Review of Slow and Fast Tuners

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Outline

- Objectives for Cavity Frequency Tuners
- Types of Tuners
- Parameters
- Examples for Recent Tuner Designs
- Performance Data
- Future Challenges

Objectives for Tuners

- Tune cavity resonance to operating frequency
  - during initial and subsequent cool-down
  - compensate slow drift of frequency
- De-tune cavities to bypass for operation
- Compensate Lorentz Force De-tuning (static and dynamic)
- Control of Microphonics (typically up to few 10 Hz)
- Long life time (~ 20 years of operation)

Objectives for Tuner (C'tnd)

- Compact design (especially longitudinal, fill factor !)
- Hysteresis free
- Tuning range limited (to avoid plastic deformation of cavity)
- Maintain field flatness of accelerating mode
- No "cross"-tuning of neighboring cavities
- No significant cryo heatload
- Easy to maintain and repair
- Cost efficient

Types of Frequency Tuners

- Mechanical length change or other deformation of the cavity
  - based on a motor driven mechanism (slow)
  - based on PZT or magnetostrictive Element (fast)
- VXC (external reactance) or ferrite based tuner
- Other: Pneumatic, thermal, electronic damping

Note: Tuners which control in addition to frequency also loaded Q and incident phase are possible.

Accelerator facility	KEK	CERN/LEP	DESY	CERN/SPS
Type of accelerator	e^-e^+ collider 8–29 GeV at 15 mA	e^-e^+ collider 20–46 GeV at 40 mA	e^- collider 26–40 GeV at 70 mA	$e^-, e^+, p, \bar{p}$ collider, booster
Cavity material (RRR)	Nb (200)	Nb (280) and Nb/Cu (30)	Niobium (280)	Niobium
Operating temperature (K)	4.2	4.2	4.2	4.2
Cavities installed (operational)	32 (32)	8 Nb + 4 Nb/Cu (8+4)	16 (16)	1 (1)
Number of cells	5	4	4	4
Frequency (MHz)	508	352	500	352
Q_0/Q_L	$2\cdot10^9$ / $1\cdot10^6$	$3\cdot10^9$ / $2.2\cdot10^6$	$2\cdot10^9$ / $2.4\cdot10^5$variable	$3\cdot10^9$ / N.A.
Design (average) operating gradient (MV/m)	5 (3.5 – 4.7)	5 (3.7) Nb, 6 (4) Nb/Cu	5 (4)	5 (5)
Normal operating gradient control range (MV/m)	2.5–4.5	2–4	1–5	4–6
Gradient control range for conditioning (MV/m)	0.1–9.0	1–7	1–7	N/A
Power amplifier	Klystron 1 MW	Klystron 1.2 MW	Klystron 1.6 MW	Tetrode 50 kW
# Cavities/power amplifier	4	16	16	1
Beam time (h)	25,000	several 100	15,000	30,000
Mechanical sensitivity (Hz/µm)	80	40	80	≈40
Pressure sensitivity (Hz/mBar)	30	8	-90	8
Gradient sensitivity (Hz/(MV/m)**2)				
Frequency predictability for first cooldown (kHz)	±100	±30	±90	
Frequency predictability for repeated cool down (kHz)		<5	±few kHz	
Tuning principle	length variation	length variation	length variation	length variation
Tuning mechanism	stepping motor + piezoelectric	thermal expansion + magnetostrictive	stepping motor	thermal expansion + magnetostrictive
Frequency range and settability of coarse tuner (kHz)	350	50	800	50
Frequency range and (settability) of fine tuner (Hz)	6000 (N.A.)	2000 (N.A.)	N.A.	2000 (N.A.)
Tuner control automated or manual	automated	automated	automated	automated
Bandwidth of tuner control (Hz)	10	< 1 Hz	< 1	

Accelerator facility	CEBAF	S-DALINAC	LISA	MACSE	HEPL
Type of accelerator	e^- recyclotron (5-pass) 0.5-4.0 GeV at 200 μA	e^- recyclotron (3-pass) 20-130 MeV at 20 μA	e^- linac 25 MeV linac for FEL	electron accelerator test facility	e^- recyclotron Nucl. Phys. and FEL
Cavity material (RRR)	Nb (300)	Nb (100 – 280)	Nb (100 – 200)	Nb	Nb
Operating temperature (K)	2.0	2.0	4.2	2.0	2.0
Cavities installed (operational)	306 (258)	10+1 (10+1)	4 (3)	4+1 (4+1)	7 (7)
Number of cells	5	20/5	4	4-5	7/23/55
Frequency (MHz)	1497	2997	500	1497	1300
Q_0/Q_L	$6\cdot10^9$ / $6\cdot10^6$	$2\cdot10^9$ / $3\cdot10^7$	$1\cdot10^9$ / $5\cdot10^6$	$5\cdot10^9$ / $5\cdot10^6$	$2\cdot10^9$ / $4\cdot10^6$
Design (average) operating gradient (MV/m)	5 (7.2)	5 (3.0)	5 (3.5)	5 (4–5)	5 (3.5/2.5)
Normal operating gradient control range (MV/m)	3–7	2–4		4–5	2–5
Gradient control range for conditioning (MV/m)	0.5–7	1–10 (variable coupler)		N.A.	0.1–9.0
Power amplifier	Klystron 5 kW	Klystron 0.5 kW	Klystron 15 kW	Klystron 5 kW	Klystron 10 KW
# Cavities/power amplifier	1	1	1	1	1
Beam time (h)	4,000	7,000	> 200	100	30,000
Mechanical sensitivity (Hz/μm)	500	500	60	500	N.A.
Pressure sensitivity (Hz/mBar)	-60(-10)	-15		-60	
Gradient sensitivity (Hz/(MV/m)**2)	-3	-4		-3	
Frequency predictability for first cooldown (kHz)	±20	±200		±50	13
Frequency predictability for repeated cool down (kHz)	±2	±20		±25	1
Tuning principle	length variation	length variation	length variation	length variation	length variation
Tuning mechanism	stepping motor	DC-motor+ magnetostrictive	stepping motor	stepping motor + magnetostrictive	stepping motor
Frequency range and settability of coarse tuner (kHz)	400 (0.002)	1000 (0.01)	600 (<0.01)	1500	25
Frequency range of fine tuner (Hz)		1500			
Tuner control automated or manual	automated	automated	automated	automated	N/A
Bandwidth of tuner control (Hz)	0.1	1			

Accelerator facility	Atlas	Stony Brook	ALPI
Type of accelerator	Heavy in Linac	Heavy ion linac	Heavy ion linac
Cavity material (RRR)	Nb (20 – 200)	Pb/Cu	Pb/Cu
Operating temperature (K)	4.7	4.5	4.2
Cavities installed (operational)	62 (62)	42 (40)	32 (20)
Number of cells	N.A.	N.A.	N.A.
Frequency (MHz)	48,72,92,145	150.4	80, 160
Q_0/Q_L	typ. $2\cdot10^9/1\cdot10^7$	$1\cdot10^8$ / $1\cdot10^7$	$1\cdot10^8$ / $1\cdot10^7$
Design (average) operating gradient (MV/m)	3 – 4	3	3
Normal operating gradient control range (MV/m)	1 – 3.5		
Gradient control range for conditioning (MV/m)	1 – 8		
Power amplifier	200 W class A solid state	200 W class A solid state	100 W class A solid state
# Cavities/power amplifier	1	1	1
Beam time (h)	>50,000	30,000	some hours
Mechanical sensitivity (Hz/μm)	100		6
Pressure sensitivity (Hz/mBar)	2		
Gradient sensitivity (Hz/(MV/m)**2)	-100	-100	
Frequency predictability for first cool down (kHz)	< 10	<5	<10
Frequency predictability for repeated cooldown (kHz)	< 3	<1	<1
Tuning principle	Deformation	Deformation of bottom plate (QWR) or end cells (SLR)	Deformation of bottom plate
Tuning mechanism	He-pressure actuated	Stepping motor, screw, lever	Stepping motor +step reducer
Frequency range and settability of coarse tuner (kHz)	100 (0.001)	±5 kHz (QWR) ±20 kHz (SLR)	30 (0.002)
Frequency range and (settability) of fine tuner (Hz)	200 (2°rf phase)		
Tuner control automated or manual	automated	coarse tuner manual fine tuner automated	manual
Average tuner control (Hz/day)	> 1000 for slow tuner		
Bandwidth of tuner control (Hz)	< 1 for slow tuner		1

Typical Parameters of Multi-Cell Cavities

	CEBAF	CEBAF Upgrade (SL21,FEL03)	CEBAF Upgrade (Renascence)	RIA b=0.47	SNS b=0.61	SNS b=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	Pulsed 60 Hz	Pulsed 5Hz
Bandwidth (Hz)	220	75	75	40	1100	1100	520
Loaded Q (1e6)	6.6	20	20	20	0.7	0.7	3.0
Lorentz Force detuning (Hz)	75	312	324	1600	470	1200	434
Micro-phonics (Hz, 6 s)	-	+-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/mm)	373	267	~300 (calc)	> 100	290	230	315

compiled by E. Daly (ERL workshop 2005)

