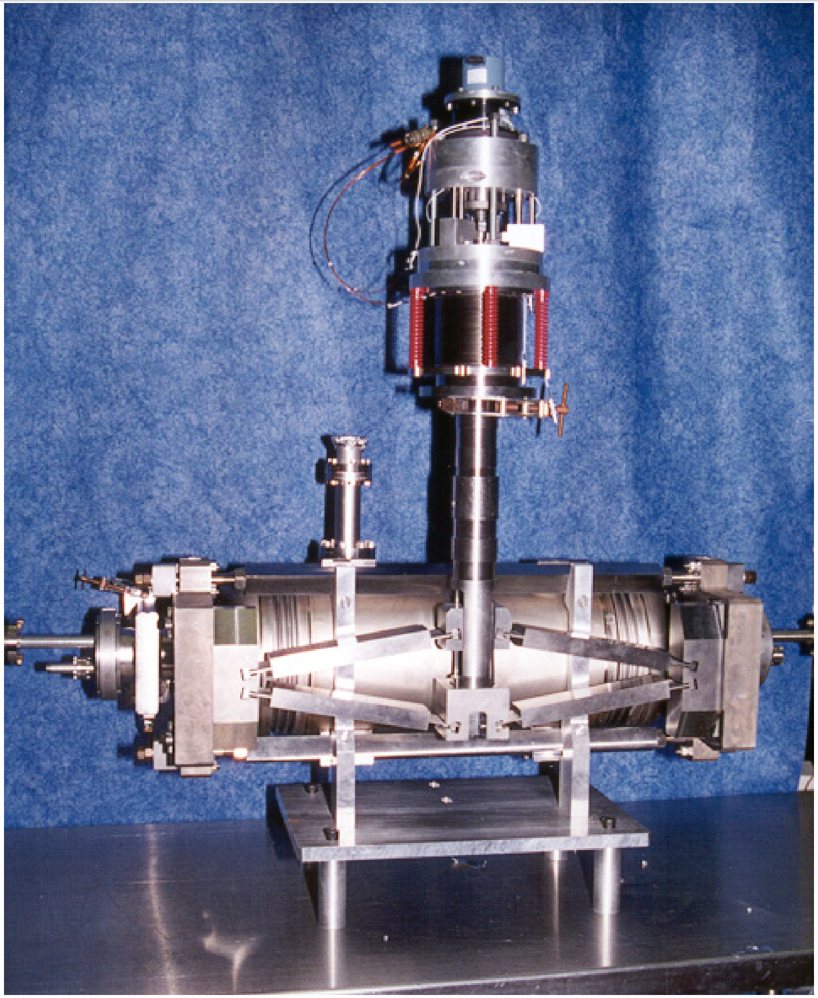
	CEBAF	CEBAF Upgrade (SL21,FEL03)	CEBAF Upgrade (Renascence)	RIA, =0.47	SNS, =0.61	SNS, =0.81	TESLA 500
Coarse Range (kHz)	**±200**	**±200**	**±400**	**950**	**±245**	**±220**	**±220**
Coarse Resolution (Hz)	**NA**	< 2	2 - 3	< 1	2 - 3	2 - 3	< 1
Backlash (Hz)	**>> 100**	< 3	< 3	**NR**	**< 10**	**< 10**	**NR**
Fine Range	**No Fine Tuner**	> 550 Hz / 150 V	1.2 kHz / 1000 V 30 kHz / 30 A	11 kHz / 100 V	> 2.5 kHz / 1000 V	>2.5 kHz / 1000 V	**No Fine Tuner**
Fine Resolution (Hz)	**NA**	< 1	< 1	< 1	< 1	< 1	< 1
Demo of Active Microphonics Damped?	**No**	**?**	**No**	Yes	**No**	**No**	**No**
Tuning Method	**Tens. & Comp.**	Tension	Tension	**NA**	Comp.	Comp.	**Tens. & Comp.**
Mechanism, Drive Comp.	**Immersed,** Vac/Warm	**Vacuum,** Vac/Warm	**Vacuum, Vac/Cold**	**Vacuum,** Vac/Ext	**Vacuum, Vac/Cold**	**Vacuum, Vac/Cold**	**Vacuum, Vac/Cold**

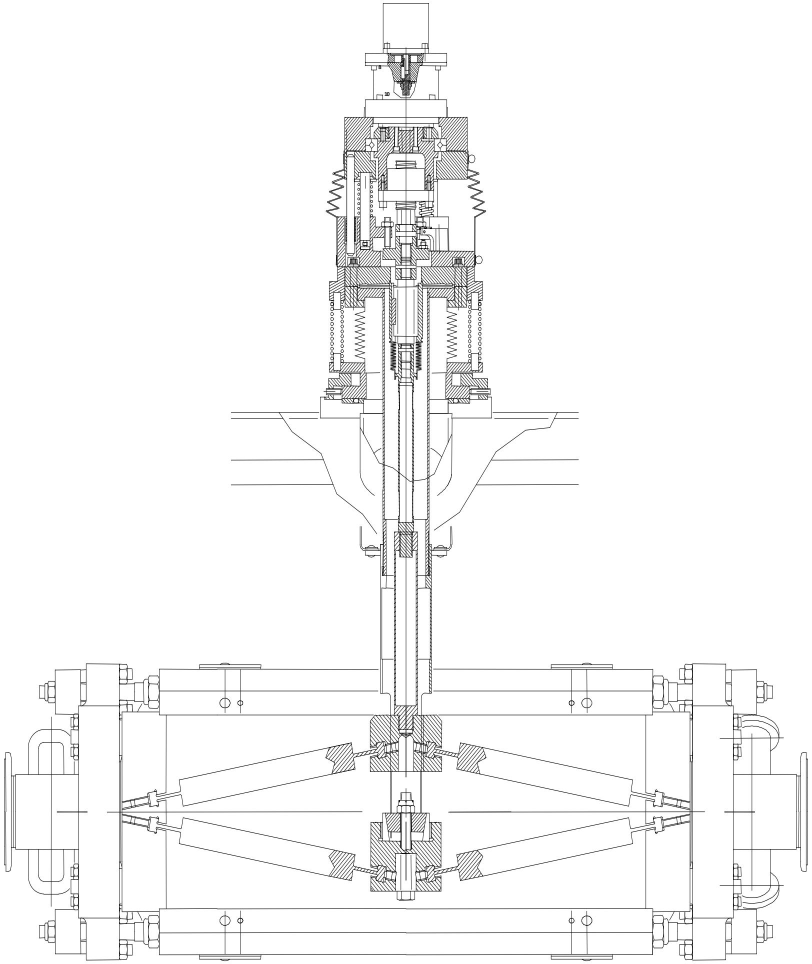
Upgrade Tuner for SL21 and FEL03 Cryomodules - Description

- Scissor jack mechanism
  - Ti-6Al-4V Cold flexures & fulcrum bars
  - Cavity tuned in tension only
  - Attaches on hubs on cavity
- Warm transmission
  - Stepper motor, harmonic drive, piezo and ball screw mounted on top of CM
  - Openings required in shielding and vacuum tank
- No bellows between cavities
  - Need to accommodate thermal contraction of cavity string
  - Pre-load and offset each tuner while warm



Prototype Tuner for CEBAF Ugrade

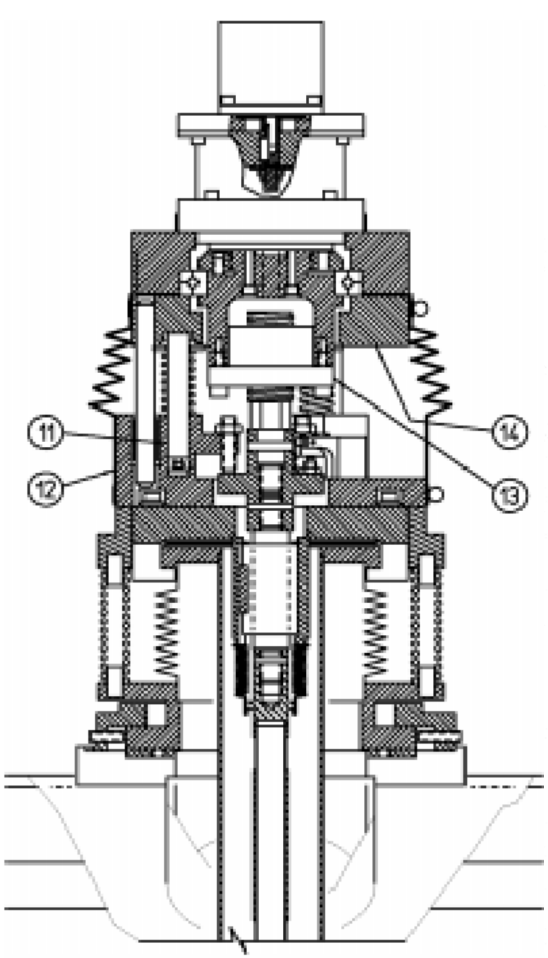


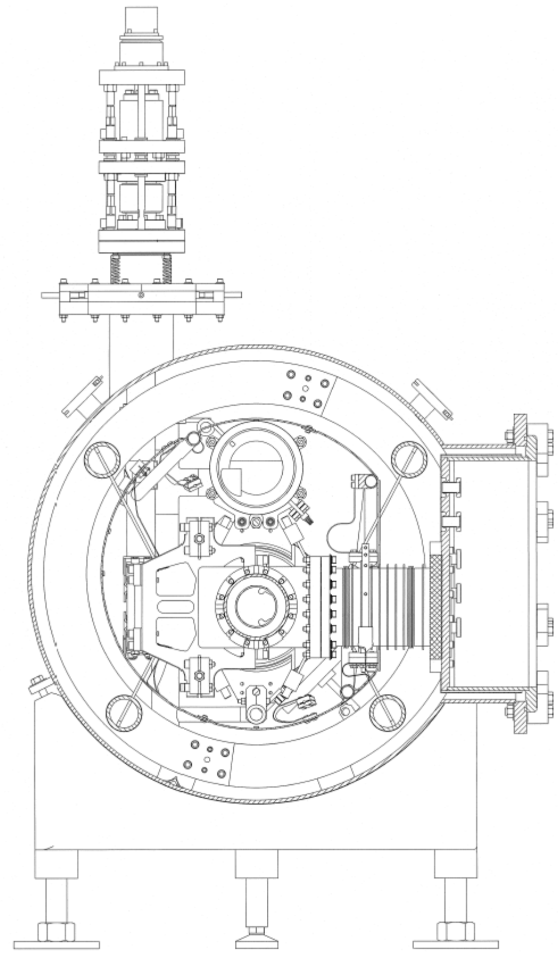


Prototype Tuner for CEBAF Ugrade

Warm Drive Components and Cross Section of Upgrade CM

- Stepper Motor
  - 200 step/rev
  - 300 RPM
- Low voltage piezo
  - 150 V
  - 50 m stroke
- Harmonic Drive
  - Gear Reduction = 80:1
- Ball screw
  - Lead = 4 mm
  - Pitch = 25.75 mm
- Bellows/slides
  - axial thermal contraction

