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Electromechanical Properties of Superconducting Cavities: Couplers and Tuners

SCRF Series: Talk III

Beams and Applications Seminar

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Background: Superconducting Radio-Frequency (SRF) Accelerators

- Increasing the accelerating gradient and producing cavities with lower RF residual surface resistance are two major goals of superconducting accelerator cavity research and development.

- Mechanical properties of a superconducting cavity are extremely important due to their small loaded cavity bandwidth

- This tutorial will focus on:
  - Mechanical Properties of Cavities
  - Cavity Tuning
  - Cavity Couplers (Fundamental and Higher Order Mode (HOM))

Outline

- Mechanical Properties of Cavities and Tuners
  - When do we need tuners?
  - What options are available?
  - Examples

- Couplers
  - What are the different types of couplers?
  - Design constraints
  - Examples

RF Power Requirements

- ***Every cavity's RF field must be phase locked to the particle beam bunches.***
- Accelerator cavities require RF power:
  - to excite the cavity to the design field level
  - to accelerate the particle beam
  - to control the amplitude and phase of the cavity RF field which in turn controls the particle energy spread.

$$P_{amp} \propto \frac{\delta f}{\Delta f_L}$$

- Where P_{amp} = output from RF amplifier required to drive the cavity, δf = difference between the resonator RF frequency and the RF drive frequency, and Δf_L = loaded cavity bandwidth [1].

Boltzmann Ehrenfest Theorem [2]

$$\frac{\delta f}{f} = \frac{\text{Mechanical Work}}{\text{Stored RF Energy}}$$

$$\frac{\delta f}{f} = \frac{\Delta U}{U}$$

$$\delta f \propto \frac{1}{4} \int_{\Gamma} \left[\mu_0 \left| \vec{H}_0(\vec{x}) \right|^2 - \varepsilon_0 \left| \vec{E}_0(\vec{x}) \right|^2 \right] u(\vec{x}, t)\, da$$

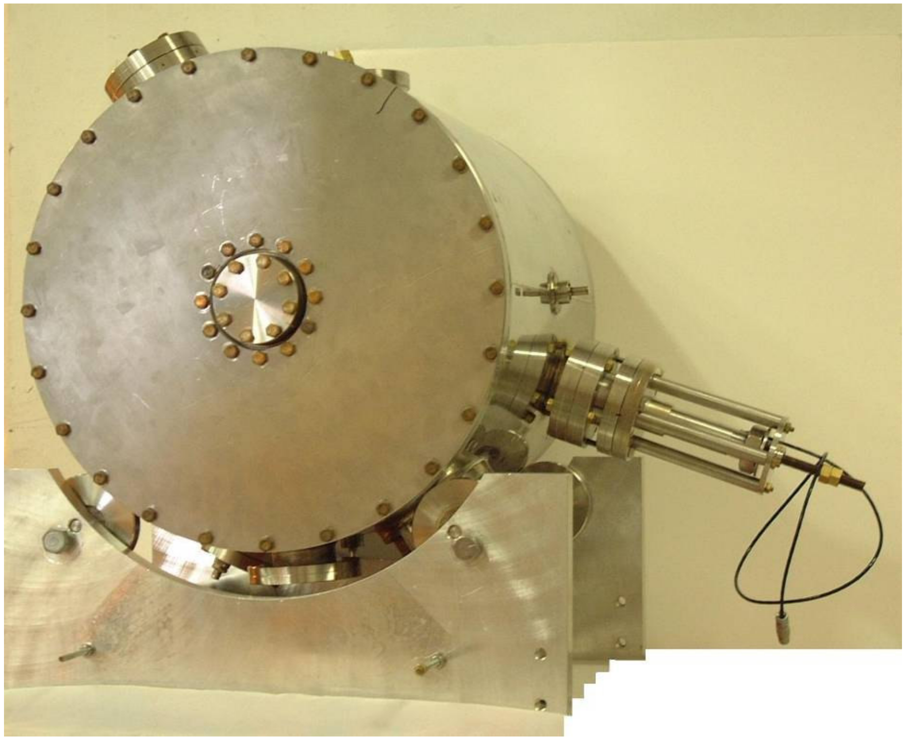
where Δf is the change in the RF frequency of the cavity, $\vec{H}_0(\vec{x}, t)$ and $\vec{E}_0(\vec{x}, t)$ are the magnetic and electric fields of the eigenmode excited in the cavity, and $u(\vec{x}, t)$ is the displacement of the cavity surface due to an external force or the Lorentz force.

Definitions

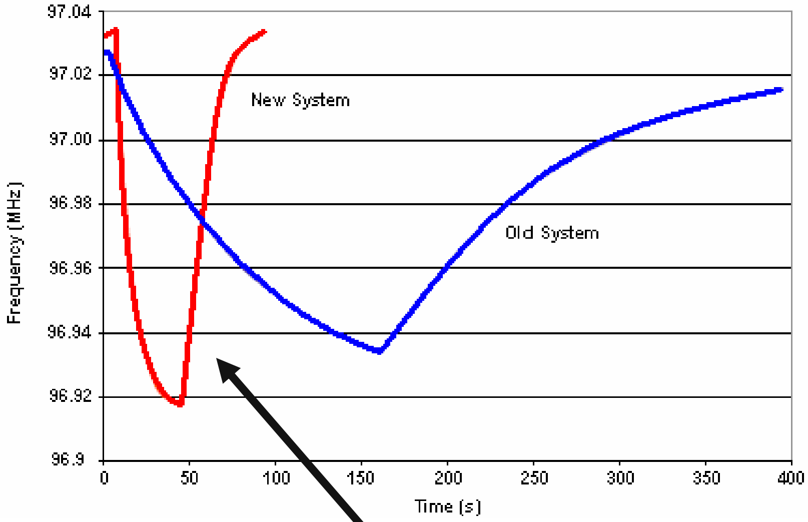
- **Microphonics**, in accelerating cavities, is the general term used to describe the process where resonant cavities couple externally driven mechanical vibrations into cavity RF frequency variations [3].
  - Vibrations
  - Pressure Variations
- **Lorentz detuning** (Ponderomotive) is the general term used to describe changes in the cavity RF frequency due to the cavity electromagnetic field, radiation pressure [3, 4].
  - Static Lorentz Detuning (continuous wave operation, cw)
  - Dynamic Lorentz Detuning (pulsed operation)

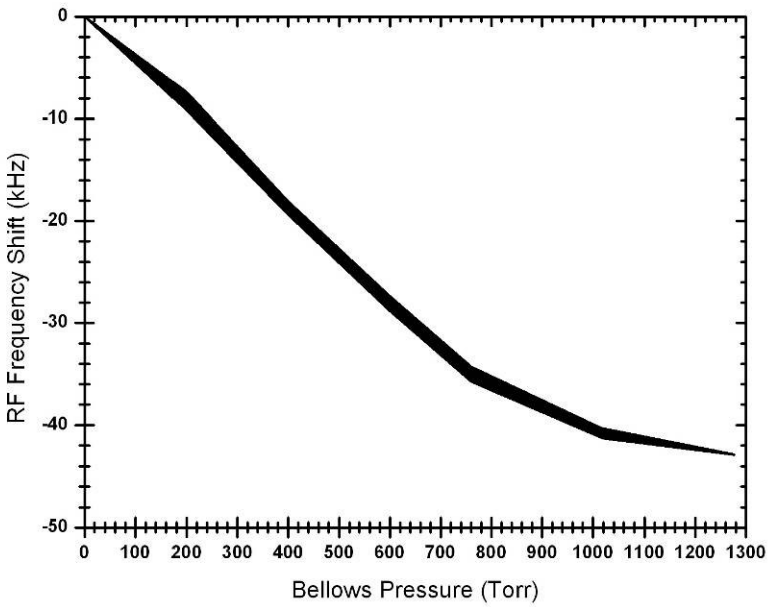
Tuners: Types

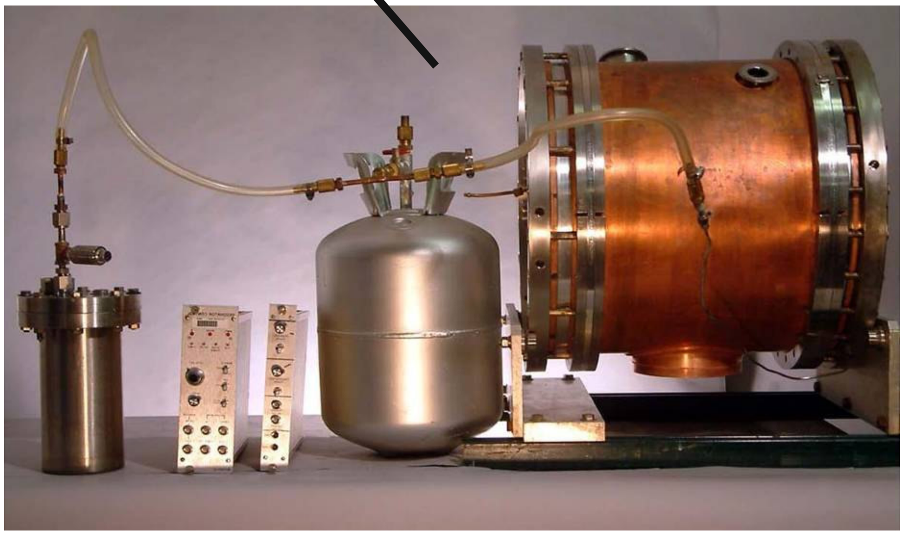
- Slow Tuners
  - Large tuning range (~10s of kHz)
  - Slow response time (~seconds)
  - Provide coarse RF frequency control such that all of the cavities are operating approximately at the design frequency.
    - *Thermal Contraction*
    - *Cavity fabrication tolerances*
    - *Static Lorentz Force*
    - *He Bath Pressure*
- Fast Tuners
  - Small tuning ranges (~100s of Hz)
  - Fast response time (~ ms)
  - Provide fine RF frequency control to compensate the effects of microphonics and/or the dynamic Lorentz force.



Tuners: Slow Tuners [5]







Tuners: Fast Tuners

- Overcoupling to control RF field phase and amplitude
  - Additional RF power ~ $\delta f/\Delta f_L$
  - Useful in applications with heavy beam loading

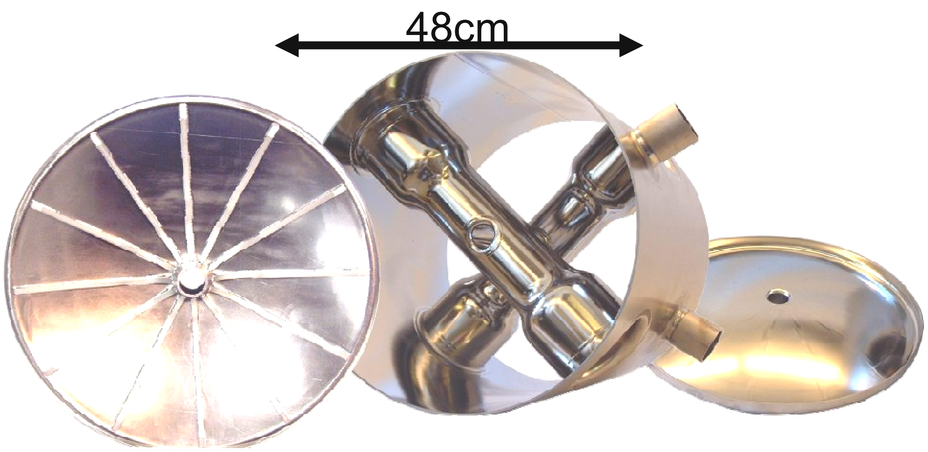
- VCX fast tuners [7]
  - Couple an external reactance to the cavity.
  - Damp the cavity Q.
  - Cavities operating at small stored energy
  - R&D needed to expand application range

- Cornell Electron Synchrotron Storage Ring (CESR) [6]
  - Each cavity couples 300 kW of power to the electron beam
  - Beam loaded cavity bandwidth = 420 Hz
  - Microphonics ~ 41 Hz
  - 1% modulation in RF power to compensate detuning