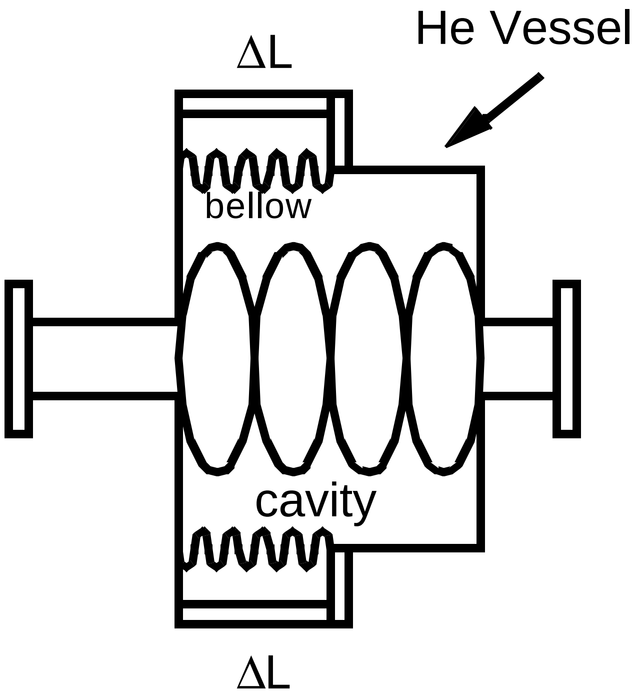
Tuner Requirements & Specifications

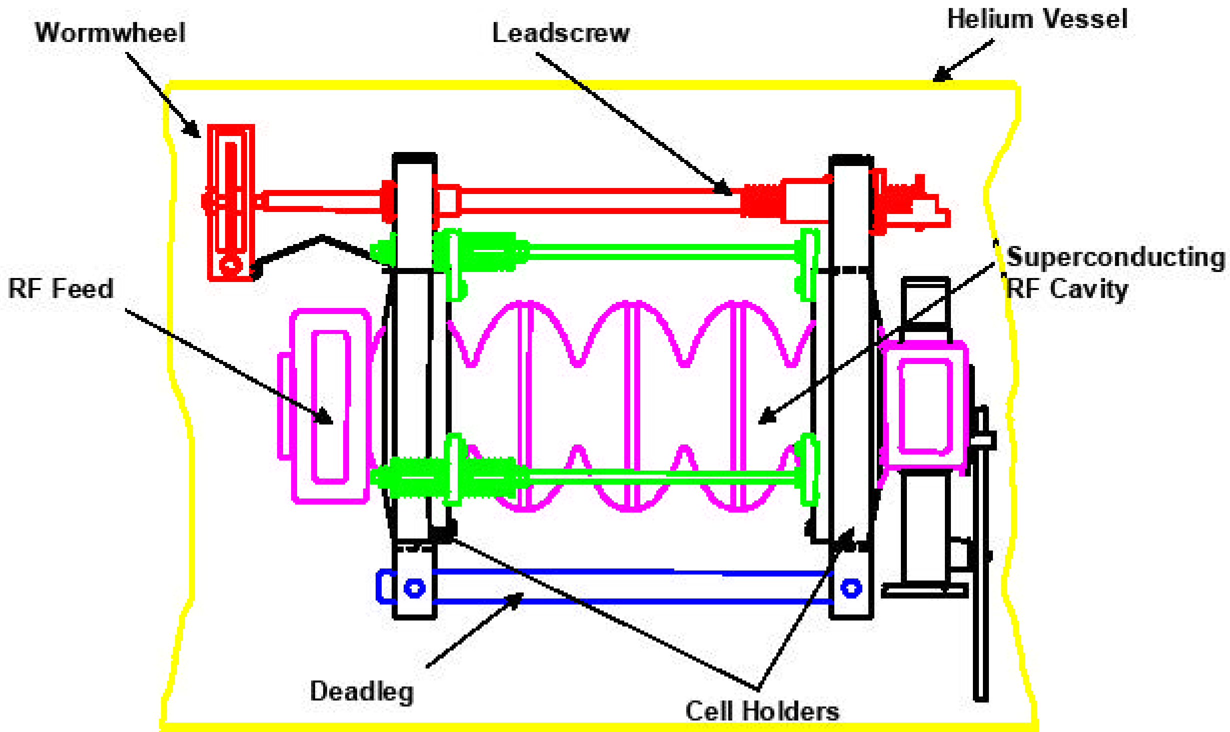
	CEBAF	CEBAF Upgrade (SL21,FEL03)	CEBAF Upgrade (Renascence)	RIA b=0.47	SNS b=0.61	SNS b=0.81	TESLA 500
Coarse Range (kHz)	+-200	+-200	+-40	950	+-245	+-220	+-220
Coarse Resolution (Hz)	NA	<2	2-3	<1	2-3	2-3	<1
Backlash (Hz)	>>100	<3	<3	NR	<10	<10	NR
Fine Range (Hz)	NA	>550 @ 150V	1.2k @ 1 kV	11k @ 100 V	>2.5k @ 1KV	>2.5k @1kV	NA
Fine Resolution (Hz)	NA	<1	<1	<1	<1	<1	
Demo of active Microphonics Damp-ing	No		No	Yes	No	No	No
Tuning Method	Tens. & Comp.	Tension	Tension	NA	Comp.	Comp.	Comp.
Mechanism	Immersed	Vacuum	Vacuum	Vacuum	Vacuum	Vacuum	Vacuum
Drive Comp.	Vac/Warm	Vac/Warm	Vac/Cold	Vac/Ext.	Vac/Cold	Vac/Cold	Vac/Cold

compiled by E. Daly (ERL workshop 2005)

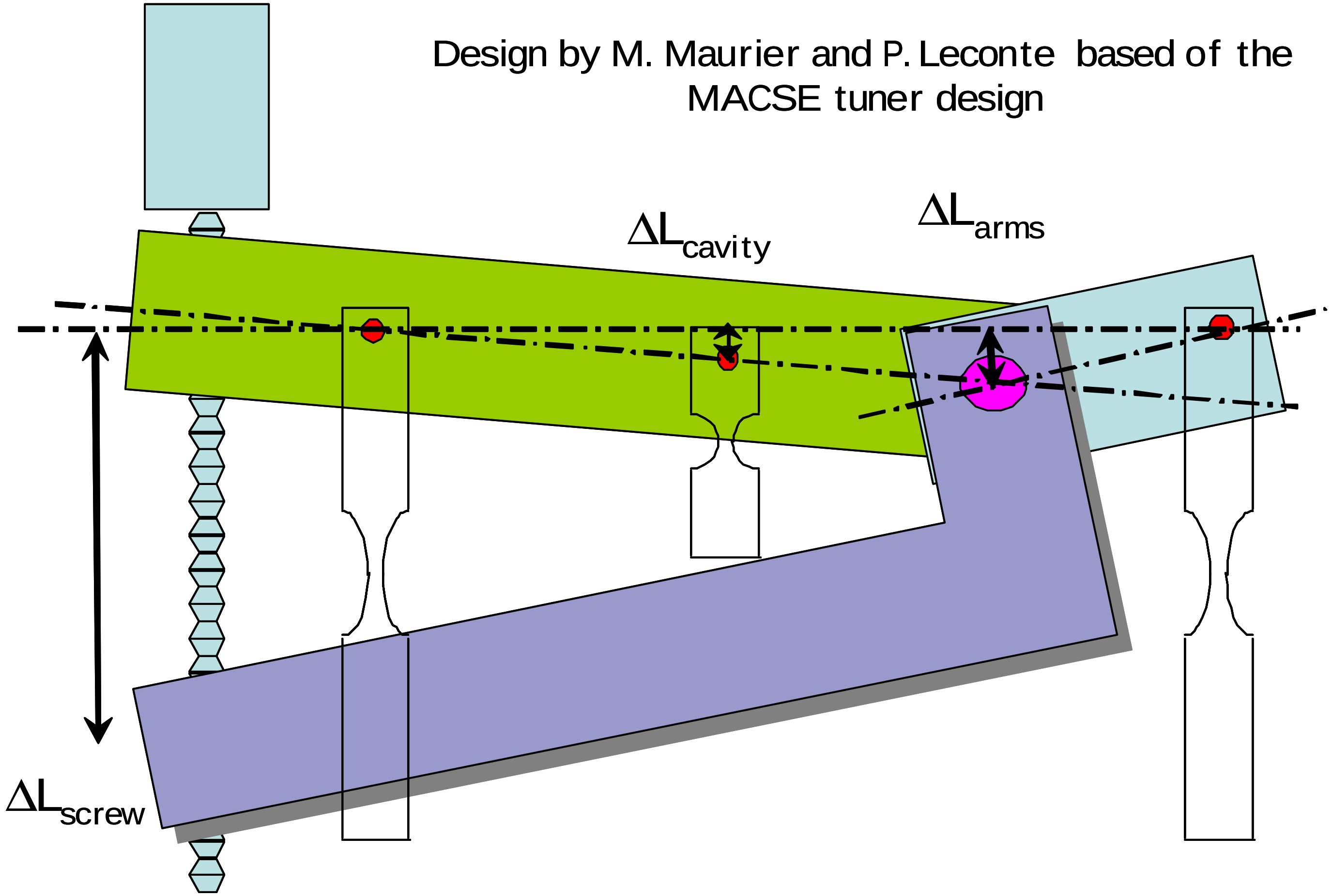
Mechanical Tuner

- Principle: Mechanical change of length or mechanical deformation of the cavity





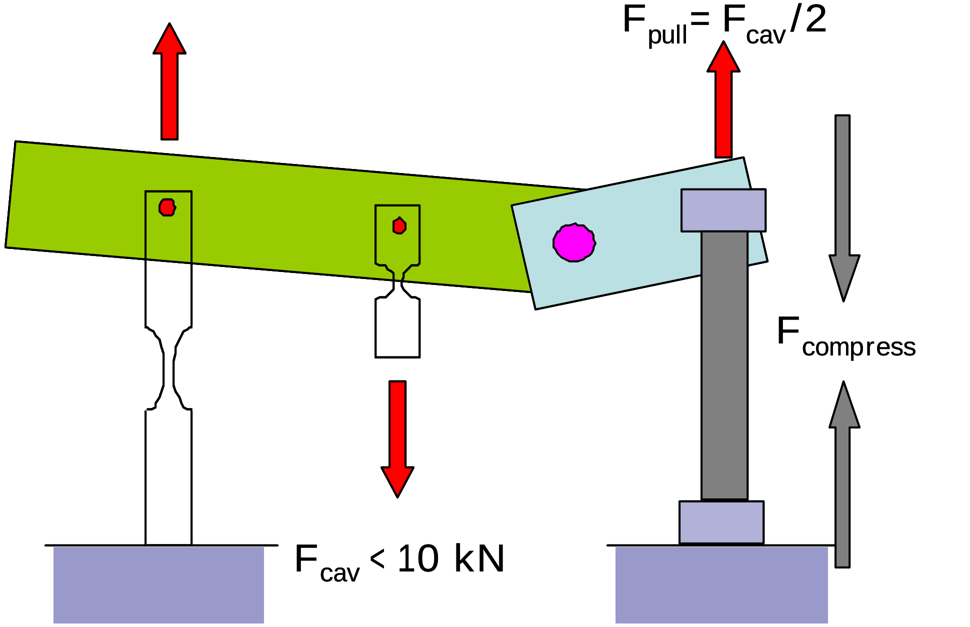
Mechanical Principle of Present TTF Tuner

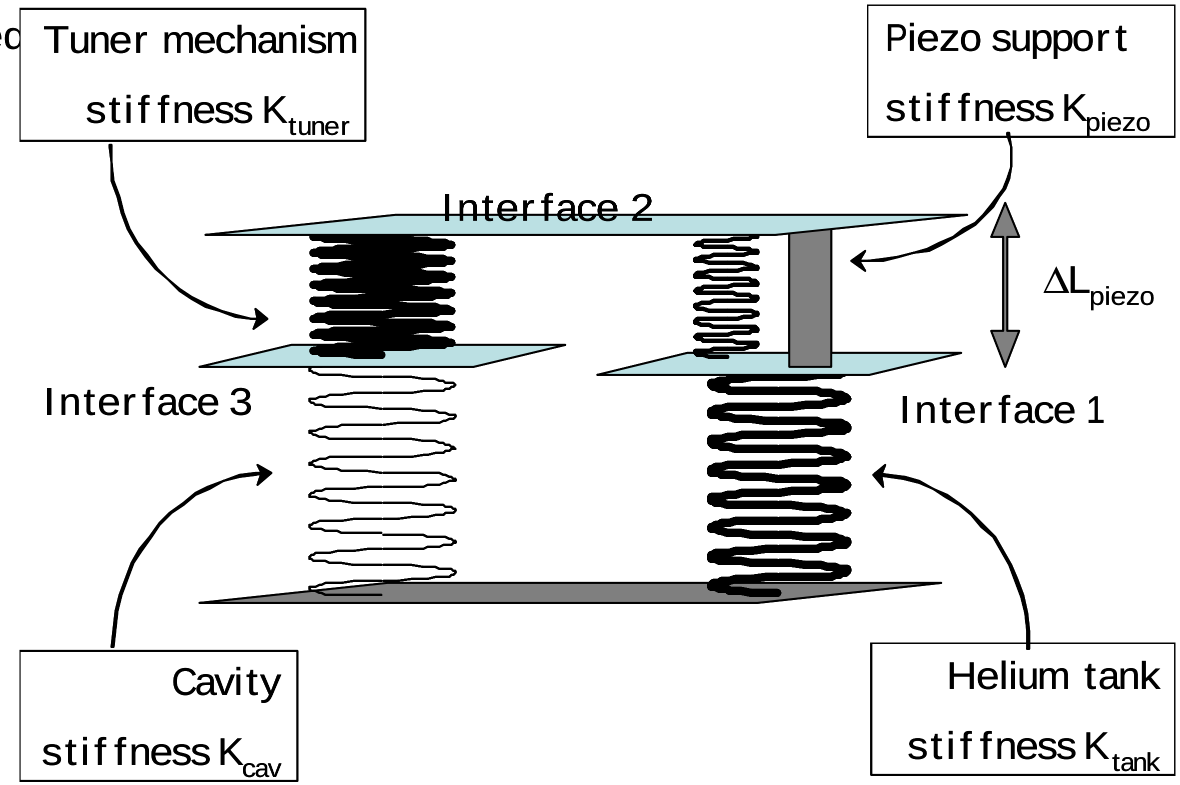


- Double lever system ratio ~1:17
- Stepping motor with harmonic drive gear box
- Screw-nut system : lubricant treatment (balzers Balinit C coating) for working at cold and in vacuum
- ΔZ = +- 5 mm and Δf = +- 2.6 MHz
- Theoretical resolution : δz = 1.5 nm !