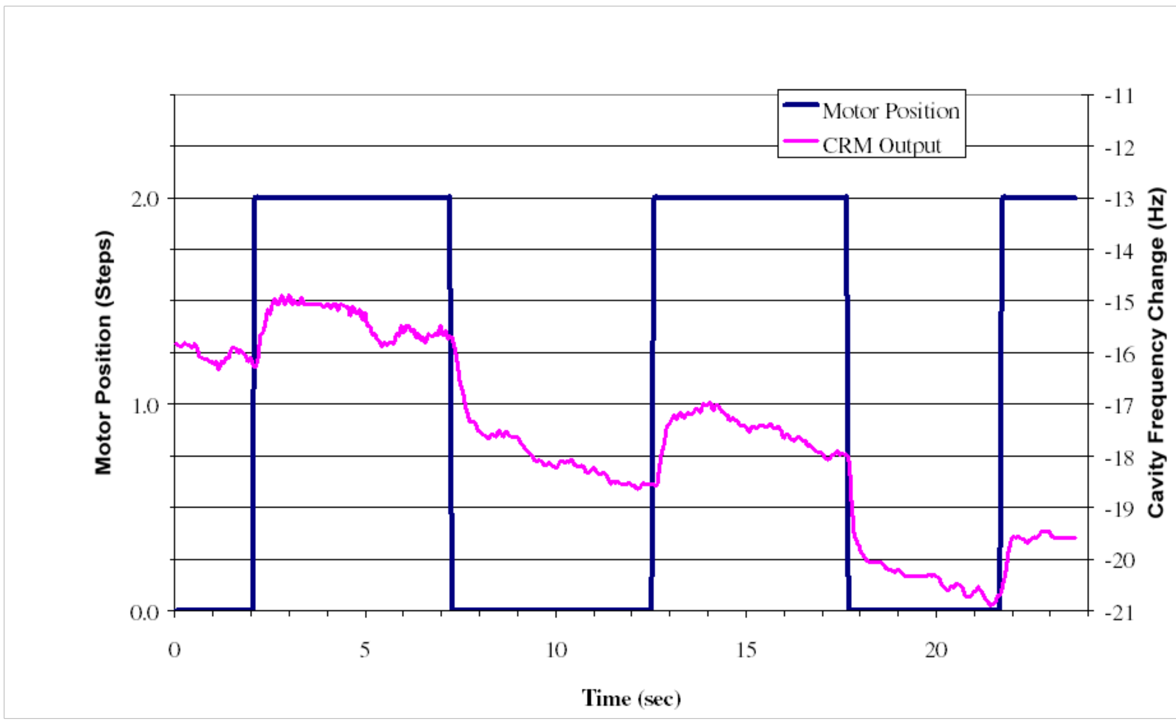


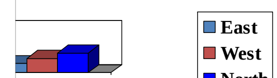


CEBAF Upgrade Coarse Tuner Resolution/Deadband Test

Resolution/Deadband < 2 Hz

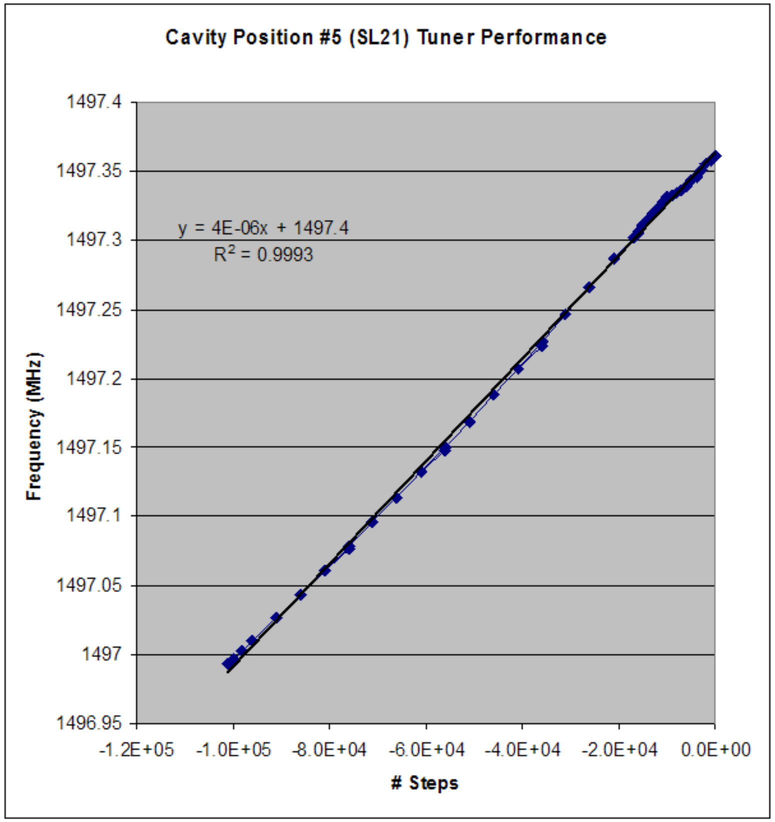
Drift due to Helium pressure fluctuations

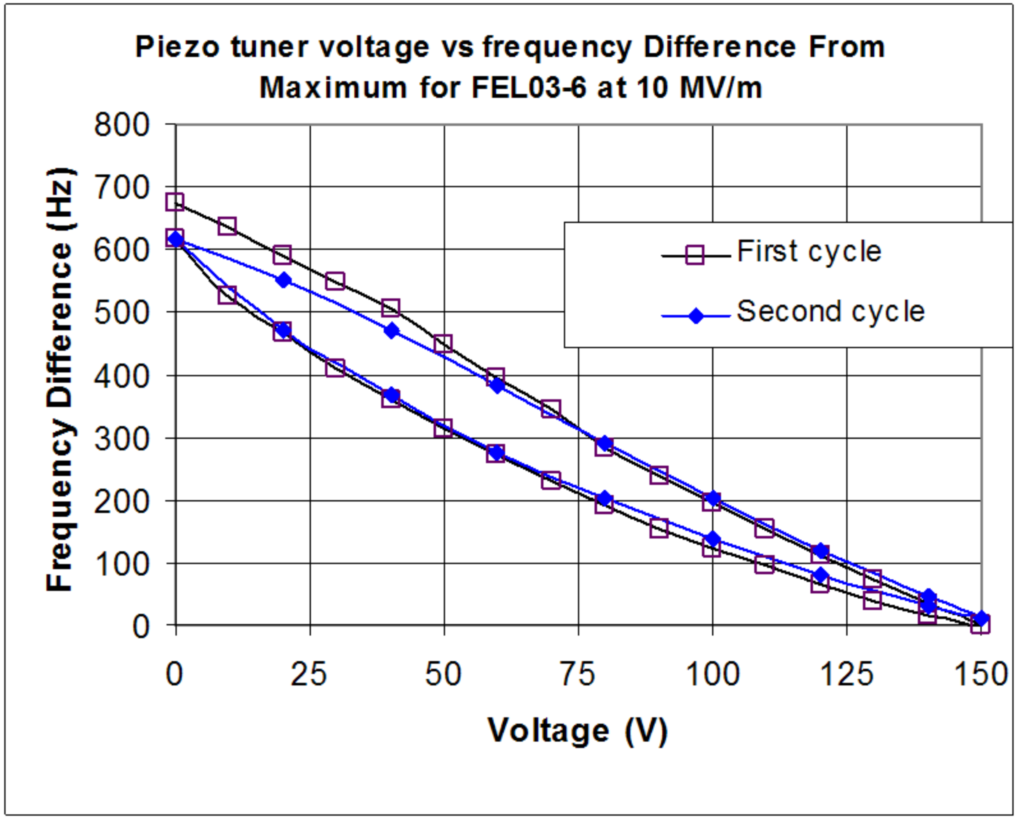




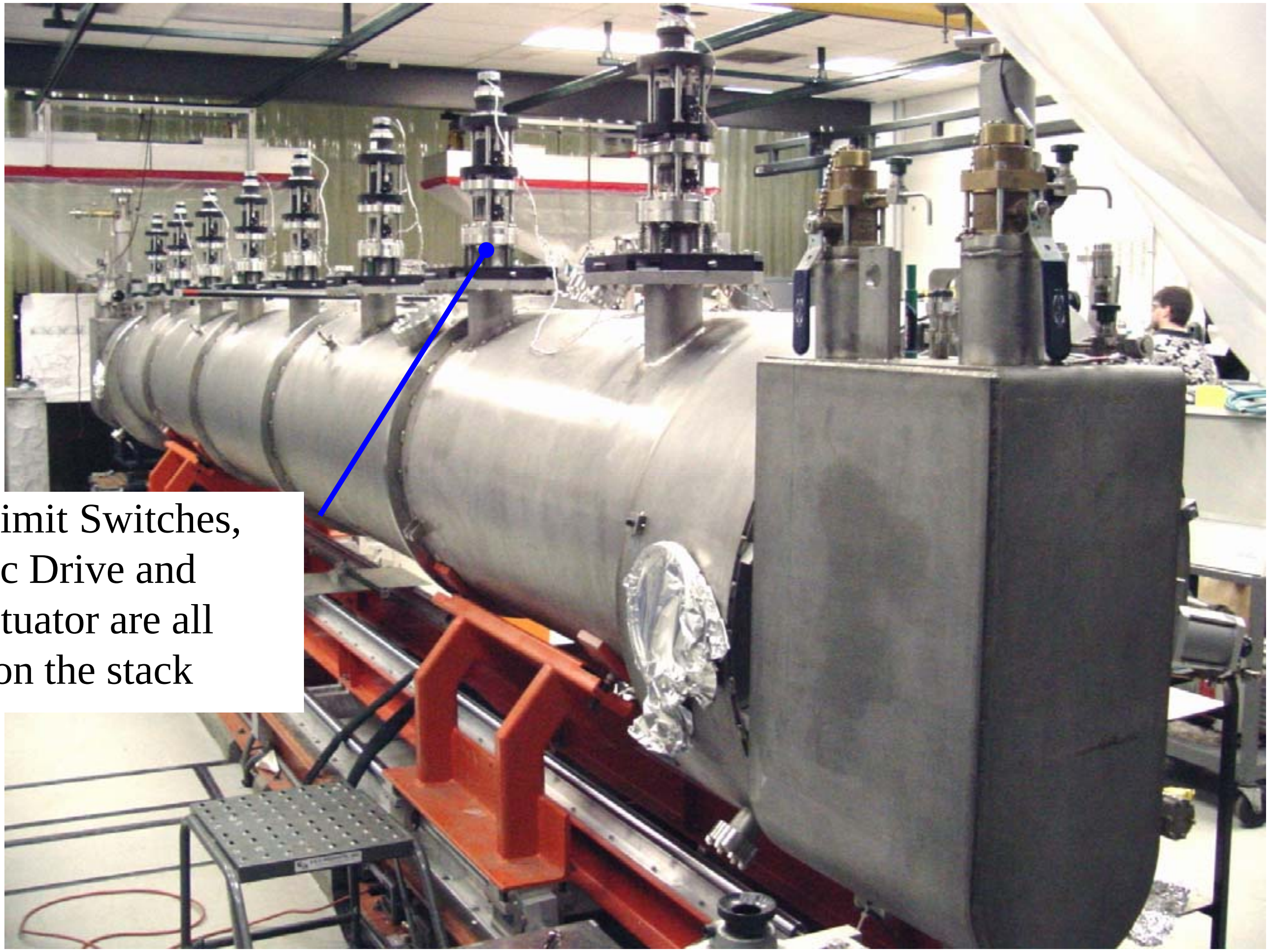
Upgrade Tuner – SL21 / FEL03 :

Range and Resolution (Piezo Hysteresis)



