SECOND TOPICAL WORKSHOP ON CRYOMODULE MICROPHONICS AND RESONANCE CONTROL – LLRF MRCW’18

Argonne NATIONAL LABORATORY

CONTINUOUS WAVE CRYOMODULE DESIGN: CRYO-MECHANICAL PERSPECTIVE

Z.A. CONWAY
Physics Division
Argonne National Laboratory

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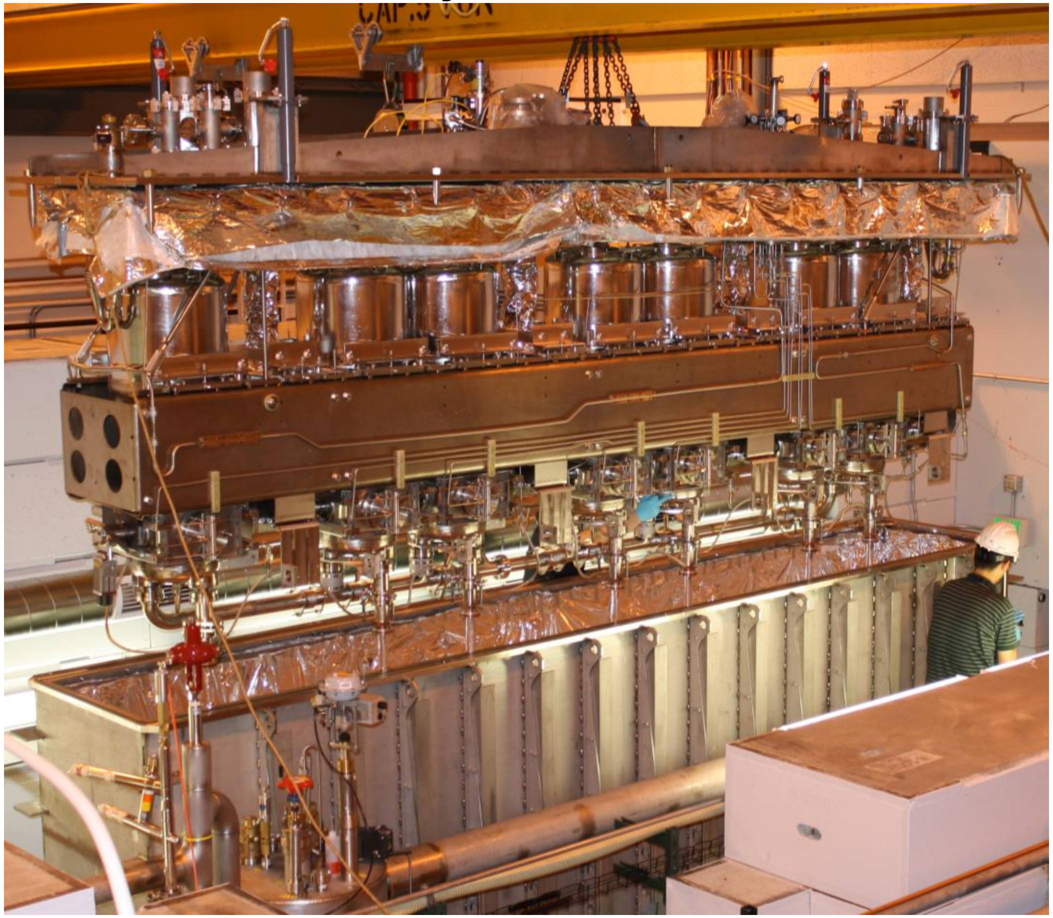
Argonne, Illinois 60439

ACKNOWLEDGEMENTS

People who deserve more credit than they receive.