P. Bosland

Integration of Piezo Tuner and Calculation of Forces





- The Piezo actuator is kept under compression by the support $F_{compress}$
- The effective pre-load strength on the stack is $F_{preload} = F_{compress} - F_{cav}/2$

- $\Delta L_{cav} = \Delta L_{piezo}/2$ if
  - tuner is infinit rigid (100 kN/mm vs 3 kN/mm for the cavity)
- the piezo displacemet speed is slow compared to the system response
- the tuner is not at the neutral point

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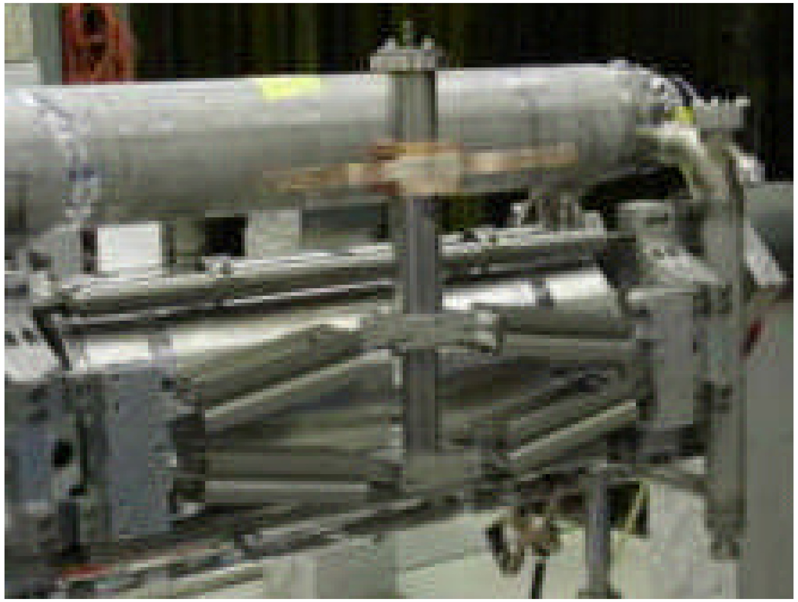
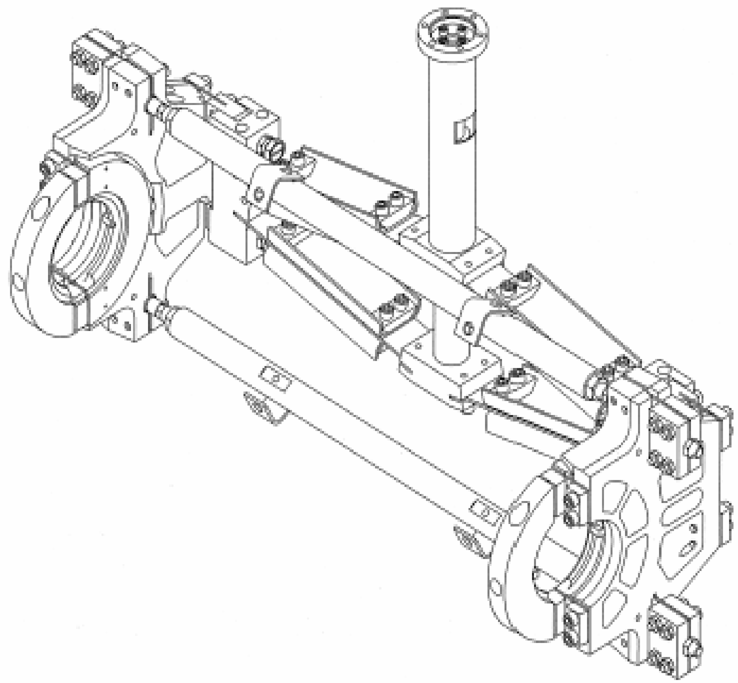
Upgrade Tuner for SL21 und FEL03

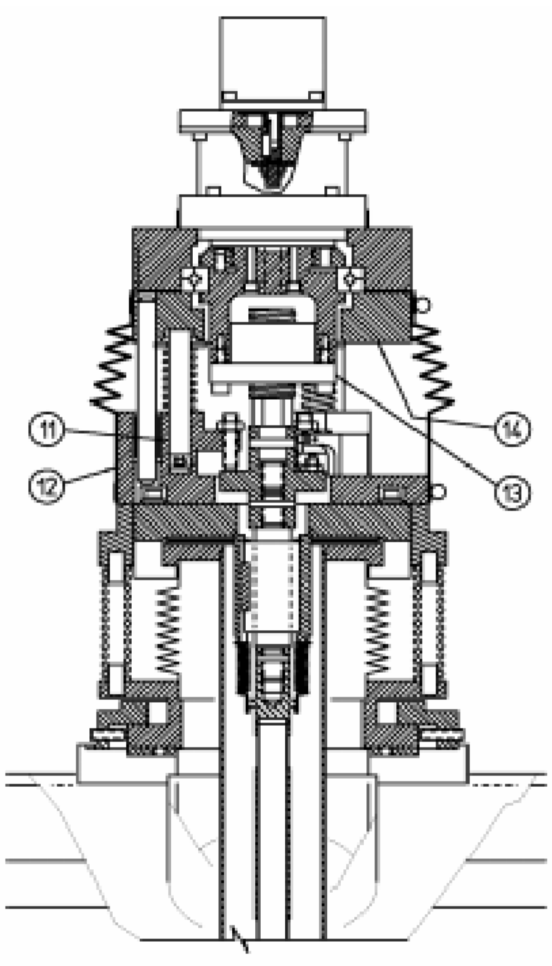
- Scissor jack mechanism
  - Ti-6Al-4V Cold flexures & fulcrum bars
  - Cavity tuner in tension only
  - Attaches on hubs of cavity
- Warm transmission
  - Stepper motor, harmonic drive, ball screw and piezo mounted on top of CM
  - Openings required in shielding and vacuum tank
- No bellows between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

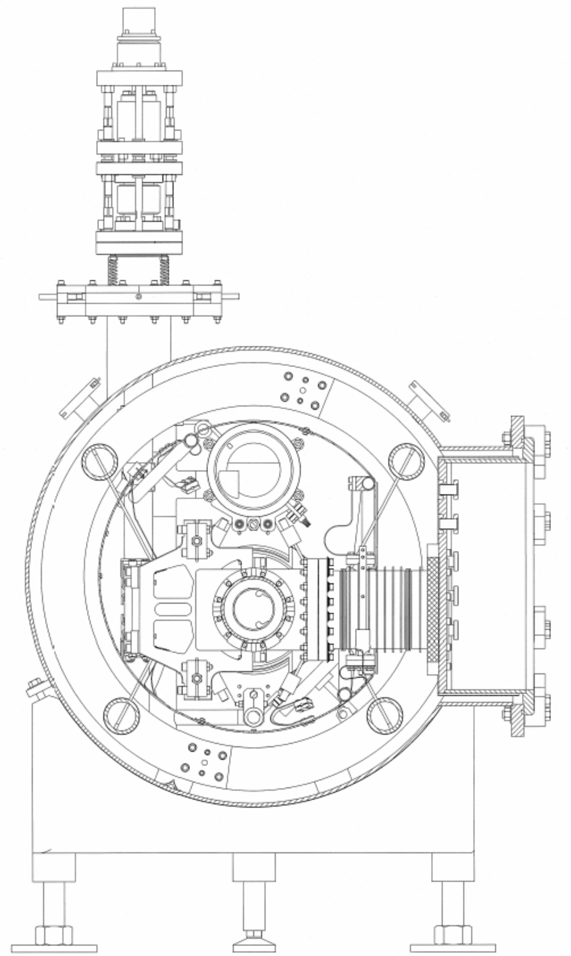




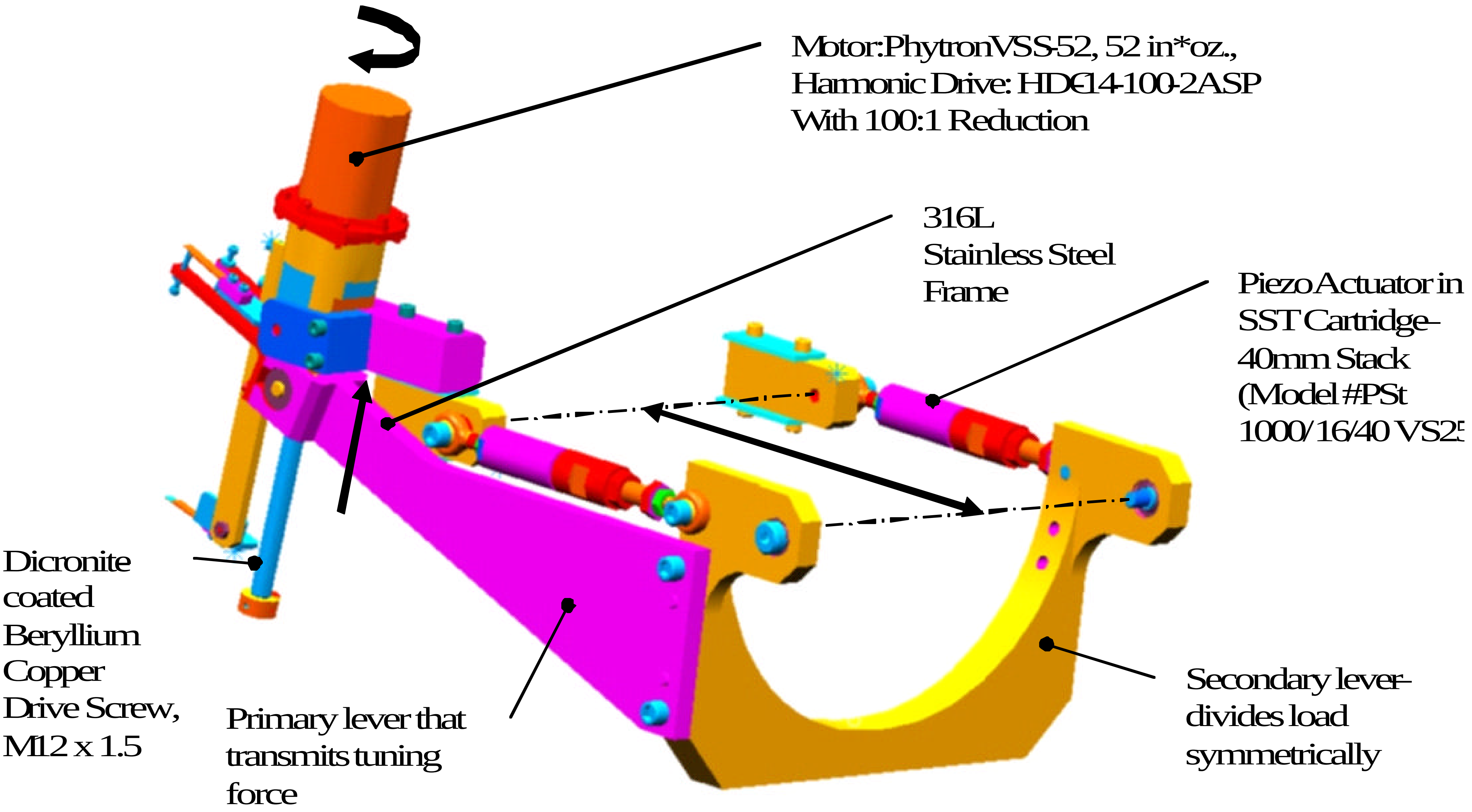
Warm Drive Components of Upgrade

- Stepper Motor
  - 200 step/rev
  - 300 RPM
- Low Voltage Piezo
  - 150V
  - 50 μm stroke
- Harmonic Drive
  - Gear Reduction 80:1
- Ball Screw
  - Lead = 4 mm
  - Pitch = 25.75 mm
- Bellows/slide
  - axial thermal
  - contraction