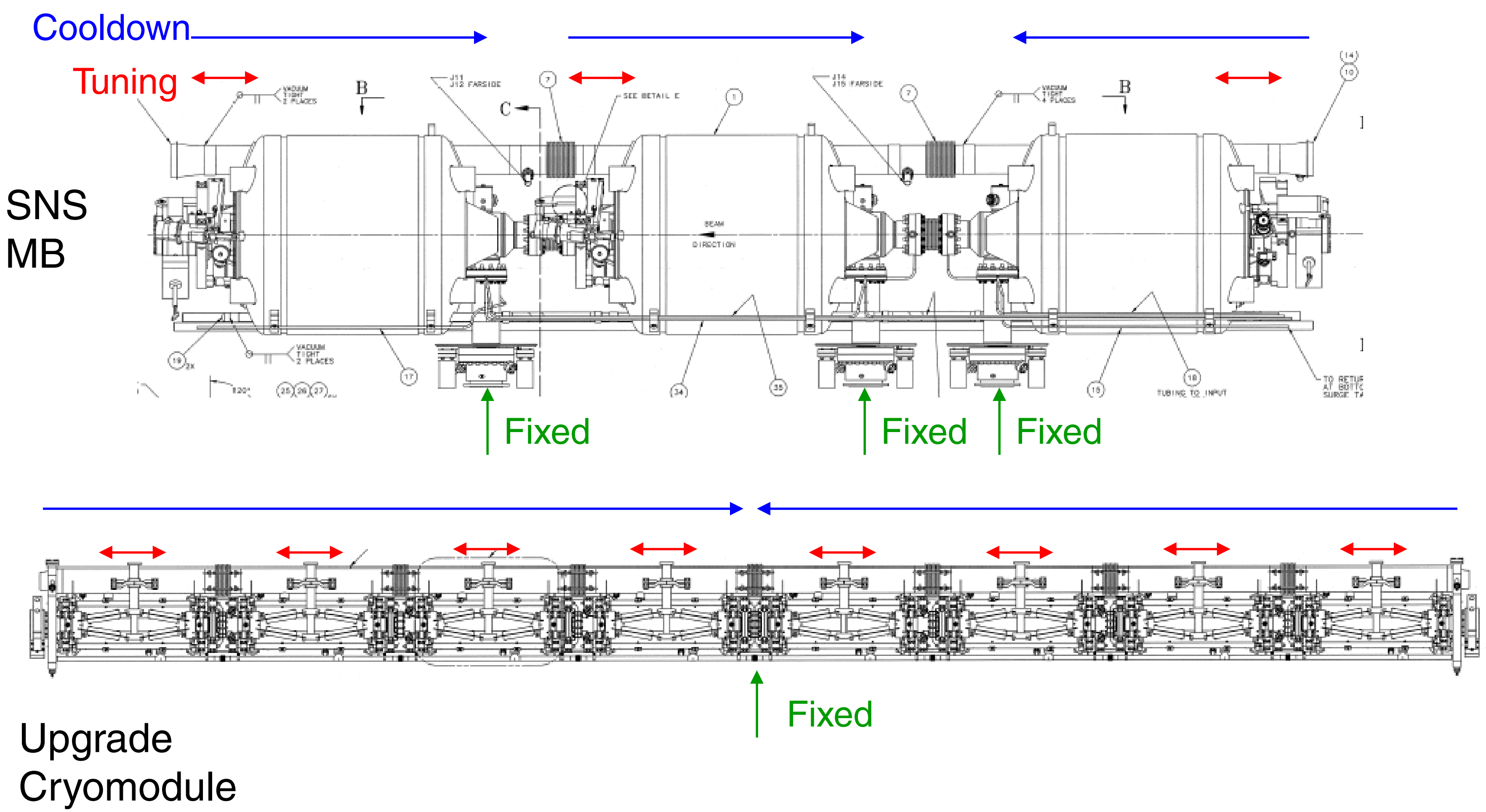


Upgrade Cryomodule –
Access to Tuner Drive Components

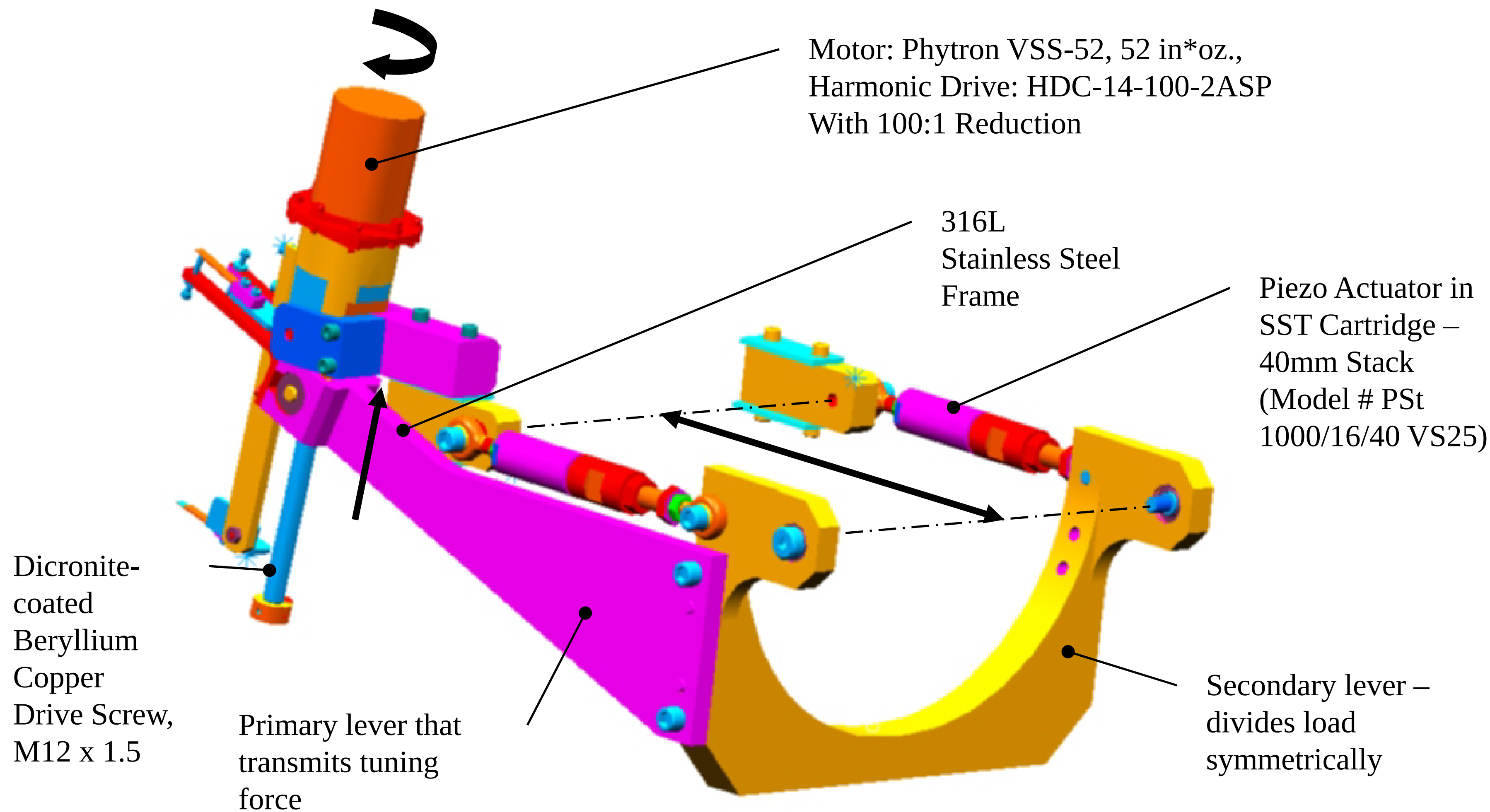


Motor, Limit Switches, Harmonic Drive and Piezo Actuator are all situated on the stack

Cavity String Support Schemes : Tuning approach affect supports



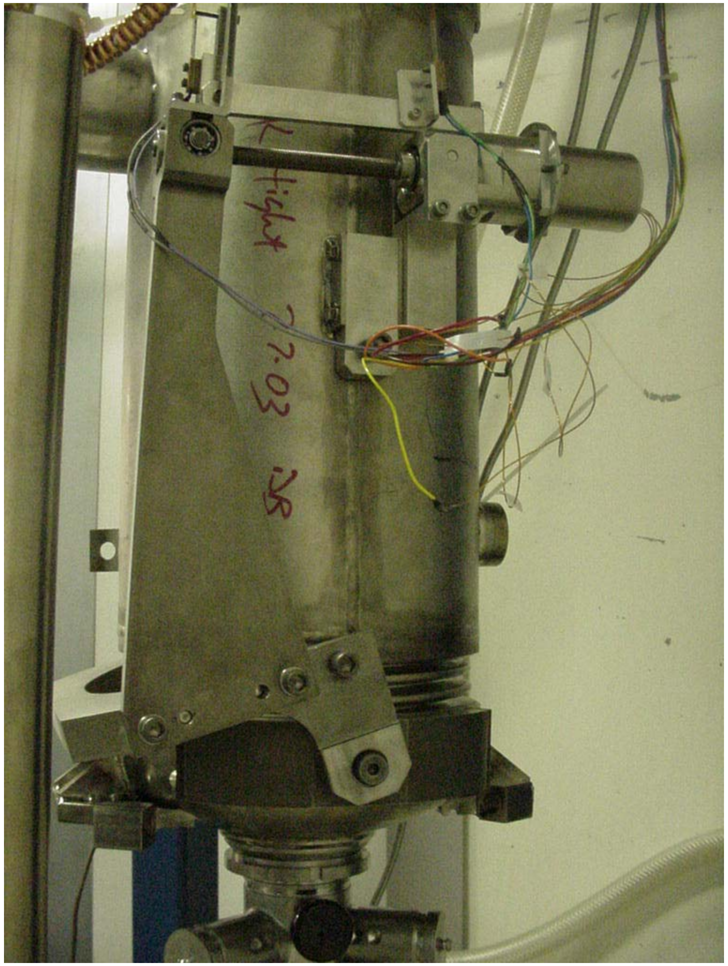
Renascence Tuner Assembly with Two Cold Piezo Actuators



Renascence Tuner Description

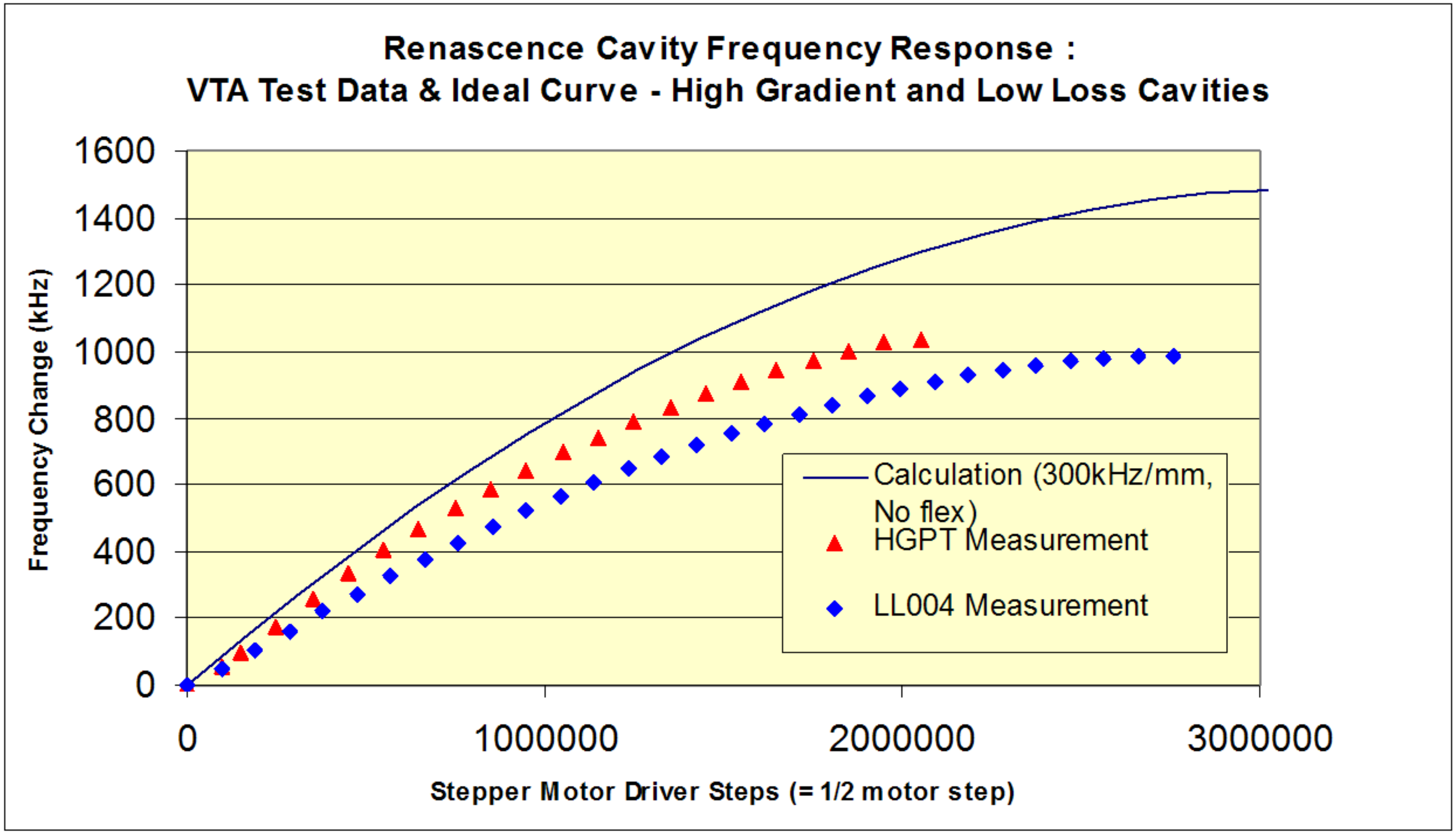
- Mechanism – "Rock Crusher" – All cold, in vacuum components
  - Stainless steel frame
  - Attaches to chocks on cavity
  - Attaches via shoulder bolts to helium vessel head
  - Dicronite coating on bearings and drive screw
  - Cavity tuned in tension only

