

TUNING SYSTEMS

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“Big Picture” for Tuners

- SRF/RF system should consume RF power efficiently
 - Minimizes klystron size and capital cost
 - Higher $Q_{\text{external}} (> 10^7) \leftrightarrow$ more efficient ER
 - Reduced Microphonics – actively controlled?
 - RF Stability
 - Attained by controlling cavity RF phase (0.05° , RMS) and RF amplitude (2×10^{-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

Pertinent Cavity Information

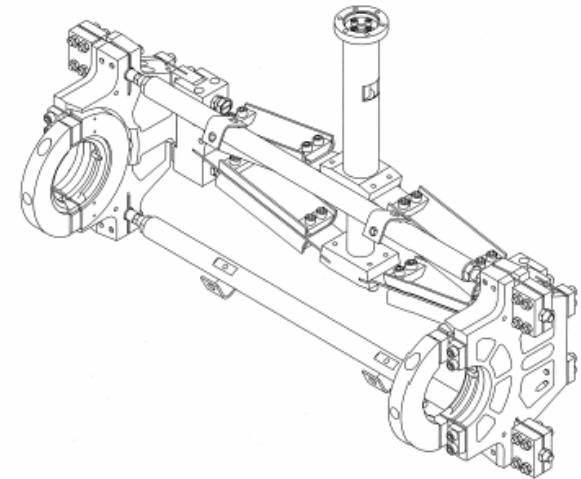
	CEBAF	CEBAF Upgrade (SL21,FEL03)	CEBAF Upgrade (Renascence)	RIA, $\beta=0.47$	SNS, $\beta=0.61$	SNS, $\beta=0.81$	TESLA 500
Frequency (MHz)	1497	1497	1497	805	805	805	1300
Gradient (MV/m)	5	12.5	18	10	10.3	12.1	23.4
Operating Mode	CW	CW	CW	CW	Pulsed, 60 Hz, 7%	Pulsed, 60 Hz, 7%	Pulsed, 60 Hz, 1%
Bandwidth (Hz) Q_{external}	220 6.6×10^6	75 2.0×10^7	75 2.0×10^7	40 2.0×10^7	1100 7.0×10^5	1100 7.0×10^5	520 3.0×10^6
Lorentz Detuning (Hz)	75	312	324	1600	470	1200	434
Microphonics (Hz, 6σ)	-	± 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/ μm)	373	267	~300 (calc)	> 100	290	230	315

Tuner Requirements & Specifications

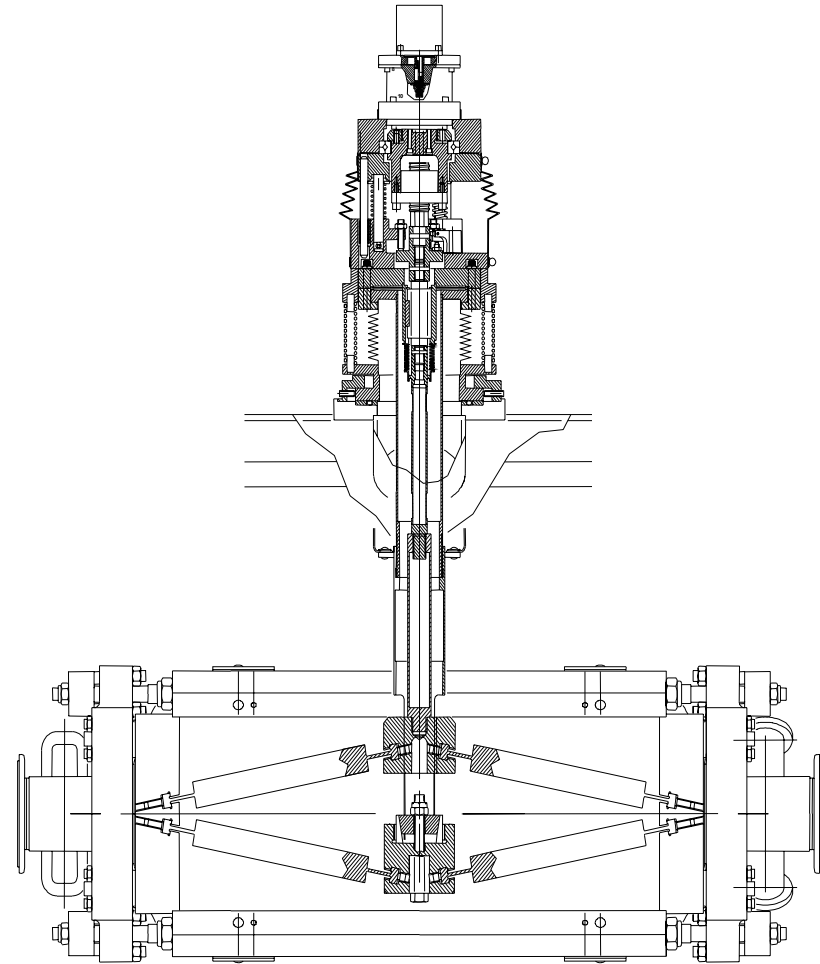
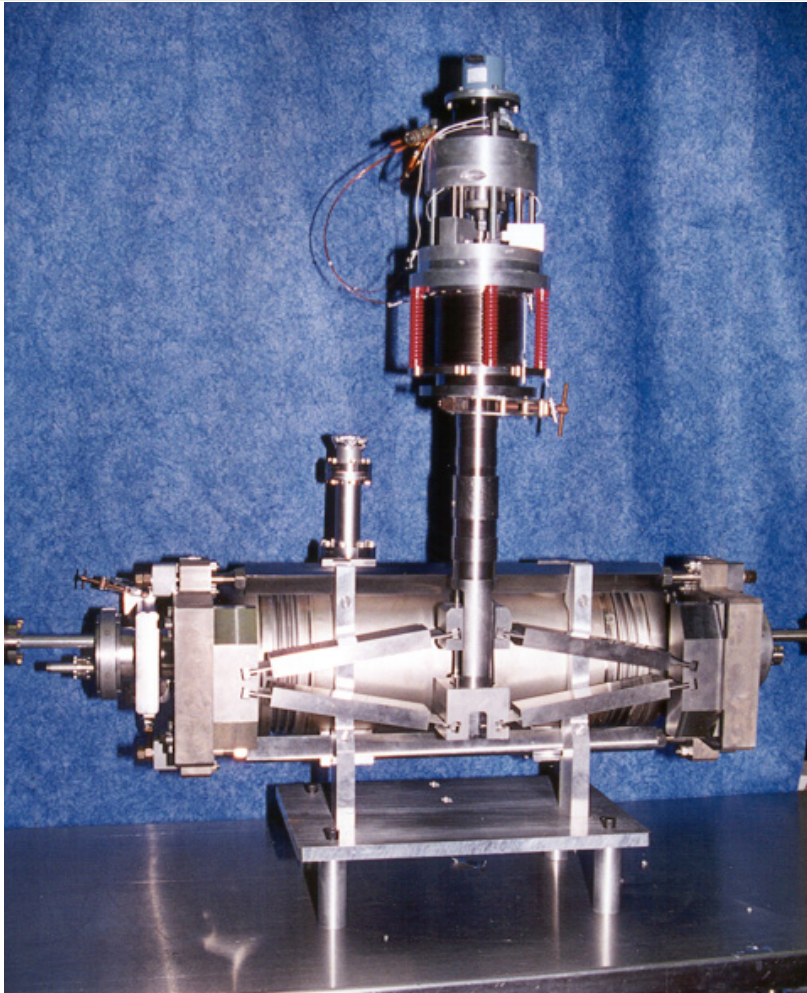
	CEBAF	CEBAF Upgrade (SL21,FEL03)	CEBAF Upgrade (Renascence)	RIA, $\beta=0.47$	SNS, $\beta=0.61$	SNS, $\beta=0.81$	TESLA 500
Coarse Range (kHz)	±200	±200	±400	950	±245	±220	±220
Coarse Resolution (Hz)	NA	< 2	2 - 3	< 1	2 - 3	2 - 3	< 1
Backlash (Hz)	>> 100	< 3	< 3	NR	< 10	< 10	NR
Fine Range	No Fine Tuner	> 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 Upgrade