ANL 72.75 MHz, $\beta = 0.077$, Quarter-Wave Cryomodule



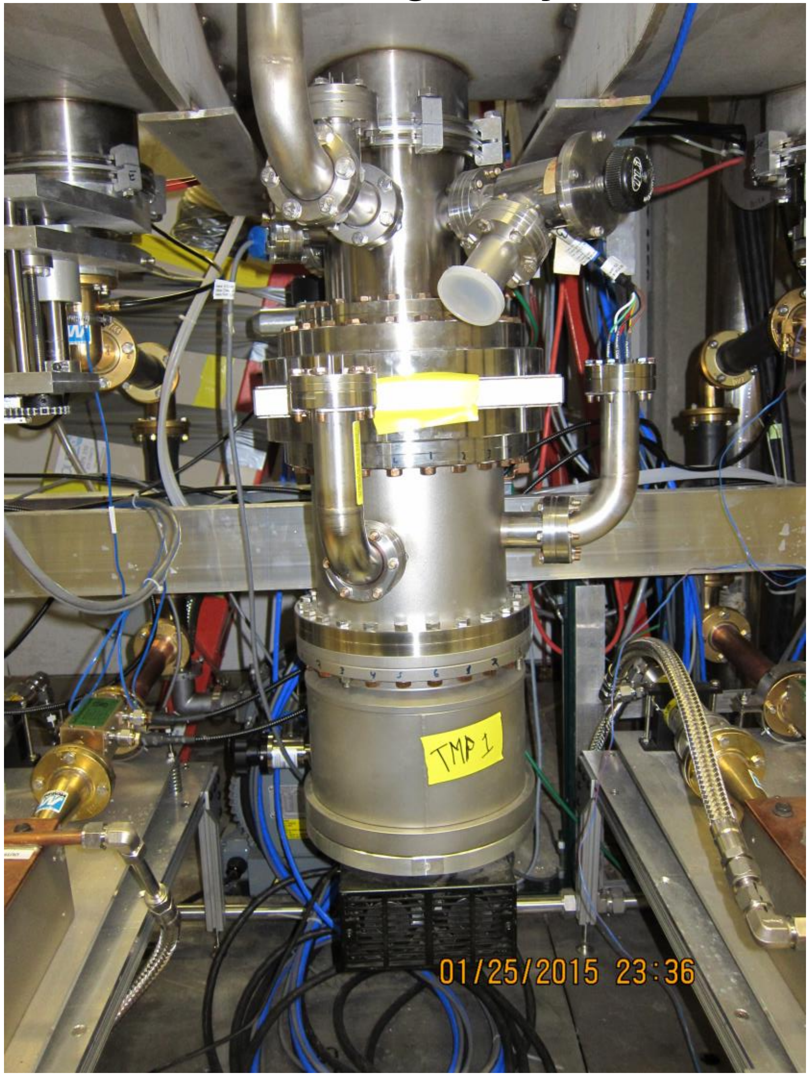
- **Michael Kelly, Albert Barcikowski, Glenn Cherry, Richard Fischer, Mark Kedzie, Jacob Kilbane, Tom Reid, and Gary Zinkann (ANL-PHY);**
- **Andrei Lunin and Joe Ozelis (FNAL);**
- **J. Fuerst (ANL-APS); and**
- **S.-h. Kim (MSU-FRIB).**

OVERVIEW

Covered Content

- **Motivation.**
- **Microphonic sources:**
  - **Mechanical vibration and couplings,**
  - **Cryogenics.**
- **Resonator design.**
- **Cryomodule design considerations:**
  - **Cryogenic distribution,**
  - **Mechanical coupling strength,**
  - **Vibration damping, and**
  - **Cavity isolation.**

Cryomodule Turbo Pump Shaking Away



SOURCES OF MICROPHONIC NOISE

Cryomodule Considerations

- Any physical interaction between the resonant cavity mechanical and RF structures which couples mechanical vibrations into undesirable RF noise.
- Resonator mechanical structure:
  - Helium bath boiling, tuner vibration, appurtenance loading, etc.
- Cryomodule design and mechanical couplings:
  - Thermal acoustic oscillations:
    - J. Holzbauer’s upcoming presentation,
  - Coolant flow rates: turbulent flow, water hammer, slug flow, sub-atmospheric cryogenic system, etc.
  - Ground motion.
  - Accelerator vibrations: vacuum pumps, fans, RF sources, magnet supplies, etc.
- M. Kelly – tomorrow – for ANL tuning methods.

DESIGN AND MICROPHONIC SOURCES

Coupling mechanical vibrations and RF eigenmodes

- **Cavity RF frequency variations are due to coupling between the RF field and mechanical vibrations (changing boundary conditions and/or sources).**

- **Cavity RF frequency variations due to oscillations in a mechanical eigenmode α driven by a generalized force, F_α, obey:**

$$\frac{d^2\Delta\omega_\alpha}{dt^2}+\frac{2\Omega_\alpha}{Q_\alpha}\frac{d\Delta\omega_\alpha}{dt}+\Omega_\alpha^2\Delta\omega_\alpha=-\frac{\omega\Omega_\alpha^2F_\alpha^2}{c_\alpha U}$$

$$\Delta\omega=\sum_\alpha\Delta\omega_\alpha$$

- **The cavity frequency variations are only driven by mechanical modes which couple to the RF fields.**