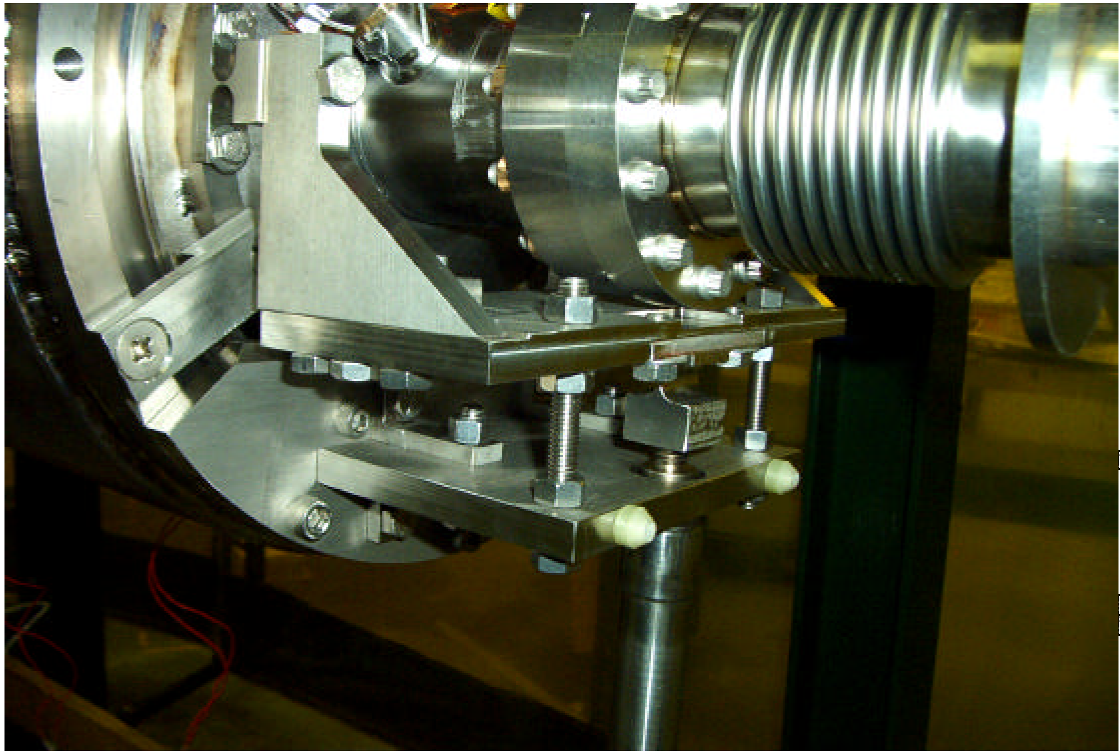


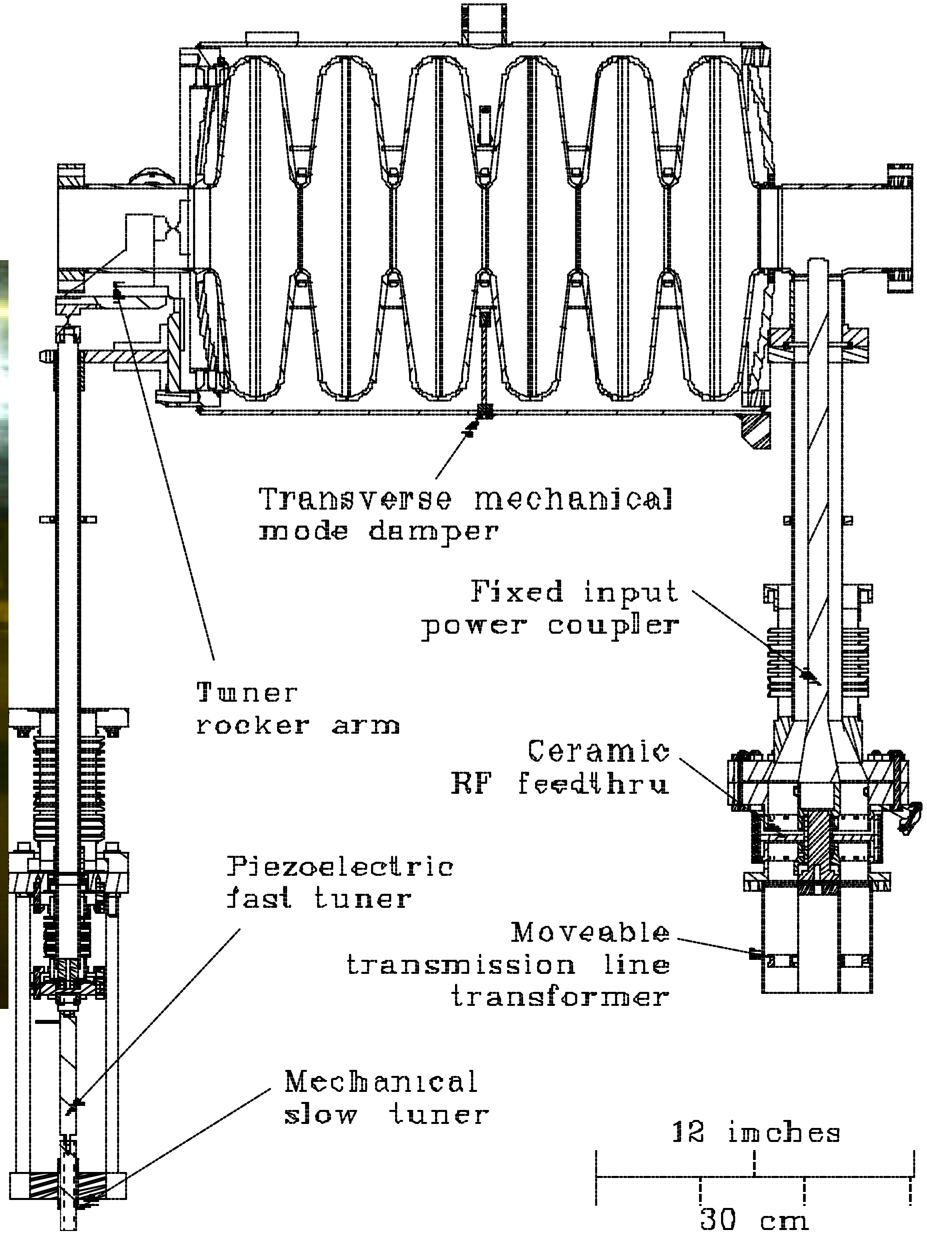


Renascense Tuner Assembly with Cold PZT

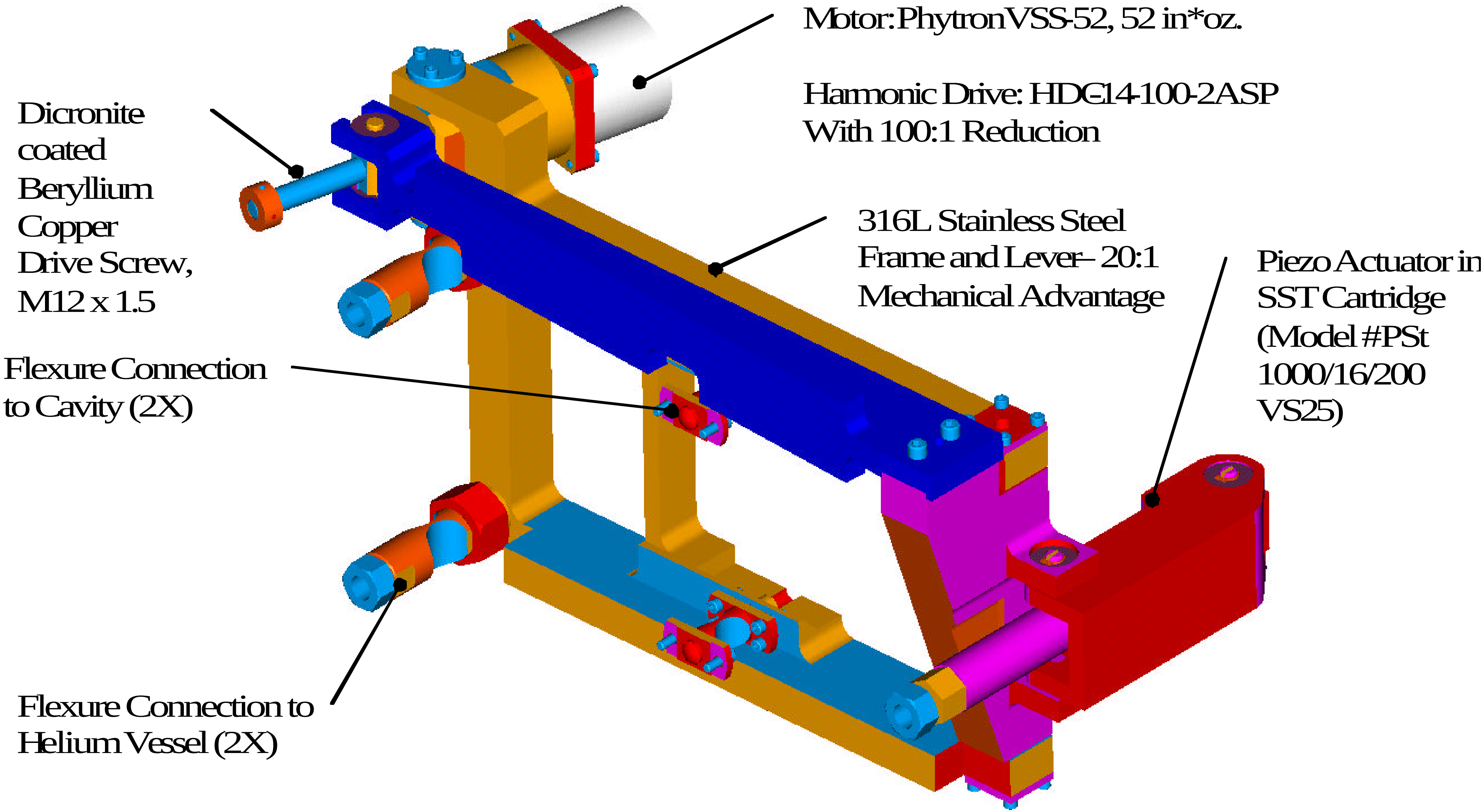


RIA Tuner - Rocker Arm / Schematic

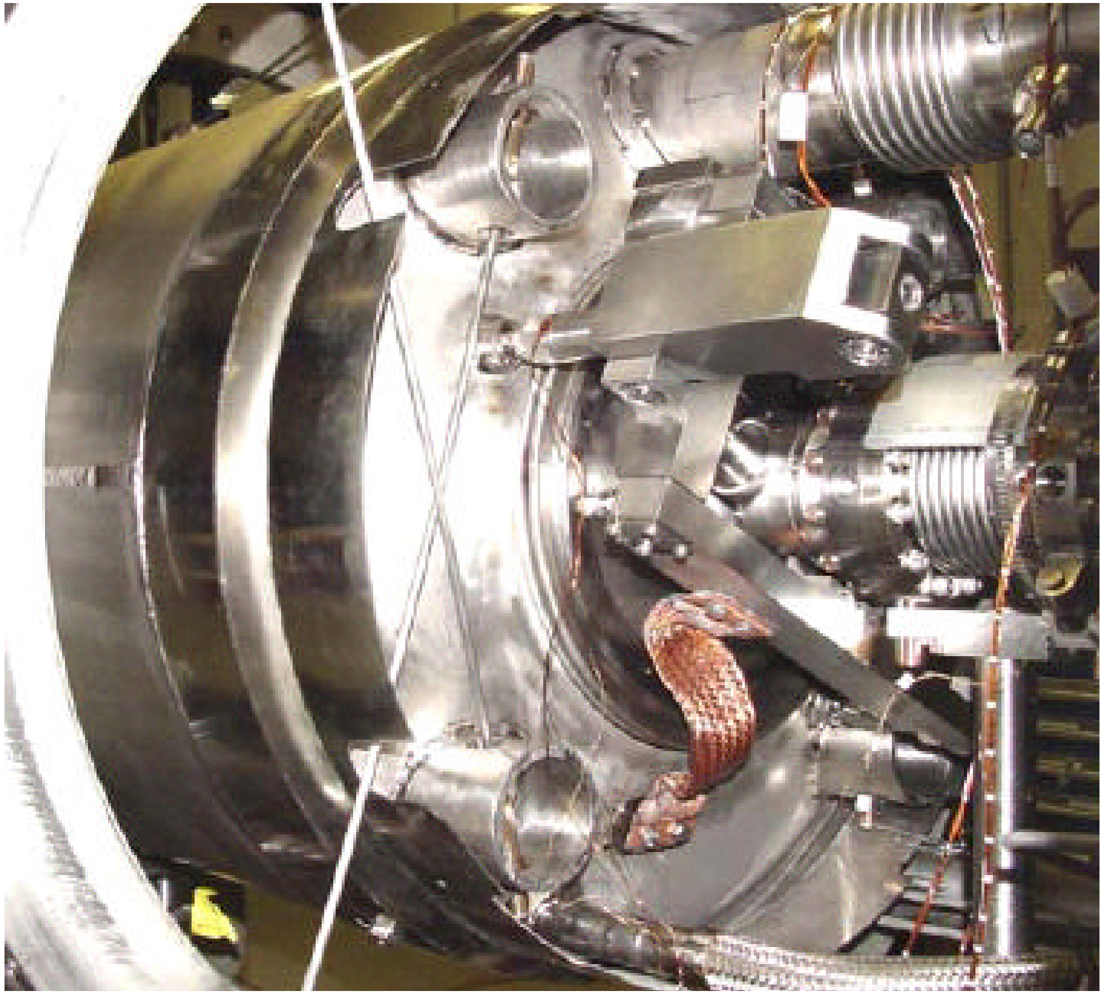


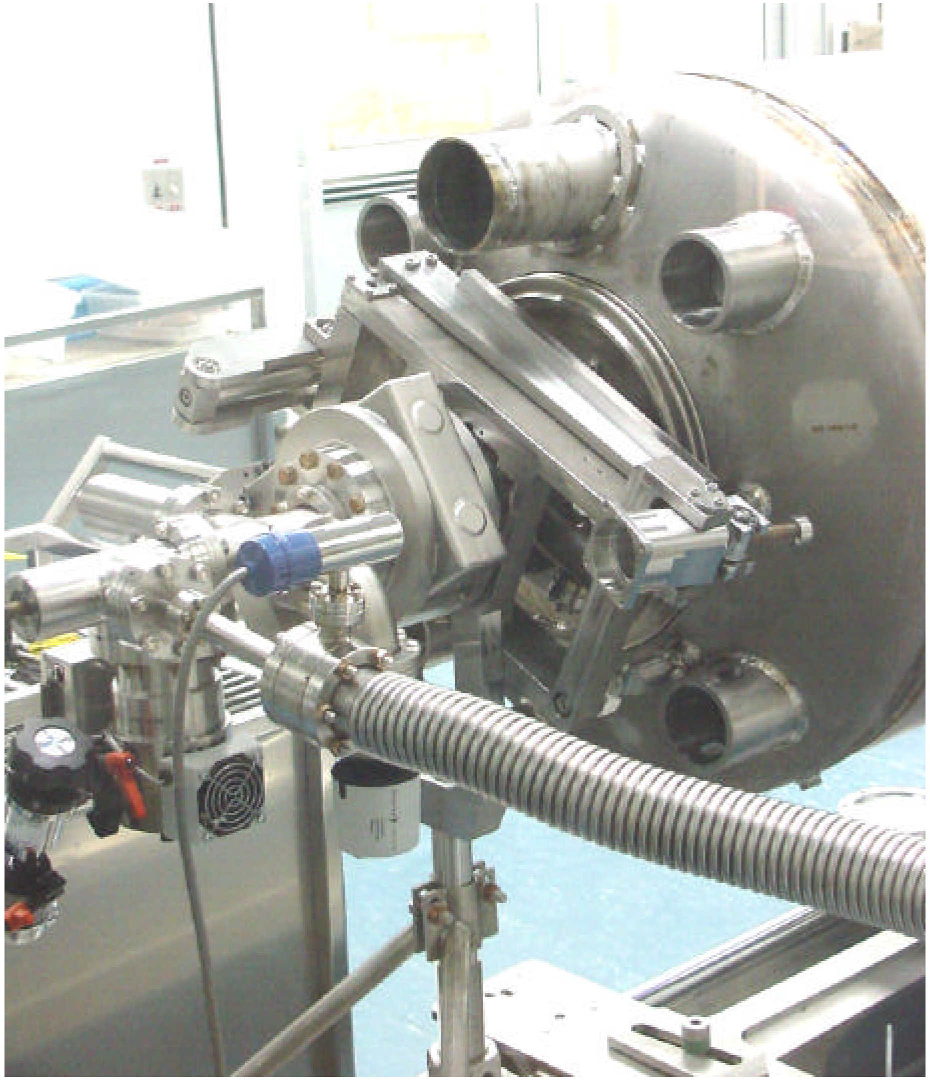