Shown hanging in VTA Test Stand, attached to EP3 cavity, ready for cold testing



Renascence Tuner – VTA Testing :

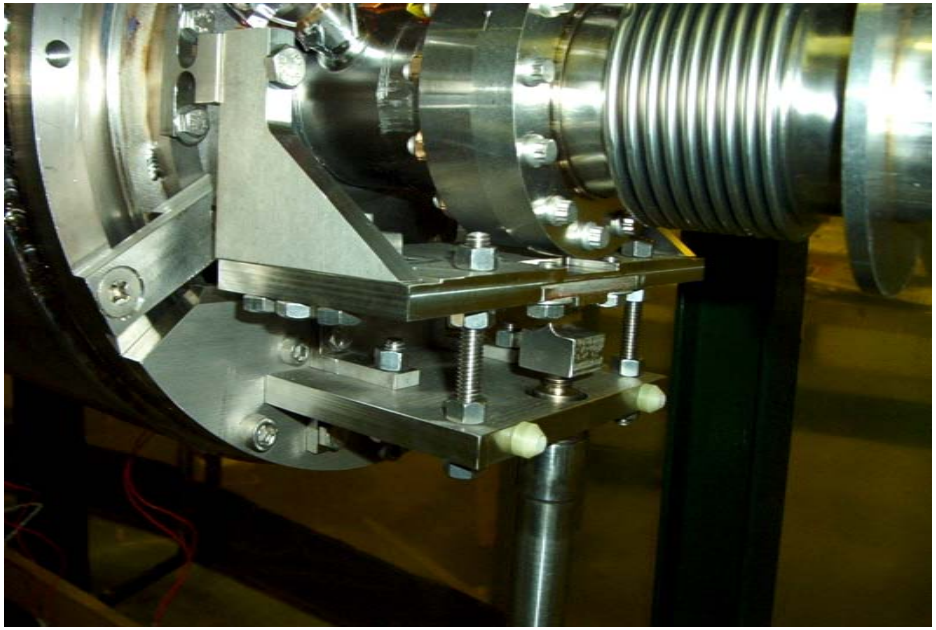
Range (Helium vessel compliance reduces actual stroke)

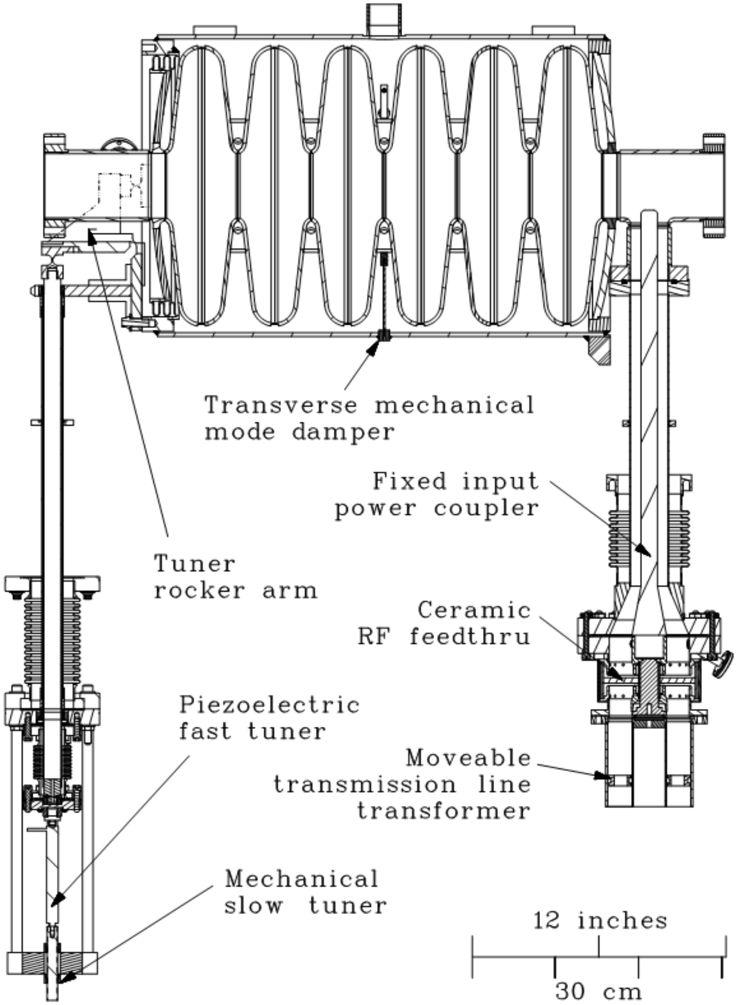


RIA Tuner (MSU)

- Mechanism
  - Stainless steel rocker arm and drive rod
    - Attaches to chocks on cavity
    - Attaches via flexures and threaded studs to helium vessel head
  - Cavity tuned in compression or tension
- Cold transmission – compressive/tensile force on drive rod
- Stepper motor and piezo external to vacuum tank
- Bellows on vacuum tank
  - Need to accommodate relative thermal contraction of cavities
  - Allow tuner transmission to float (unlocked) during cooldown
  - Pre-load each tuner while warm, account for vacuum loading on bellows

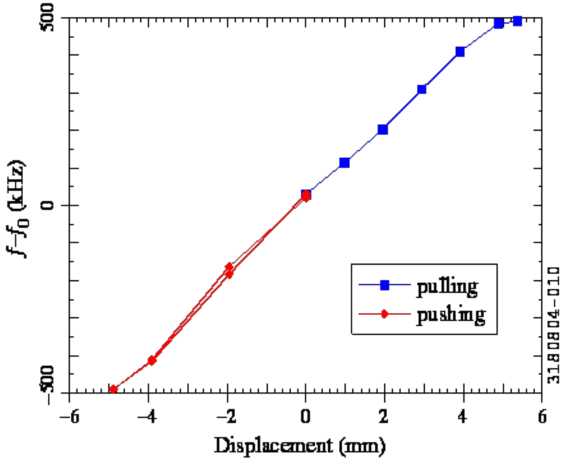
RIA Tuner (MSU) – Rocker Arm / Schematic

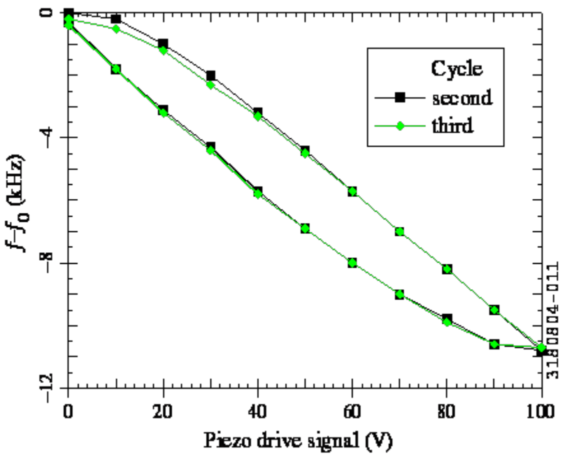


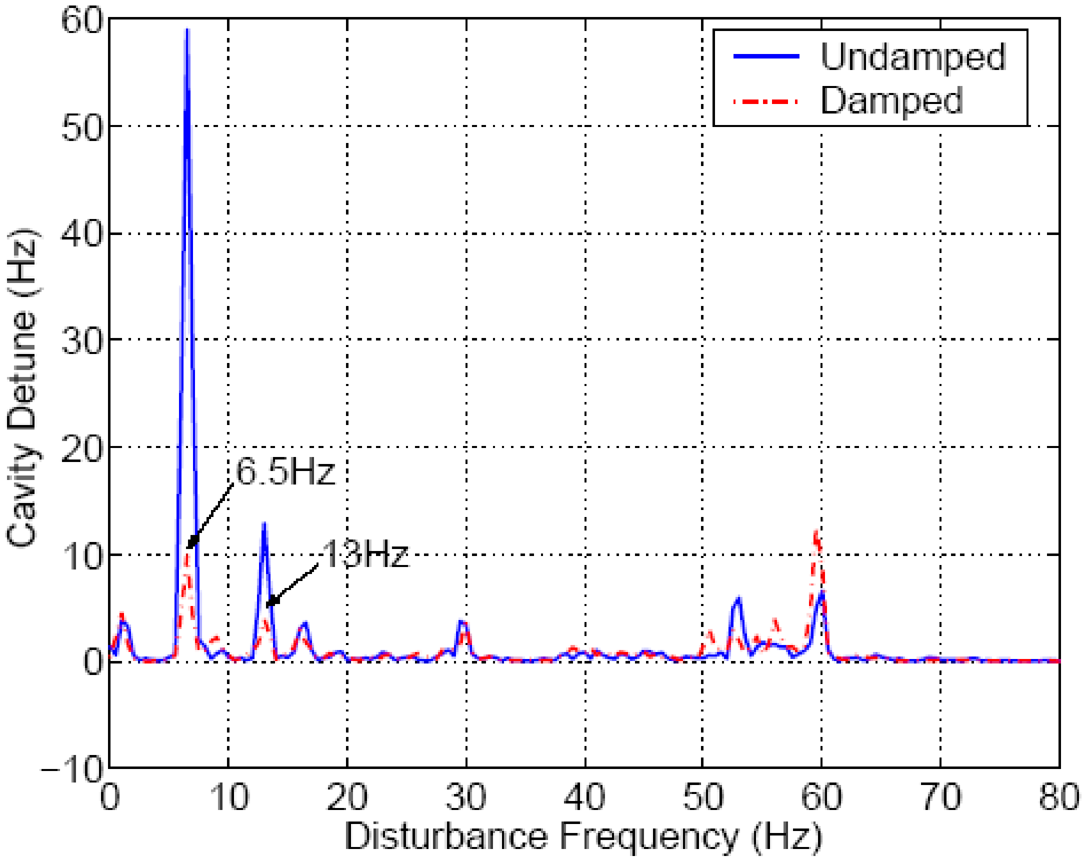


RIA Tuner – Test Results:

Coarse and Fine Tuner Range; Active Feedback Control



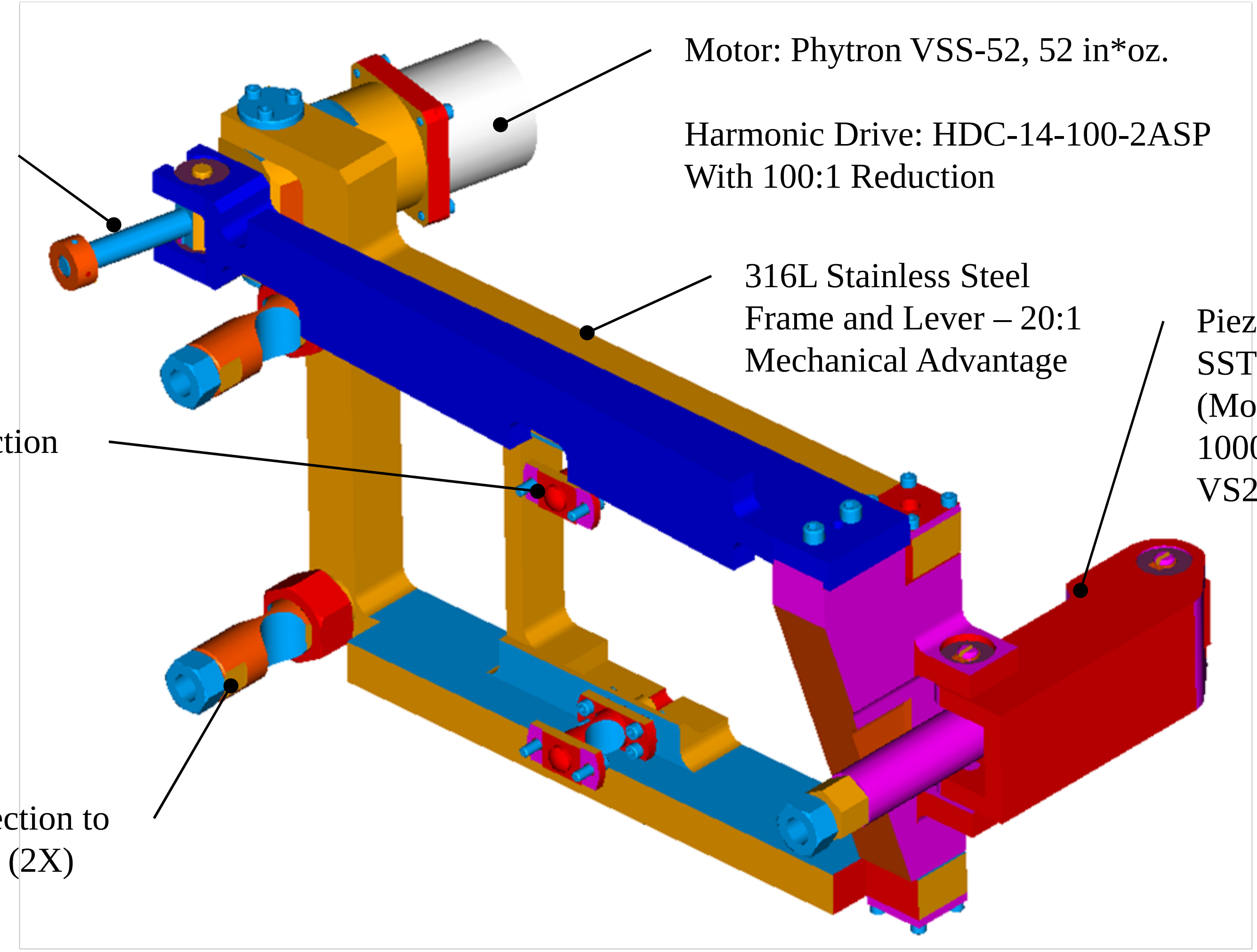




SNS Tuner - Description

- Mechanism scaled from original DESY/Saclay design
  - Stainless steel frame
    - Attaches to chocks on cavity
    - Attaches via flexures and threaded studs to helium vessel head
  - Dicronite coating on bearings and drive screw
  - Cavity tuned in compression only
- Cold transmission
  - Components in insulating vacuum space
  - Stepper motor and harmonic drive rated for UHV, cryogenic and radiation environment (www.phytron.com)
- Bellows between cavities
  - Need to accommodate relative thermal contraction of cavities
  - Pre-load each tuner while warm

SNS Tuner Assembly w/ Piezo Actuator



Motor: Phytron VSS-52, 52 in*oz.

Harmonic Drive: HDC-14-100-2ASP
With 100:1 Reduction

Dicronite-coated Beryllium Copper Drive Screw, M12 x 1.5

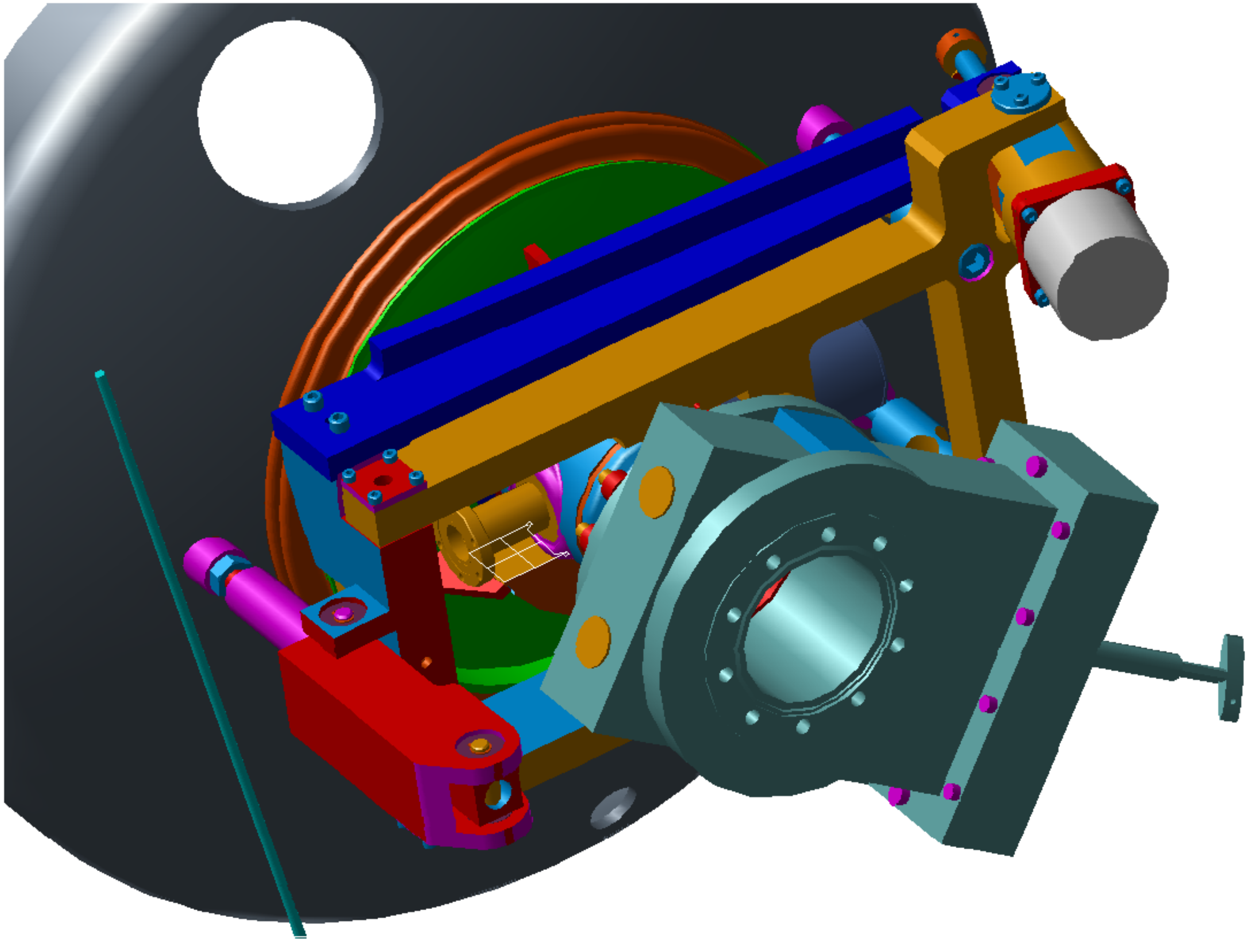
316L Stainless Steel Frame and Lever – 20:1 Mechanical Advantage

Piezo Actuator in SST Cartridge (Model # PSt 1000/16/200 VS25)

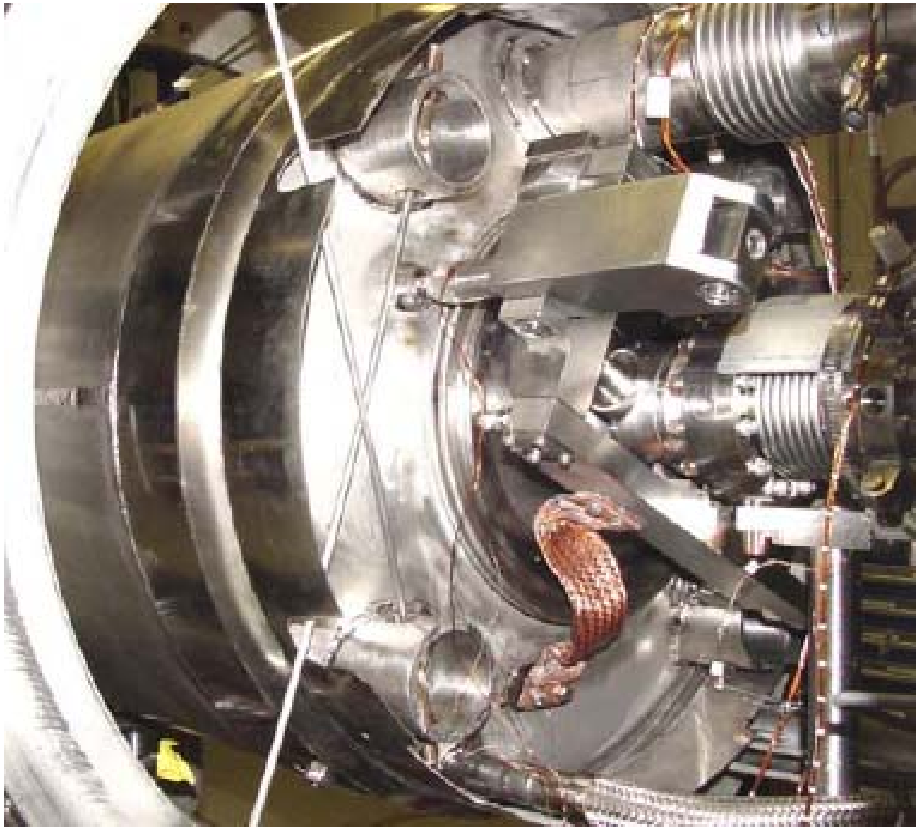
Flexure Connection to Cavity (2X)

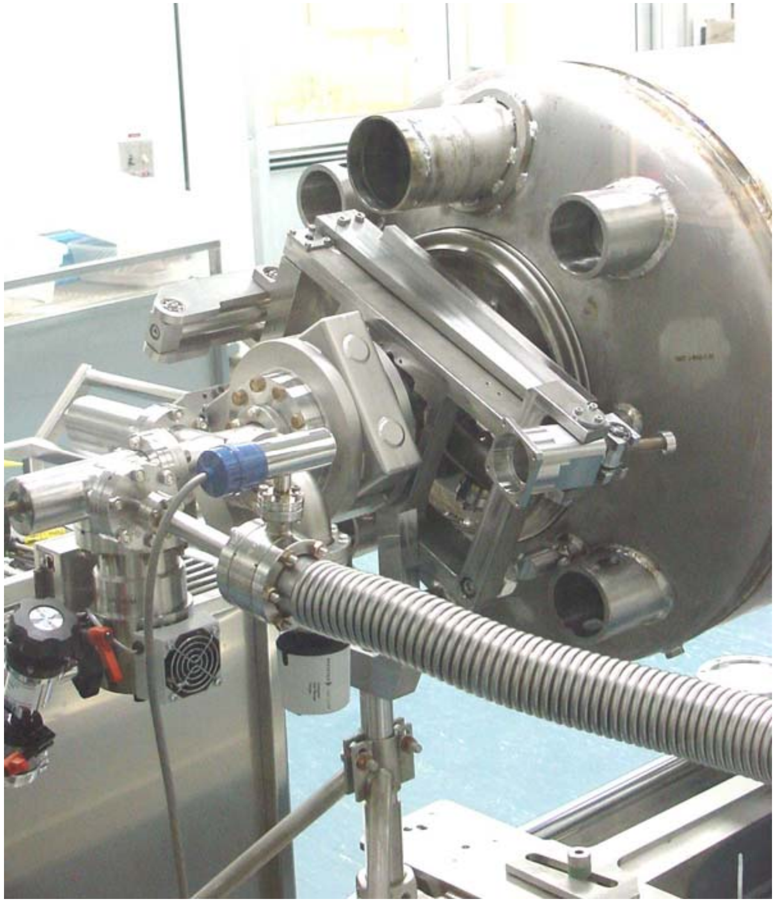
Flexure Connection to Helium Vessel (2X)

