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Superconducting RF for storage rings, ERLs, and linac-based FELs:

- Lecture 11 ***Frequency tuners***

Frequency tuner functions & design issues

Why do SRF cavities need frequency tuners?

- Tune cavity resonance to operating frequency after cool-down
- Actively compensate reactive part of beam loading
- Detune cavity on purpose for bypass operation
- Find resonance after RF trips
- Compensate slow frequency drift
- Compensate static Lorentz force detuning (CW operation)
- Compensate dynamic Lorentz force detuning (in pulsed machines)
- Compensate microphonics (in CW-machines)

Design issues

- long lifetime
- tuner resolution
- compact
- low hysteresis / backlash
- limit range to avoid plastic deformation of the cavity
- limit cross-talk to neighboring cavities
- limit cryogenic heat load
- provide serviceability

Frequency tuner types

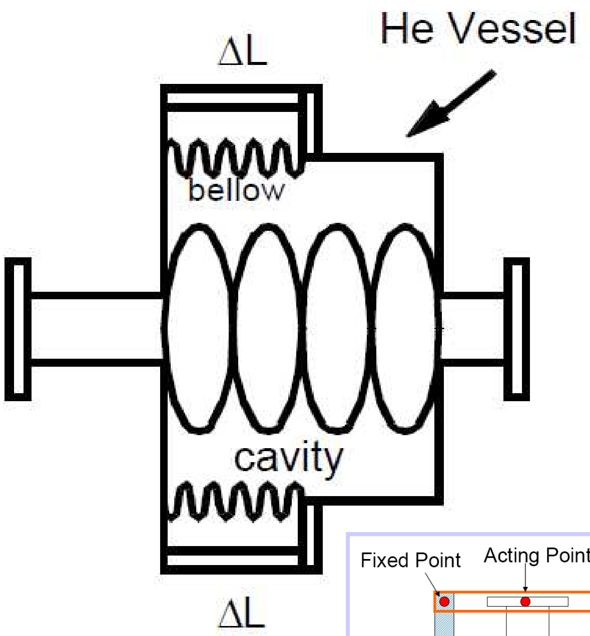
- **Mechanical length change or other deformation of the cavity**
  - **based on a motor driven mechanism (slow/coarse) → compensate slow He pressure fluctuations and beam loading; two versions: 1) warm motor + lever + tuning plate = large size, but good serviceability; 2) cold motor = compact; wide tuning range of several 100 kHz, required resolution is ~1 Hz. Typical sensitivity is ~500 Hz/μm.**
  - **based on PZT or magnetostrictive element (fast) compensate microphonics and LF detuning in pulsed machines; still under development; narrow tuning range (several cavity bandwidths), but fast response (~1 kHz).**
  - **thermal tuners (LEP).**
- **VXC (external reactance) or ferrite based tuner**
- **Other: Pneumatic, thermal, electronic damping**

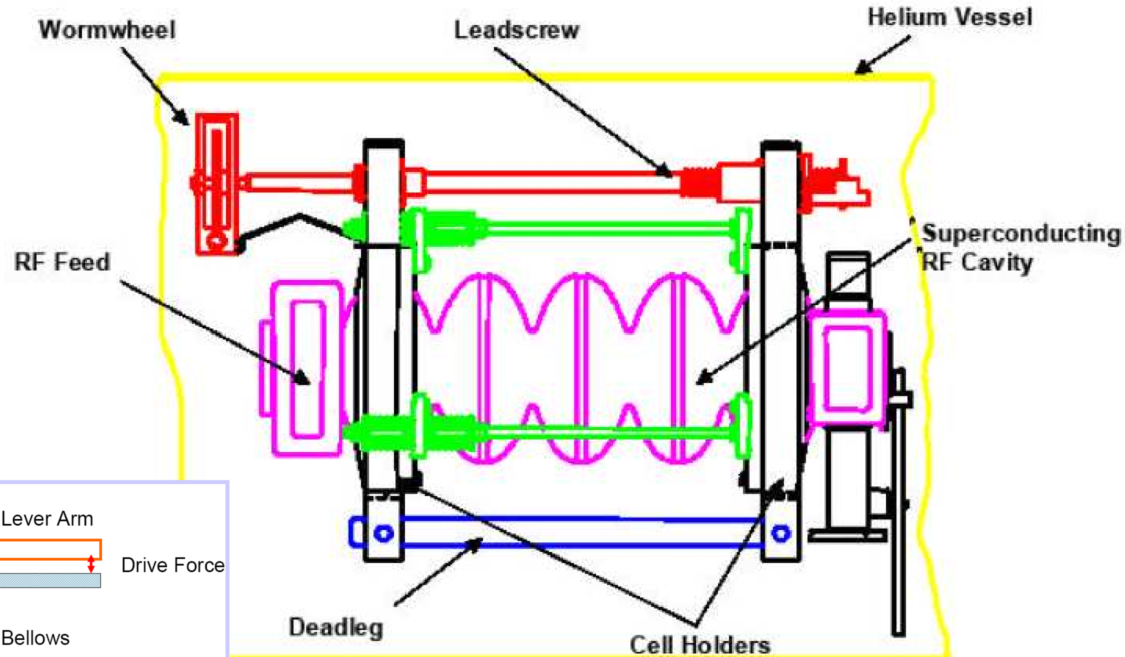
Note: **Tuners which control in addition to frequency also loaded *Q* and incident phase are possible (three stub tuner).**

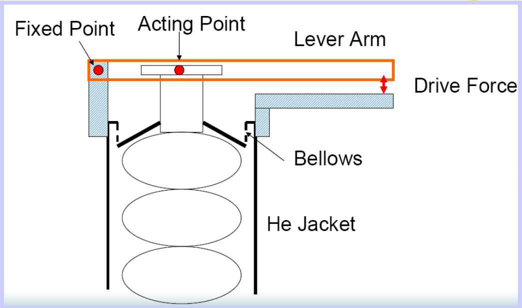
We will review only mechanical tuners as this is the only type used in high-β cavities.

Many tuners incorporate piezo elements for fast tuning.