SNS Tuner Assembly with PZT

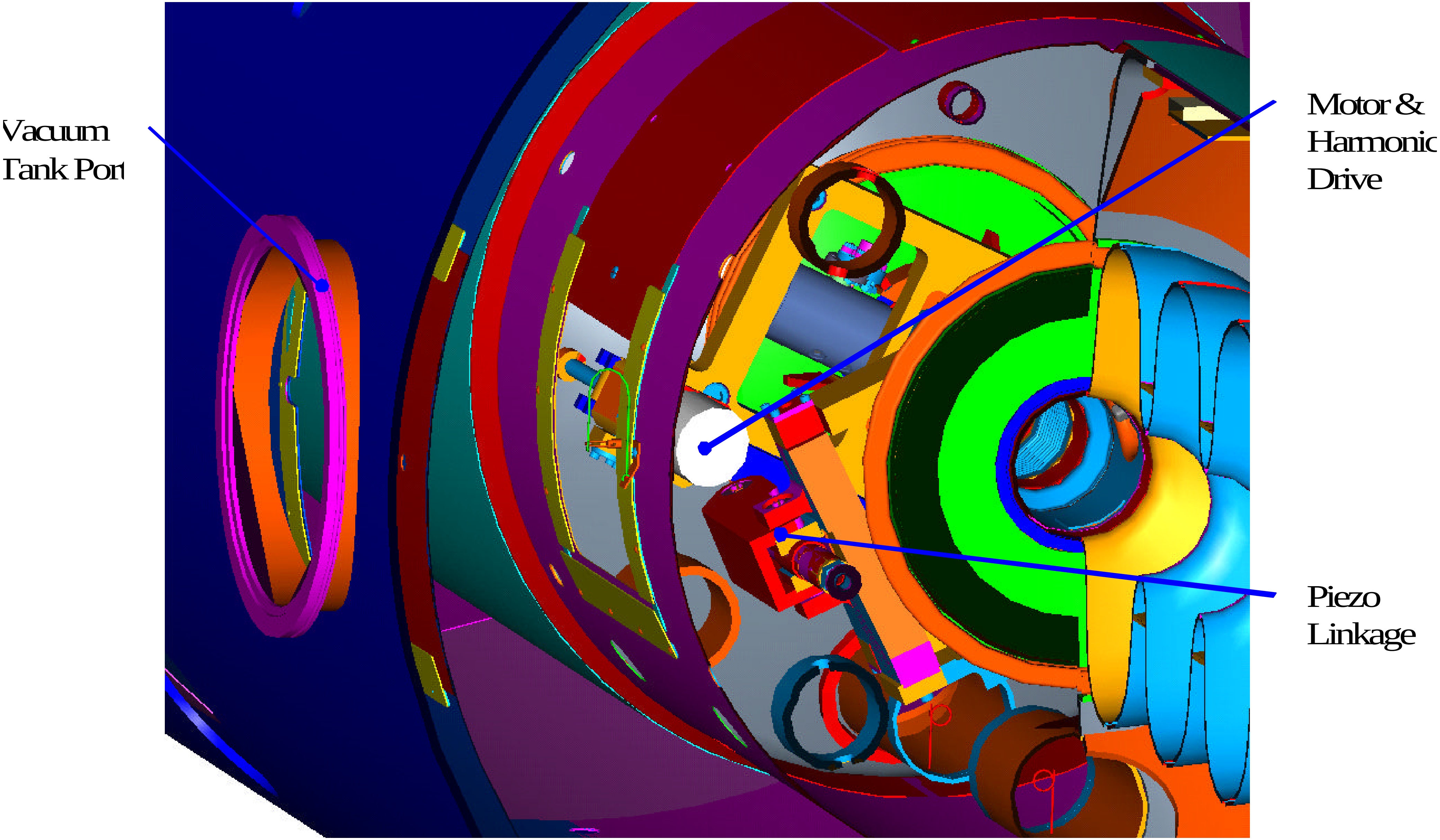


SNS Tuner Installed

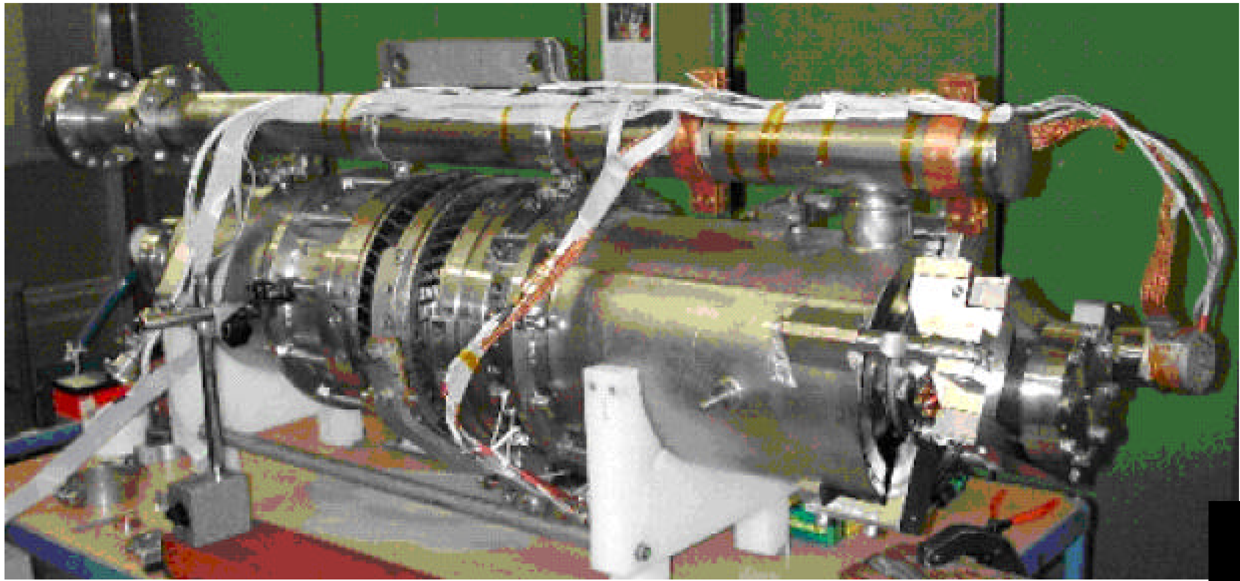


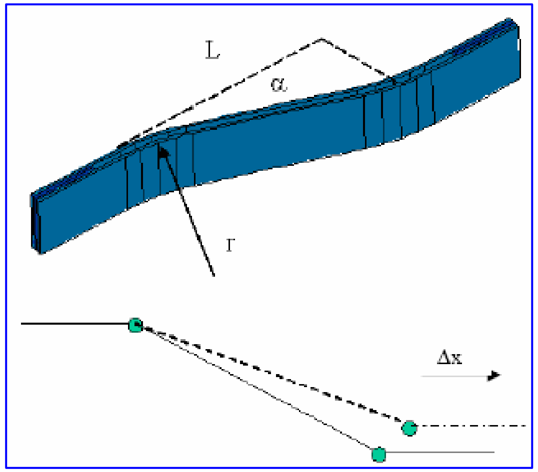


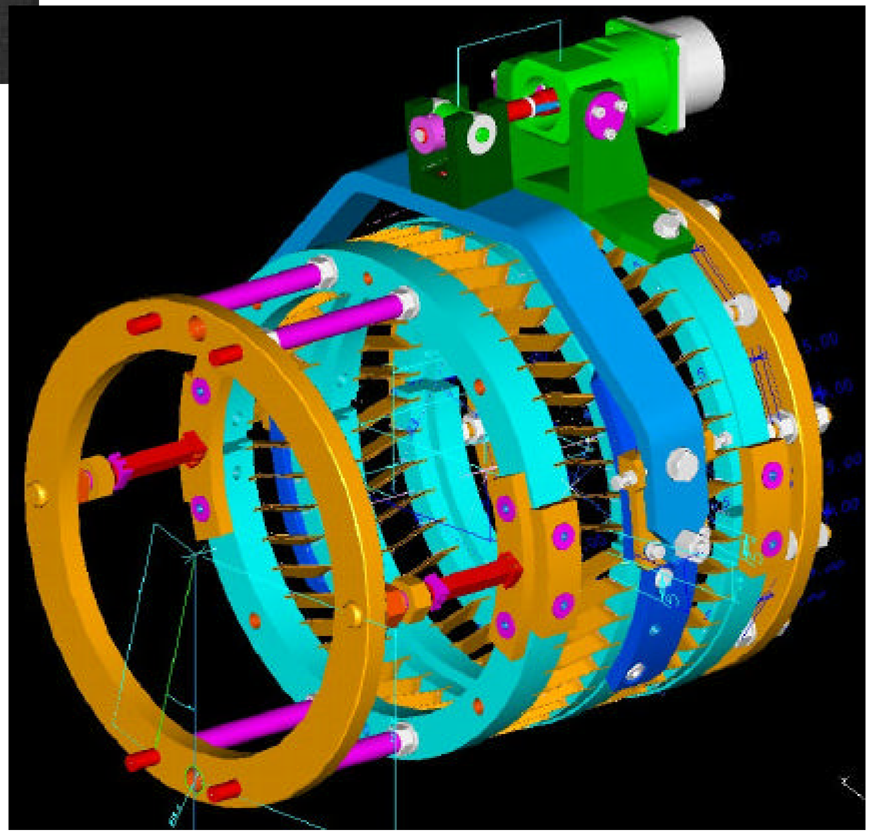
SNS Cryomodule



TESLA Blade Tuner with Piezo Tuner

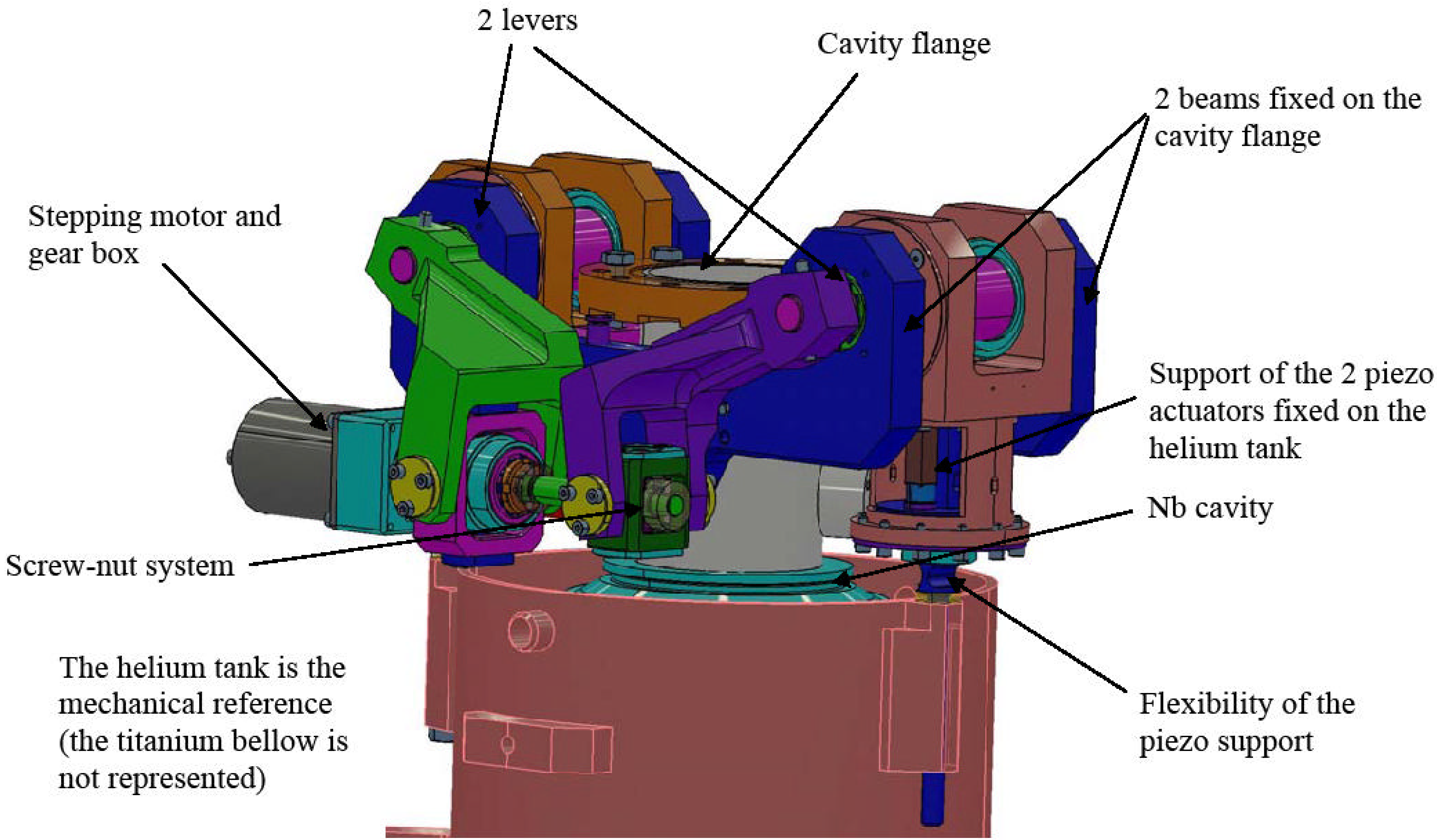