SNS Tuner Assembly w/ Piezo Actuator



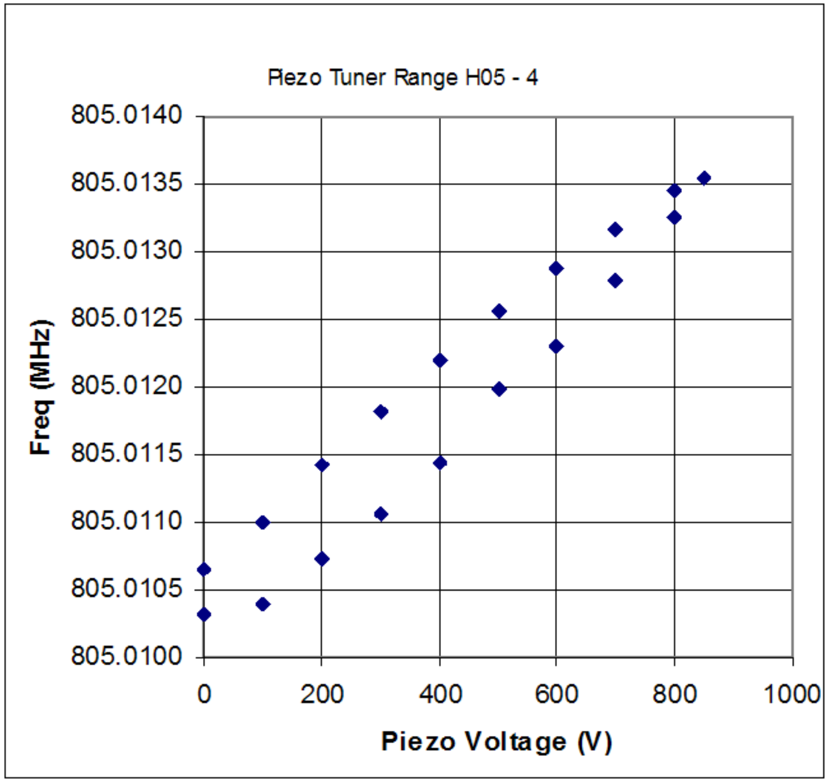
SNS Tuner with Piezo Actuator Installed on Helium Vessel & Cavity

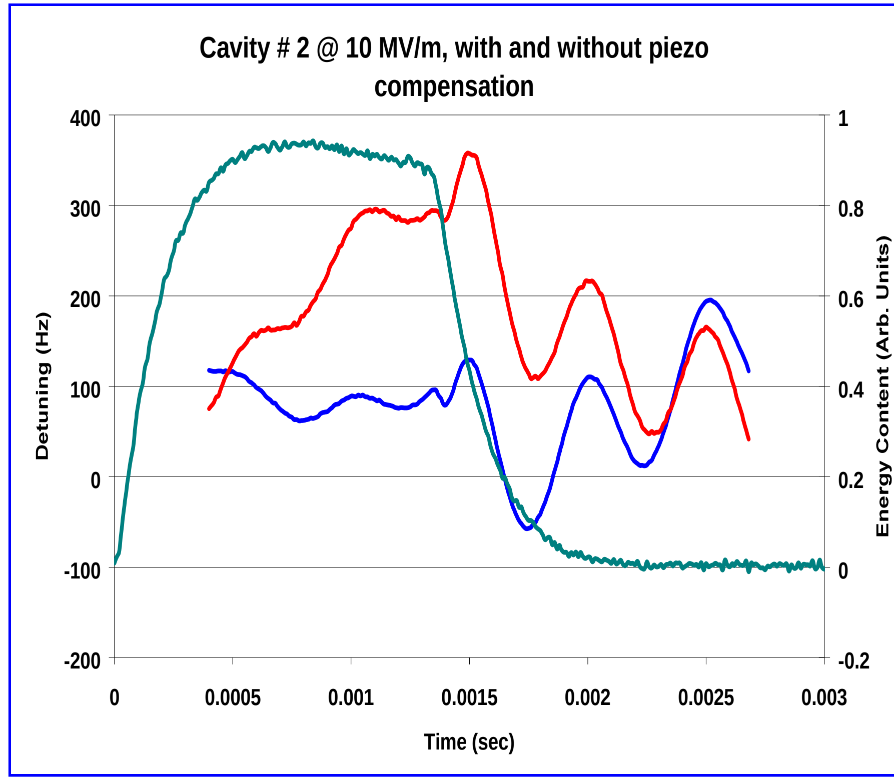




SNS Tuner – CMTF Test Results:

Fine Tuner Range and Hysteresis; Piezo Compensation

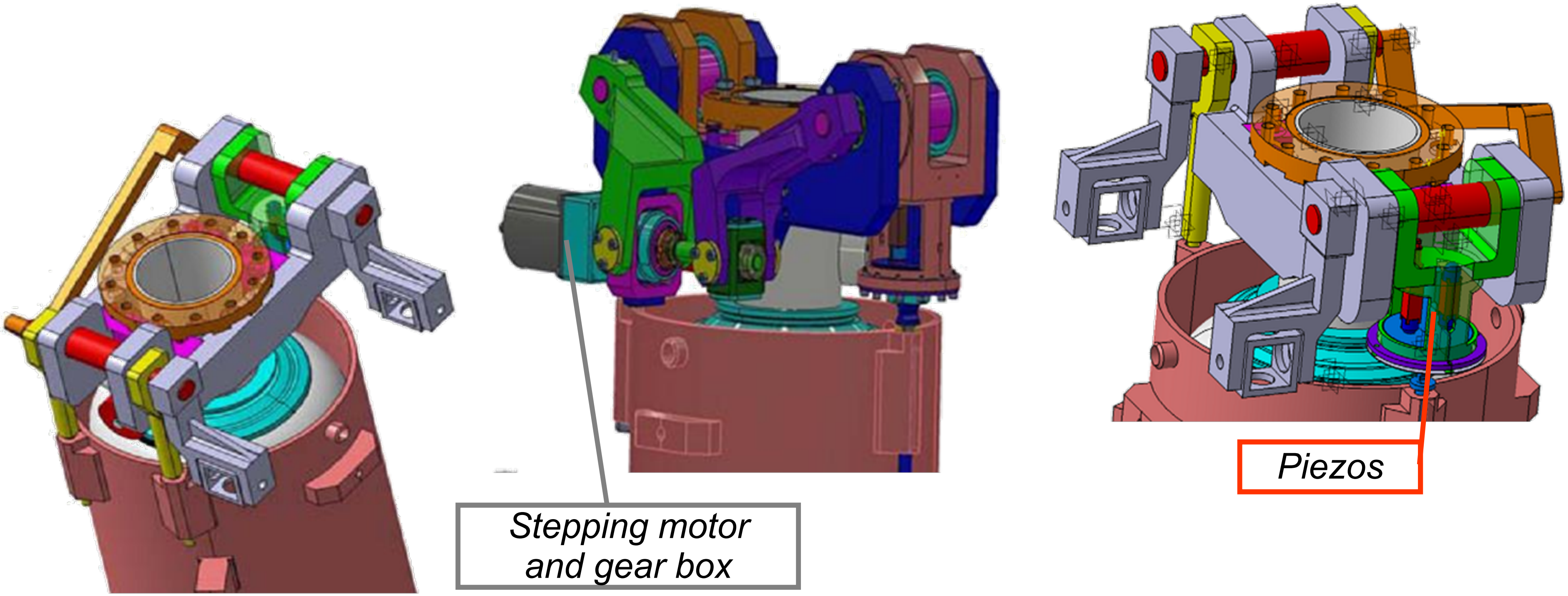




Frequency Tuners

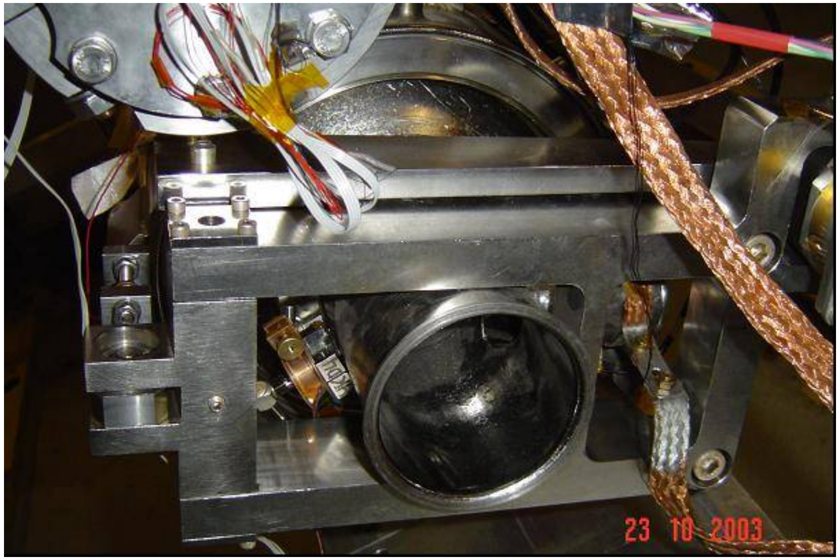
Saclay Lever Tuner spec.

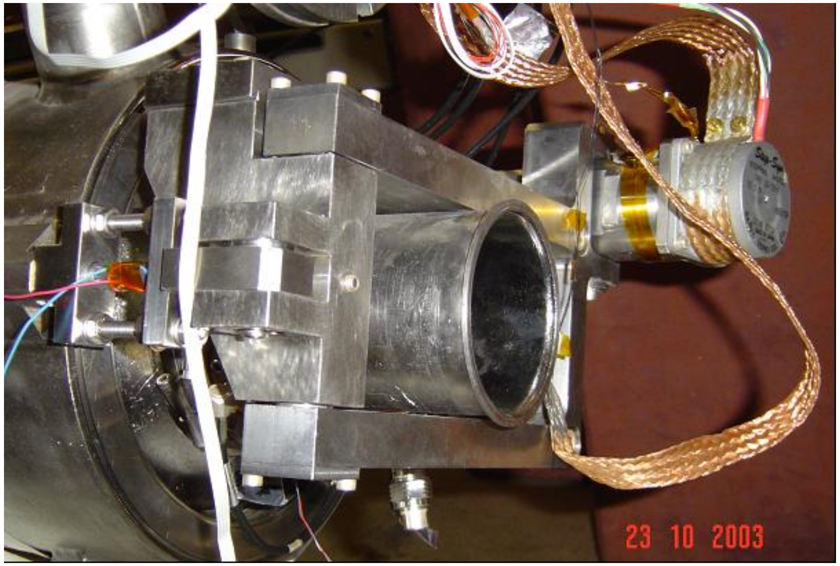
- *460 kHz tuning range*
- *4 nm resolution = 1.2 Hz (sufficient if <5Hz)*
- *~ 1kHz fast compensation by piezo*



Current Saclay Tuner

- Double lever system: ratio ~ 1/17
- Stepping motor with Harmonic Drive gear boxe
- Screw – nut system : lubricant treatment (balzers Balinit C coating) for working at cold and in vacuum
- $\Delta Z_{max} = \pm 5$ mm and $\Delta F_{max} = \pm 2.6$ MHz
- <u>theoretical</u> resolution: $\delta z = 1.5$ nm !
- calculated stiffness: 180 kN/mm (measured : 100 kN/mm to be verified)