Mechanical tuners

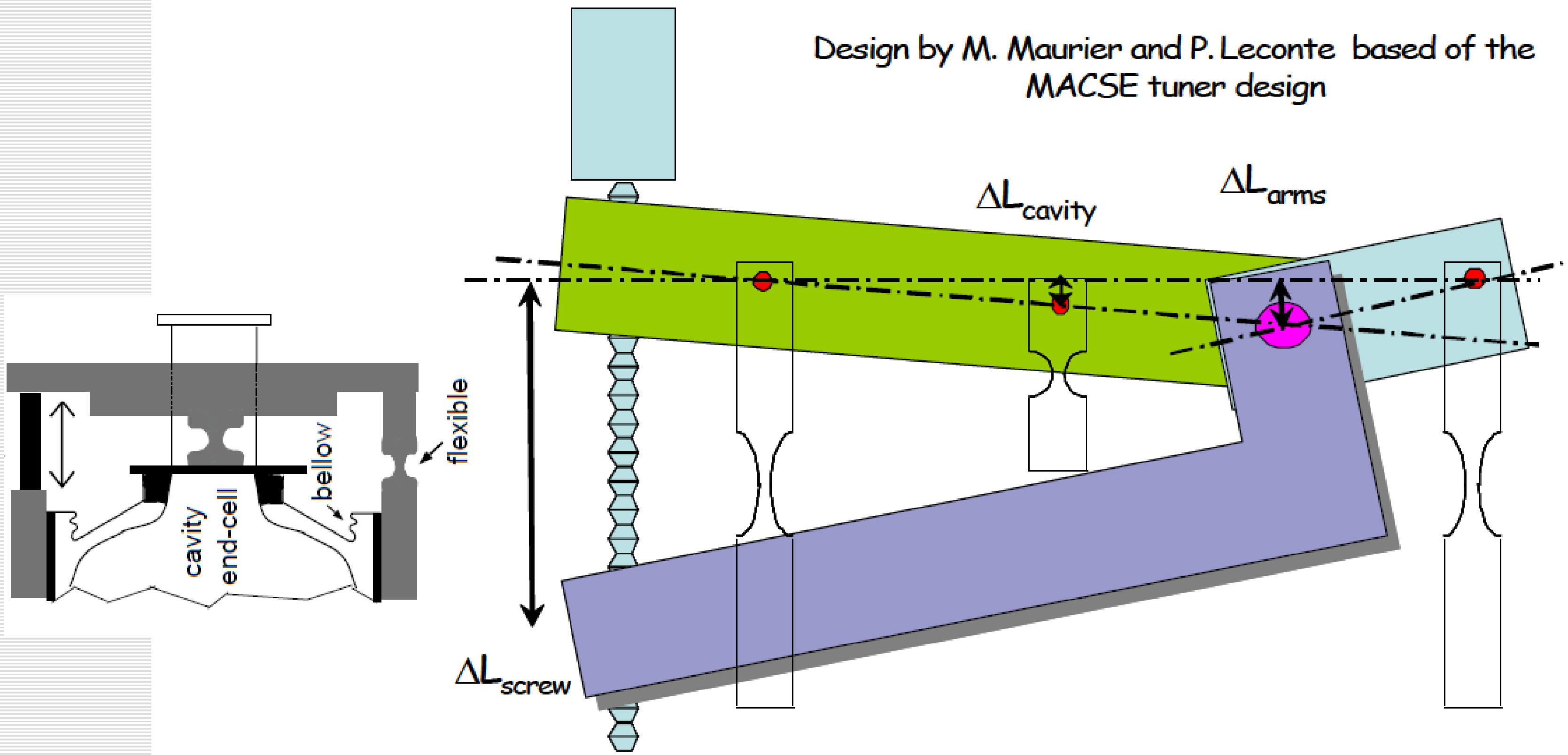






- Many tuners were developed over the years, but it seems that every mechanical engineer wants to develop his/her own design.
- We will consider how a tuner works using one example and then review several other designs.

TTF (Saclay I) 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

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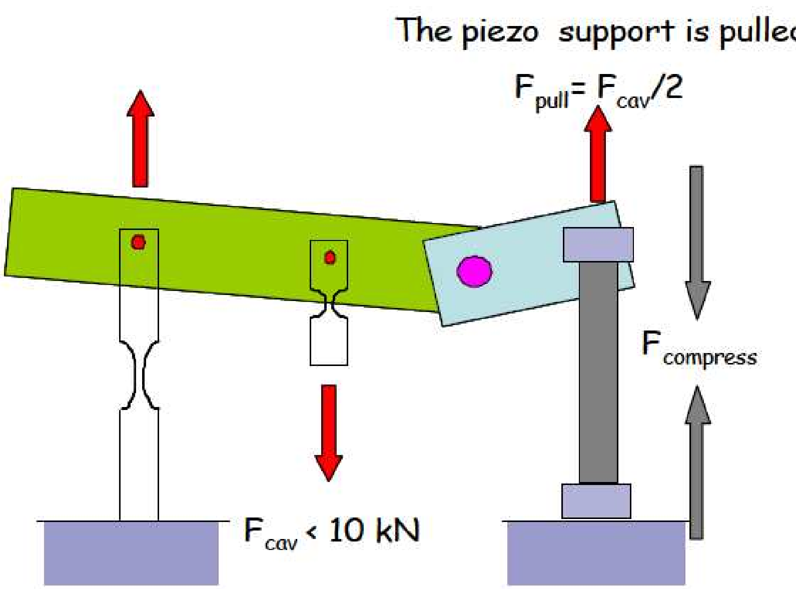
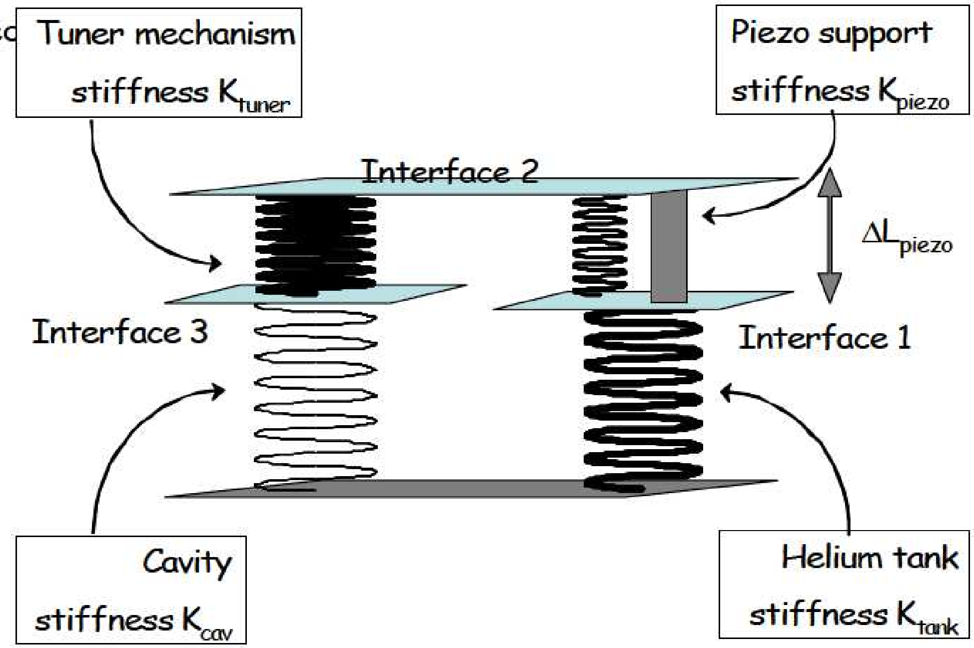
TTF tuner with piezo