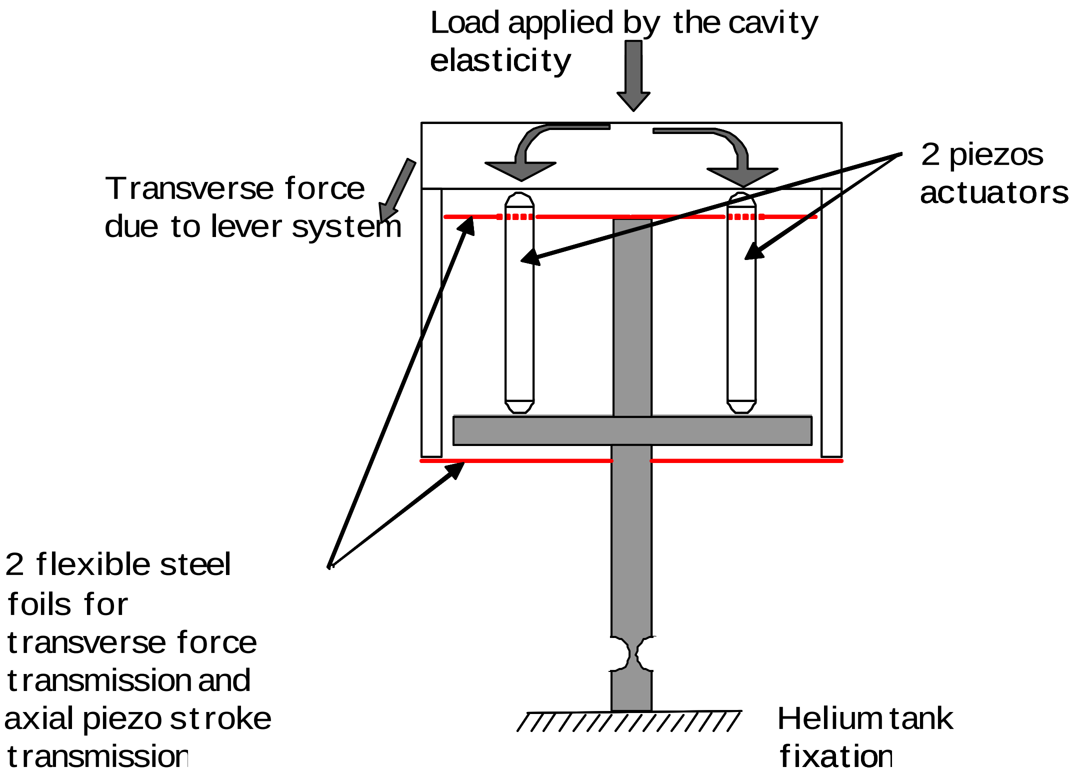


- Mechanism - All cold, in vacuum
  - Titanium fixture
  - Attaches to helium vessel
  - Pre-tune using bolts pushing on shellrings
  - Dichronite coating on bearings and drive screw
  - Cavity tuned in tension or compression - blades provide axial deflection