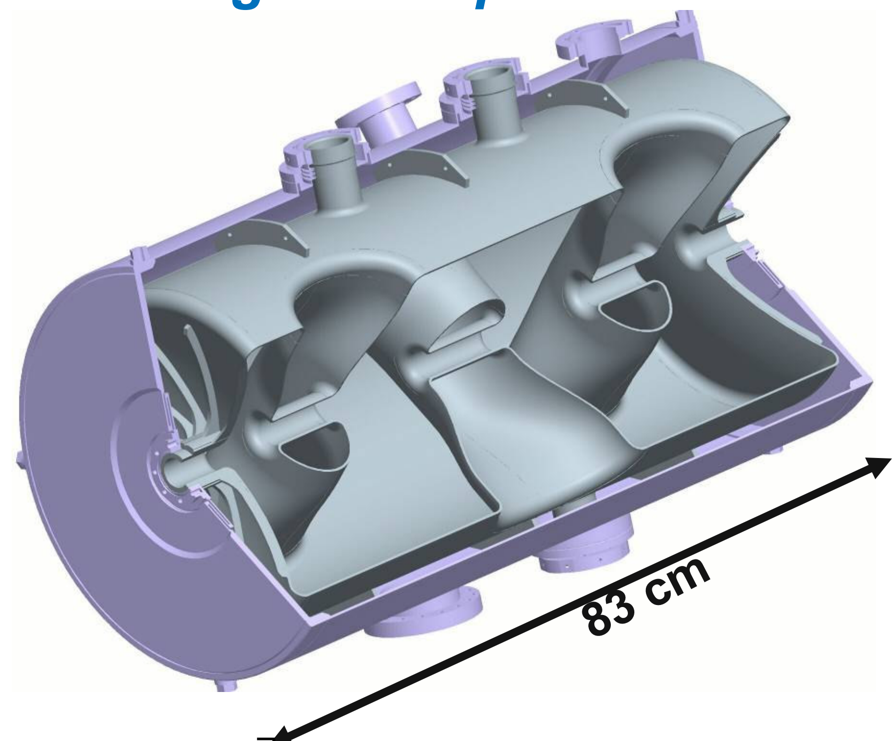
- FNAL 8 GeV Proton Driver Linac
  - Beam loaded cavity bandwidth = 800 Hz
  - Lorentz Detuning ~ 1 kHz
  - 13% modulation in RF power to compensate detuning

- Fast Mechanical Tuners
  - Deform the cavity to introduce a controllable change in the RF frequency.
  - No additional RF power
  - The fast mechanical tuner and the cavity are an integral system.

Mechanical Properties and Tuners: A Design Example



Double-spoke cavity Δf/Δp = -76 Hz/torr [8]

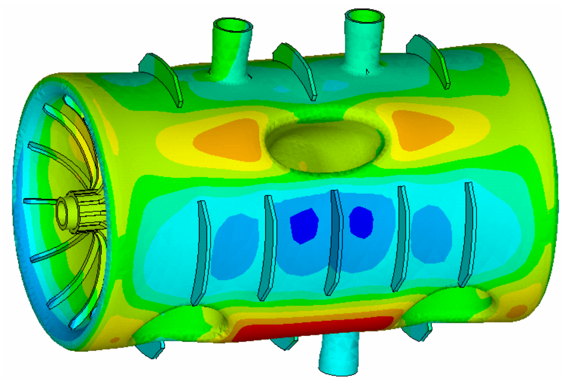


$$\delta f \propto \frac{1}{4} \int_{\Gamma} \left[\mu_0 \left| \vec{H}_0(\vec{x}) \right|^2 - \varepsilon_0 \left| \vec{E}_0(\vec{x}) \right|^2 \right] u(\vec{x},t)\, da$$

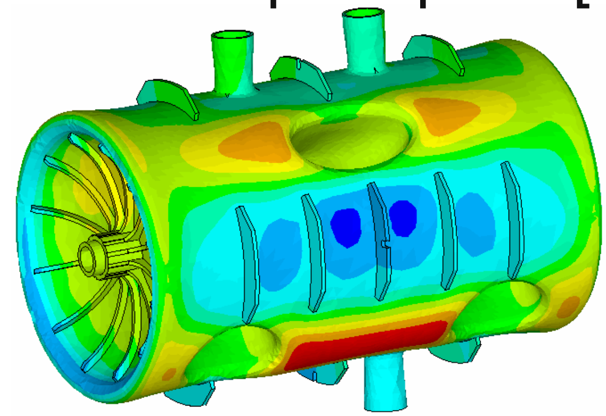
- Large Δf/Δp in double spoke
- Designed to balance the electric and magnetic field contributions to frequency shifts due to uniform external pressure.

Mechanical Properties: Cavity RF Frequency Variations

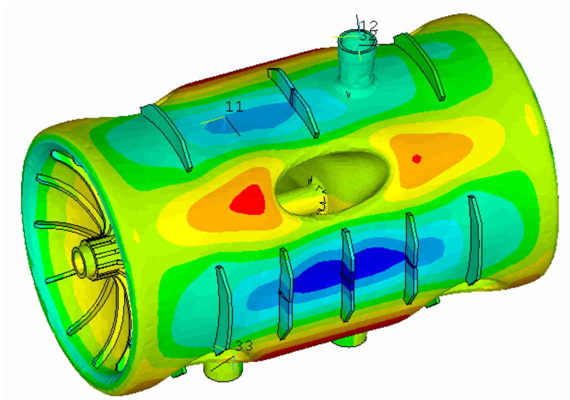
Room temperature test results for β = 0.5 Triple-Spoke [9]



measured Δf/ΔP(predicted) = -12.4(-8.7) Hz/torr

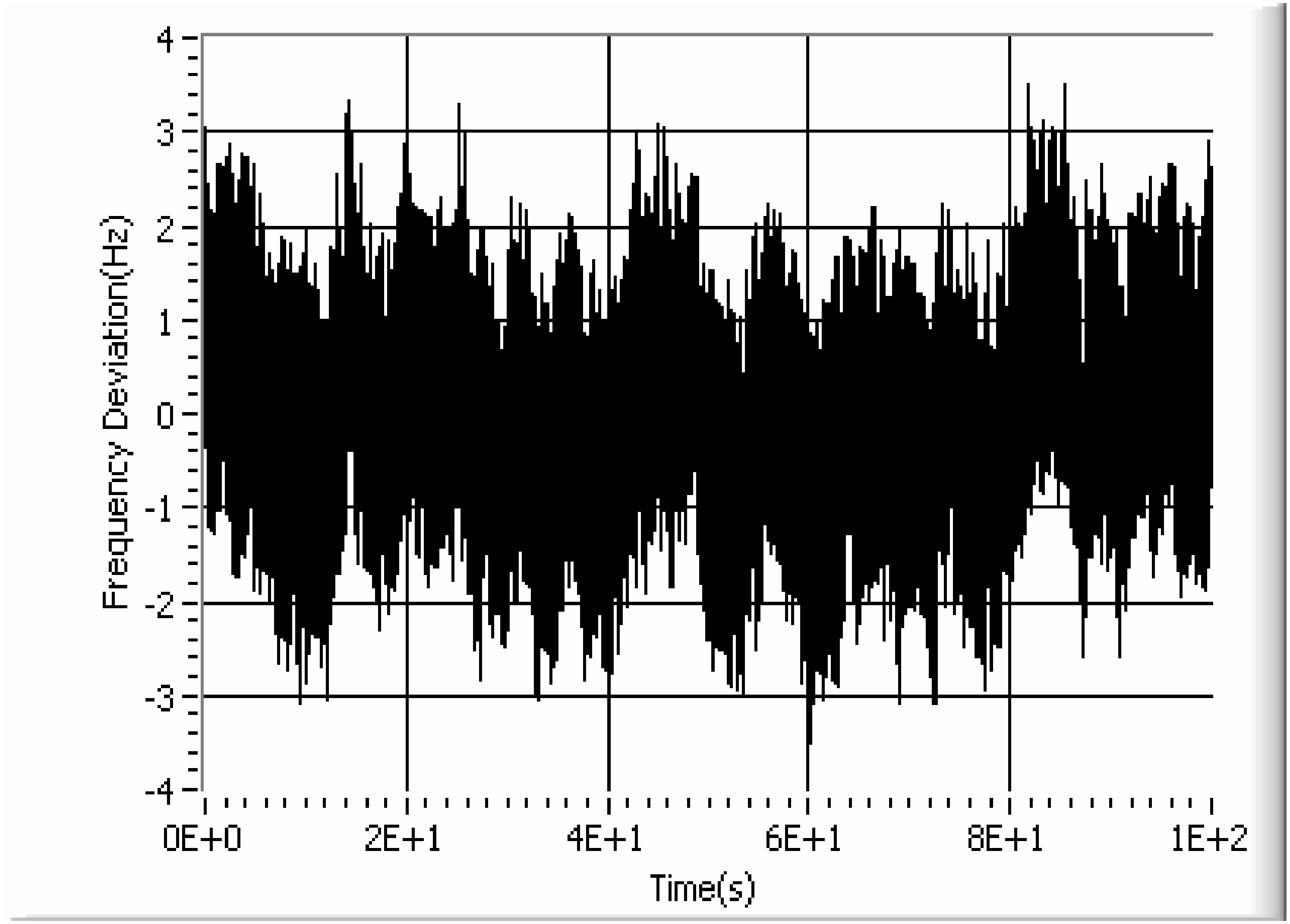


Δf/ΔP = -6.3(-4.7) Hz/torr

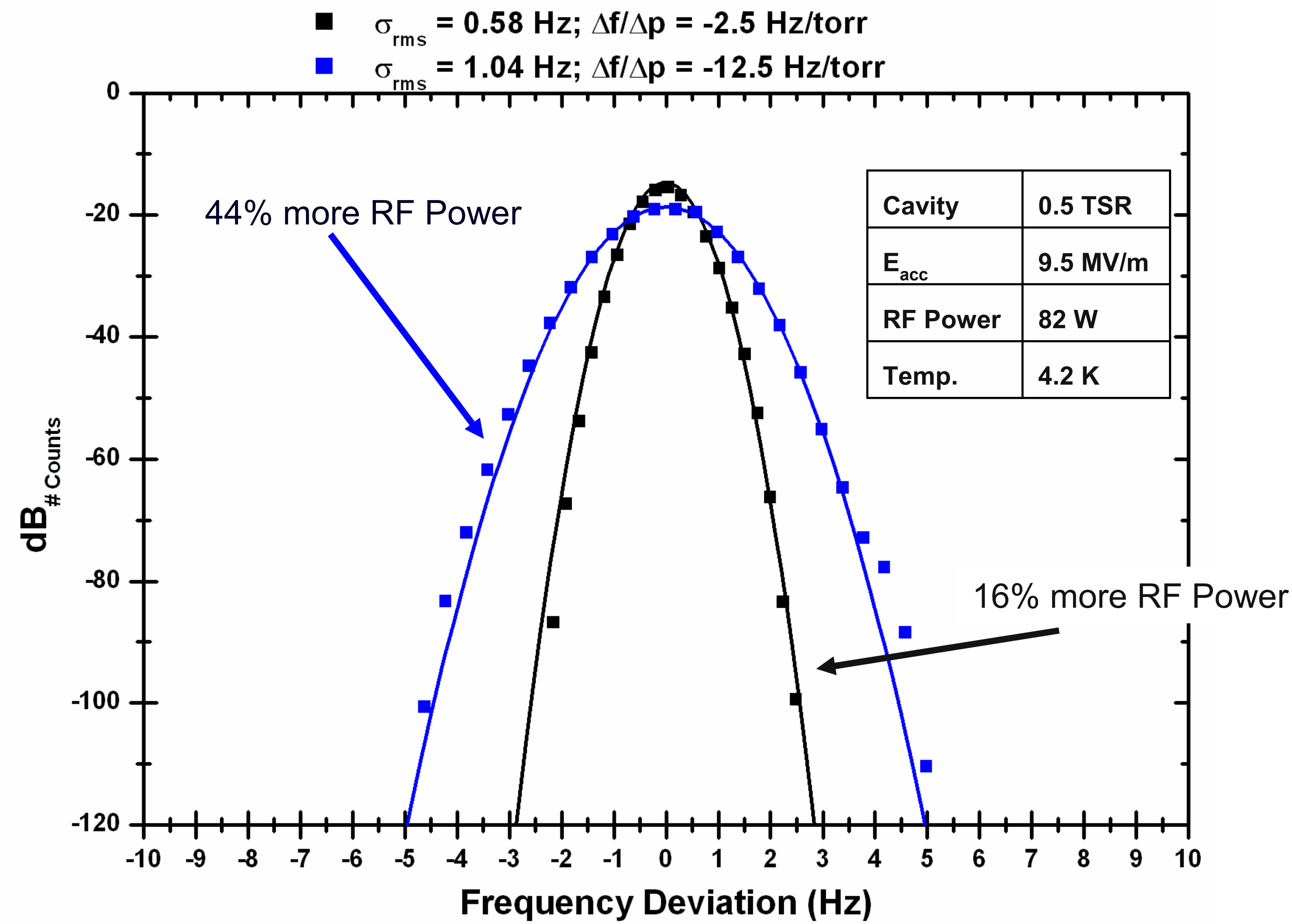


Δf/ΔP = -2.5(-0.3) Hz/torr (~30x improvement over double-spoke)