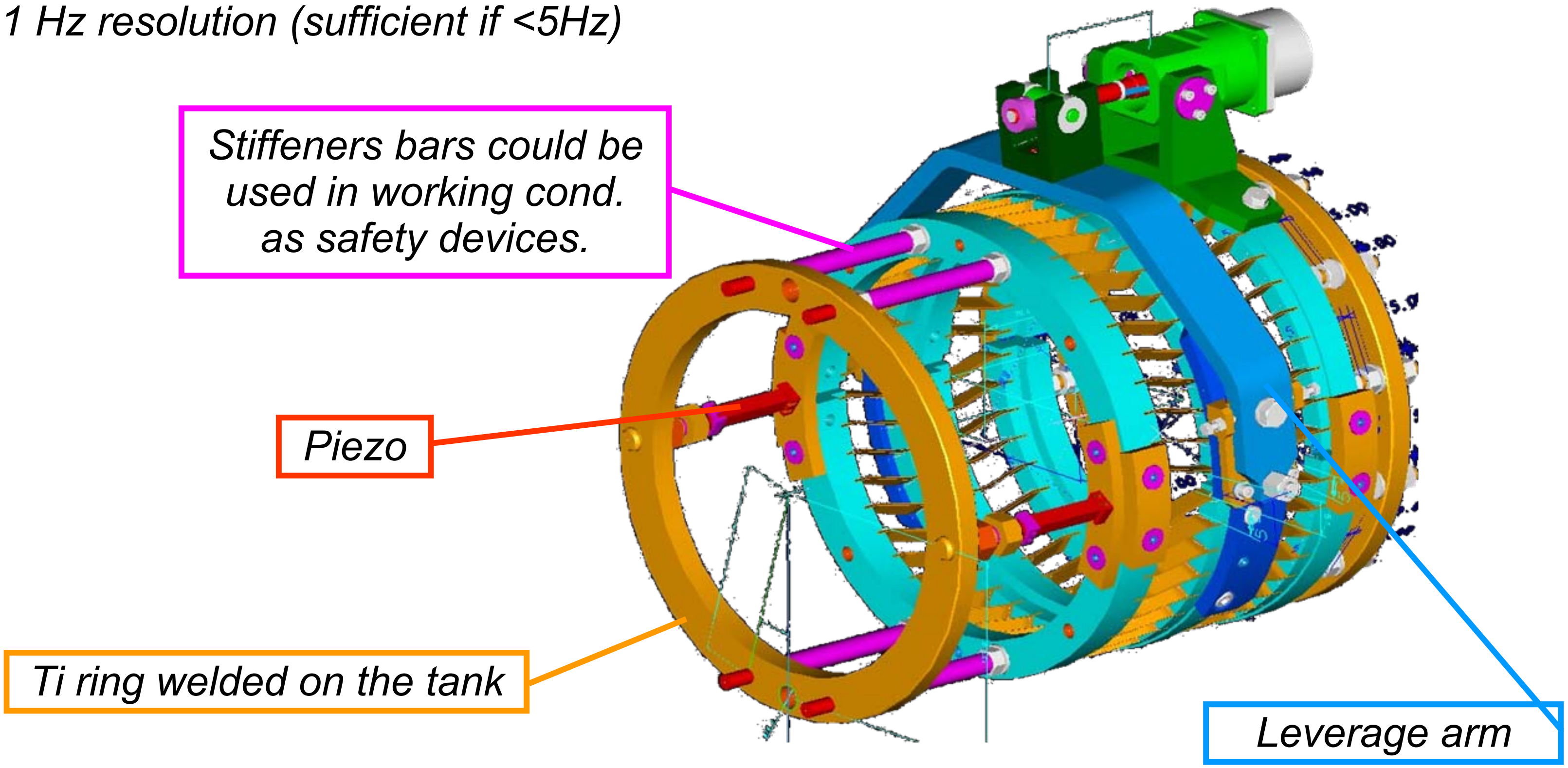




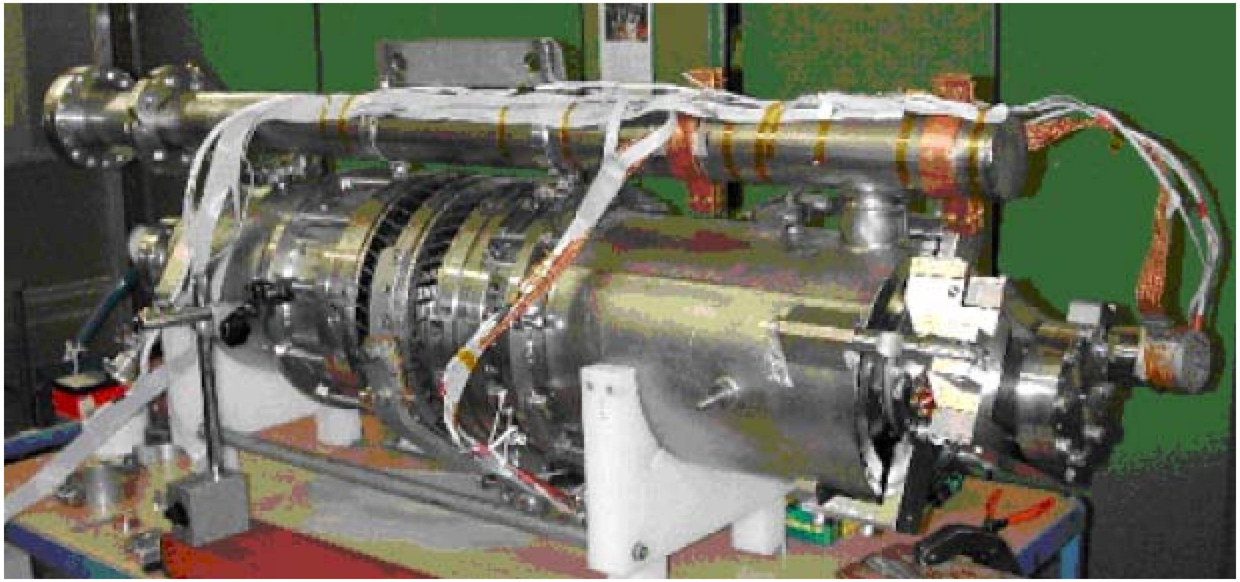
Blade Tuners

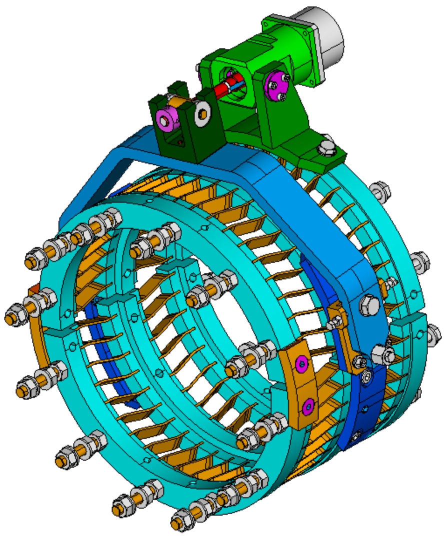
Blade Tuner spec.

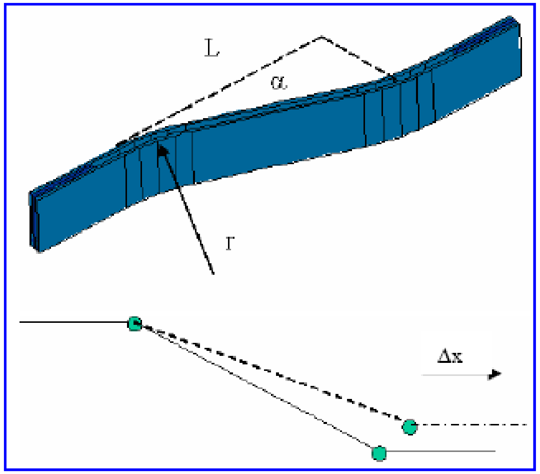
- *1 mm fine tuning (on cavity) → ΔF on all piezo (sum) ≈ 3.5 kN*
- *1 kHz fast tuning → ≈ 3 μm cavity displacement → ≈ 4 μm piezo displacement*
- *4 μm piezo displacement → ≈ Δ F on all piezo ≈ 11.0 N*
- *~1 Hz resolution (sufficient if <5Hz)*



TESLA - Blade Tuner





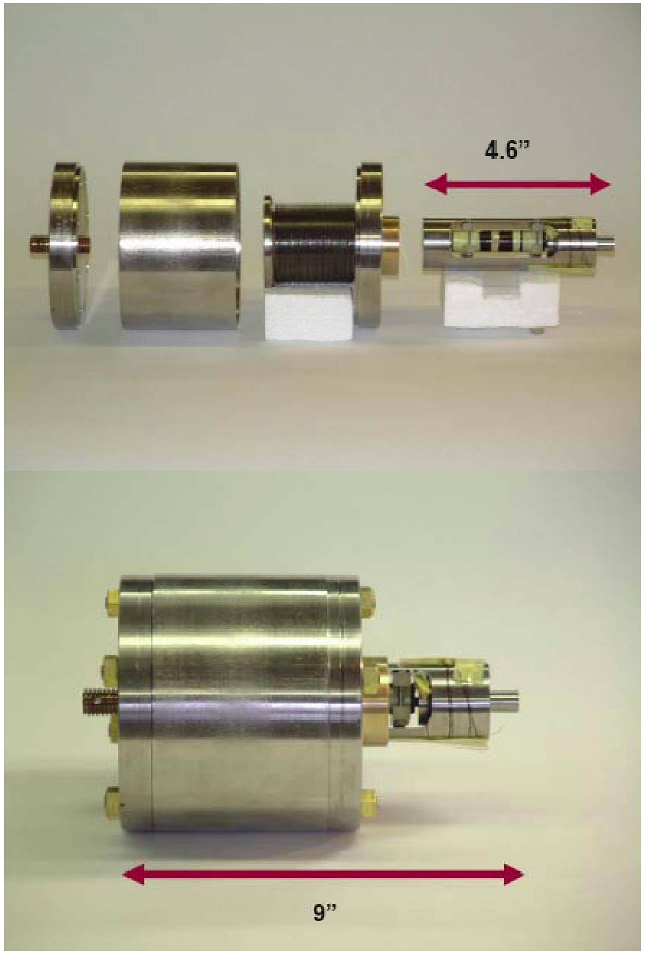


- Mechanism – All cold, in vacuum components
  - Titanium frame
  - Attaches to helium vessel shell
  - Pre-tune using bolts pushing on shell rings
  - Dicronite coating on bearings and drive screw
  - Cavity tuned in tension or compression – blades provide axial deflection

Piezoelectric Tuners

- Response time <1ms.
- Layered piezo-ceramic material electrically connected in parallel operating at 26K with a resolution of 2nm purchased from APC.
- Not designed for high frequency operation.

Magnetostrictive tuners



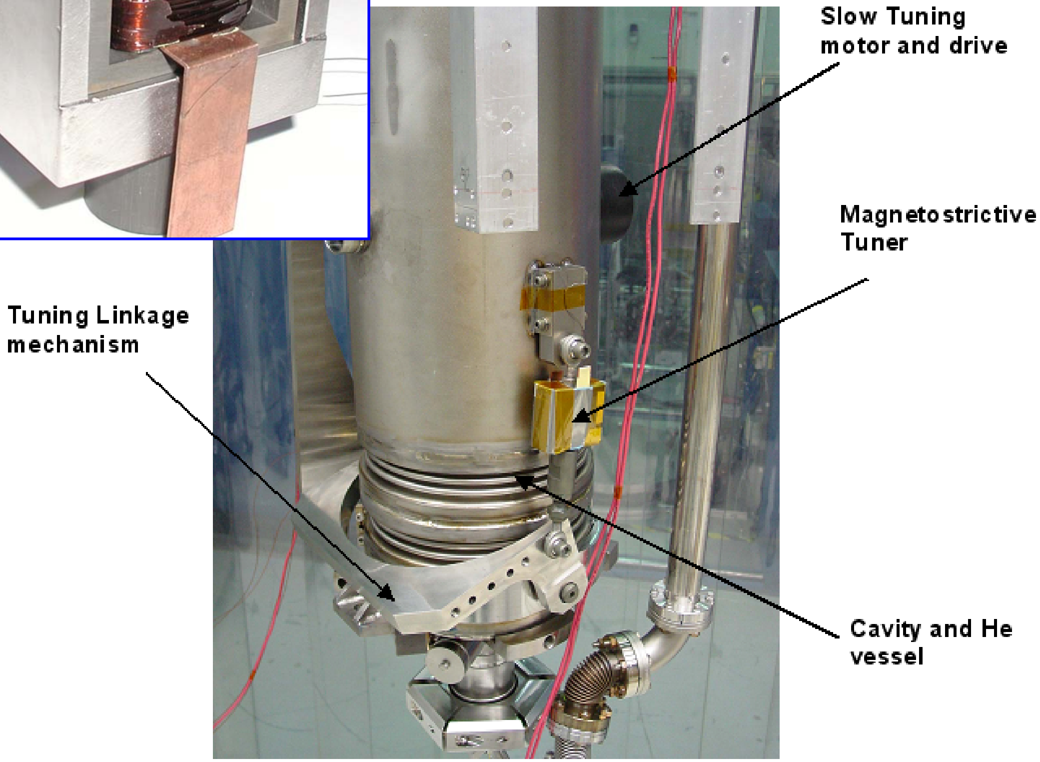
- Magnetostrictive actuator designed and built by Energen, Inc.
- Response time ~6ms.
- Magnetostrictive rod coaxial with an external solenoid operating at 4K.
- Not designed for high frequency operation.