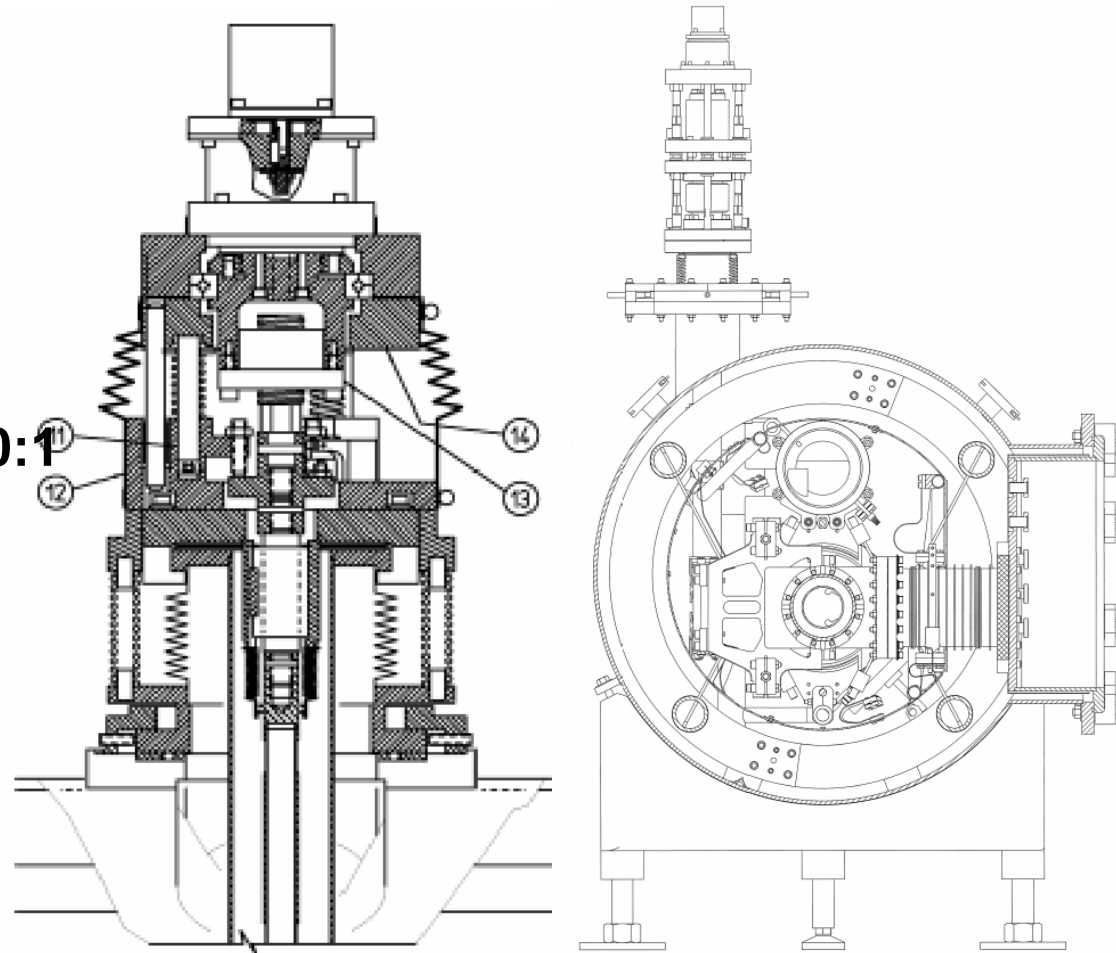


Prototype Tuner for CEBAF Upgrade



Warm Drive Components and Cross Section of Upgrade CM

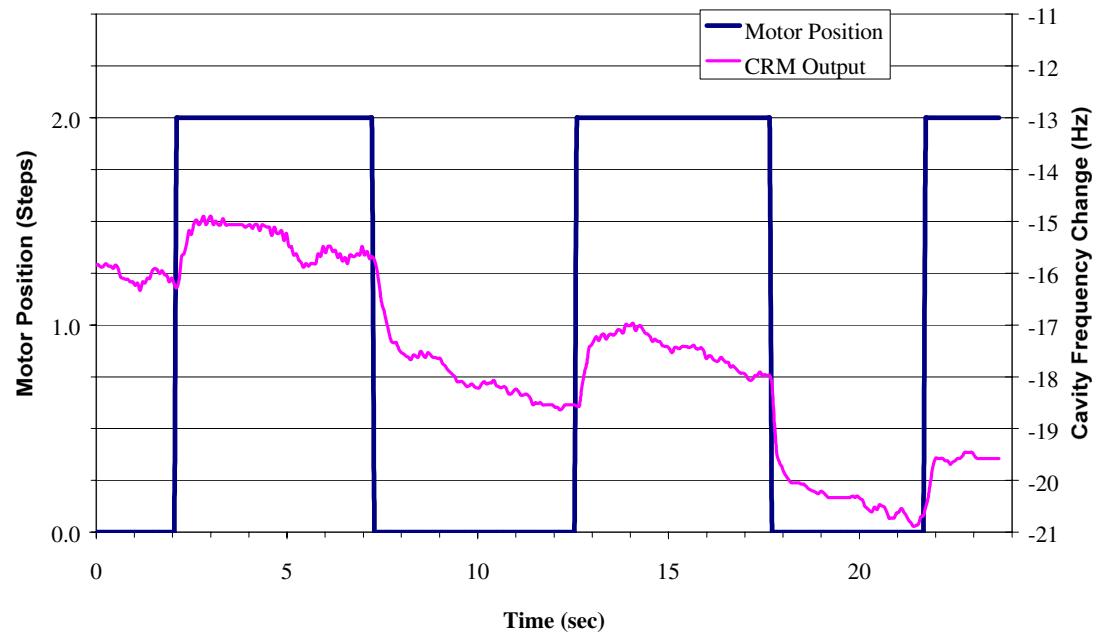
- **Stepper Motor**
 - 200 step/rev
 - 300 RPM
- **Low voltage piezo**
 - 150 V
 - 50 μm stroke
- **Harmonic Drive**
 - Gear Reduction = 80:1
- **Ball screw**
 - Lead = 4 mm
 - Pitch = 25.75 mm
- **Bellows/slides**
 - axial thermal contraction



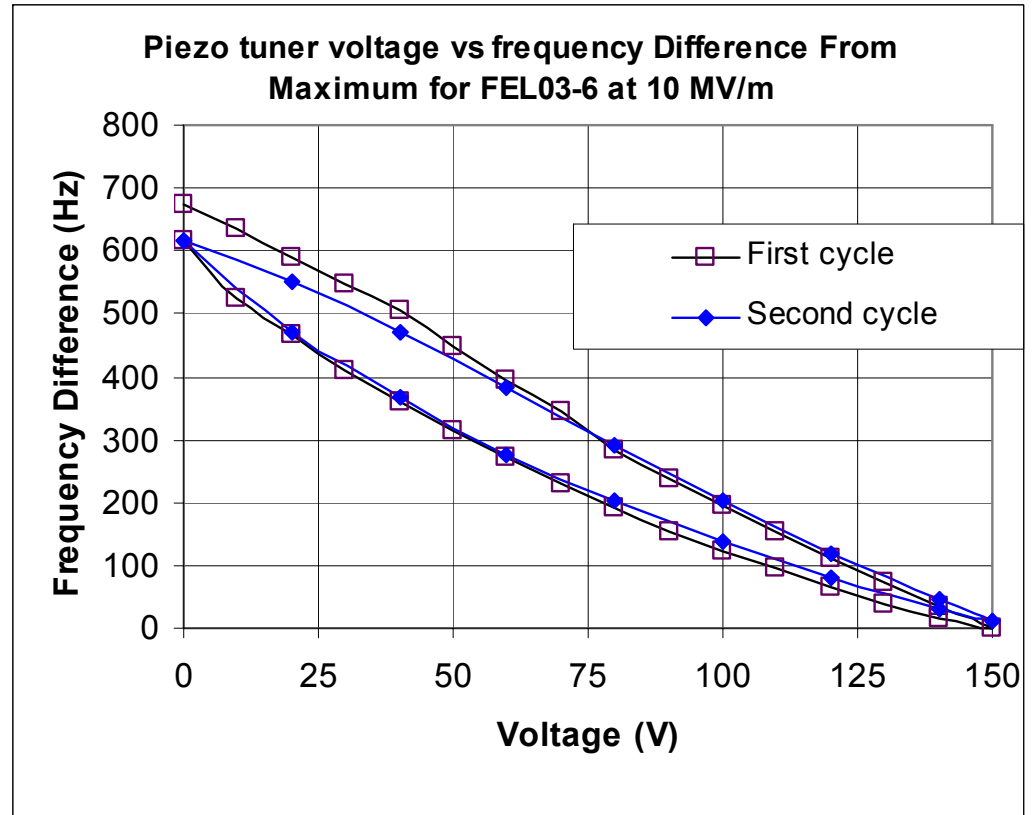
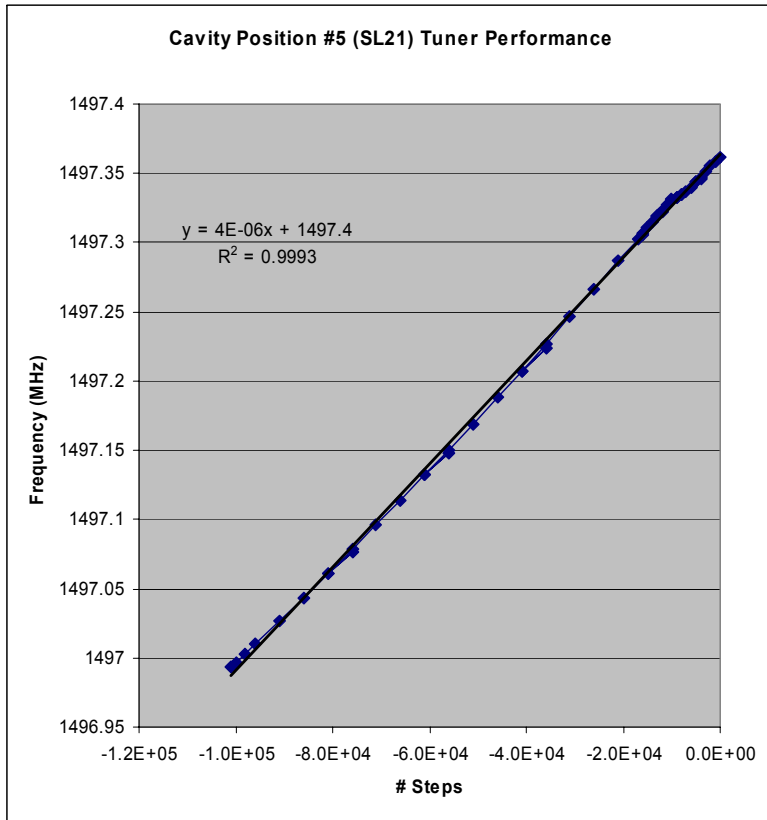
Resolution/Deadband Test

Resolution/Deadband < 2 Hz

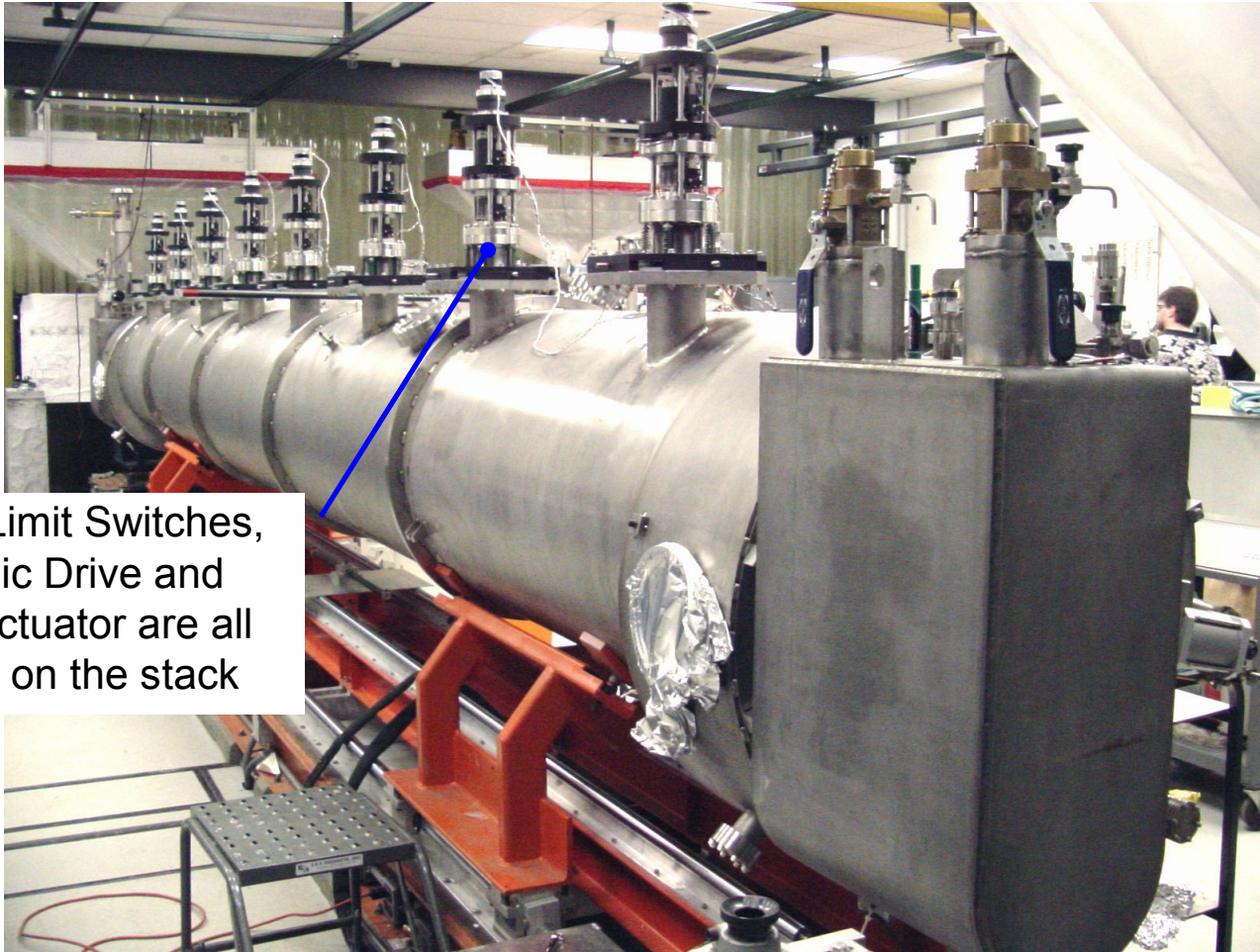
Drift due to Helium pressure fluctuations



Range and Resolution (Piezo Hysteresis)