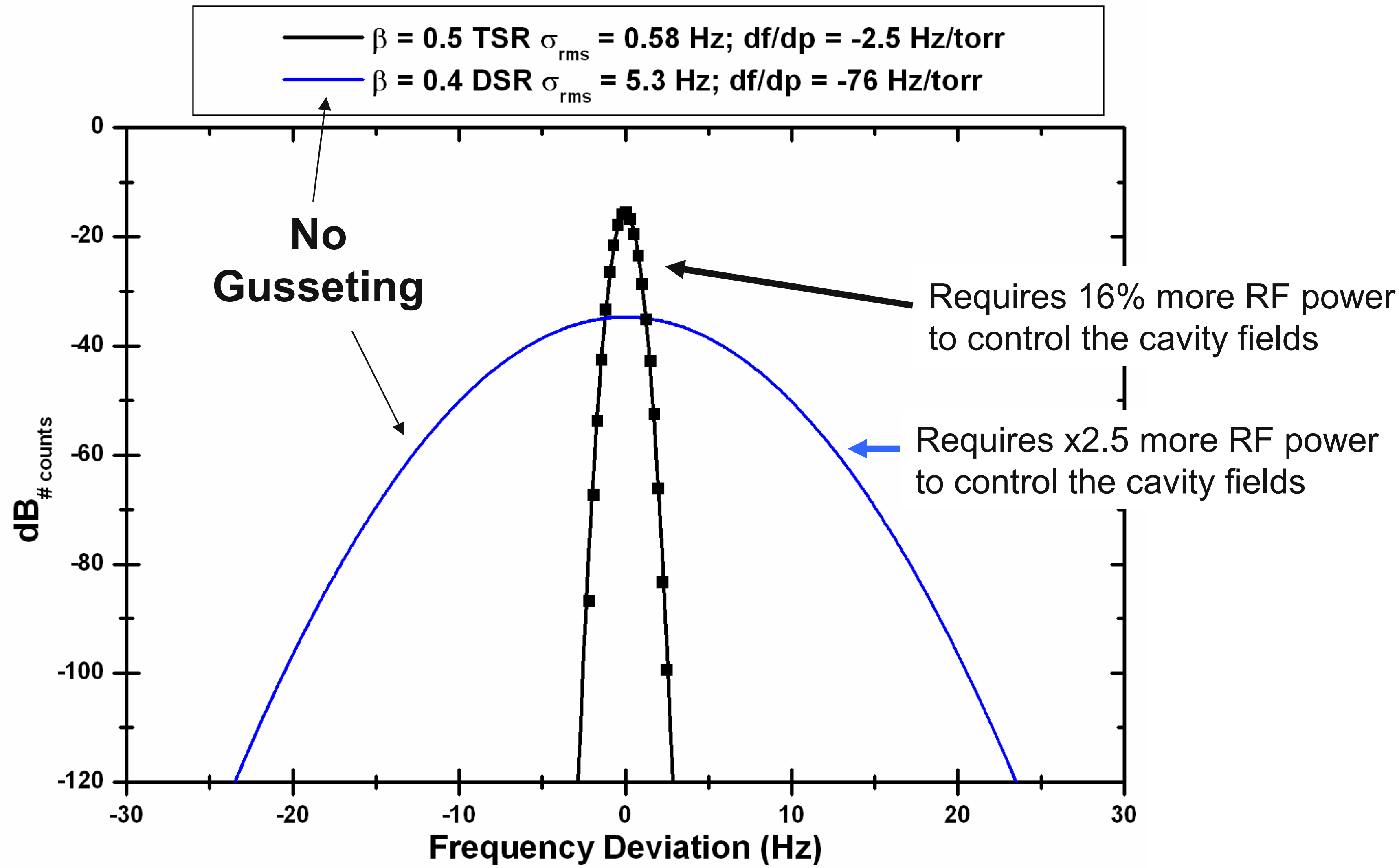
Mechanical Properties: Cavity RF Frequency Variations