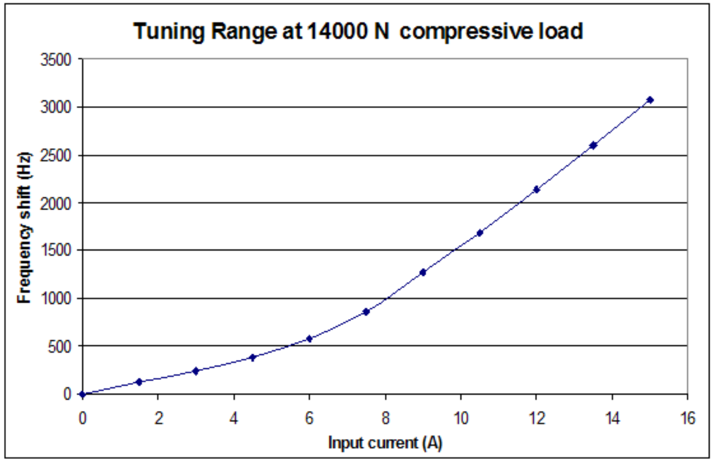
Renascence Cavity – VTA Test Results

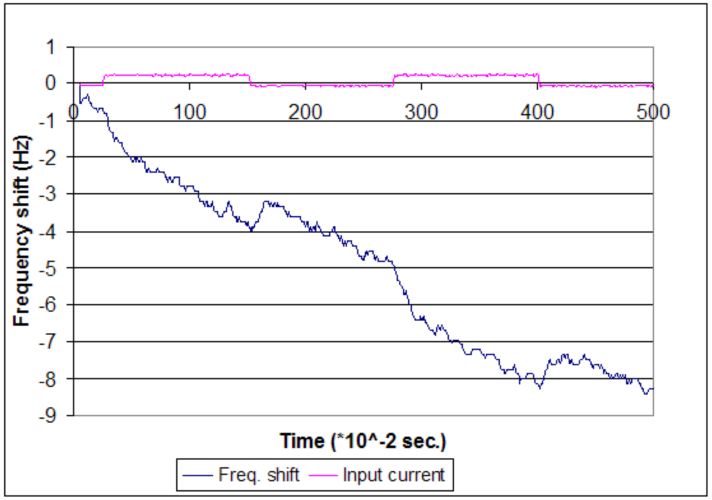
Magnetostrictive Actuator on Tuner

RANGE OF THE MAGNETOSTRICTIVE TUNER AT DIFFERENT LOADS

Compressive Load (N)	Max. Tuning Range (Hz)
No Load	2,600
7100	5,892
10,200	3,423
14,000	3,088

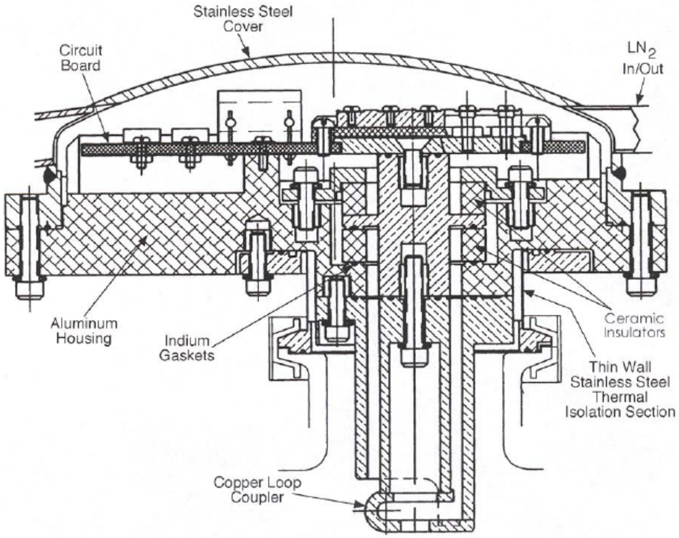


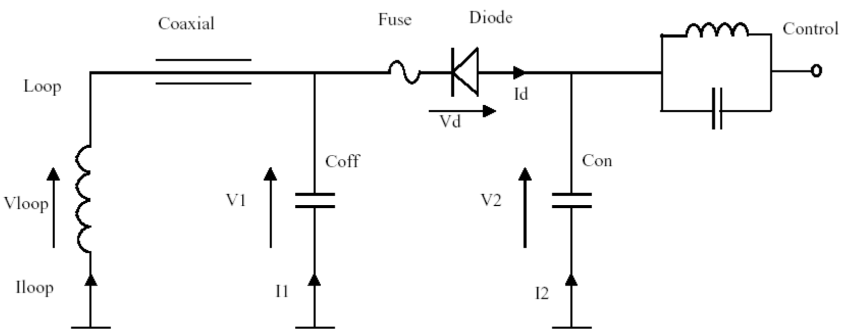




Voltage-Controlled Reactance

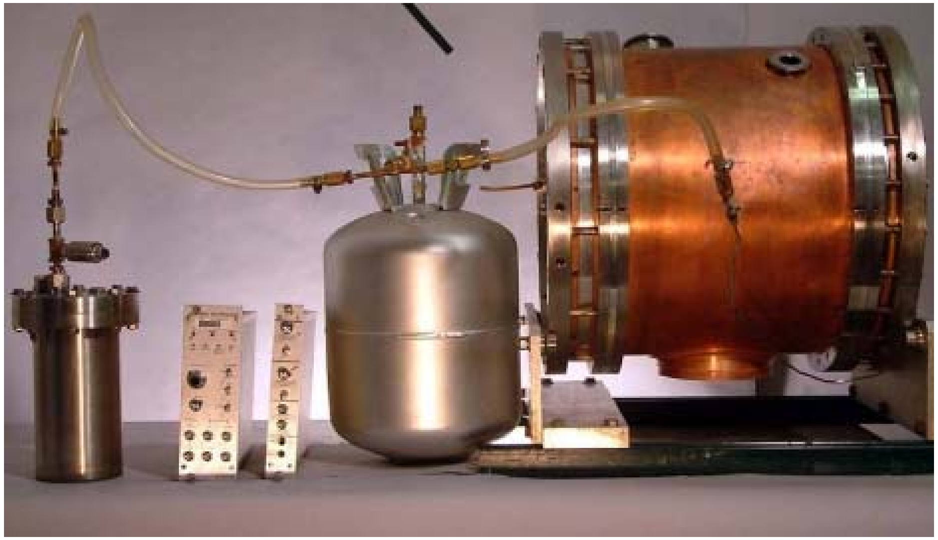
- Has been successfully applied at lower frequencies
- Unlikely to be applicable at the frequency and power levels for TM_{010} cavities



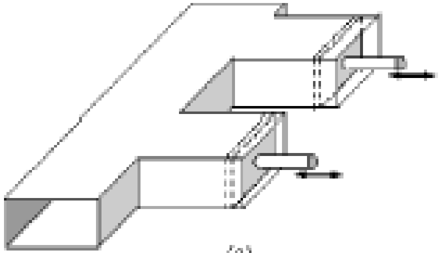


Pneumatic Tuners

Have been used successfully for many years in low velocity structures

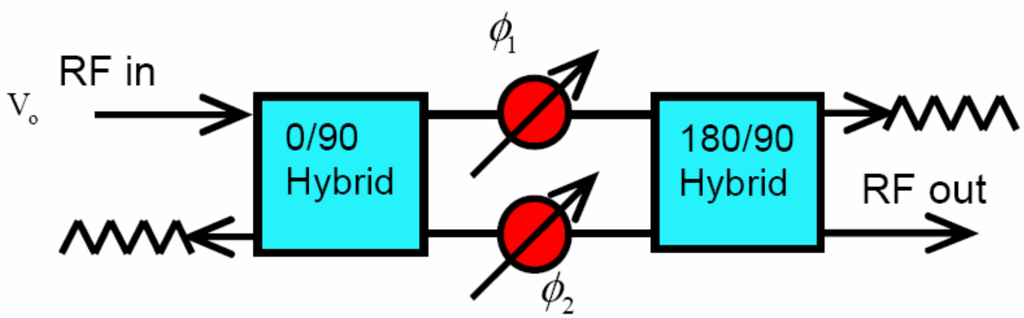


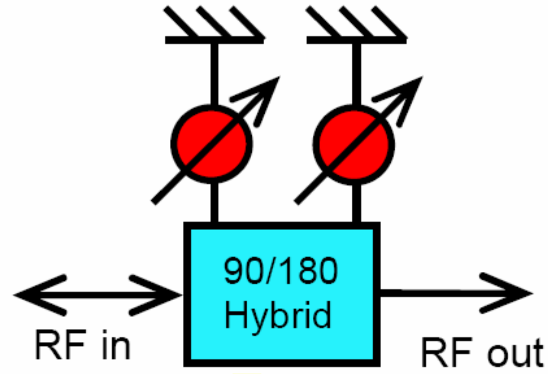
Waveguide Stubline Tuning


(a)

- Commonly used to adjust coupling
- Could also be used to compensate for detuning
- Issues:
  - Part of the waveguide becomes part of the resonant system
  - Speed for dynamic control of microphonics

High Power Vector Modulator





$$V_{out} = jV_{inc}\cos(\phi_1 - \phi_2)e^{j(\phi_1+\phi_2)}$$

Can provide simultaneous amplitude and phase control

Y. W. Kang et al, ORNL

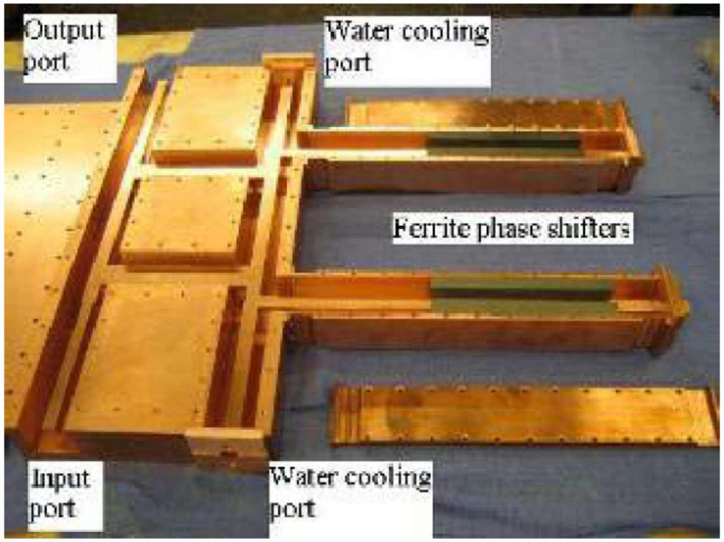


Figure 4: High power vector modulator prototype shows input and output port, water cooling port, and ferrite phase shifters.

Coarse Tuners

- Typically cold, must be reliable and maintainable → access ports
- Direct cavity drive reduces stiffness requirements on helium vessel
- Tuner/HV stiffness > 10x cavity
- Flexures exhibit reduced backlash
- Typically tune in tension or compression to avoid “dead band”

Fine Tuners

- Piezo
  - Operate in compression
  - Warm range 5-10x > cold range
  - Capacitive device, Low vs. High voltage
  - Consider hysteresis

- Magnetostrictive
  - Must operate cold
  - Consider lead thermal design, required current ~10 Amps
  - Inductive element
  - Consider hysteresis

Closing / Summary :
Comparison of Tuner Features (2 of 2)

- Transmission Location (maintainability)
  - Cold placement
    - Materials considerations (CTE, lubrication, vacuum)
    - Access for repair or replacement
    - Electrical feedthroughs
  - Warm placement
    - Cooldown/tuning compliance
    - Port for transmission
    - Bellows
- Testing (minimizes risk associated with reliability and availability)
  - Perform accelerated life tests on critical components
  - Feedback results into design <u>prior</u> to production
  - Develop thorough acceptance tests to verify operation