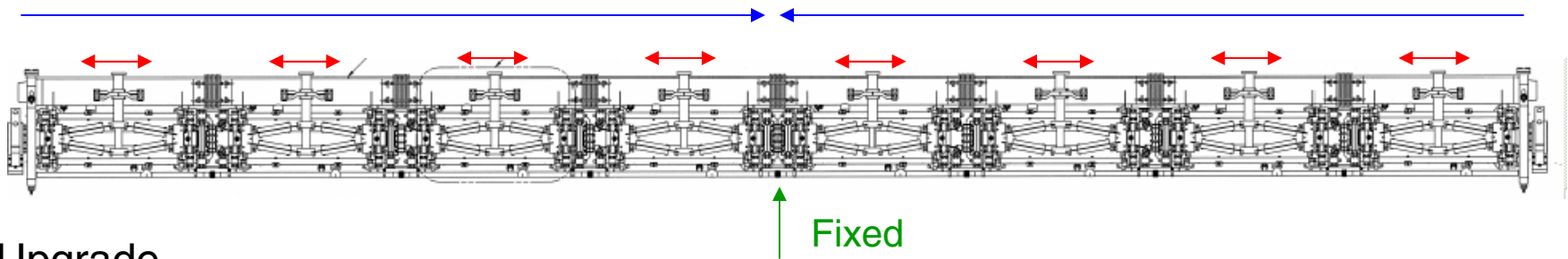
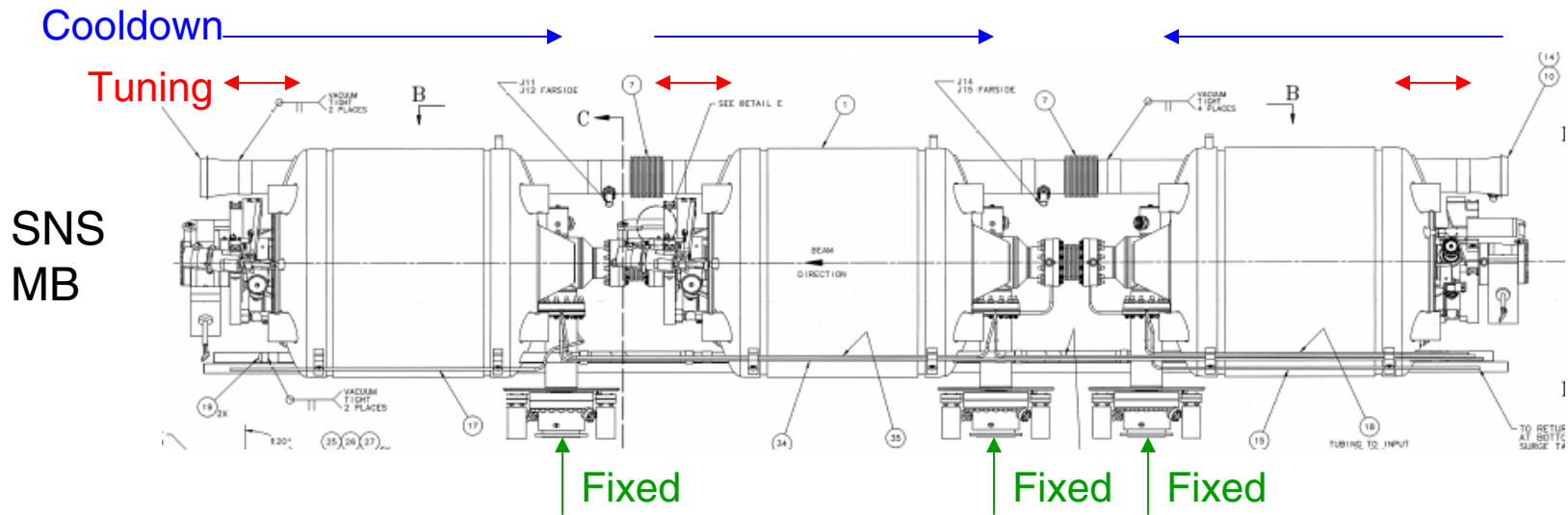


Upgrade Cryomodule – Access to Tuner Drive Components



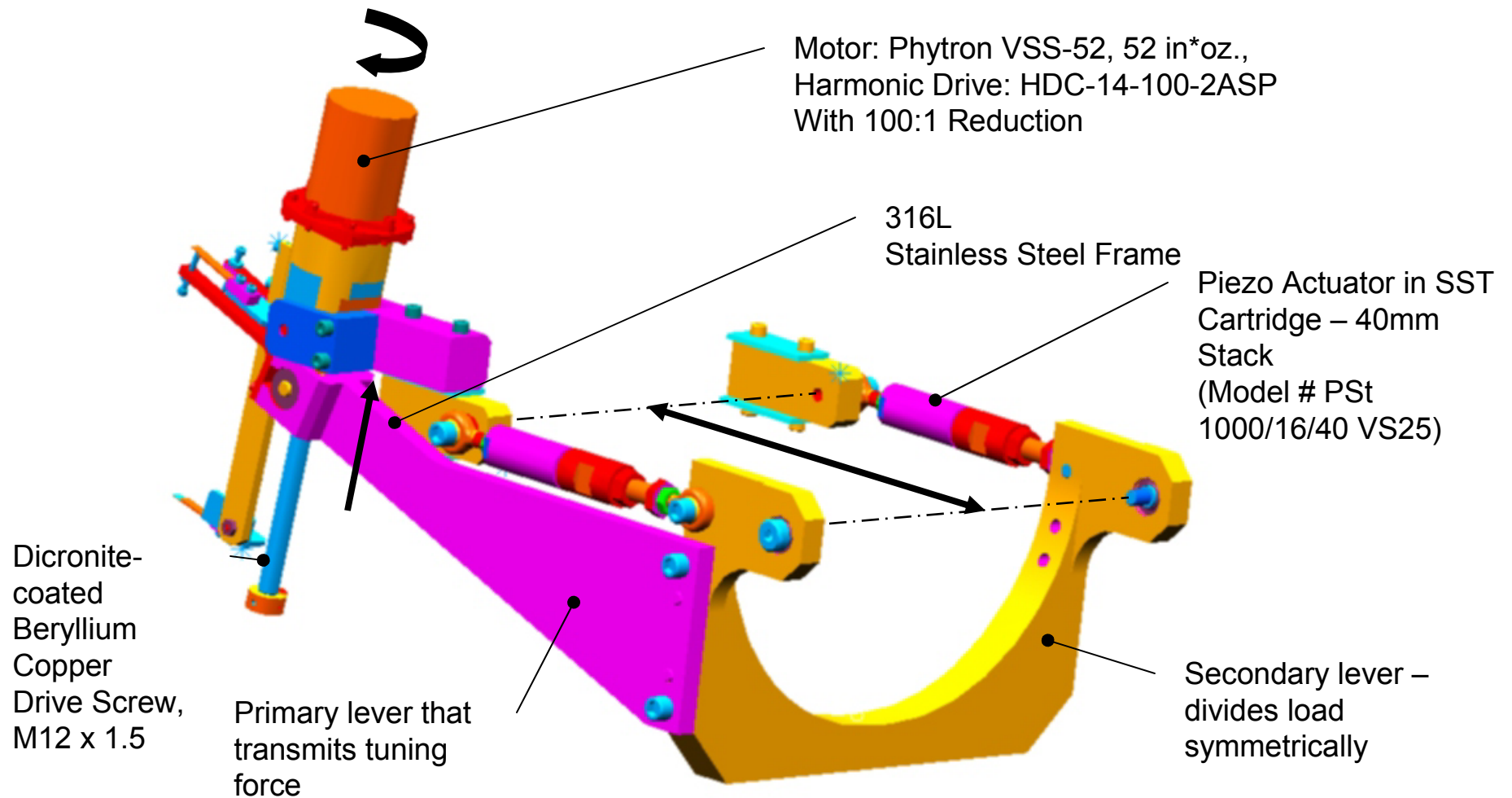
Motor, Limit Switch,
Harmonic Drive and
Piezo Actuator are all
situated on the stack

Cavity String Support Schemes : Tuning approach affect supports



Upgrade
Cryomodule

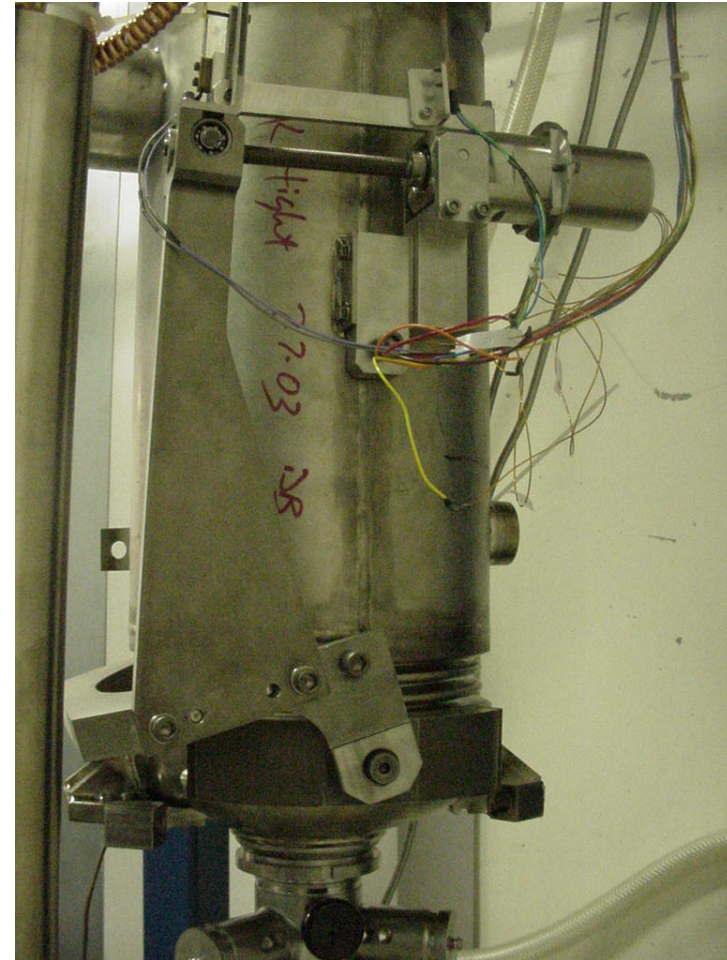
Renascence Tuner Assembly with Two Cold Piezo Actuators