Saclay Tuner II

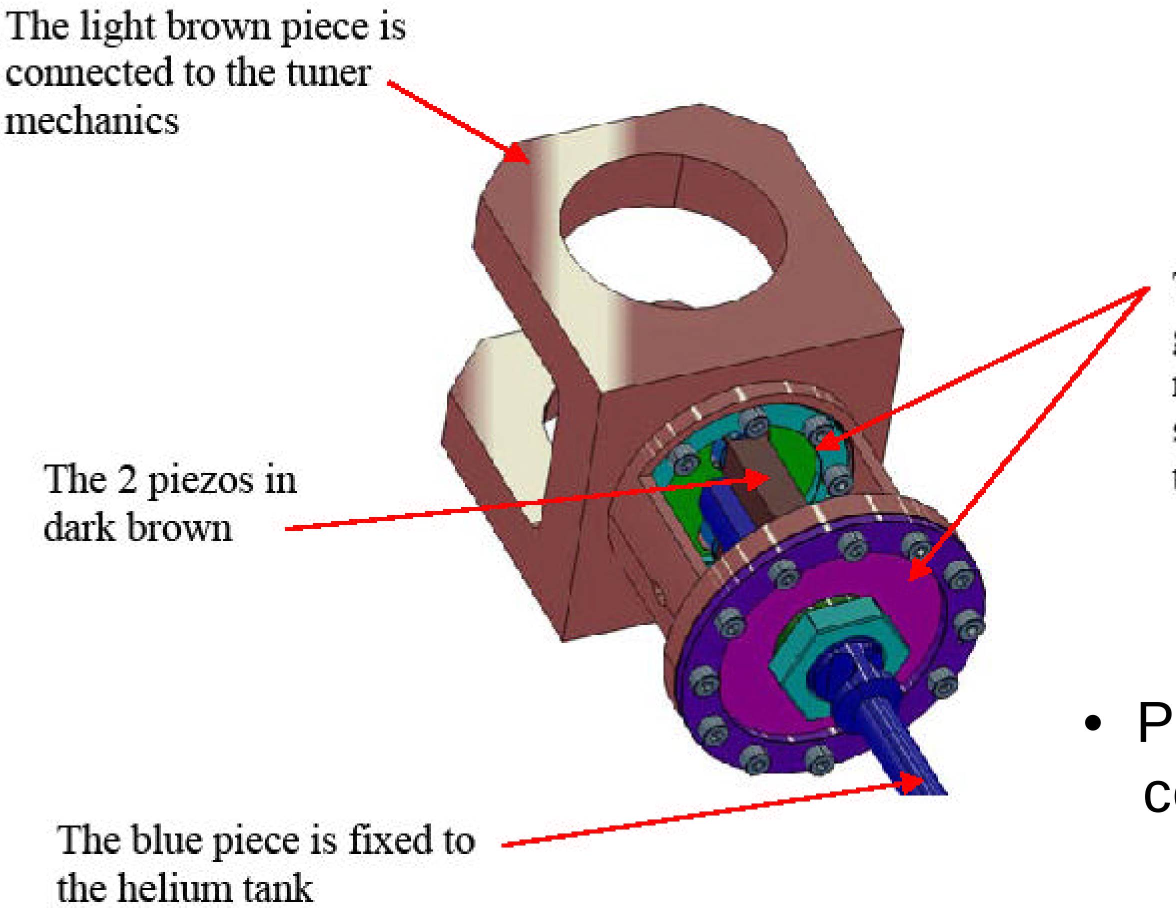


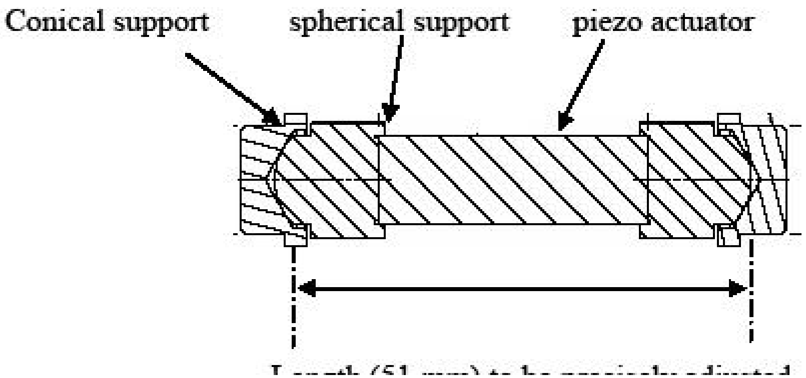
Saclay Tuner II



- Pre-load is applied to the piezo by cavity elasticity
- Will allow tuning of +-2 MHz @300K and +-460 kHz @ 2 K
- 2 piezo actuators are inserted at symmetric positions. Both can act either as actuator or sensor
- The 2 piezo actuator are guided by 2 flexible steel foils with 2 functions:
  - Allowing axial stroke. Stiffness of steel foils (1kN/mm) is small compared to piezo (300kN/mm)
  - Compensating transverse forces

Saclay Tuner II

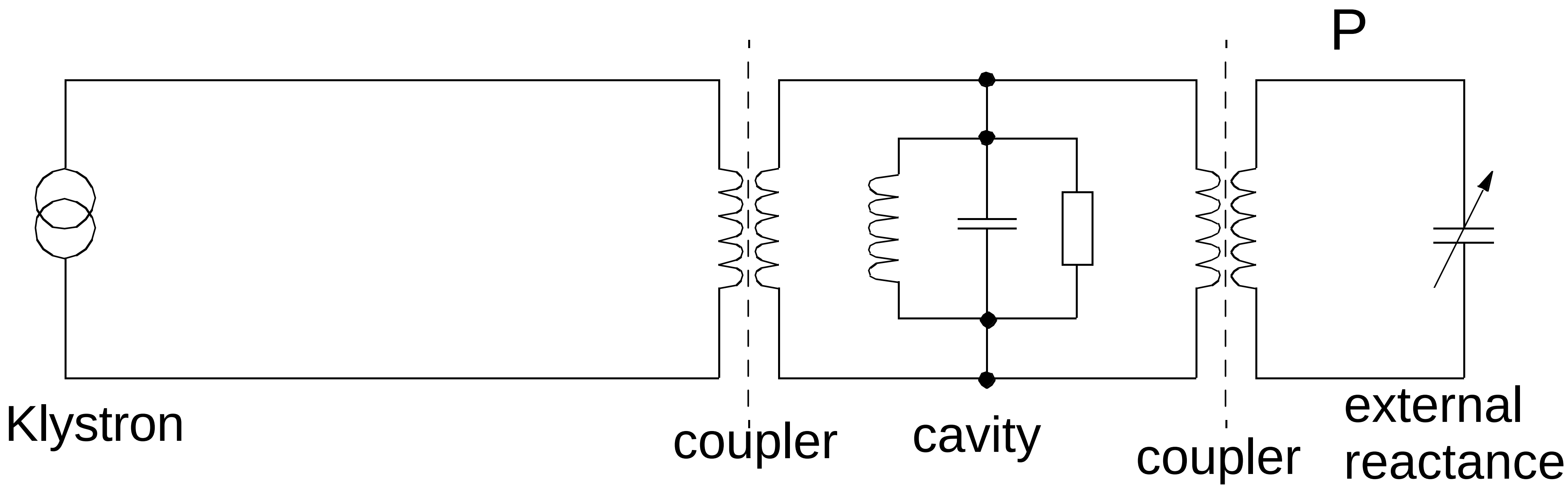




- Piezos are mounted with a sphere cone system
  - to equilibrate the forces on the 2 piezos. Poor tolerance of piezos (+-0.5mm) requires precise machining
  - mimize the deformation of the steel foils

VCX Tuner

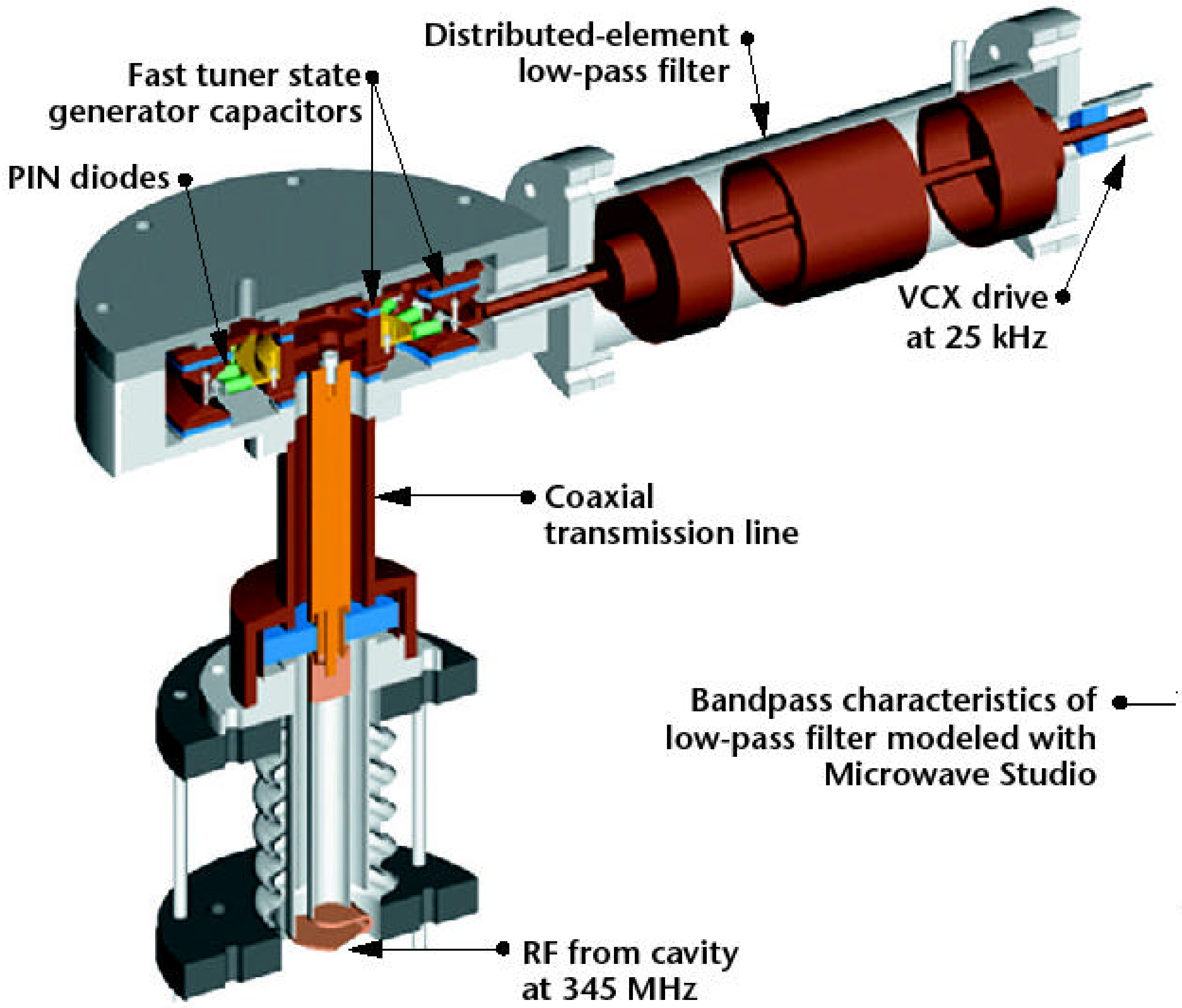
- Principle: Variable external Reactance controls Resonance frequency of System

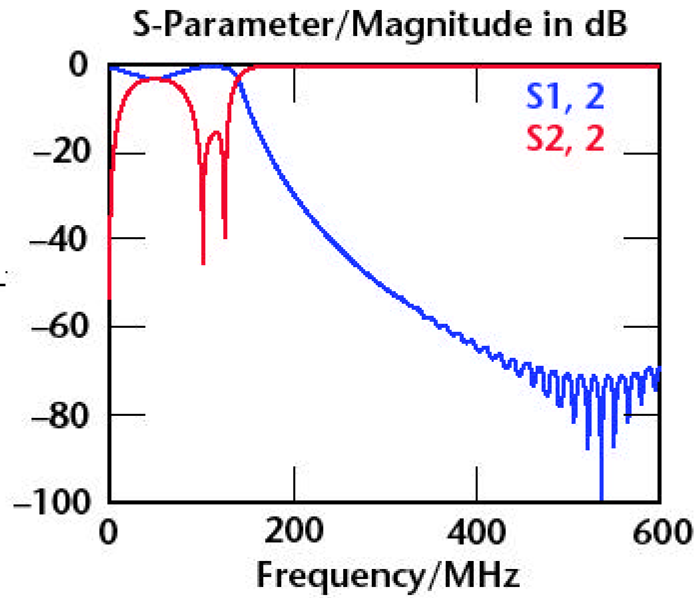


- Reactive power required: $P = 8 \times \pi \times \Delta f \times U_o$
- Example TESLA cavity @ 25MV/m and 1kHz tuning
  $P = 8 \times \pi \times 1000\ \text{Hz} \times 76\ \text{J} = 2\ \text{MW}$

VCX Tuner

- Example: VCX Tuner for RIA



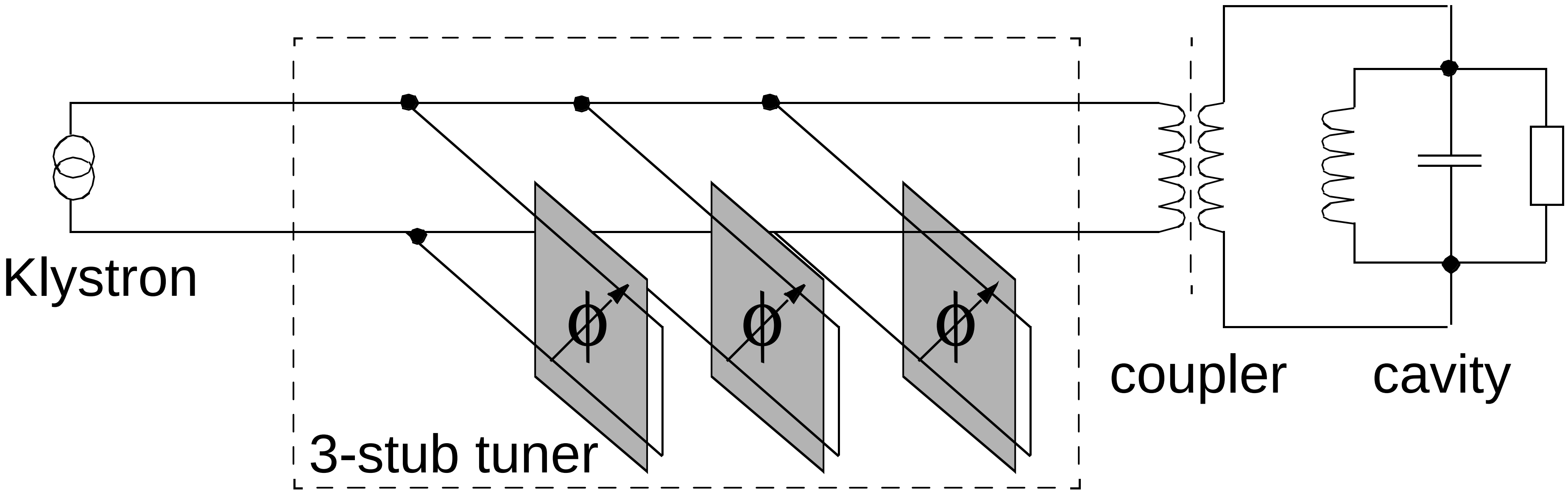


- Main objective is to provide larger tuning range at higher gradients
  =>
  higher power handling capability