- **Design cavity mechanical structure to address dominant mechanical sources.**

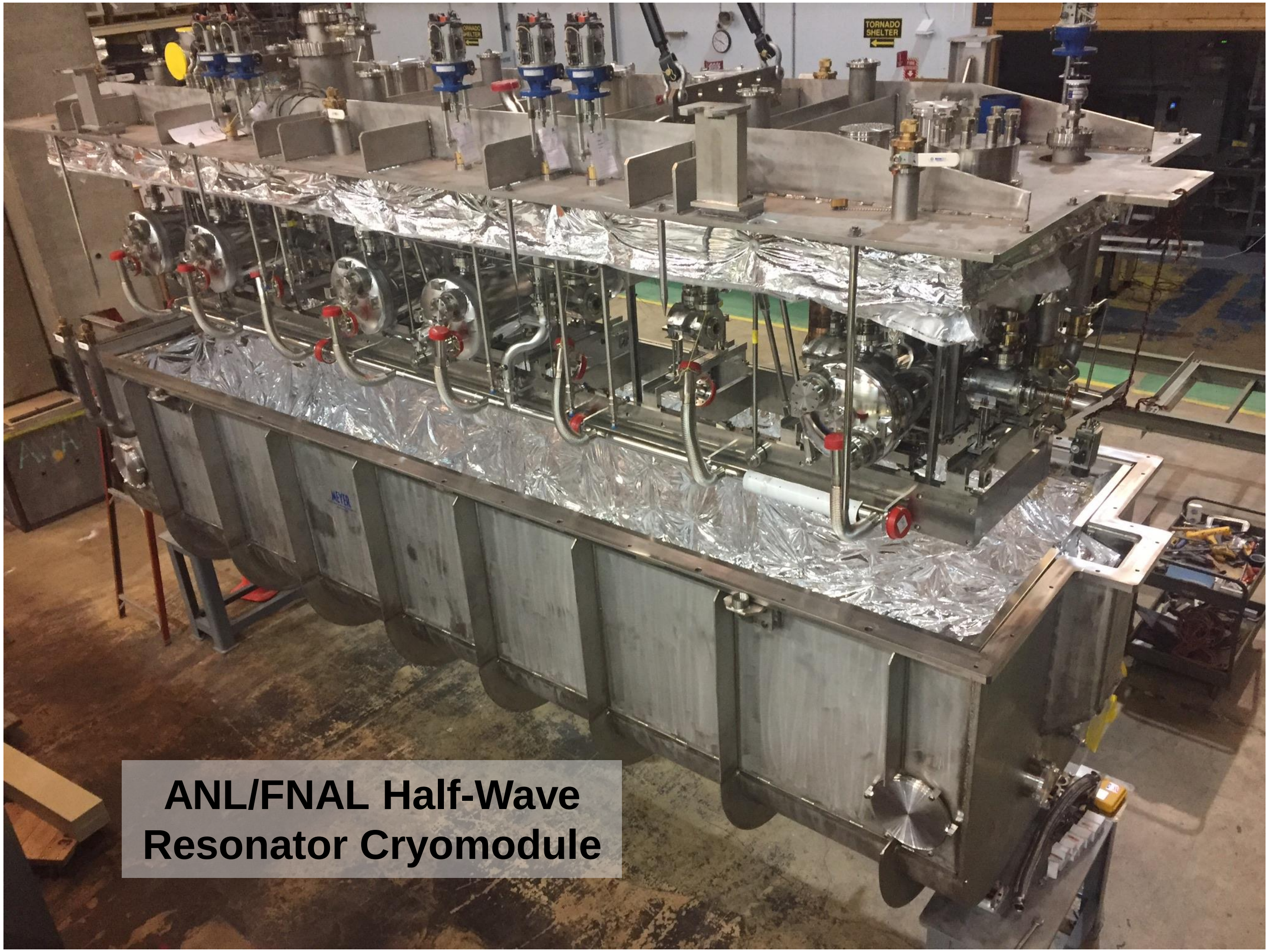
MECHANICAL VIBRATIONS

Types

- Deterministic or non-deterministic:
  - Resonant or non-resonant excitation of mechanical modes.
  - Wave types:
    - Shock wave/pulse, harmonic, random.
- Modes of Oscillation (all of which can be coupled):
  - Transverse,
  - Longitudinal,
  - Rocking, and
  - Torsion.
- Damping: good luck if you are using metals
- Next = example.