Renascence Tuner Description

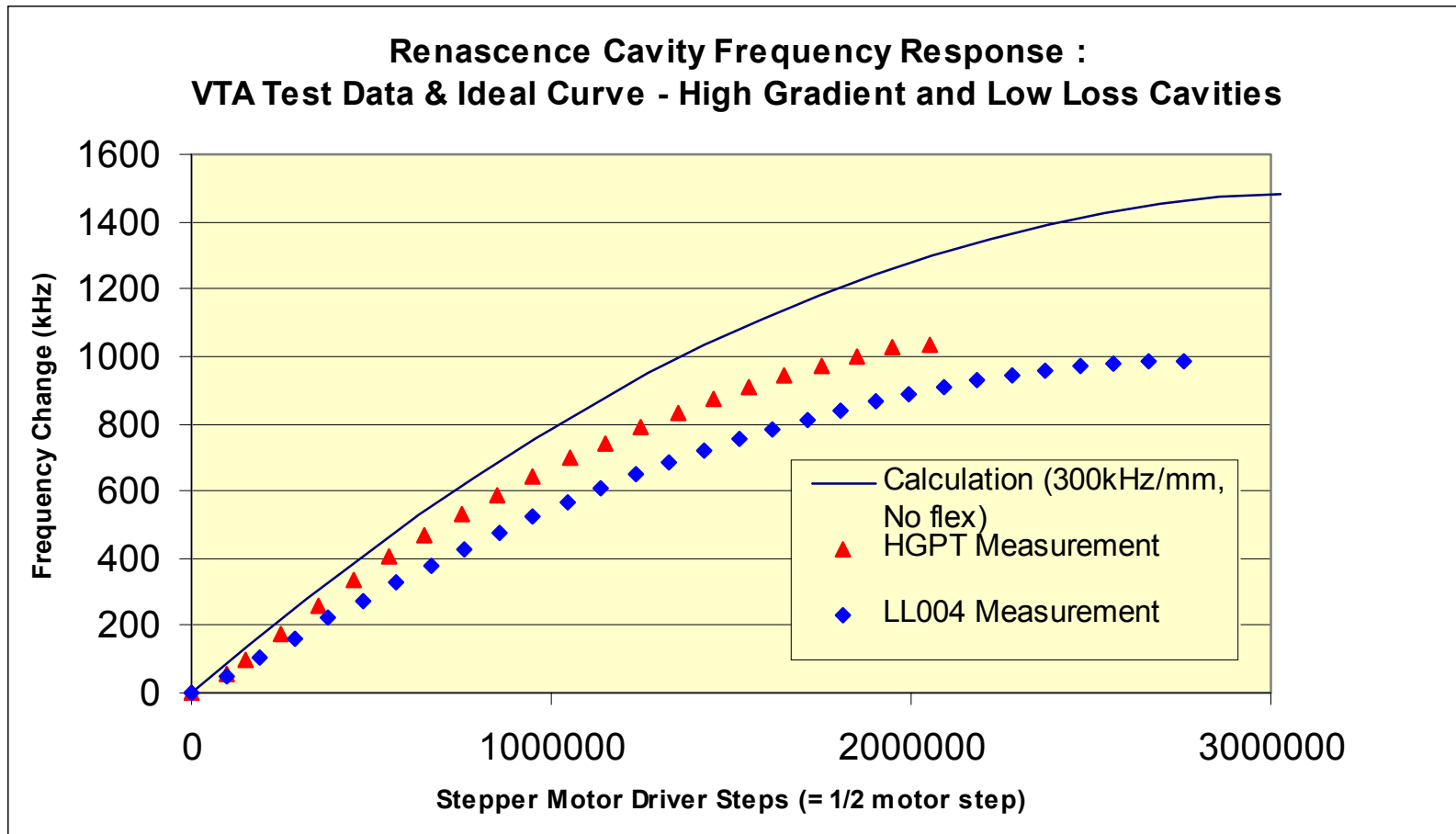
- **Mechanism – “Rock Crusher” –**
All cold, in vacuum components
 - **Stainless steel frame**
 - **Attaches to chocks on cavity**
 - **Attaches via shoulder bolts to helium vessel head**
 - **Dicronite coating on bearings and drive screw**
 - **Cavity tuned in tension only**

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



Renascence Tuner – VTA Testing :

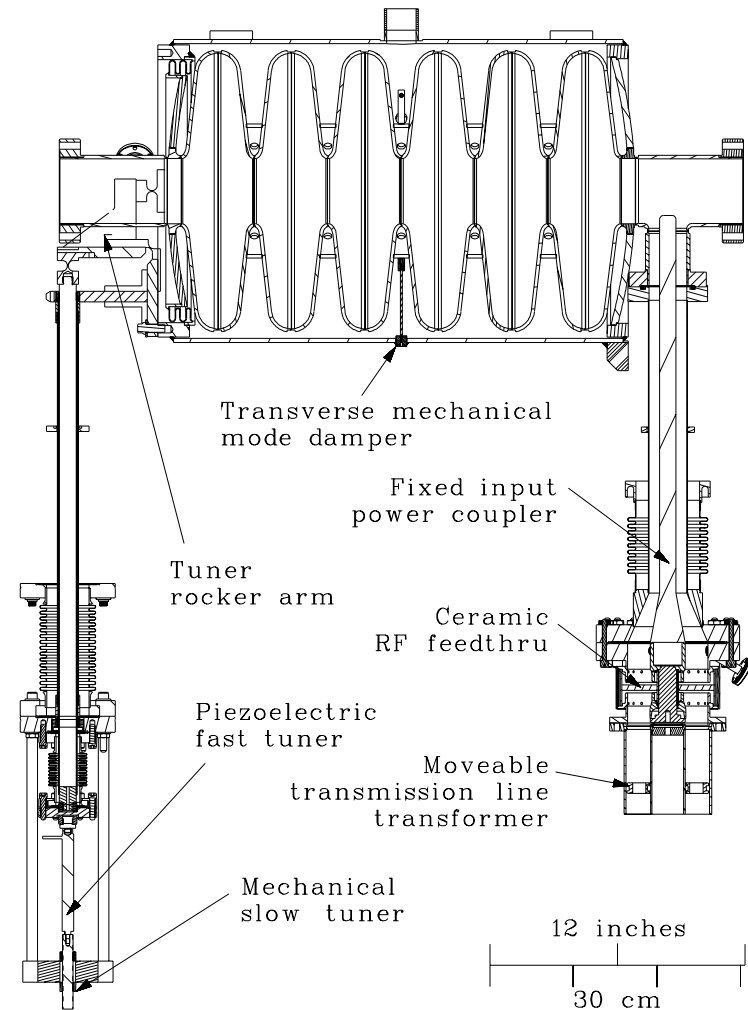
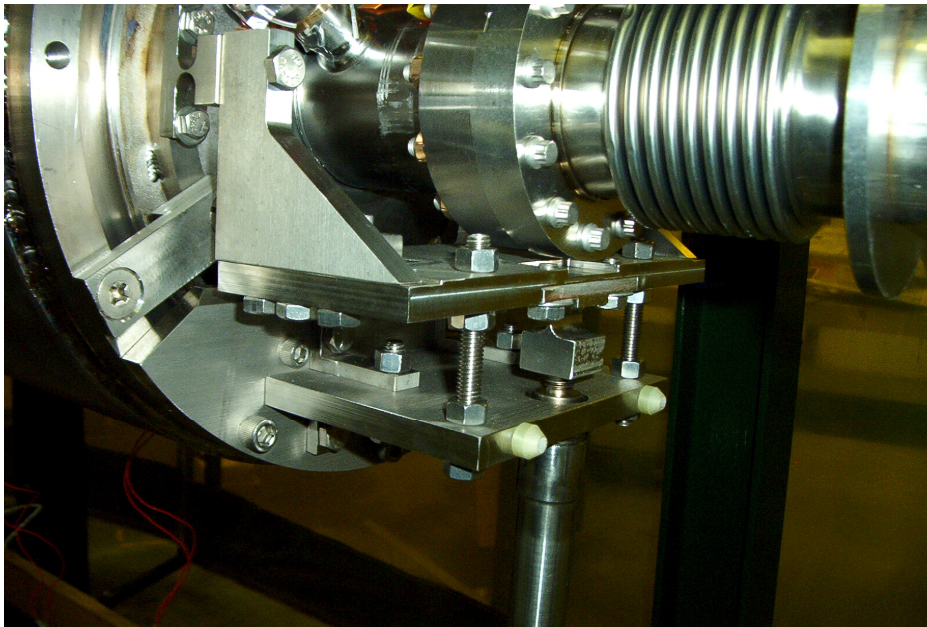
Range (Helium vessel compliance reduces actual stroke)



RIA Tuner (MSU)

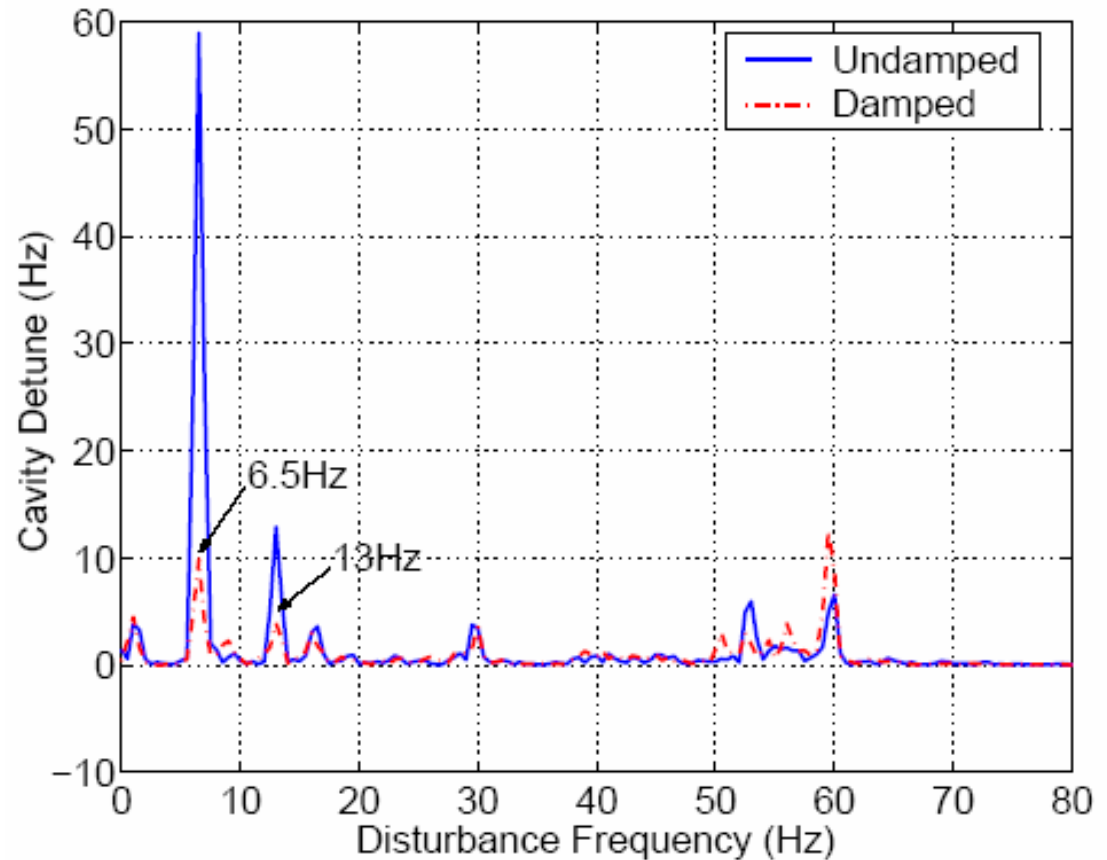
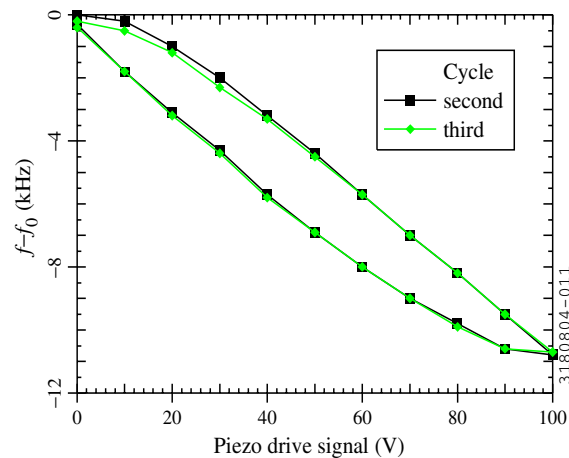
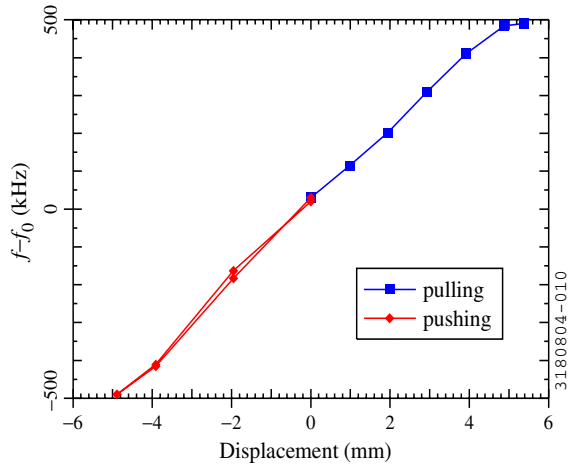
- **Mechanism**
 - **Stainless steel rocker arm and drive rod**
 - **Attaches to chocks on cavity**
 - **Attaches via flexures and threaded studs to helium vessel head**
 - **Cavity tuned in compression or tension**
- **Cold transmission – compressive/tensile force on drive rod**
- **Stepper motor and 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