- 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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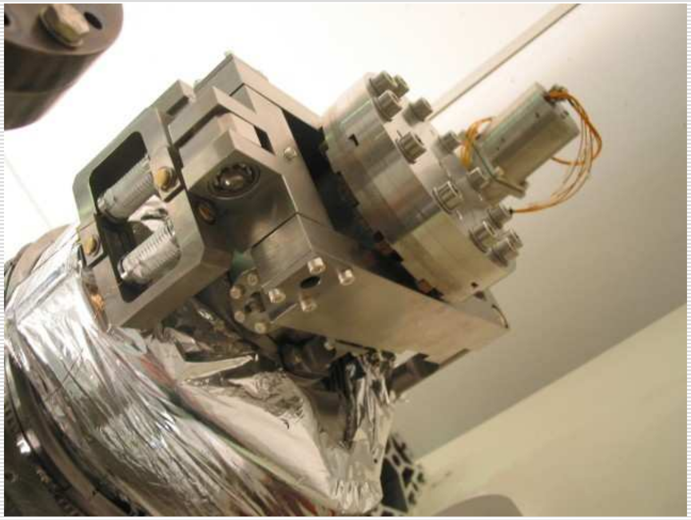
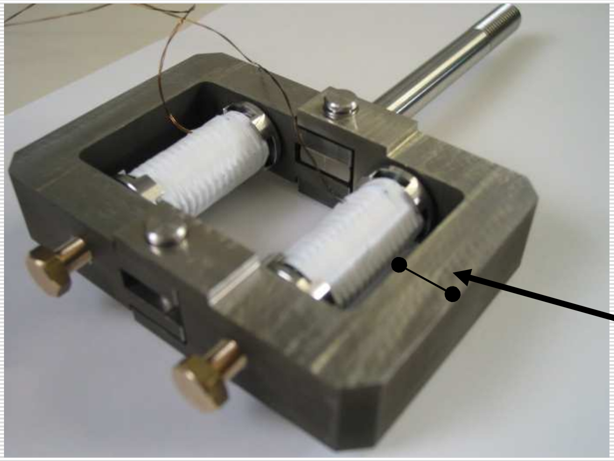
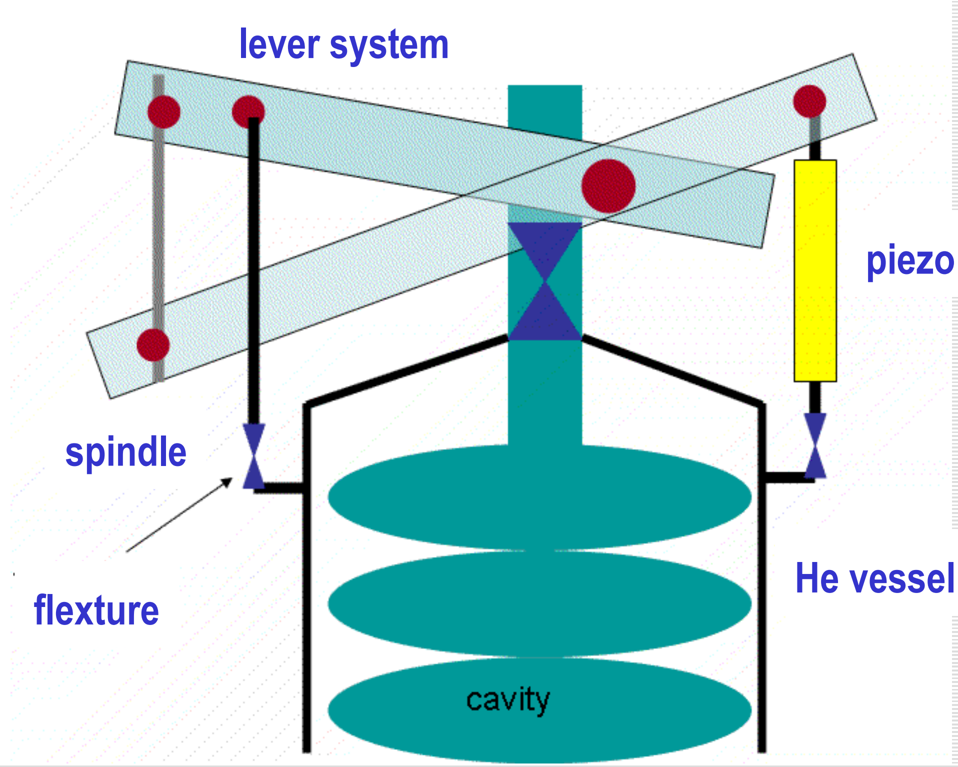
TTF tuner with piezo (2)