Mechanical Properties: Cavity RF Frequency Variations

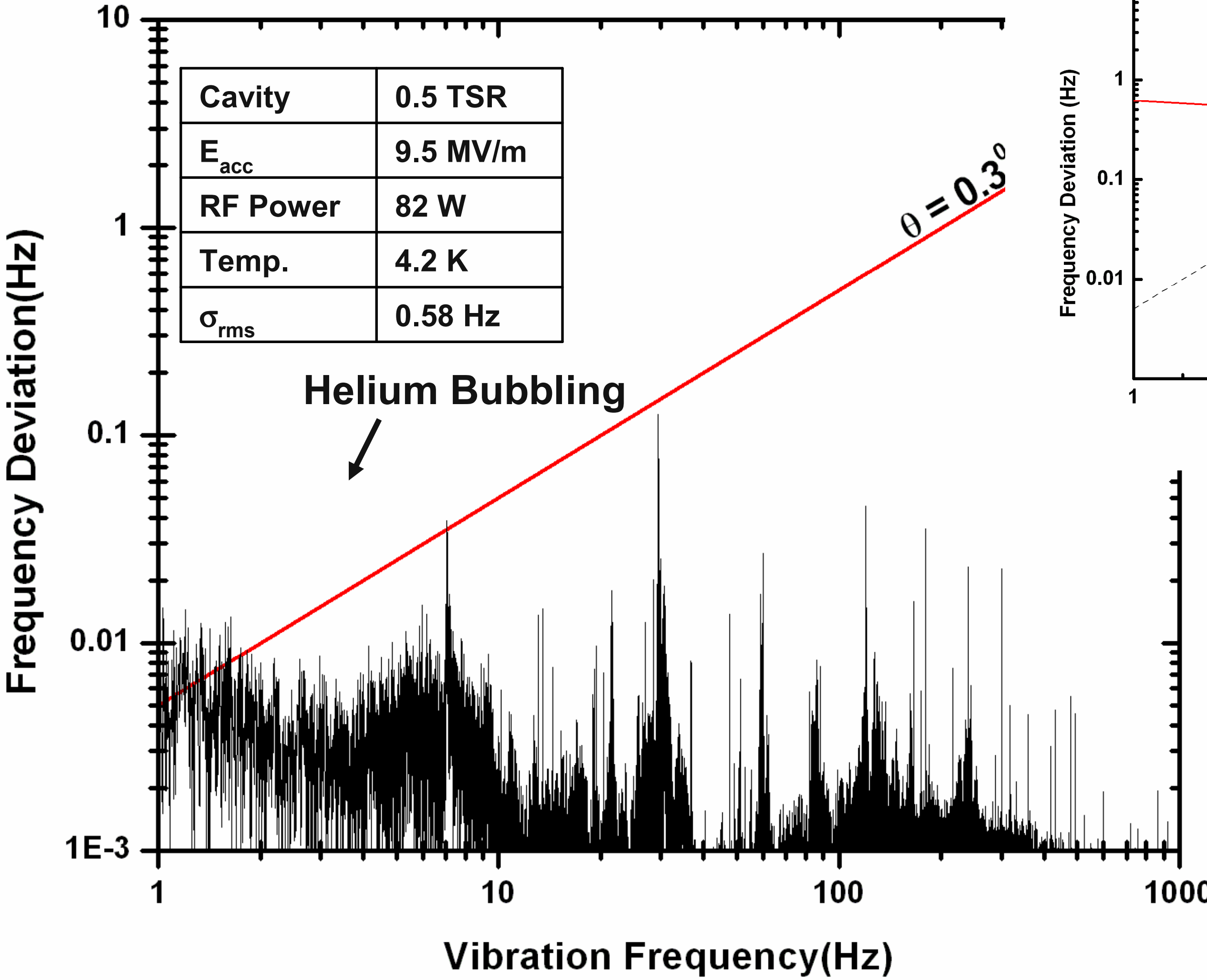


Mechanical Properties: Cavity RF Frequency Variations

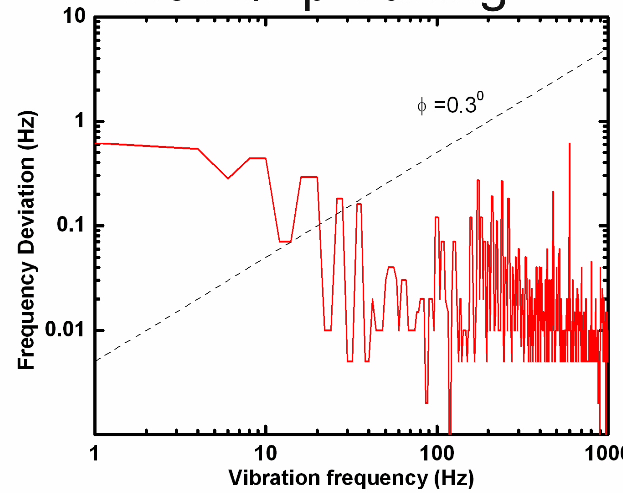


Mechanical Properties: Cavity RF Frequency Variations

Cavity	0.5 TSR
E_{acc}	9.5 MV/m
RF Power	82 W
Temp.	4.2 K
σ_{rms}	0.58 Hz



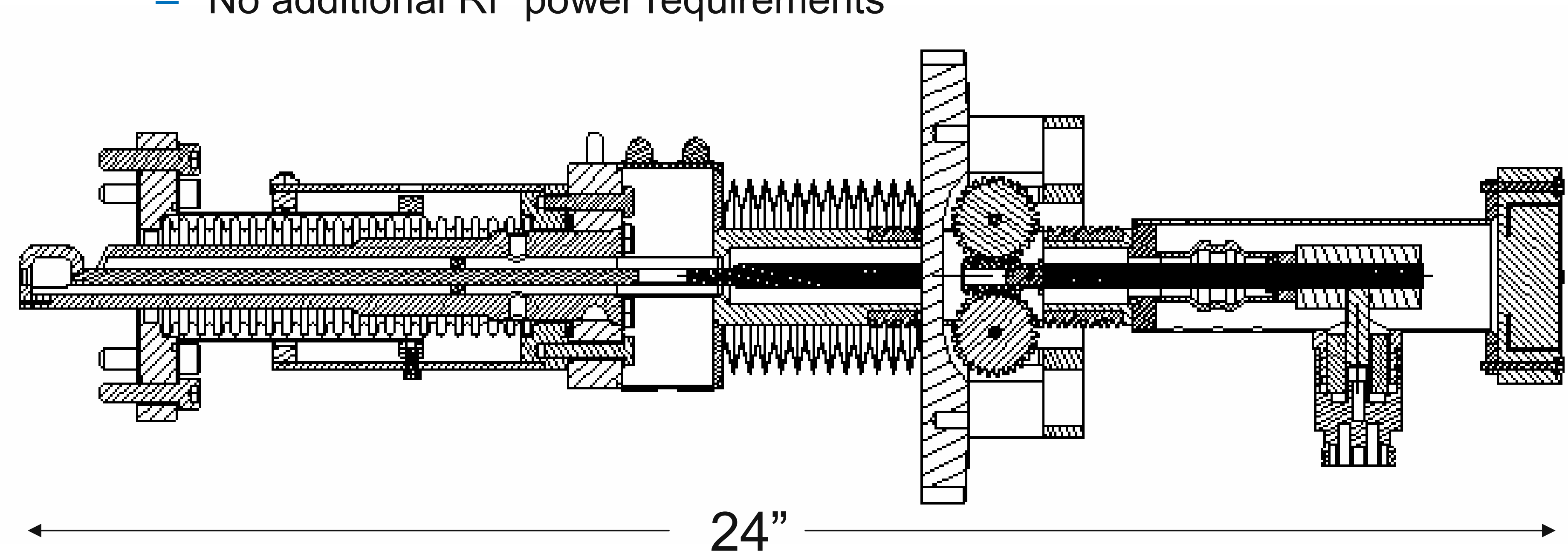
No Δf/Δp Tuning



Cavity	0.4 DSR
E_{acc}	7 MV/m
RF Power	9 W
Temp.	4.2 K
σ_{rms}	5.3 Hz

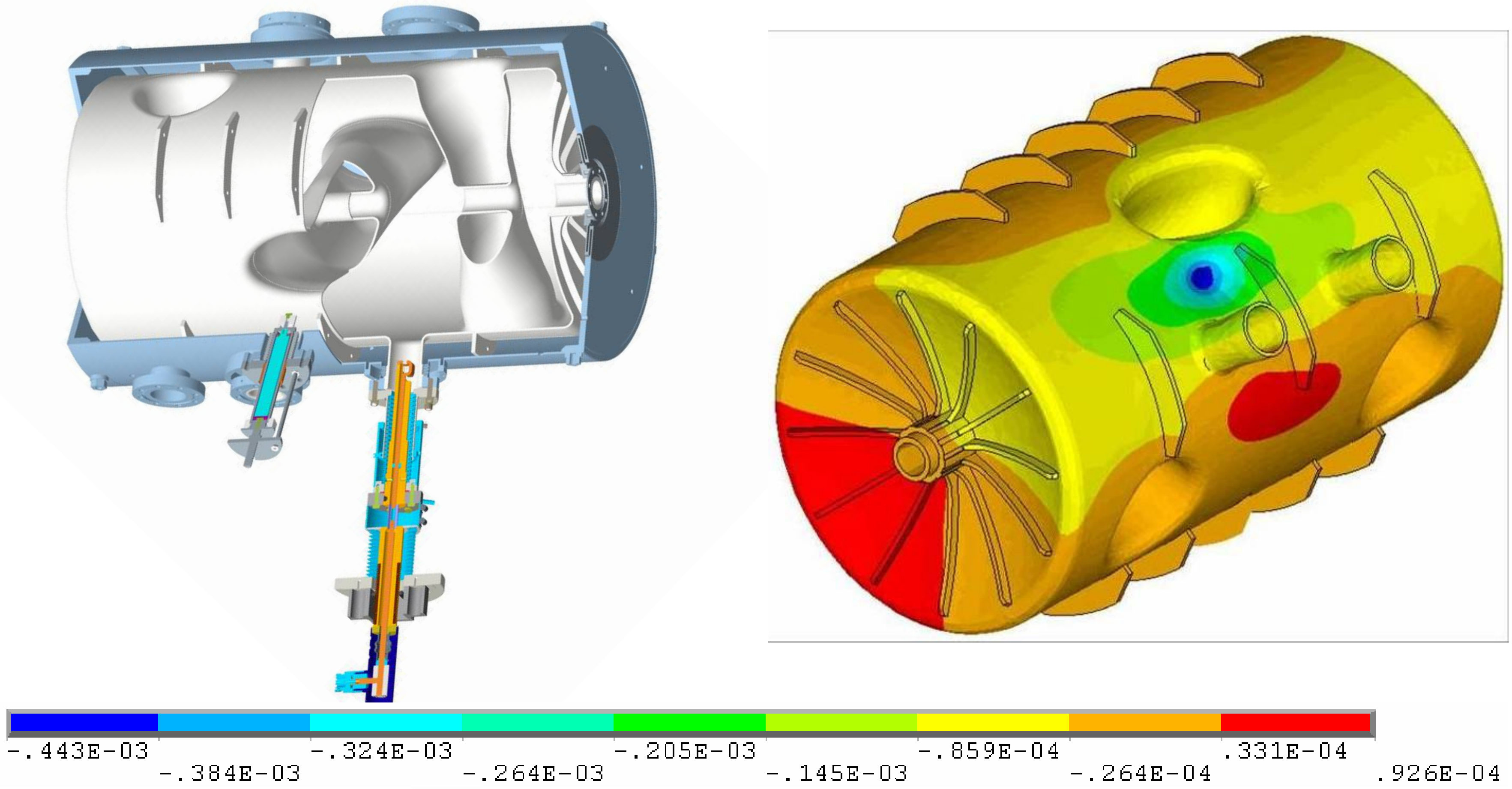
Tuners: Cavity RF Frequency Variations

- Over-couple to the cavity with the power coupler
  - RF Power ~ $\delta f/\Delta f_L$
- Fast Reactive Tuners
  - Damp the cavity bandwidth requiring additional RF power
- Fast Mechanical Tuners
  - No additional RF power requirements



ANL Triple-Spoke Fundamental Power Coupler

Tuners: Fast Mechanical Tuners



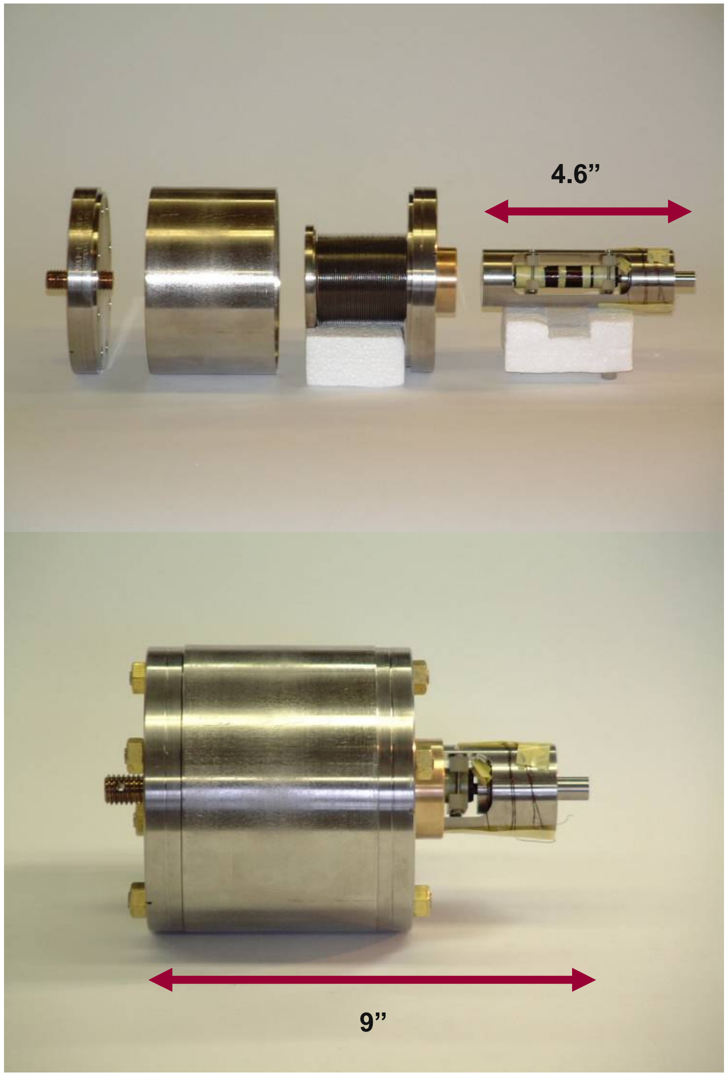
Inches

Tuners: Fast Mechanical Tuners

- We have done all we can to decouple the cavity RF frequency dependence on changes in the external pressure
- Cavity mechanical design by itself is not sufficient for phase and amplitude stable operation at 4 K
- At ANL mechanical fast tuners have been developed to compensate the low frequency cavity RF frequency variations due to low frequency microphonics

Tuner Actuator	Piezoelectric	Magnetostrictive
Manufacturer	APC	Energen
Operating Temp.	26 K	4 K
Length	11 cm	6.7cm
Stroke @ 4 K	16 μm	100 μm
Push Force	4000 N	440N

Tuners: Magnetostrictive Actuated Fast Tuner

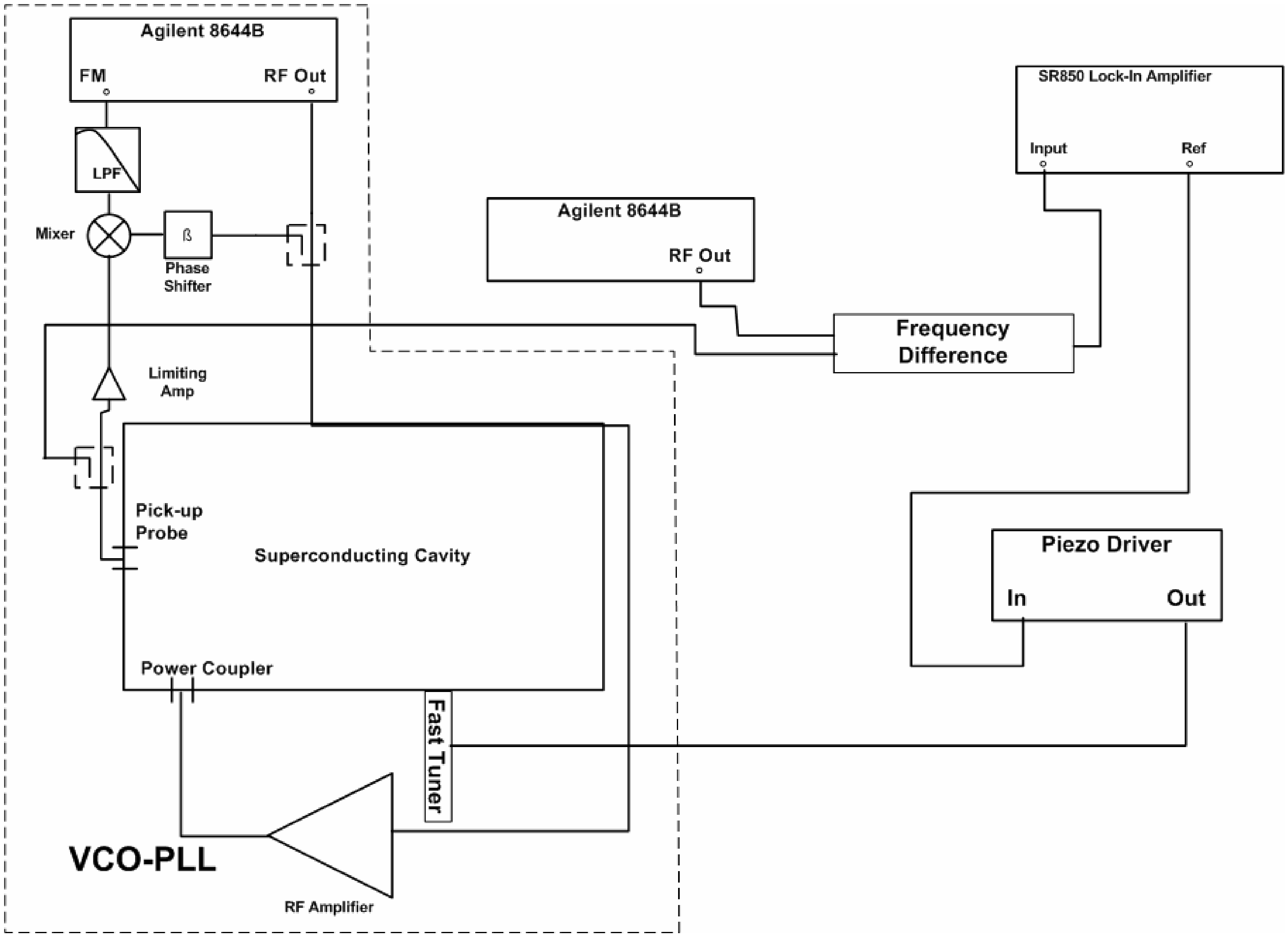


- Magnetostrictive actuator designed and built by Energen, Inc.
- Response time ~6ms.
- Magnetostrictive rod coaxial with an external solenoid operating at 4K.
- Not designed for high frequency operation.