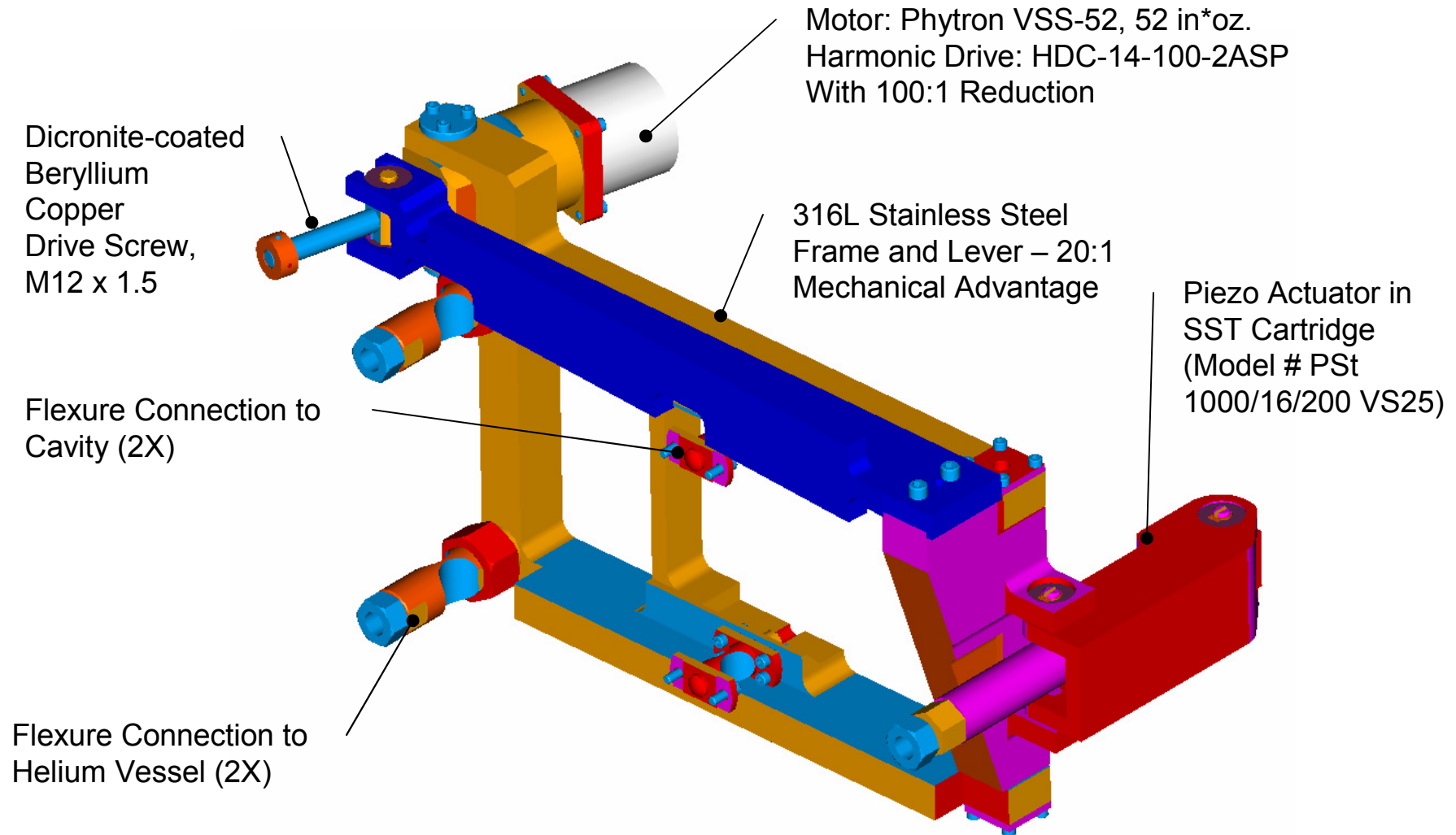
Coarse and Fine Tuner Range; Active Feedback Control



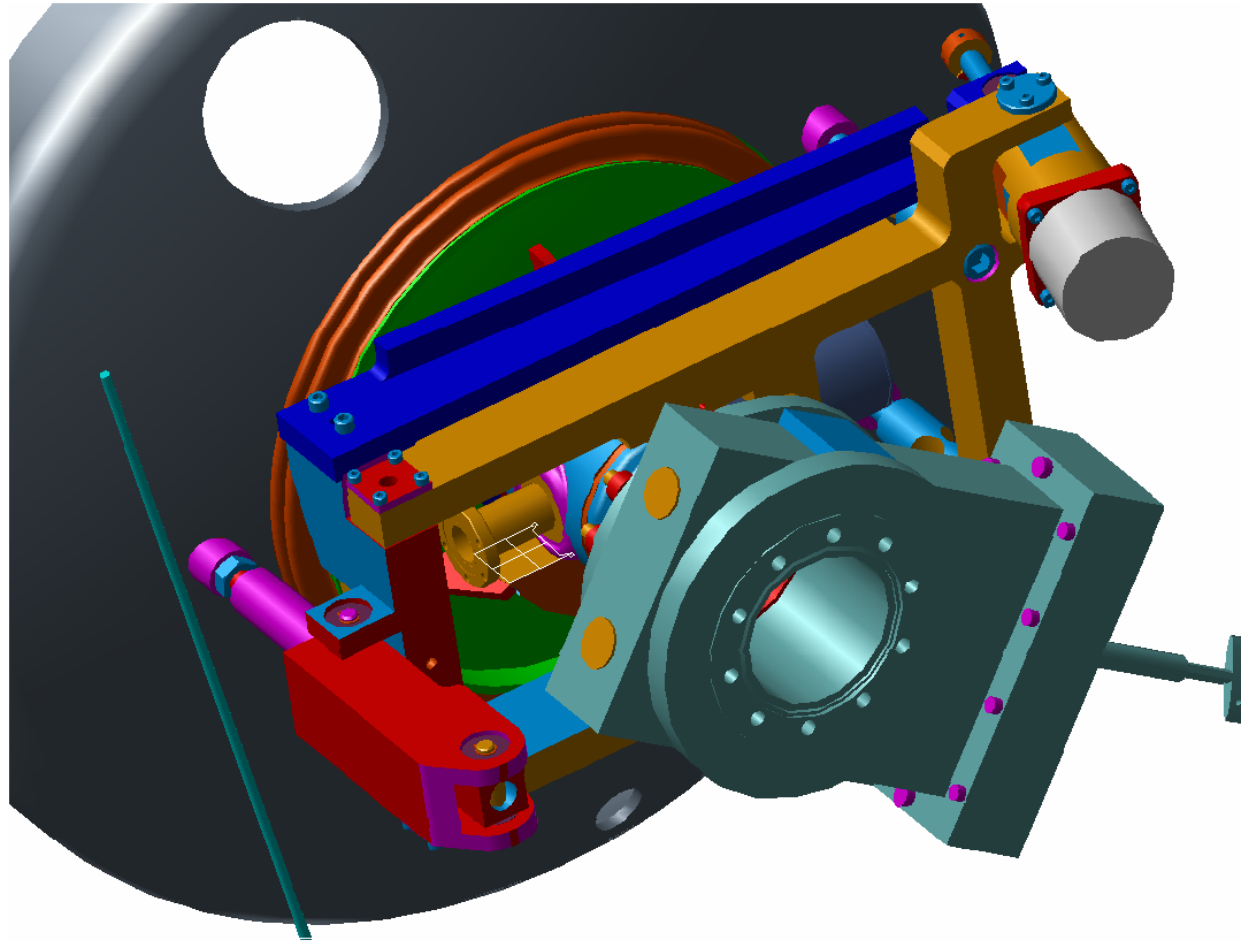
SNS Tuner - Description

- 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

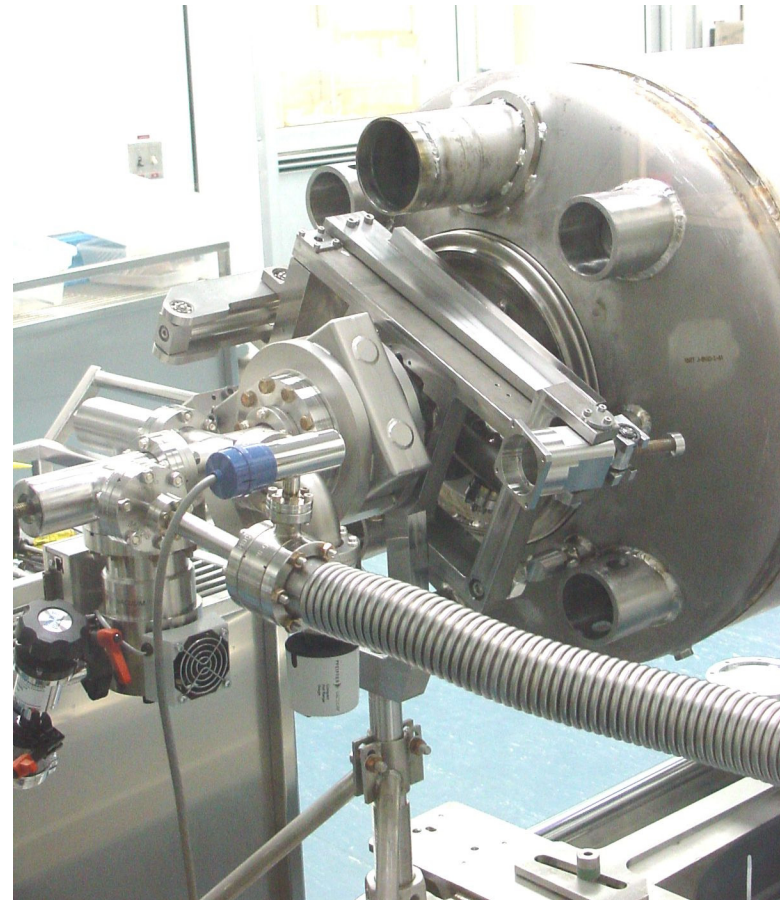
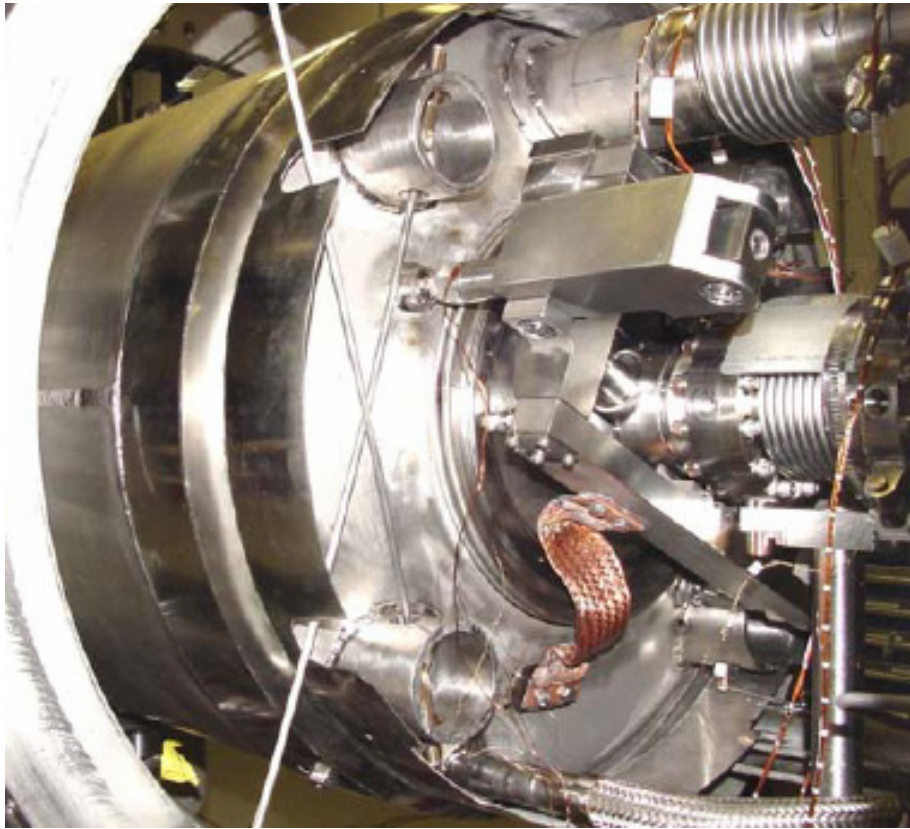
SNS Tuner Assembly w/ Piezo Actuator