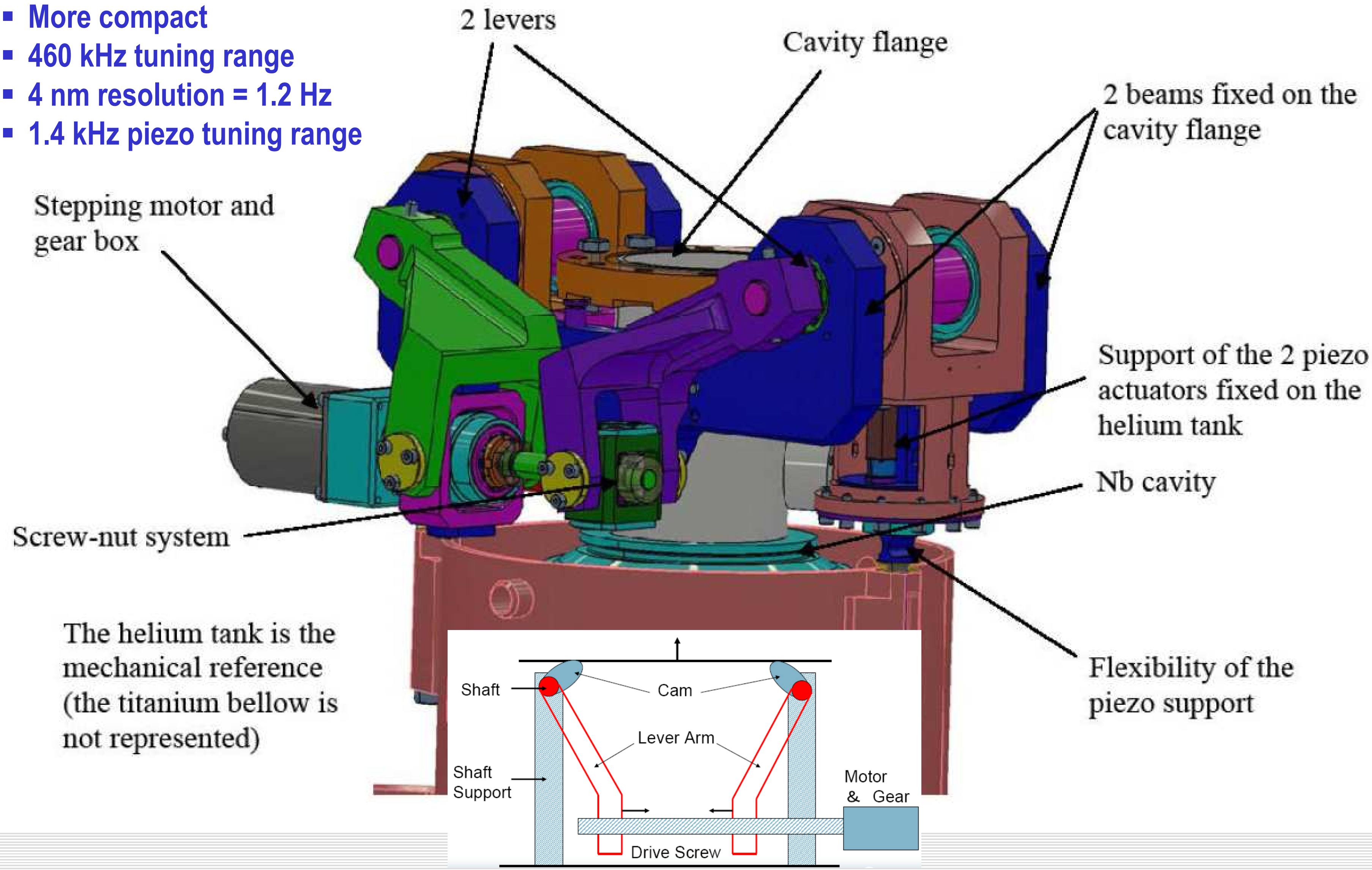




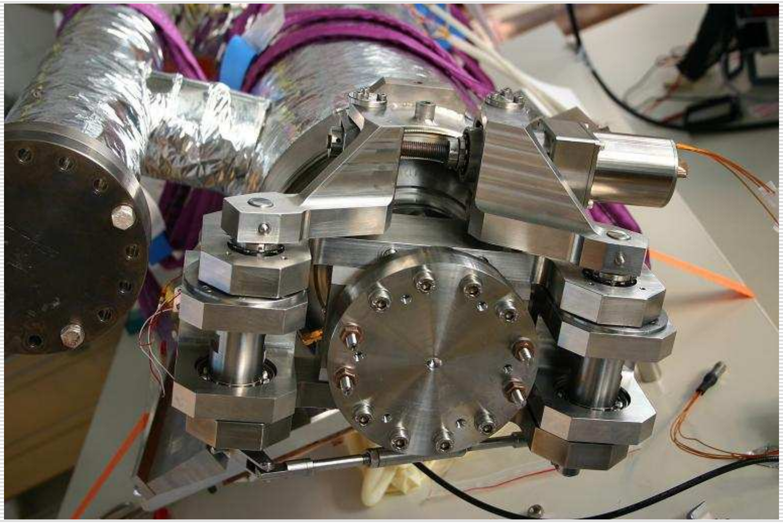
Modified piezo holder frame:
higher wall thickness

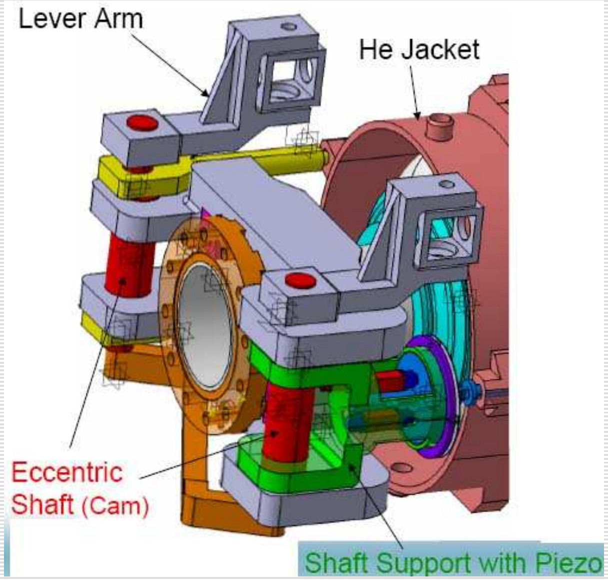
Saclay II tuner

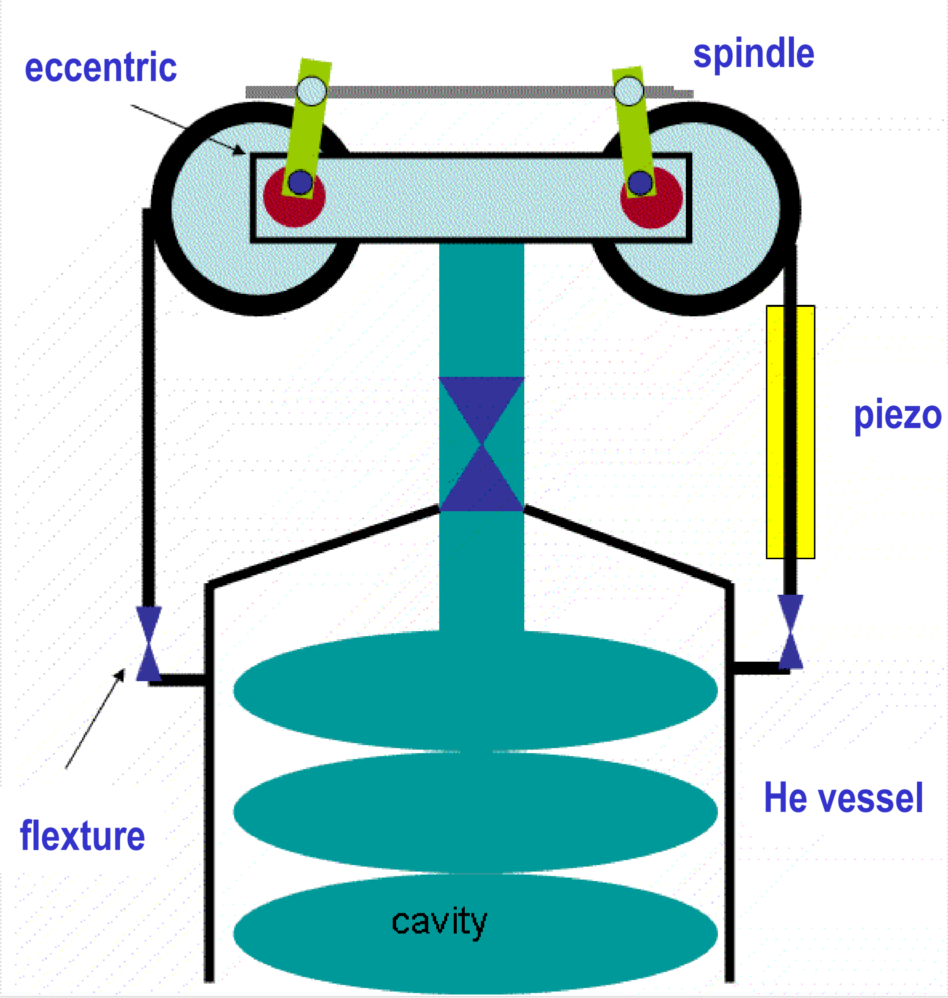
- More compact
- 460 kHz tuning range
- 4 nm resolution = 1.2 Hz
- 1.4 kHz piezo tuning range



Saclay II tuner (2)







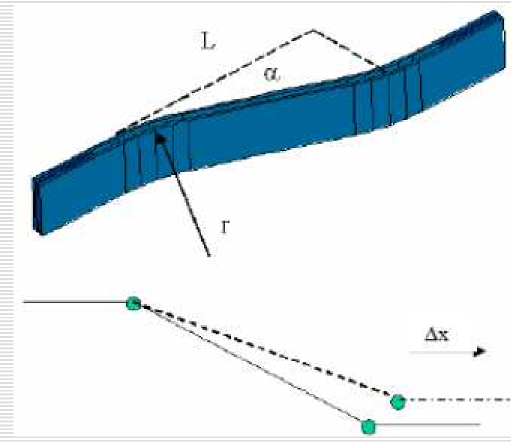
Blade tuner

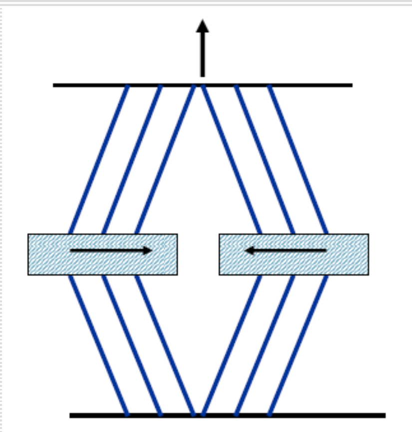
Tuner specs:

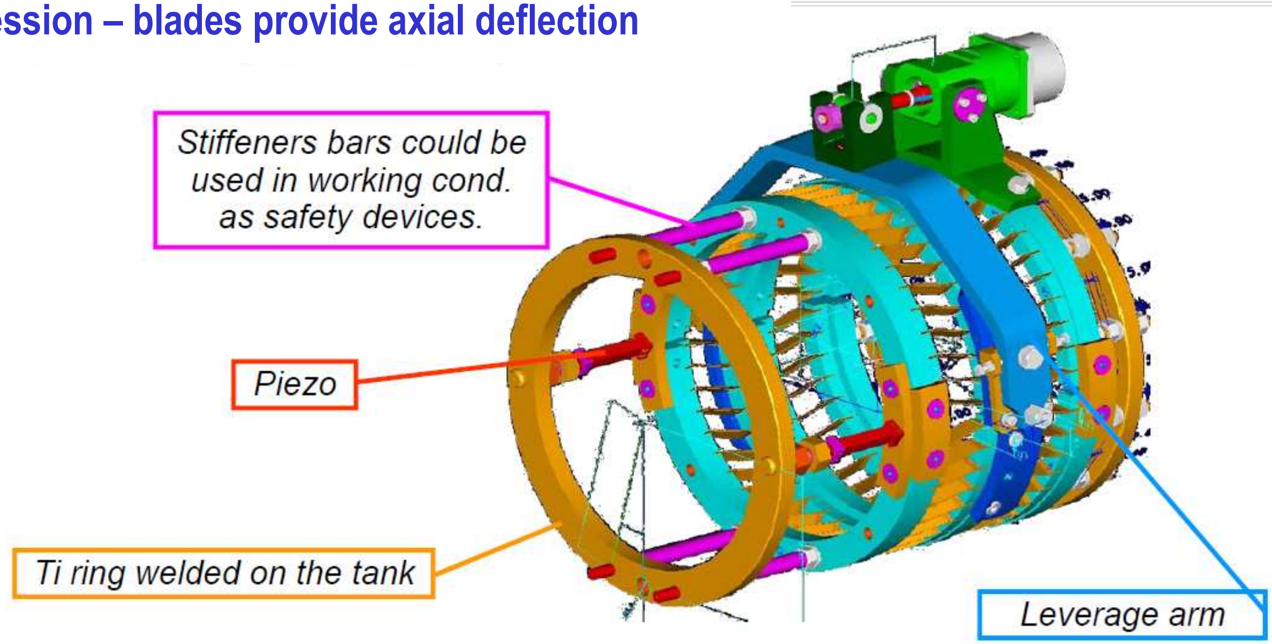
- 1 mm fine tuning (on cavity) → ΔF on all piezo (sum) ≈ 3.5 kN
- 1 kHz fast tuning → ≈ 3 μm cavity displacement → ≈ 4 μm piezo displacement
- 4 μm piezo displacement → ≈ ΔF on all piezo ≈ 11.0 N
- ~1 Hz resolution

Mechanism – all components are cold, in vacuum:

- 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

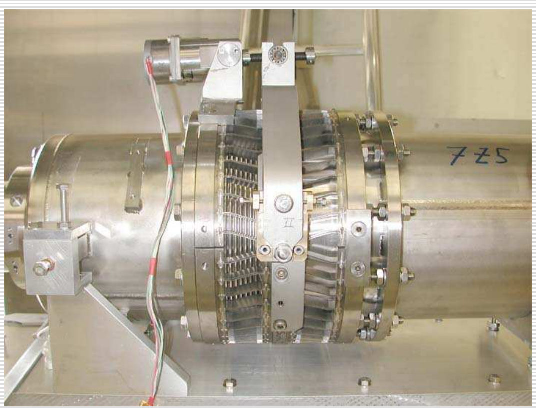






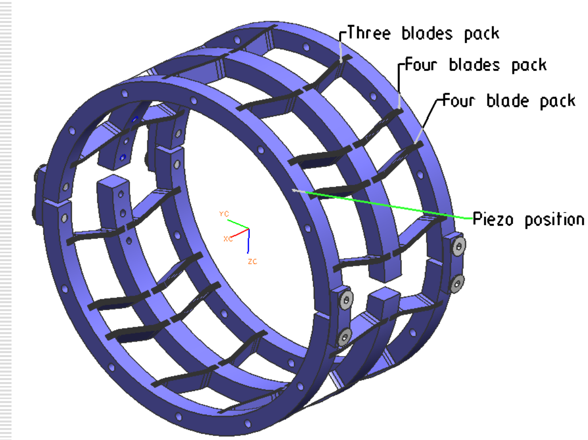
Blade tuner variations

1st DESY prototype (Kaiser, Peters)

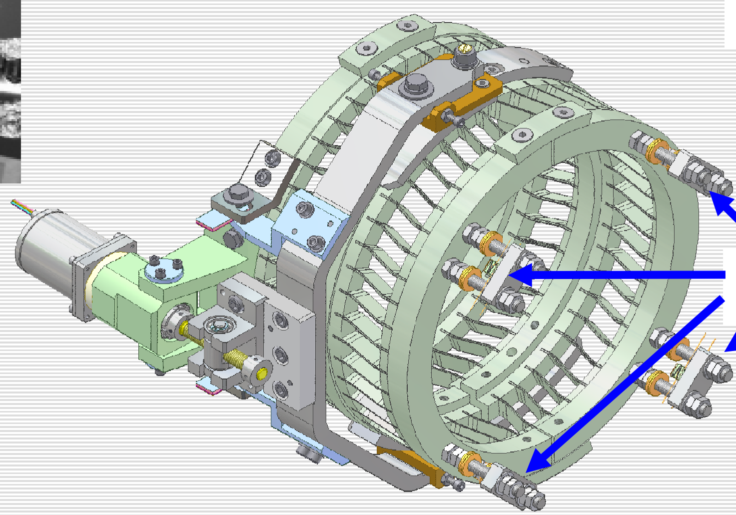


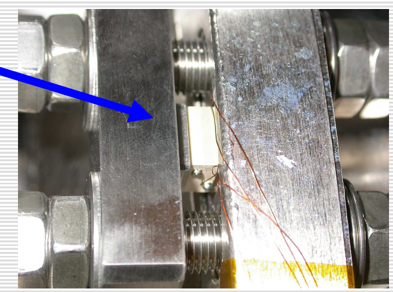
Blade tuner occupies no beam line space: it is mounted on top of the He vessel. Can be used where beam line real estate is at premium.