Tuners: Piezoelectric Actuated Fast Tuner

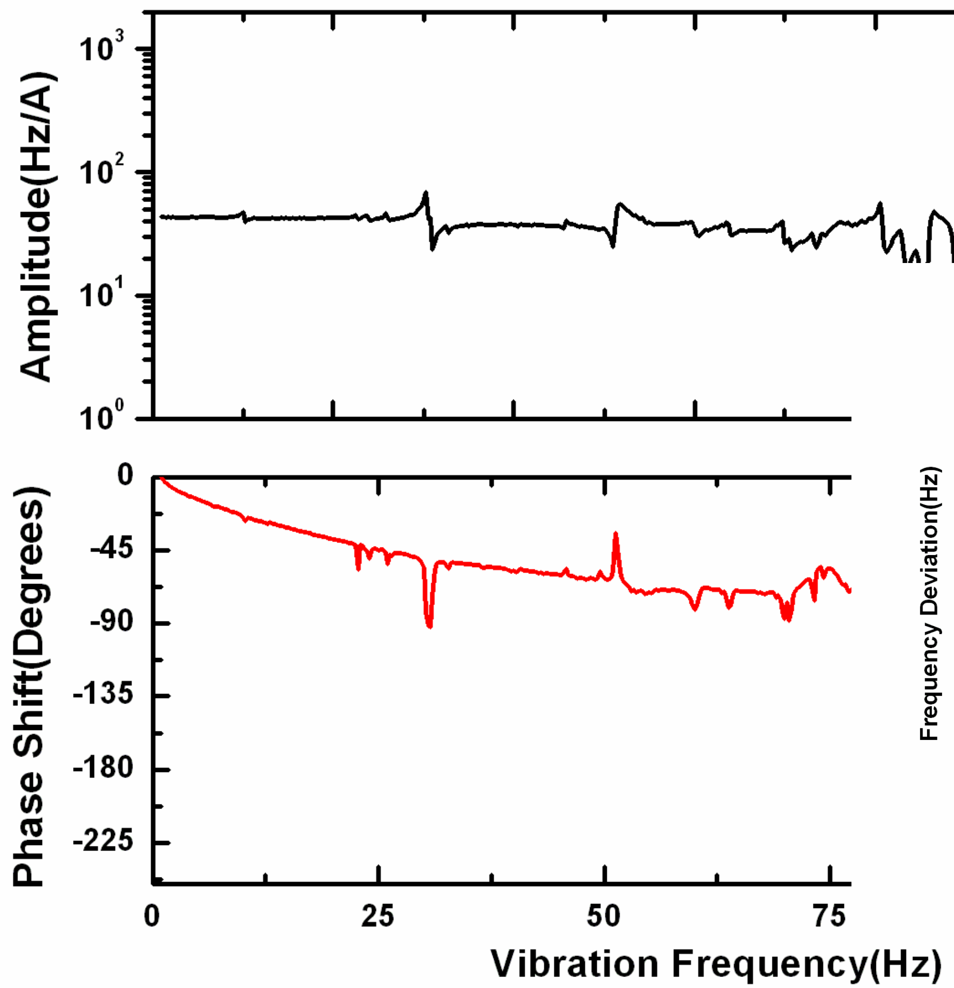
- Response time <1ms.
- Layered piezo-ceramic material electrically connected in parallel operating at 26K with a resolution of 2nm purchased from APC.
- Support structure not optimized for high frequency operation.

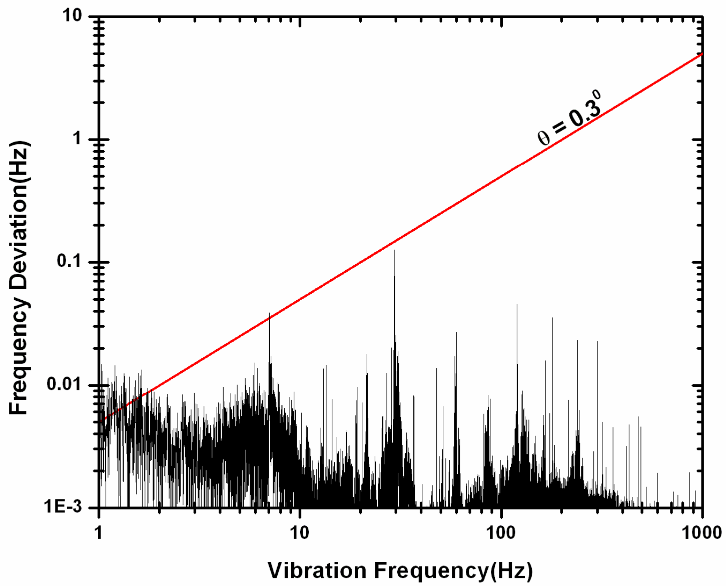
Tuners: Tuner/Cavity Transfer Function Measurement



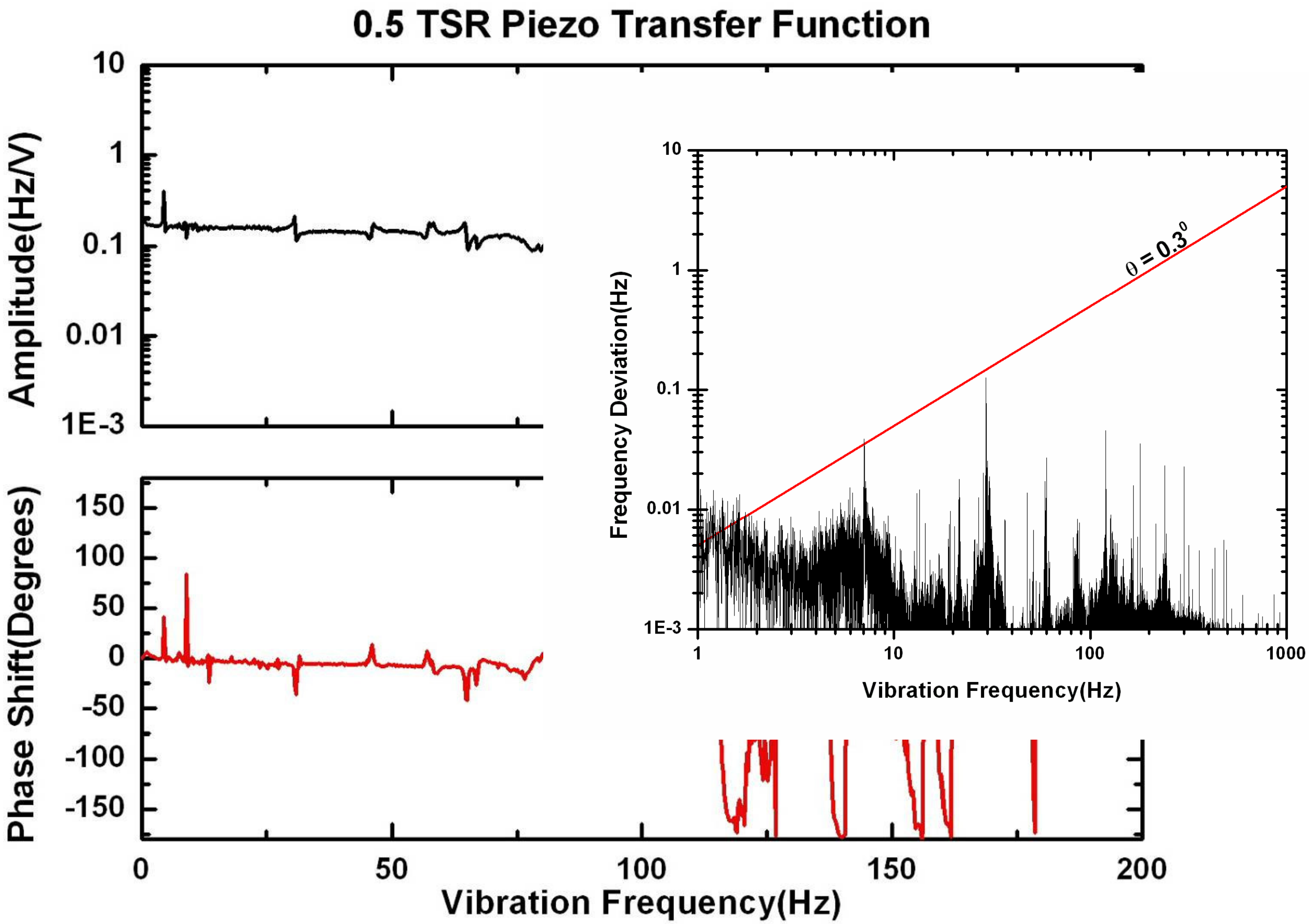
Tuners: ANL β = 0.5 TSR Magnetostrictive Tuner/Cavity Transfer Function [8]

$$\text{Cavity Response(t)} = \int_{-\infty}^{\infty} \left(\text{Transfer Function}(\omega) * \text{I}(\omega)\right) e^{-i\omega t} d\omega$$