SNS Tuner Assembly w/ Piezo Actuator

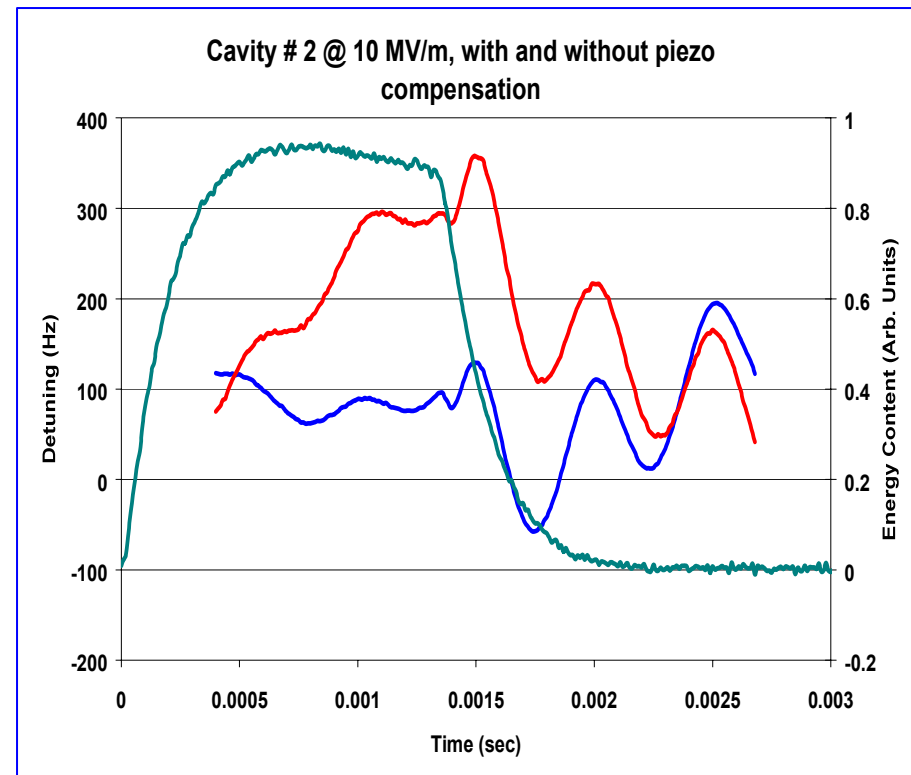
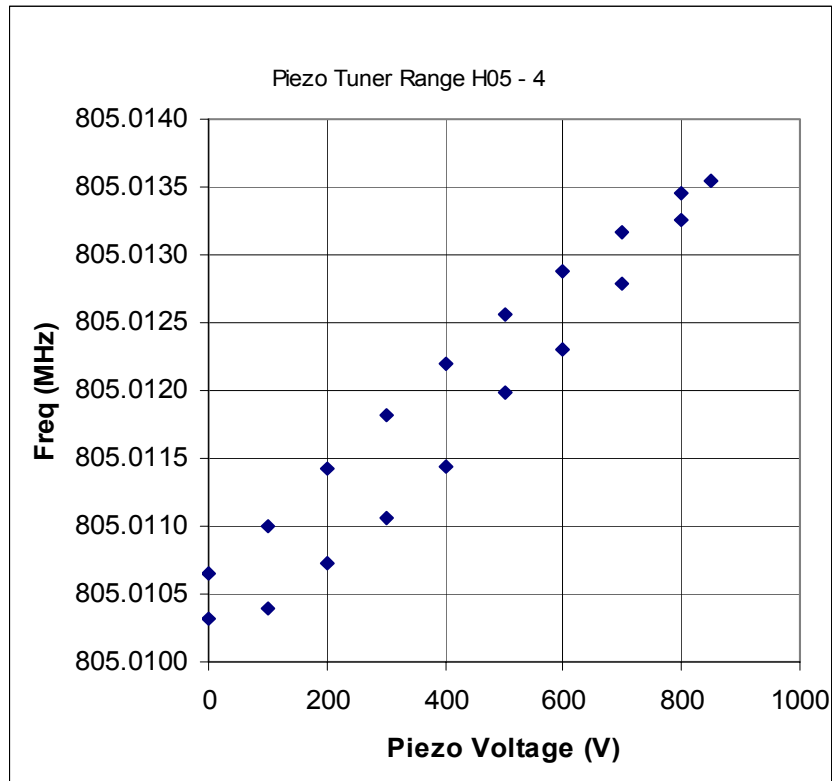


SNS Tuner with Piezo Actuator Installed on Helium Vessel & Cavity



SNS Tuner – CMTF Test Results

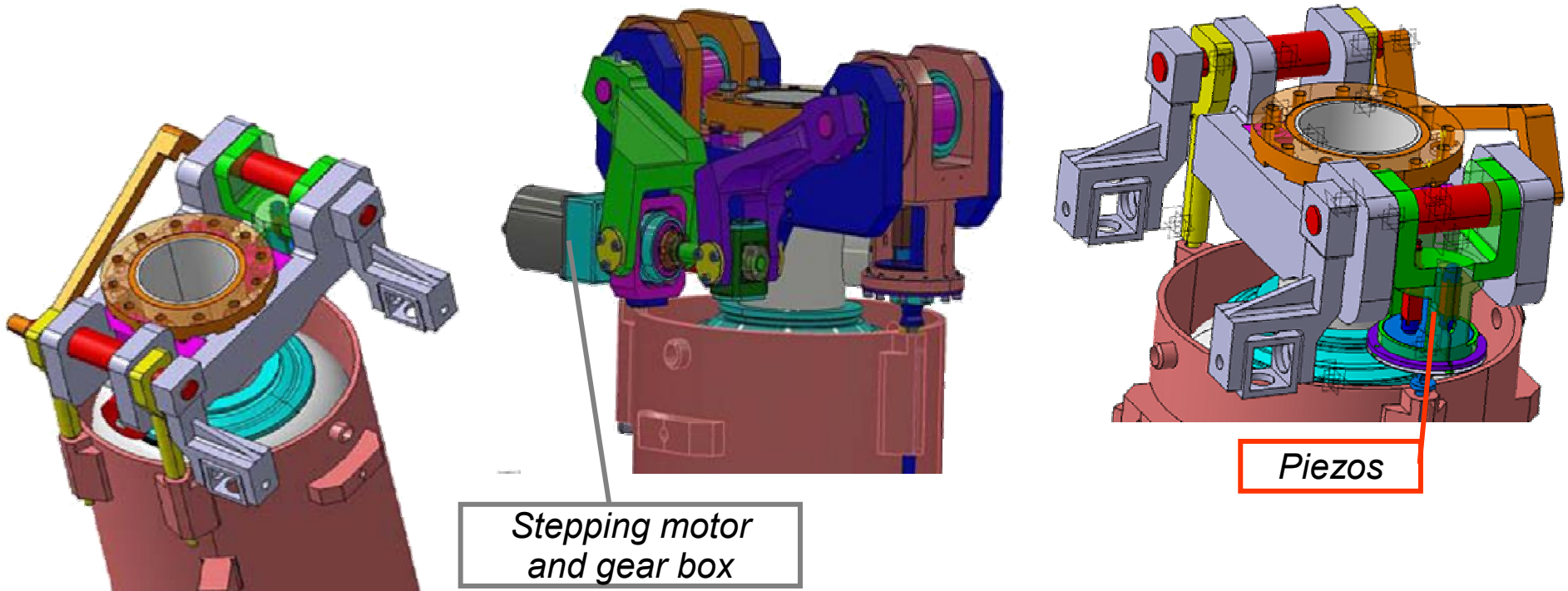
Fine Tuner Range and Hysteresis; Piezo Compensation



Frequency Tuners

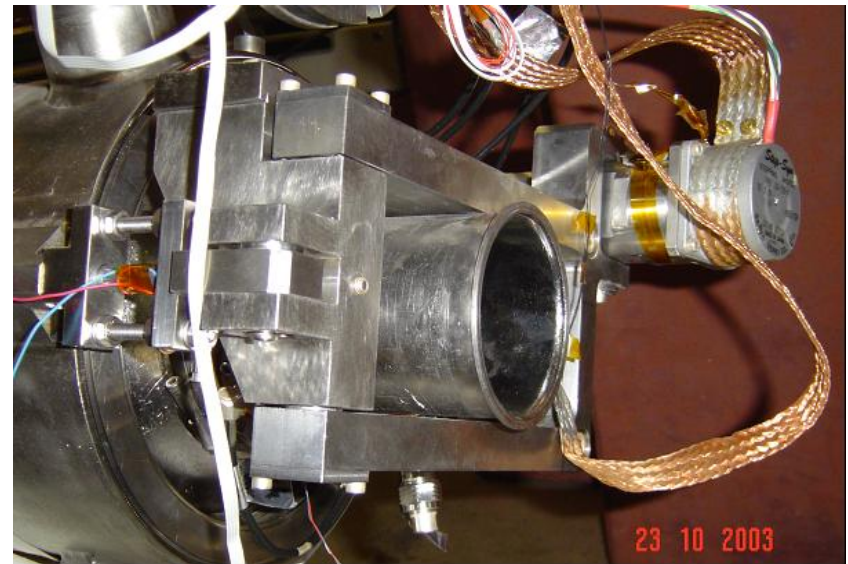
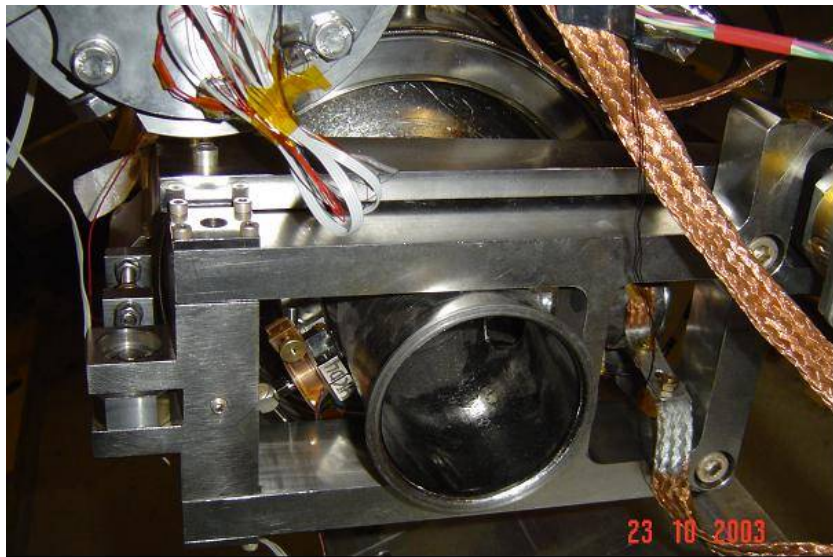
Saclay Lever Tuner spec.