ILC version (Pagani)



Cornell ERL injector

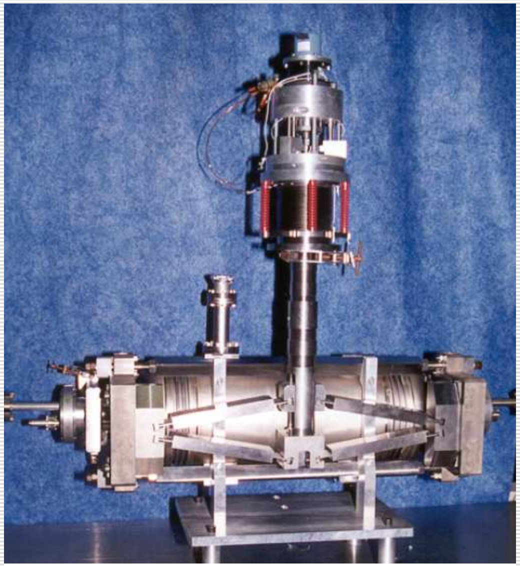


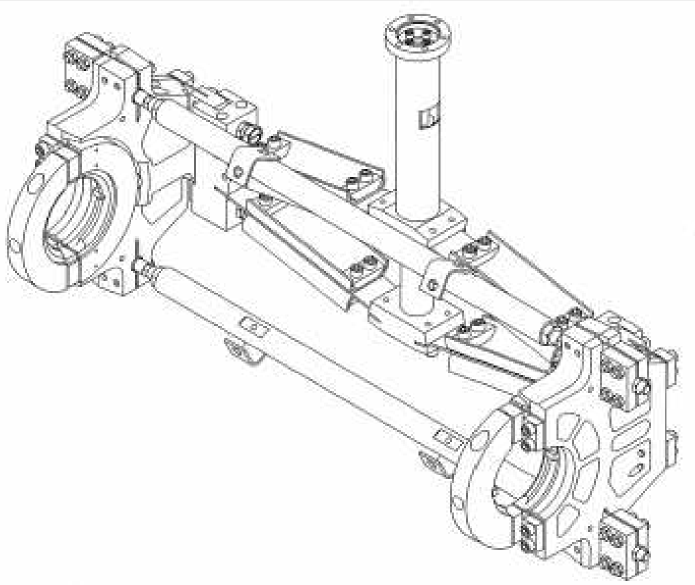


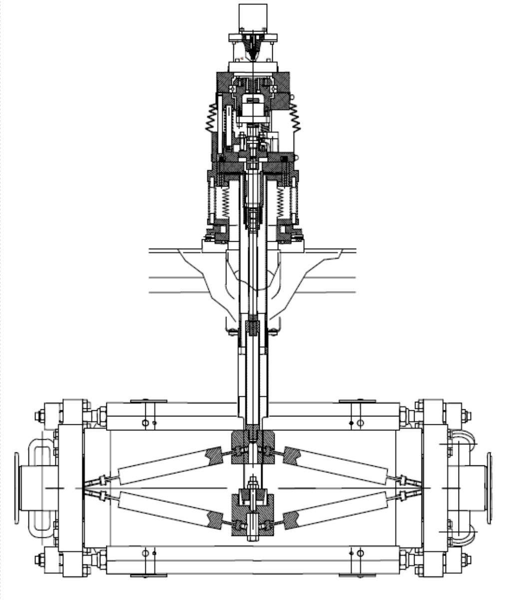
- Modification of the INFN blade tuner
- Added piezos for microphonics compensation

CEBAF Upgrade tuner

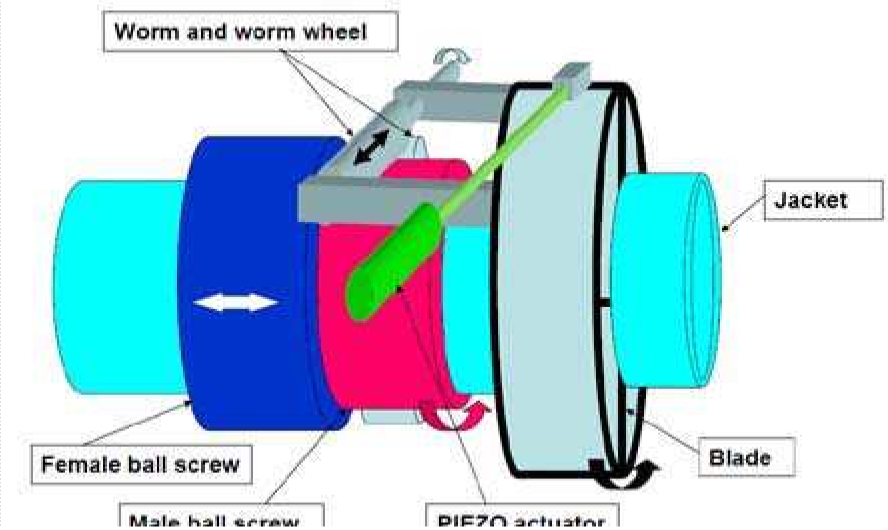
- Scissor jack mechanism
  - Ti-6Al-4V Cold flexures & fulcrum bars
  - Cavity tuner in tension only
  - Attaches on hubs of cavity
- Warm transmission
  - Stepper motor, harmonic drive, ball screw and piezo mounted on top of CM
  - Openings required in shielding and vacuum tank
- No bellows between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

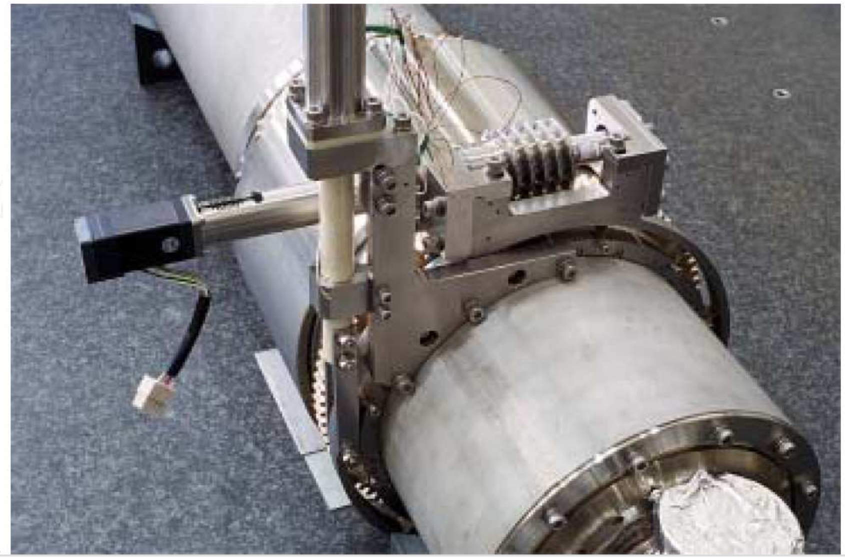






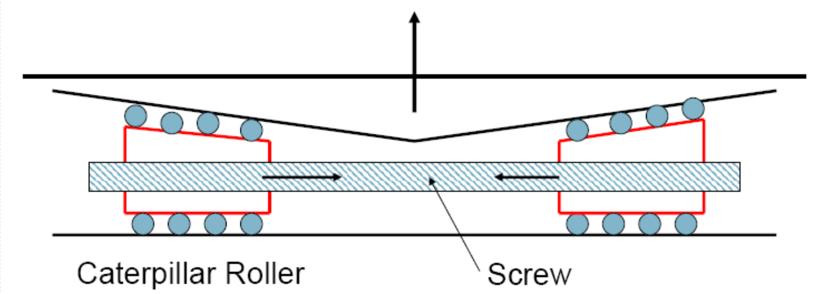
Coaxial ball screw tuner (KEK)