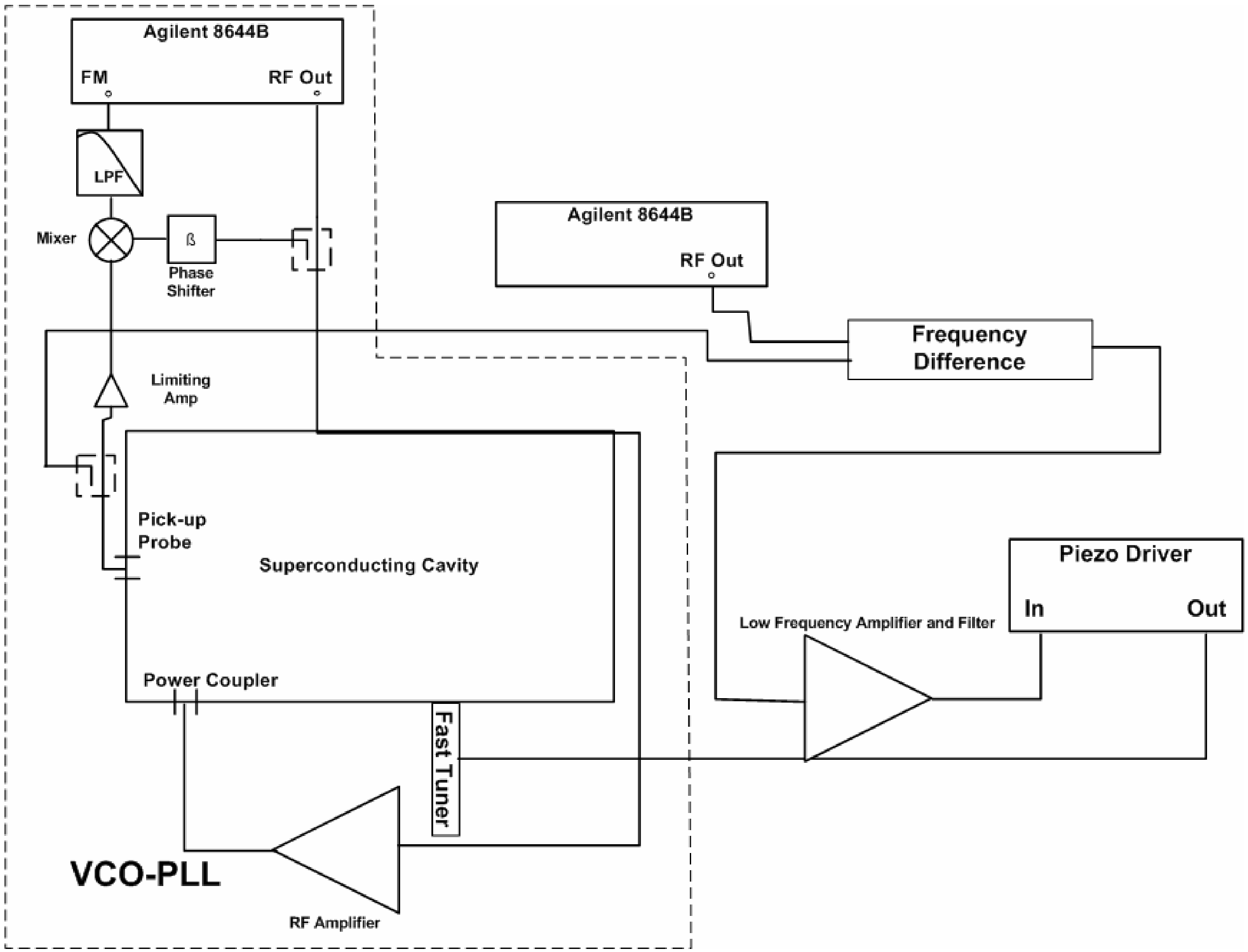




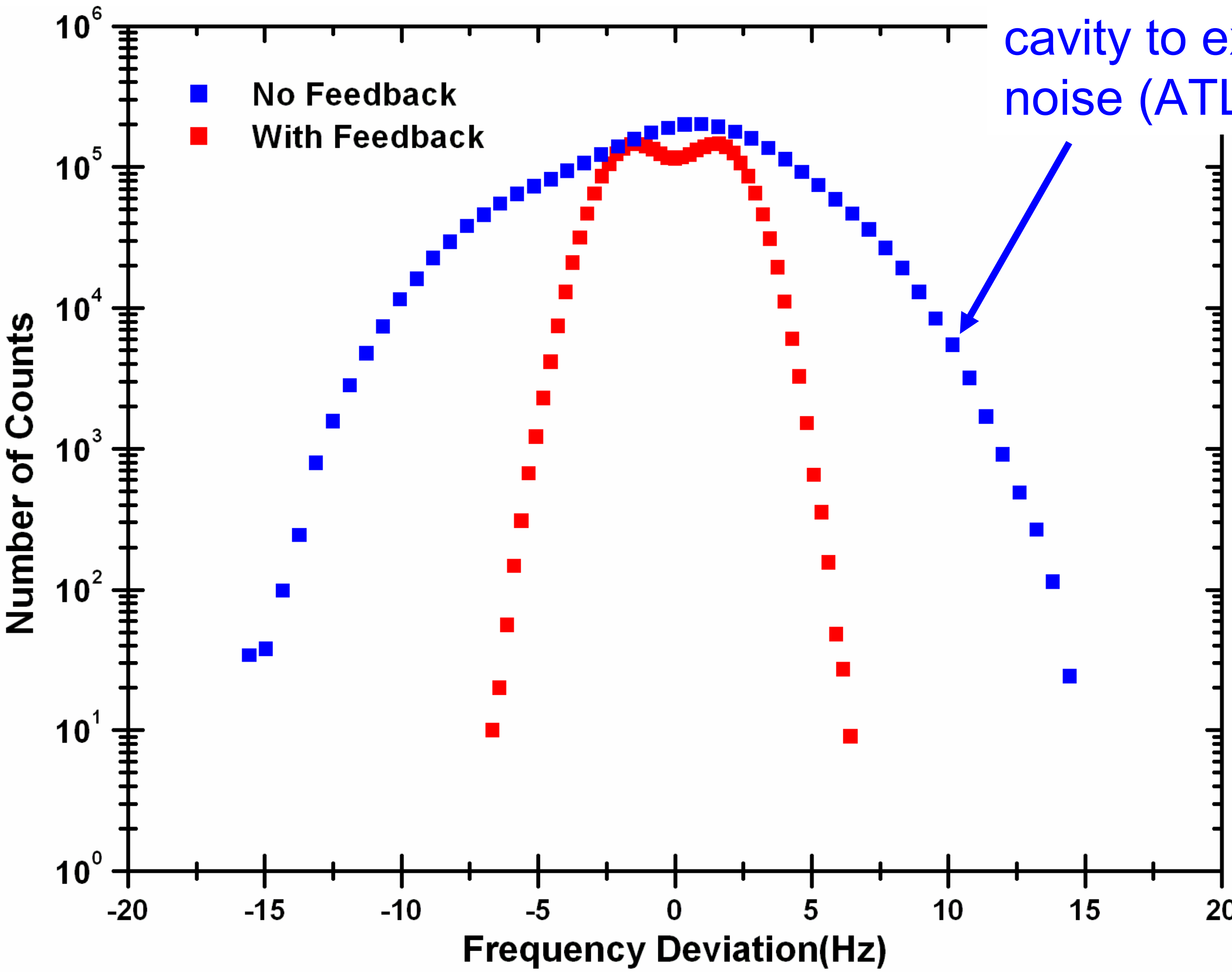
Tuners: ANL β = 0.5 Triple Spoke Piezo/Cavity Transfer Function [8]



Tuners: Fast Mechanical Tuning



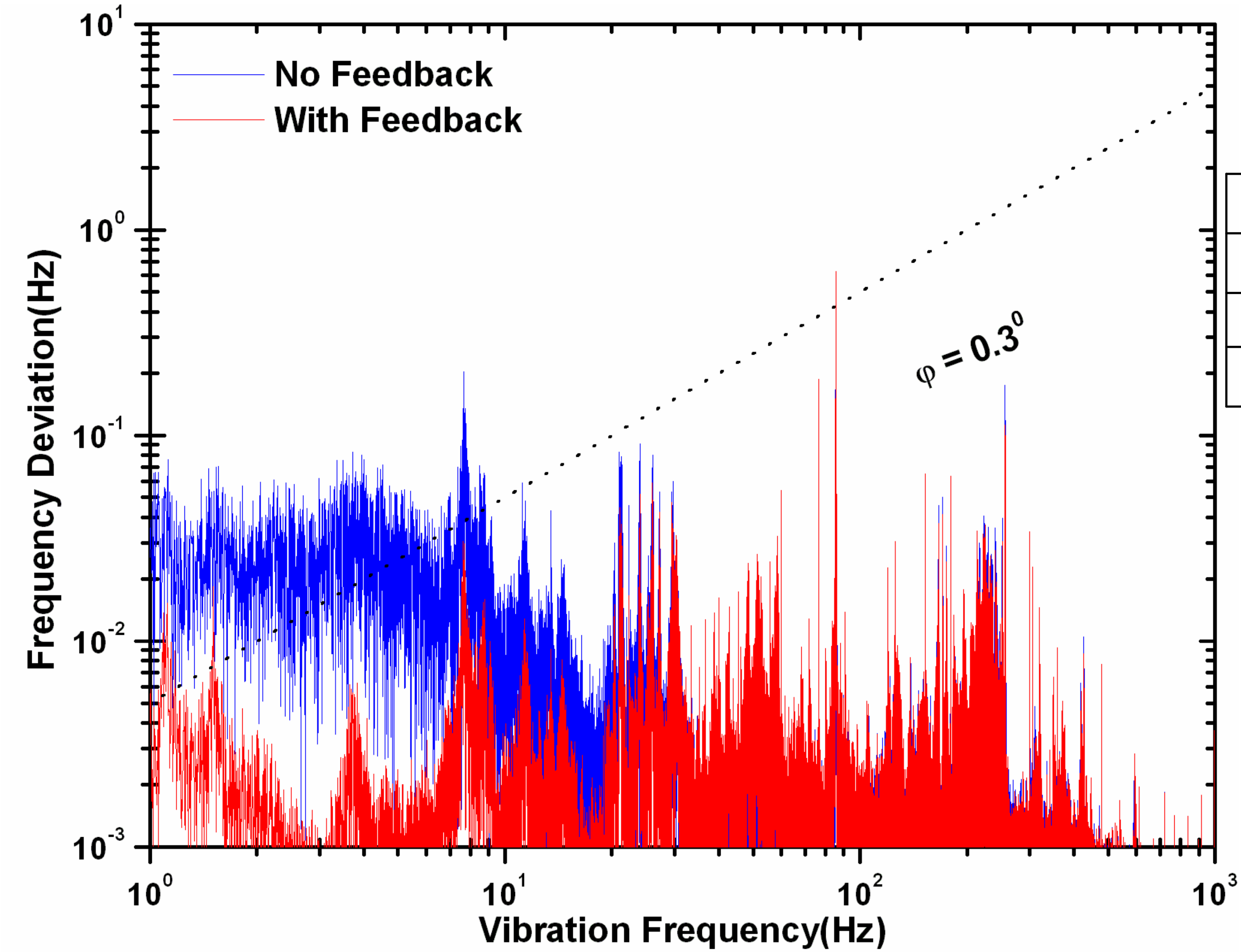
Tuners: Fast Mechanical Tuning



Deliberately coupled cavity to external noise (ATLAS).