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



Current Saclay Tuner

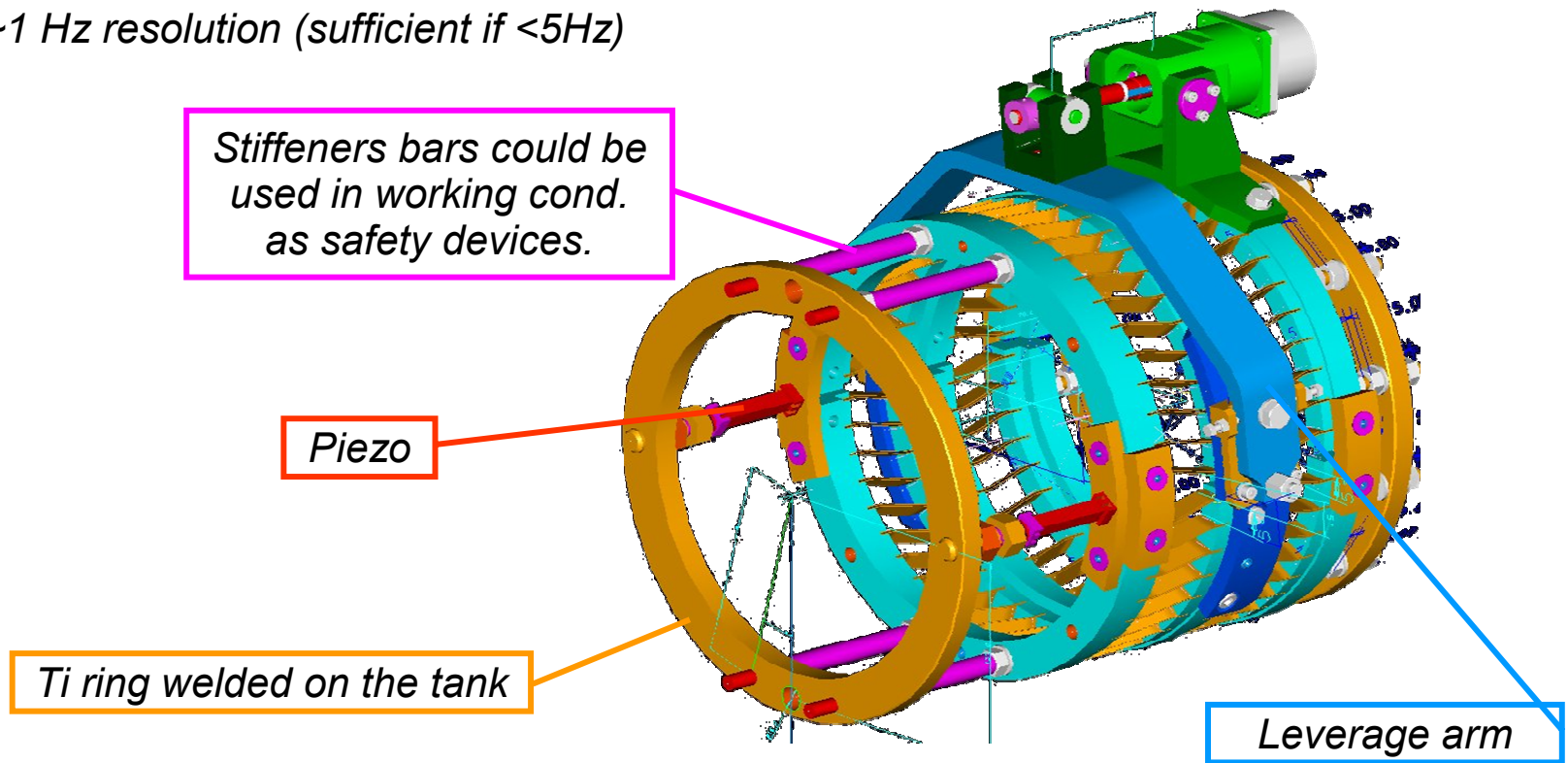
- Double lever system: ratio $\sim 1/17$
- Stepping motor with Harmonic Drive gear box
- Screw - nut system : lubricant treatment (balzers Balinit C coating) for working at cold and in vacuum
- $\Delta Z_{\max} = \pm 5 \text{ mm}$ and $\Delta F_{\max} = \pm 2.6 \text{ MHz}$
- theoretical resolution: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



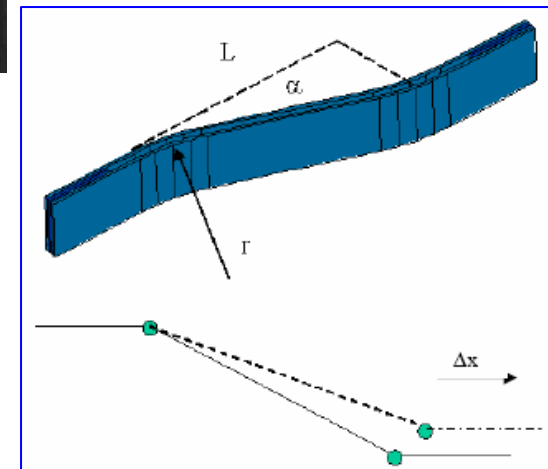
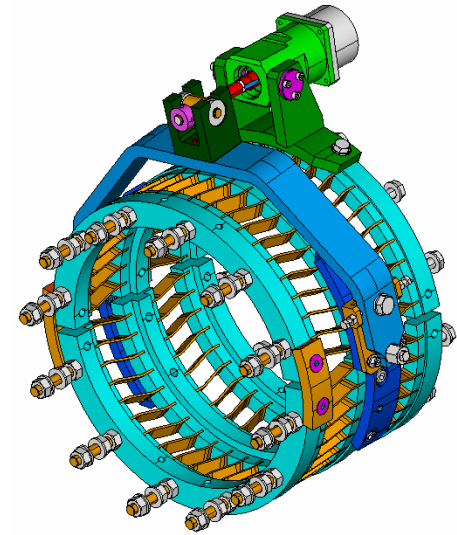
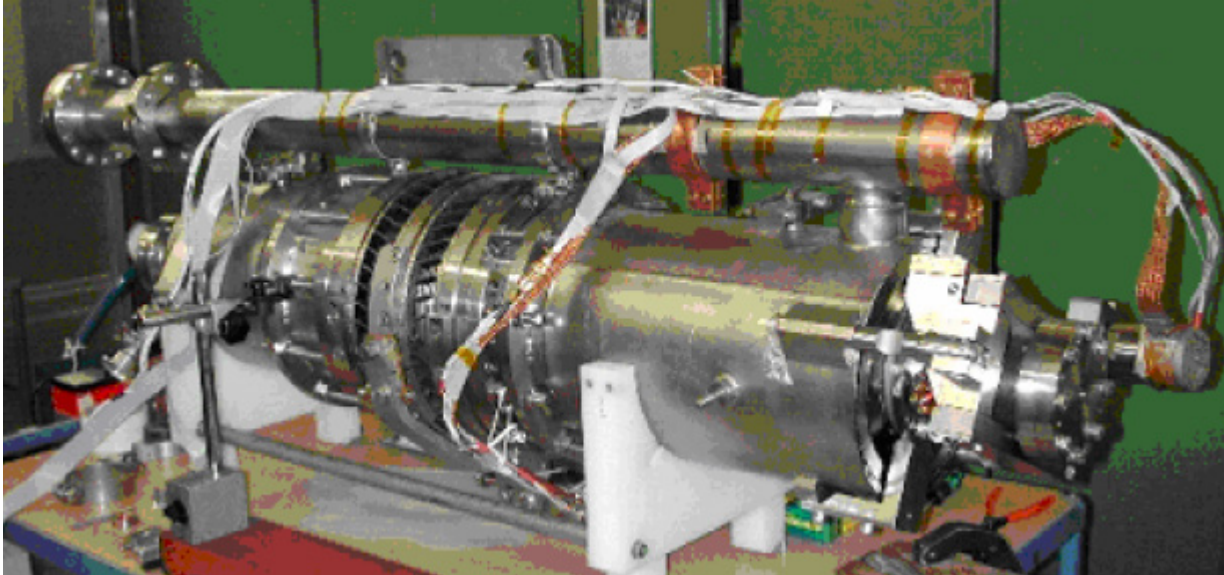
Blade Tuners

Blade Tuner spec.

- ↘ ± 1 mm fine tuning (on cavity) $\rightarrow \Delta F$ on all piezo (sum) ≈ 3.5 kN
- ↘ 1 kHz fast tuning $\rightarrow \approx 3$ μm cavity displacement $\rightarrow \approx 4$ μm piezo displacement
- ↘ 4 μm piezo displacement $\rightarrow \approx \Delta F$ on all piezo ≈ 11.0 N
- ↘ ~ 1 Hz resolution (sufficient if $< 5\text{Hz}$)



TESLA - Blade Tuner



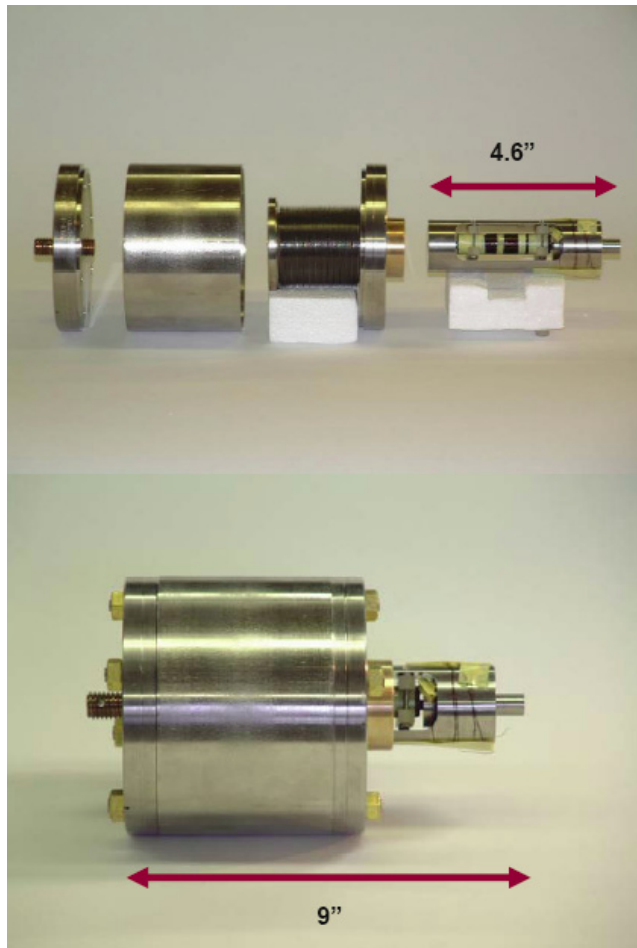
- Mechanism – All cold, in vacuum components
 - Titanium frame
 - Attaches to helium vessel shell
 - Pre-tune using bolts pushing on shell rings
 - Dicronite coating on bearings and drive screw
 - Cavity tuned in tension or compression – blades provide axial deflection

Piezoelectric Tuners



- Response time $<1\text{ms}$.
- 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.