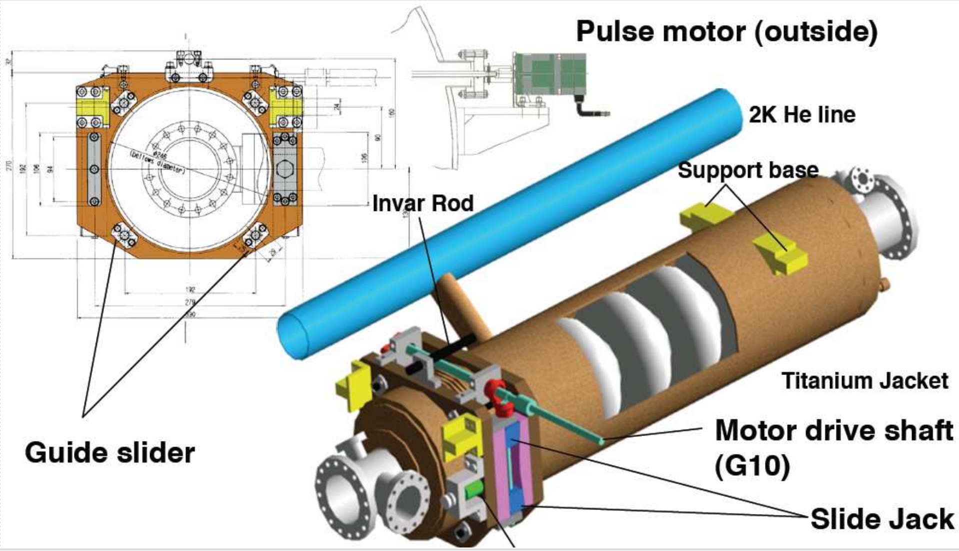


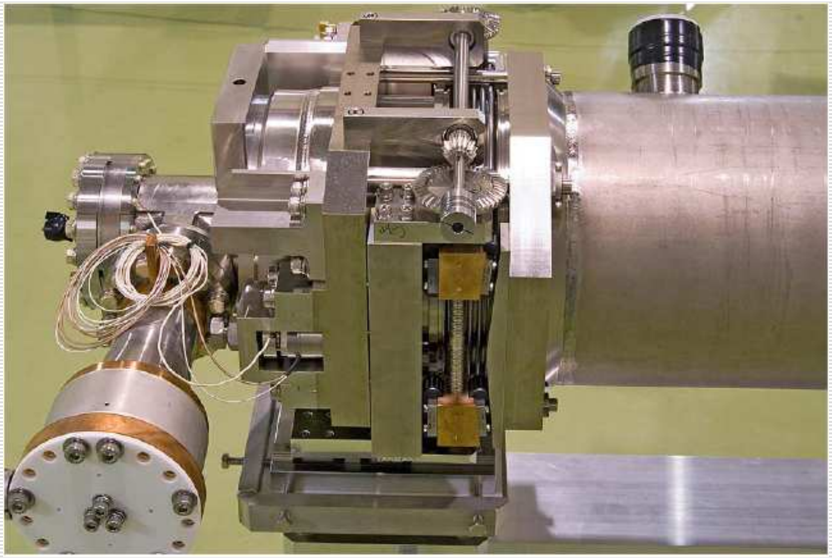


- Design objectives
  - Provide large tuning range while maintaining stiffness
  - 10 um fast tuning stroke for 3 kHz Lorentzh force detuning at 45 MV/m
- Warm transmission
  - Stepper motor, harmonic drive, ball screw and piezo mounted on top of CM
  - Openings required in shielding and vacuum tank
- No bellows between cavities
  - Need to accomodate thermal contraction of cavity string
  - Pre-load and offset each tuner while warm

Slide jack tuner (KEK)