B. Rusnak

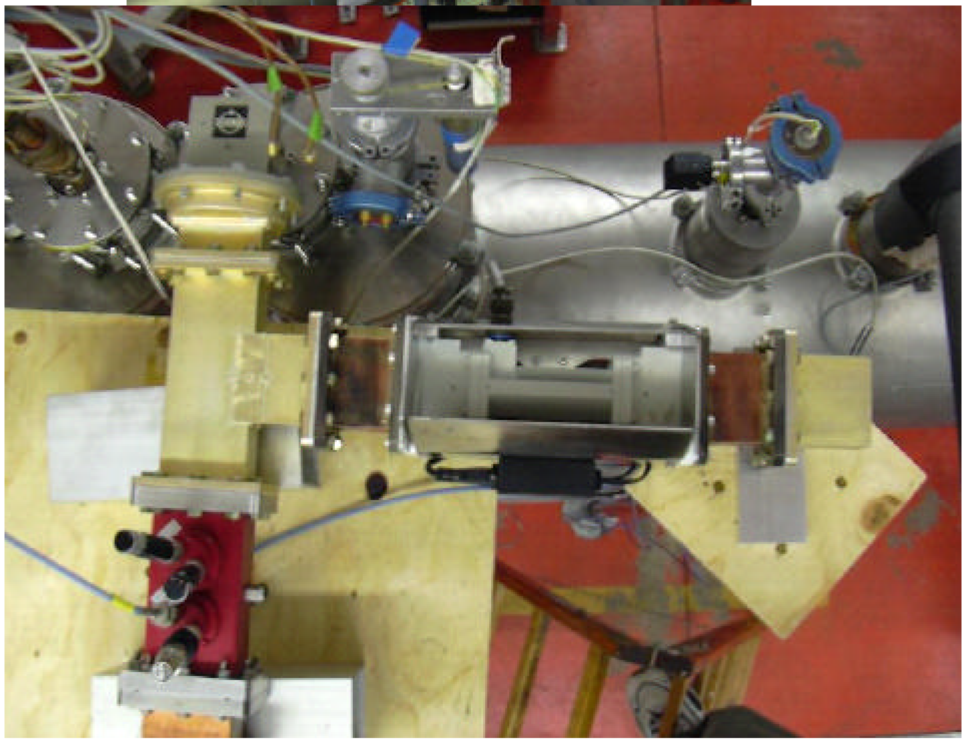
VCX Tuner

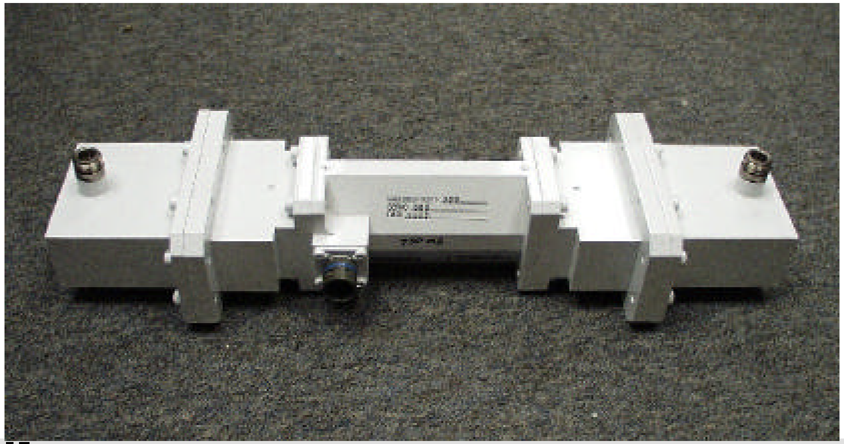
- Realization with Ferrite based Electronic Phaseshifters:

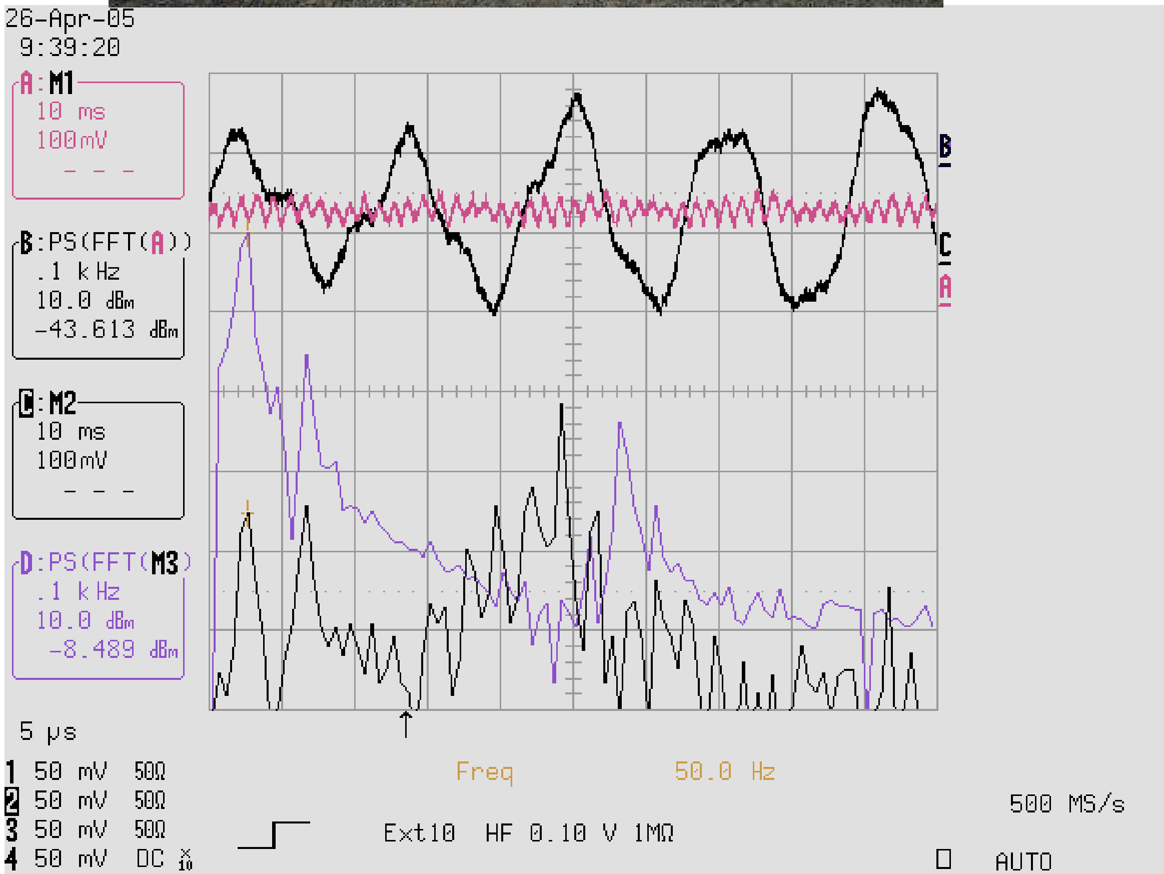


- Advantage: Controll of Q_L and Δf (within limited range)

Ferrite Tuner Test at Darmstadt







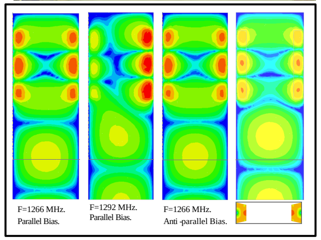
T. Zwart

Ferrite Tuner Development

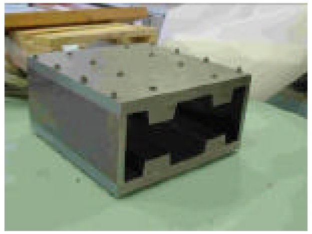
YIG Ferrite Phase Shifter Prototypes (1300 MHz Waveguide Style)

Water-Cooled Waveguide Stub

Bias Coils



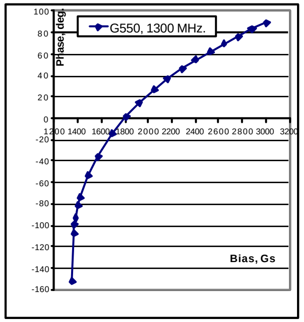
Simulation



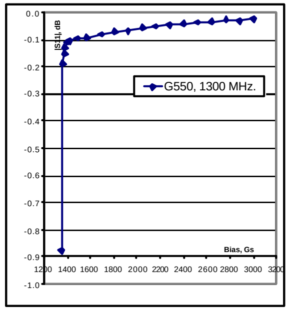
Bias Yoke

Iouri Terechkine, Timergali Khabiboulline, Ivan Gonin (TD)

1300 MHz Waveguide YIG Ferrite Phase Shifter Low Power Measurements



About 200 degree phase shift for bias range 1350-3000G.



Absorption <0.1dB with phase shift ~160 degrees

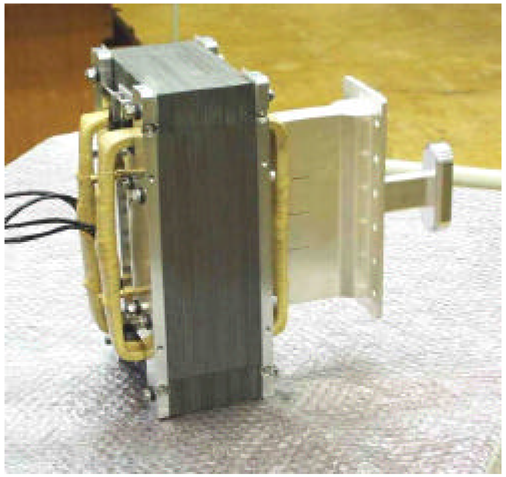
- High Power measurements coming soon

Ferrite Tuner (coax)

- Coax design is preferred at 325MHz
- In-house design tested to 660kW at 1300 MHz
- To be tested with Argonne / APS 352MHz Klystron
- Fast coil and flux return should respond in ~50us

Dave Wildman (AD), Vladimir Kashikhin, Emanuela Barzi (TD)

Development Contract Placed with AFT for full-spec 1300 MHz I/Q tuner assembly



AFT 352 MHz Single tuner built for CERN SPL

Complete I/Q Tuner Including:

- Two Phase Shifters
- Hybrid
- Control Electronics
- FNAL-Provided Power Supply

Al Moretti (AD)

B. Foster

Conclusion

- Frequency tuner designs have advanced significantly during during the last decade to meet the needs of the high gradient and/or pulsed superconducting accelerators
- A variety of technologies are available for cavity tuner designs. However no tuner will fulfill all requirements simulta-neously. The art is to find the best compromise.
- Challenges nowadays
  - Integration of slow and fast tuner with well defined pre-load on piezo-electric or magnetostrictive actuator
  - Developement of fast ferrite tuner for high power applications
  - Easy Maintenance
  - Cost Reduction