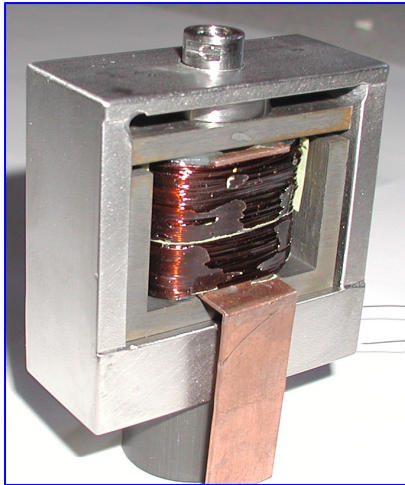
Magnetostrictive tuners



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

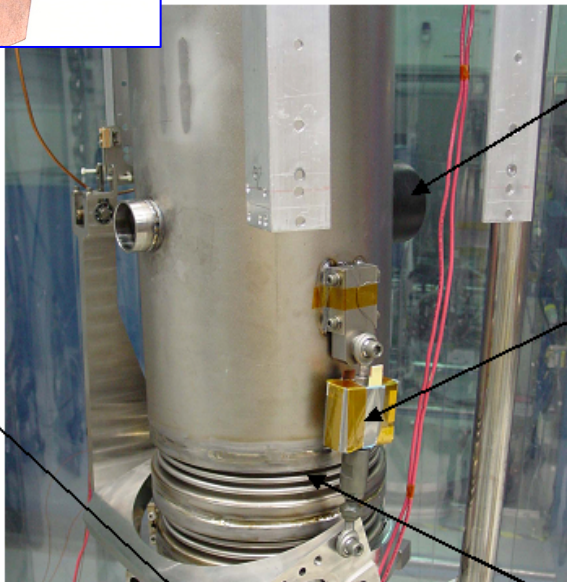
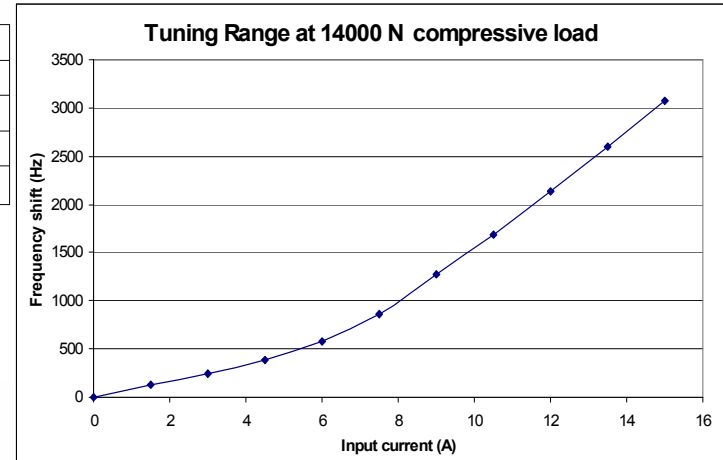
Renascence Cavity – VTA Test Results

Magnetostrictive Actuator on Tuner



RANGE OF THE MAGNETOSTRICTIVE TUNER AT DIFFERENT LOADS

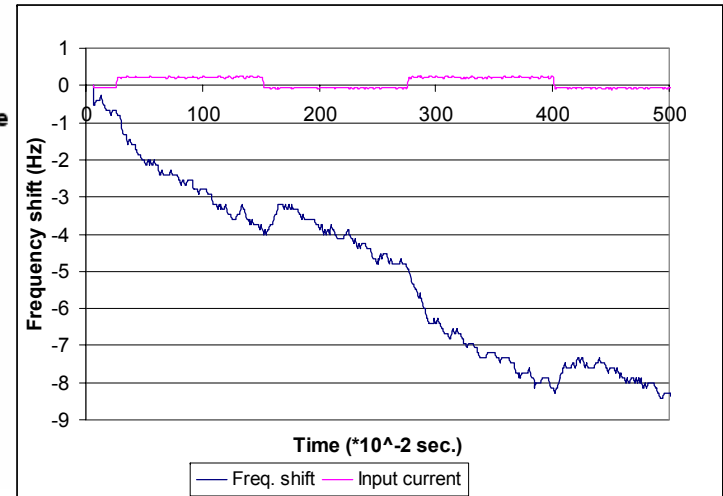
Compressive Load (N)	Max. Tuning Range (Hz)
No Load	2,600
7100	5,892
10,200	3,423
14,000	3,088



Slow Tuning motor and drive

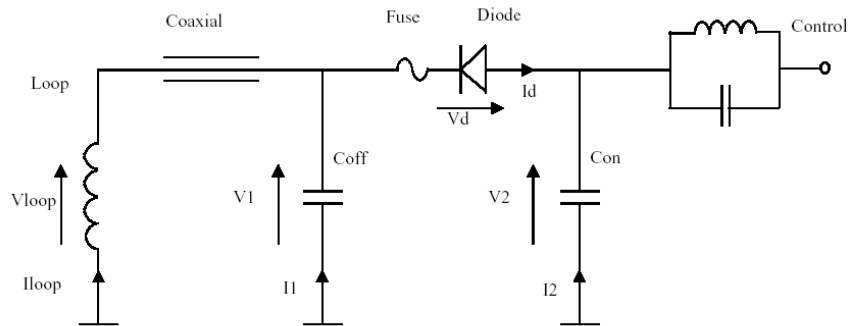
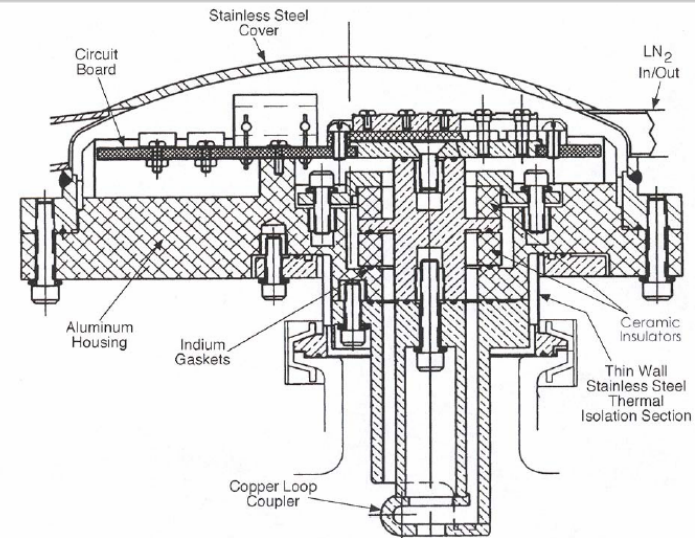
Magnetostrictive Tuner

Tuning Linkage mechanism



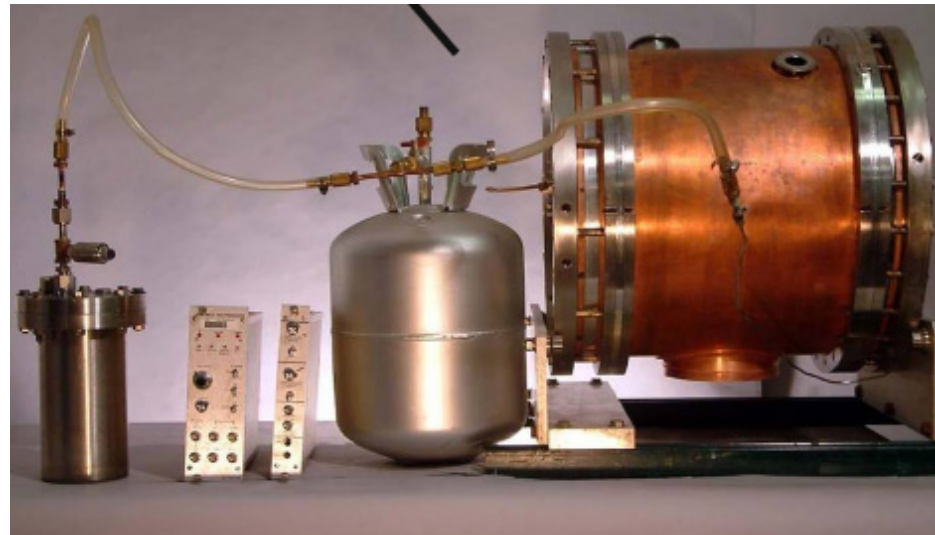
Voltage-Controlled Reactance

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

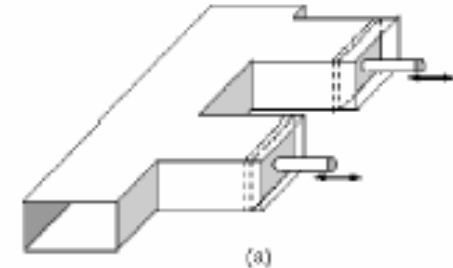


Pneumatic Tuners

Have been used successfully for many years in low velocity structures

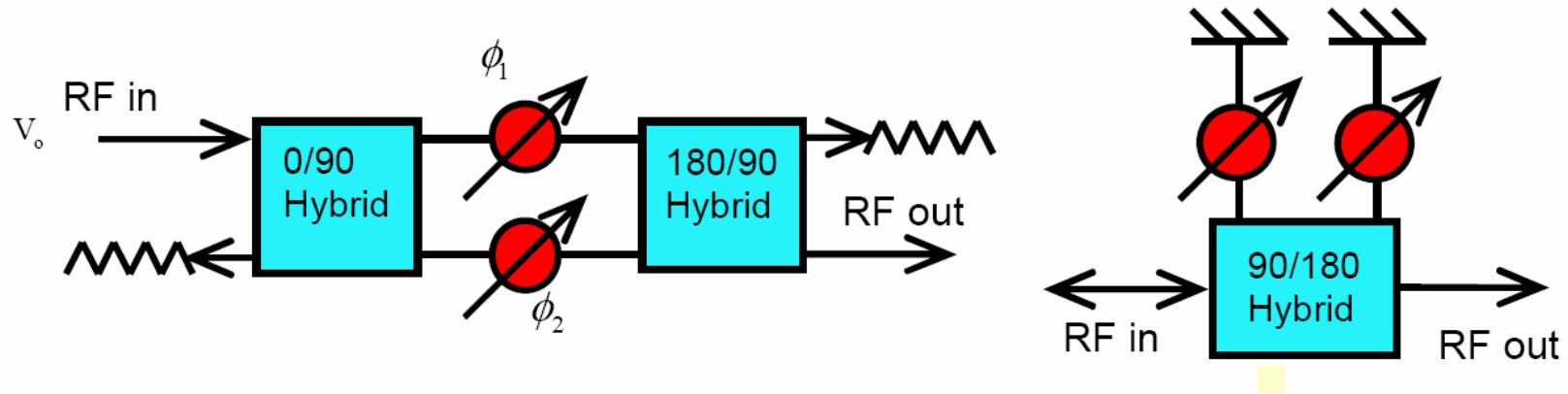


Waveguide Stubline Tuning



- **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

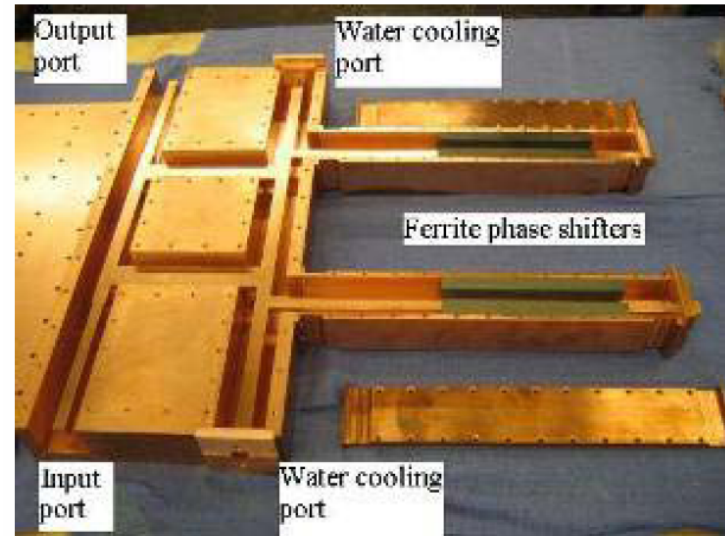


Figure 4: High power vector modulator prototype shows input and output port, water cooling port, and ferrite phase shifters.

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