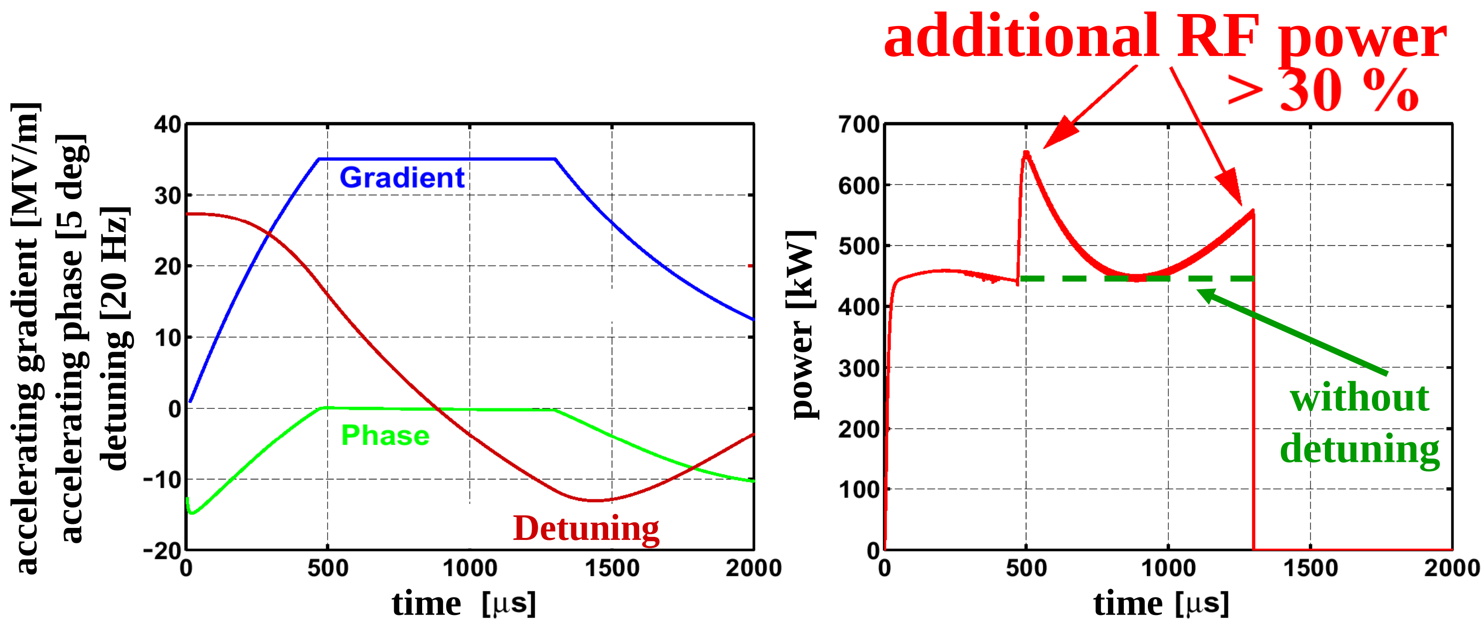


Comparison of tuners

Design	Saclay I	Saclay II	Blade Tuner	JLab upgrade	KEK slide jack	KEK coaxial ball screw
Motor tuning range	750 kHz	460 kHz	550 kHz	500 kHz	1100 kHz	>4000 kHz
Slow resolution	0.75 Hz	1.2 Hz	< 1 Hz	< 1 Hz	< 100 Hz	< 120 Hz
Motor hysteresis	satisfying	backlash	problems at low amplitudes	satisfying		
Transmission location	5 K, vacuum	5 K, vacuum	5 K, vacuum	RT, air	RT, air	80 K, vacuum
Number of piezo elements	1 - 2	2	2 - 4	2	1	1
Piezo tuning range	840 Hz	1420 Hz	1400 Hz	1000 Hz	1900 Hz	2500 Hz
Group delay	360 μs	150 μs	650 μs			
Stiffness	lower	higher	lowest			
Lowest resonance	40 Hz	40 Hz	35 Hz			
Piezo location	5 K, vacuum	5 K, vacuum	5 K, vacuum	RT, air	RT, air	80 K, vacuum

Dynamic Lorentz-force detuning in TTF

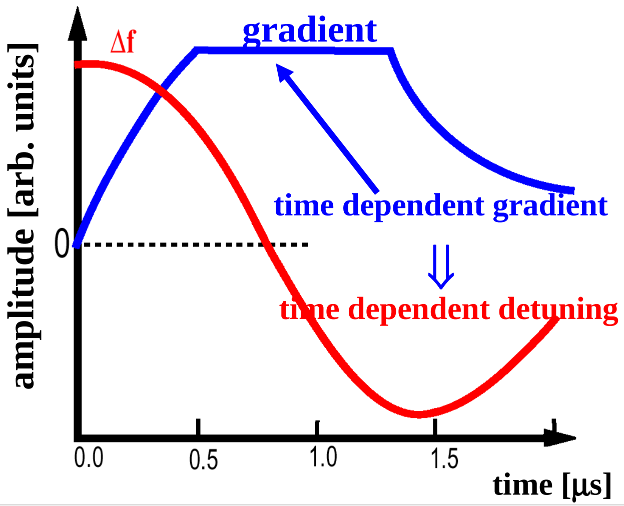
Example: TTF cavity at 35 MV/m (simulation)

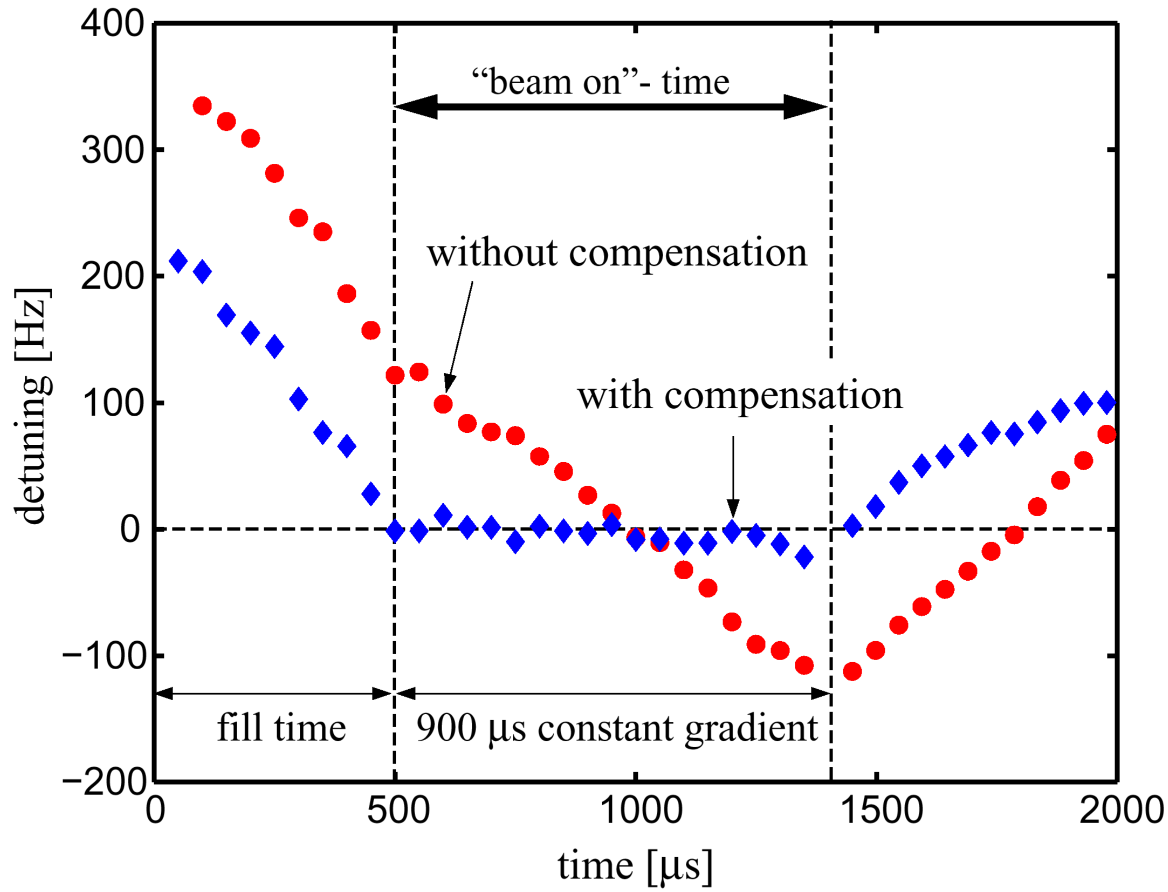


$$\frac{\Delta P}{P_{(\Delta f = 0)}} = \frac{1}{4}\left[\frac{\Delta f}{f_{1/2}}\right]^2 \propto E^4$$

Lorentz-force detuning compensation

TESLA 9-cell cavity at 23.5 MV/m with 10 Hz repetition rate:





Tuner features

Coarse tuners (stepping motor)

- Typically cold, must be reliable and maintainable →access ports
- Direct cavity drive reduces stiffness requirements on helium vessel
- Tuner / Helium vessle stiffness should be approximately factor of 10 higher than cavity stiffness
- Flexures exhibit reduced backlash
- Typically tune in tension or compression to avoid “dead band”
- Cold transmision: Materials considerations (lubrication, vacuum); Access for repair or replacement; Electrical feedthroughs
- Warm transmission: Cooldown/tuning compliance; Port for transmission; Bellows

Piezo tuners

- Operate in compression
- Warm range is 5 to 10 time larger than cold range
- Capacitive device: Low vs. High voltage (stiffer)
- Shorter piezos: reduce hysteresis; stiffer, but reduced tuning range

What have we learned?

- 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 combined stepper motor and piezo tuning is the method of choice for high-β cavities.
- Important design considerations: frequency resolution; compactness; hysteresis/backlash; cold vs warm transmission; reliability; ease of maintenance; cost.

✪ Next lecture: cavity fabrication, preparation and testing.