Cavity	0.5 TSR
E_{acc}	8.5 MV/m
RF Power	110 W
Temp.	4.5 K

Tuners: Fast Mechanical Tuning

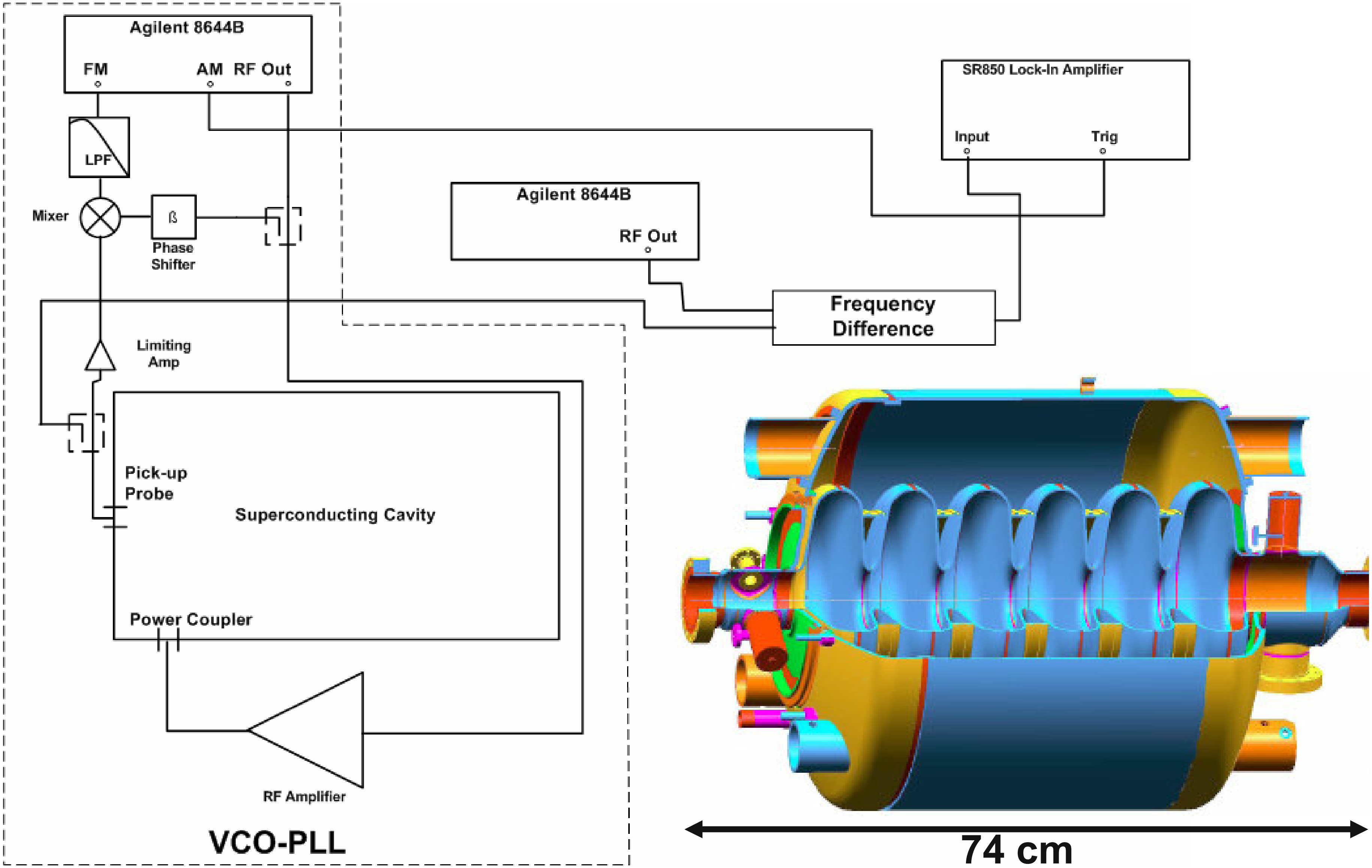


Cavity	0.5 TSR
E_{acc}	8.5 MV/m
RF Power	110 W
Temp.	4.5 K

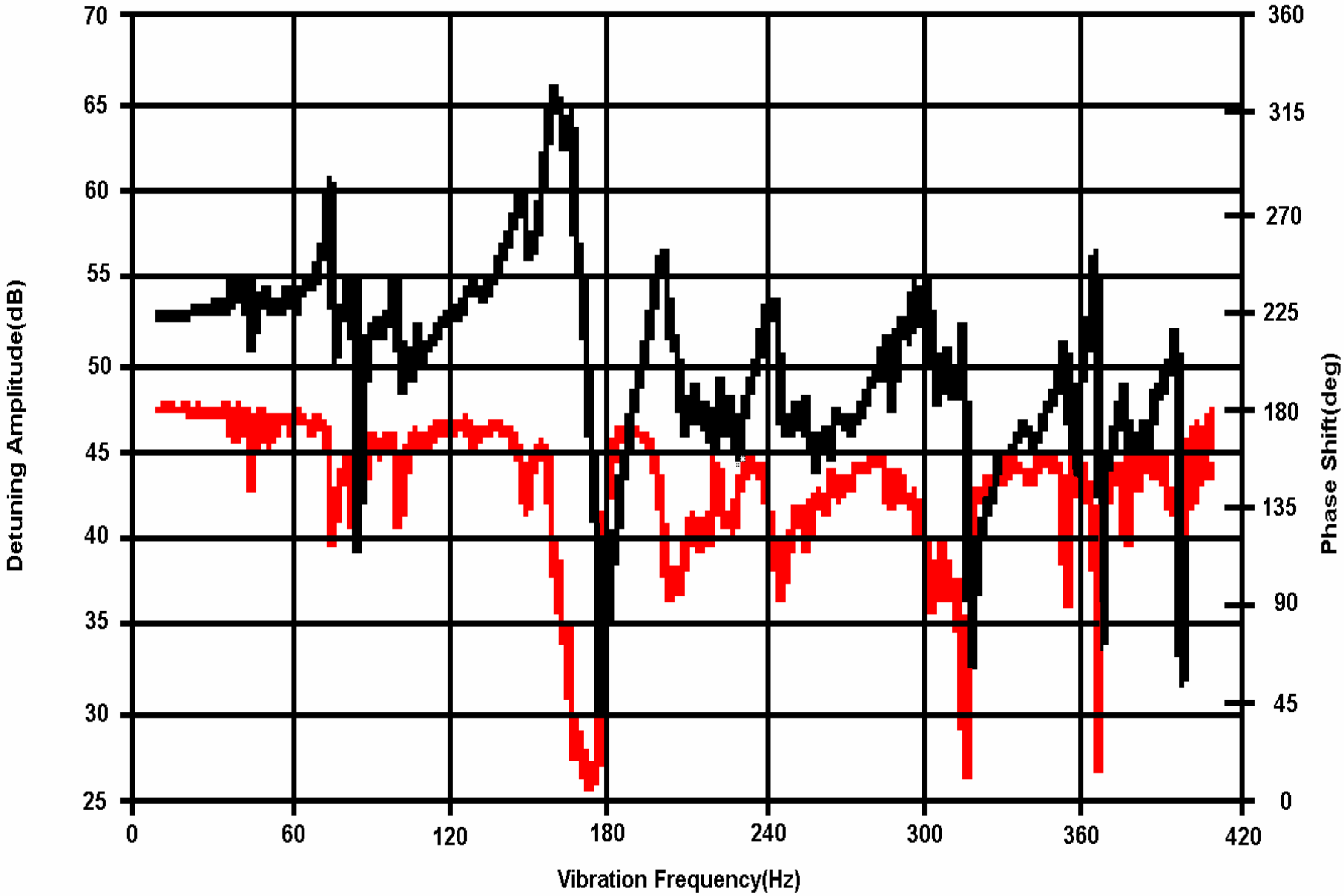
Mechanical Properties: Lorentz Detuning

- We just finished looking at continuous wave systems and how design changes effect the performance requirements of mechanical tuners.
- Pulsed accelerators have an additional force detuning the cavities, the dynamic Lorentz force
- The Lorentz force is due to the cavity RF surface fields interacting with the RF surface currents
- The Lorentz force can cause cavity ringing at much higher frequencies than the cw helium bath bubbling
- For related work on pulsed operation see reference [10].

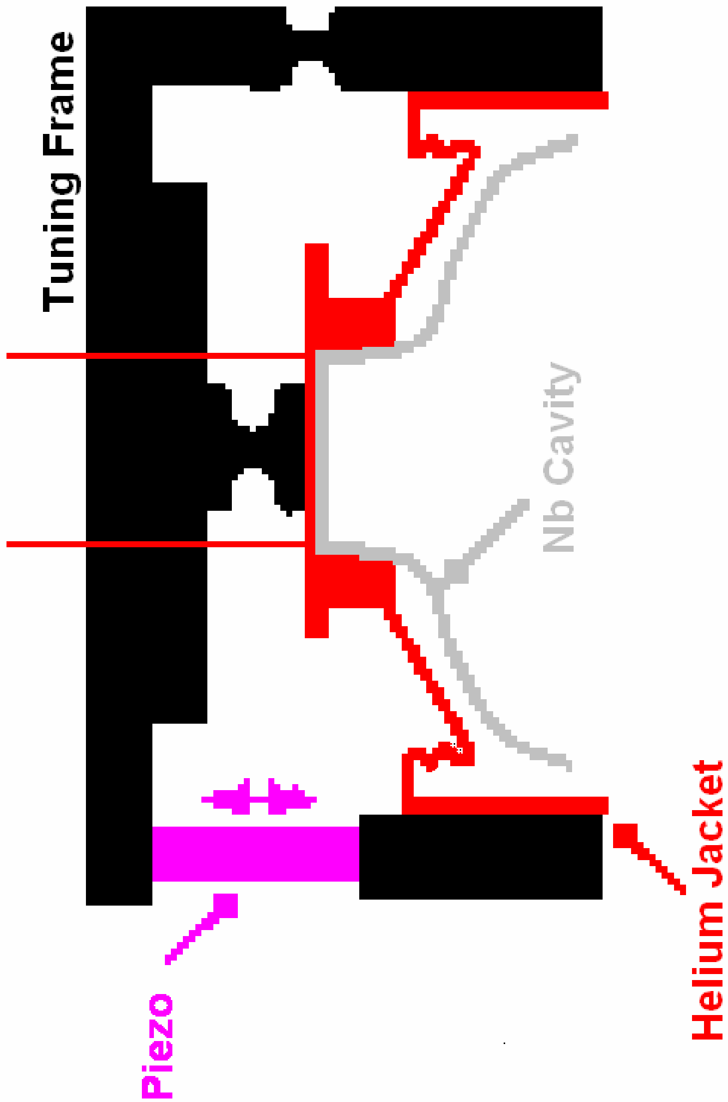
Lorentz Transfer Function Measurement

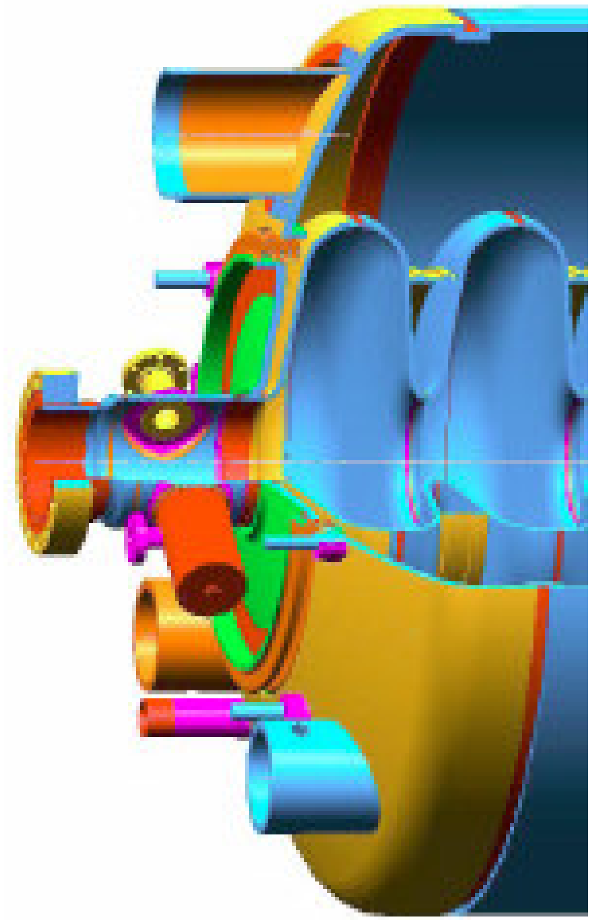


Lorentz Transfer Functions [11]



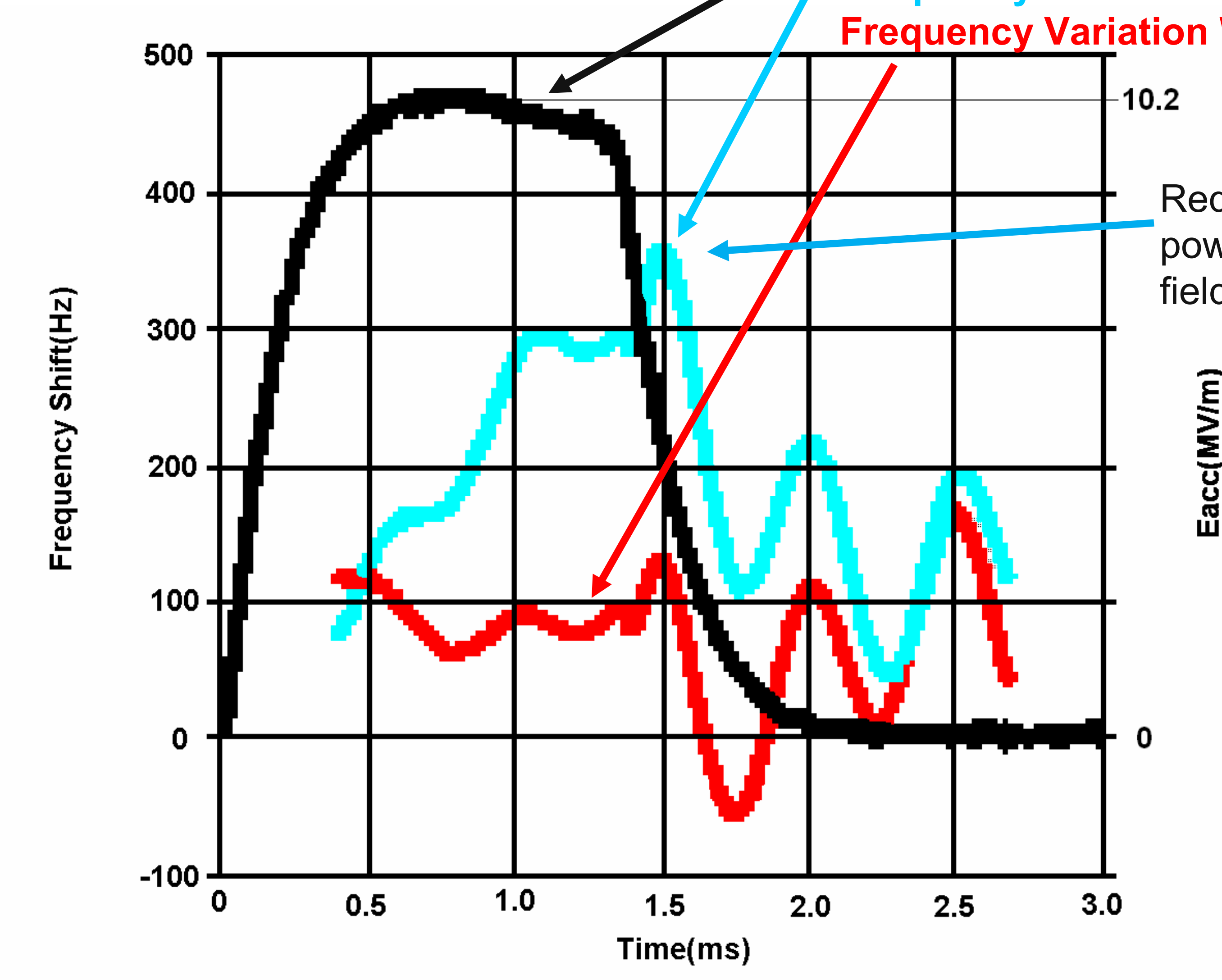
Elliptical Cell Mechanical Tuning





SNS Mechanical Tuning [11]

Cavity E_{acc} Amplitude
Frequency Variation Without Tuning
Frequency Variation With Tuning



Requires 13% more RF power to control the cavity fields.

Couplers

- I am finished talking about tuners.
- Now I am going to talk about the devices which couple power into and out of the cavity.
- Fundamental power couplers couple power from a generator/transmission line to the load. In this case the load is the cavity and the beam.
- Energy stored in the higher order electromagnetic eigenmodes contributes to emittance growth at best and at worst many break up the particle beam. HOM couplers couple this power out of the cavity to an external load.

Couplers: Requirements

- A large amount of published literature describing the development of coupler exists.
- Minimize RF losses
  - Don’t overheat the coupler
  - Don’t heat the cavity
- Impedance transition
  - Must match the impedance of the generator/transmission line system to the cavity/beam.
  - Operate over a wide coupling range
- Cleanable (Mike’s Talk), Avoid electron loading
- Reliable
- Transition from the cold superconducting cavity to room temperature
    - *Withstand thermal stresses*
    - *Act as a vacuum barrier between atmospheric pressure and cavity vacuum*
    - *Minimal heat leak*

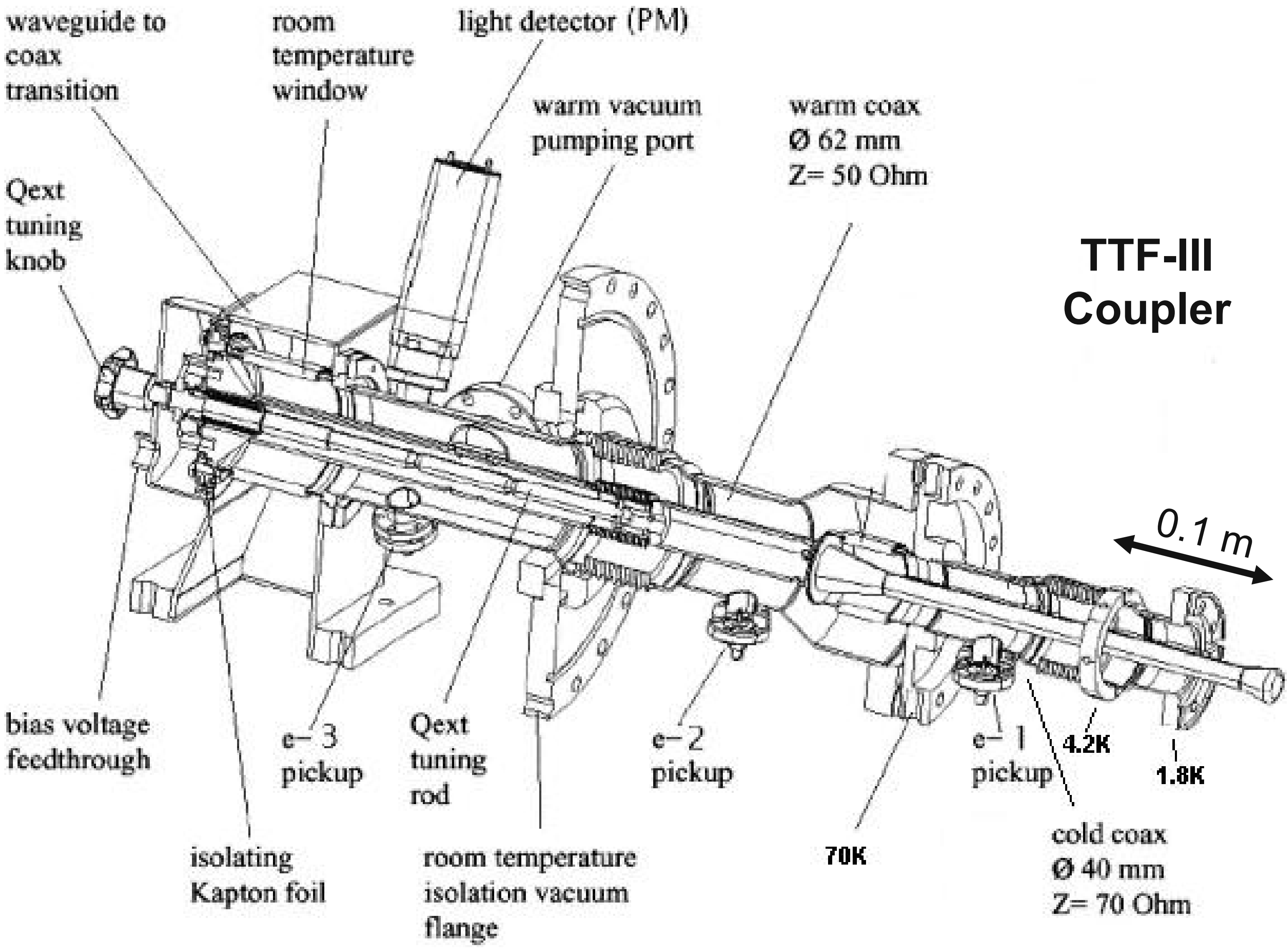
Couplers: Weidmann-Franz Law

- Couplers transition from the warm room to the cryogenic cavity system.
- Minimize the thermal conductivity to reduce the heat leak between the warm room and the cryogenic cavity.
- Maximize the electrical conductivity to limit RF losses

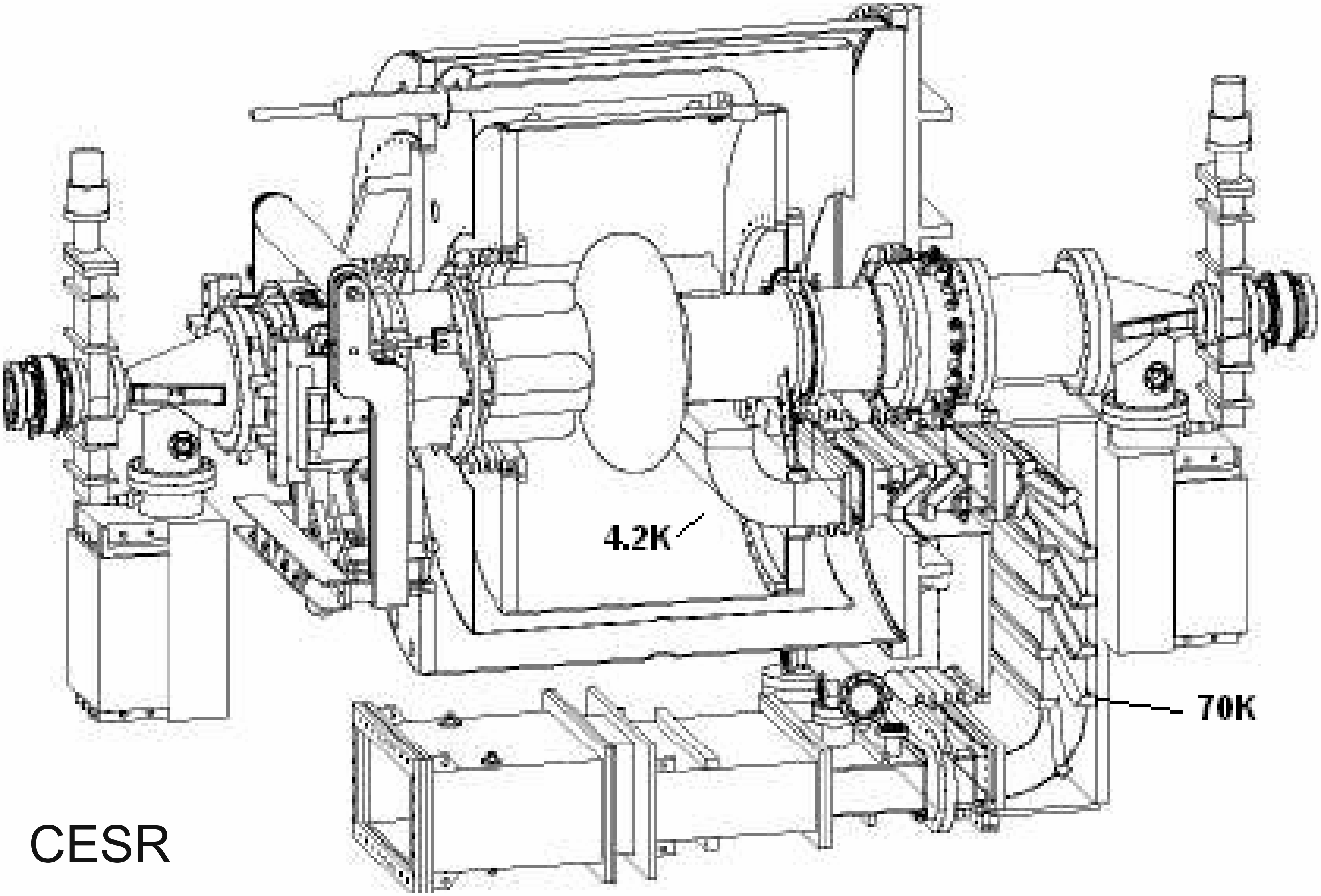
$$\frac{\lambda}{\sigma} = L * T$$

Where λ is the thermal conductivity, s is the electrical conductivity, L is the Lorentz number = 2.44E-8 W-Ω/K^2, and T is the temperature.

Couplers: Coaxial High-Peak Pulsed Power Coupler[12]



Couplers: cw High Power Waveguide Coupler [13]



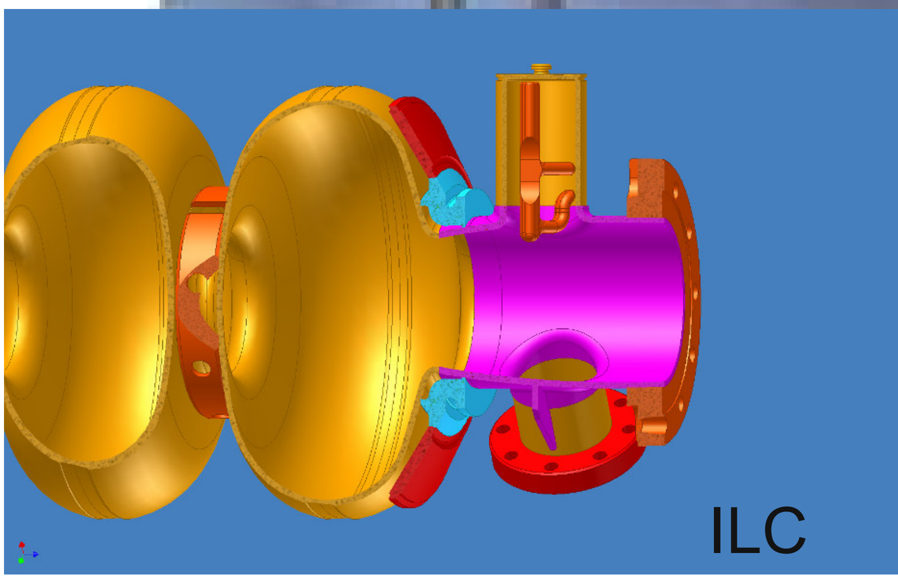
CESR

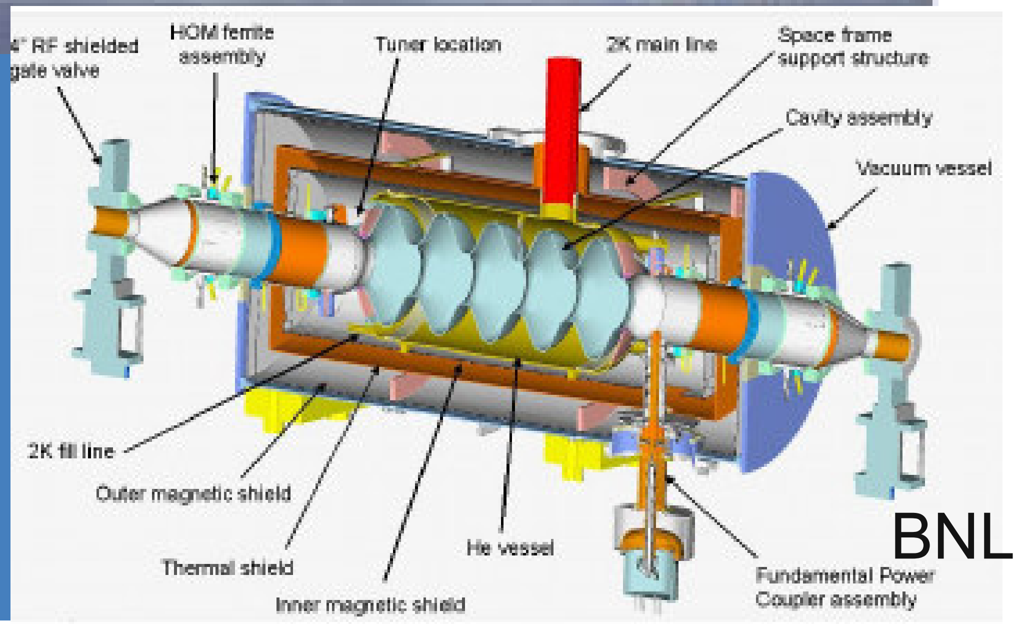
HOM Couplers

- HOM design requirements are extremely similar to the fundamental power coupler's requirements, except:
  - The HOM coupler should not damp the fundamental mode cavity RF field.
  - The dissipated RF power should not heat the cavity

- HOM Couplers damp unwanted electromagnetic cavity modes.

HOM Coupler Example [14]





Summary

- R&D toward higher gradients and larger quality factors must be combined with R&D focusing on the physics of resonators and the interactions between the cavity RF field and the particle beam.

- We have briefly reviewed the mechanical properties of resonators, tuners, and couplers.

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