CRYOMODULE OVERVIEW

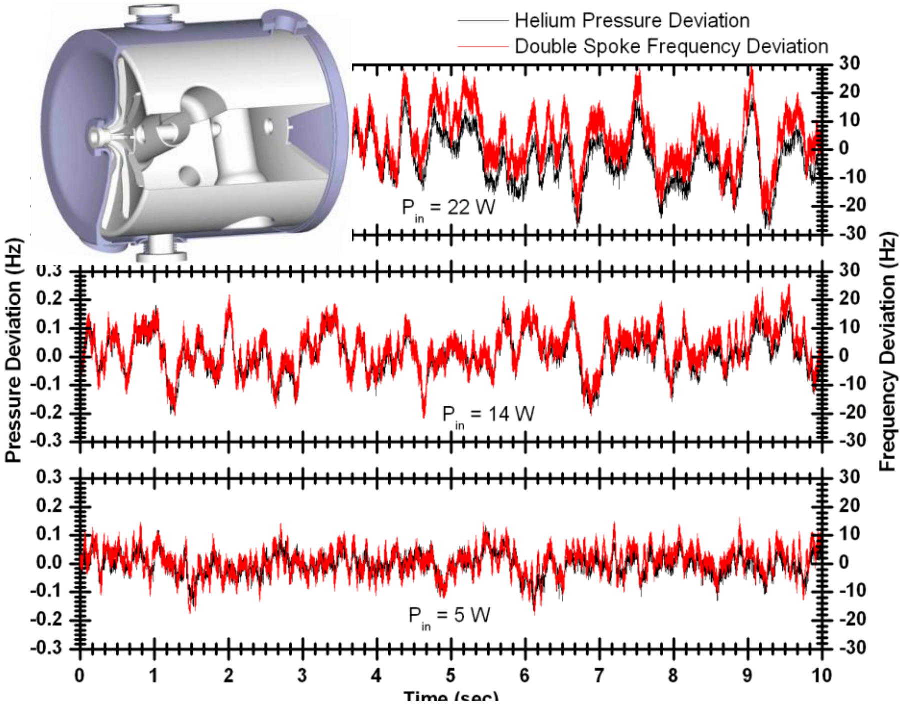
Top Loading Cryomodule Not The Only Option – K. Jensch Next

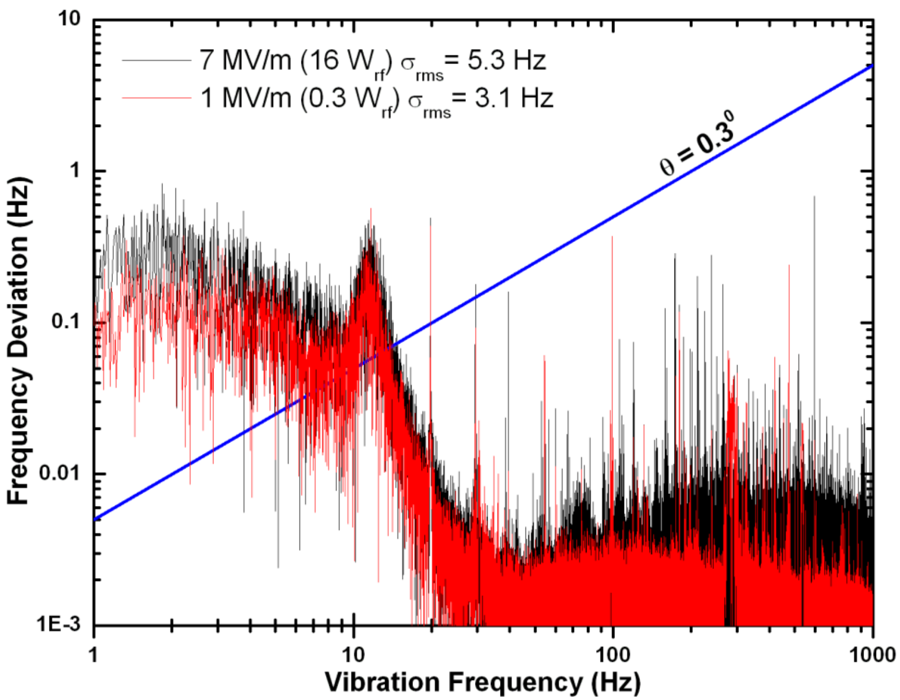


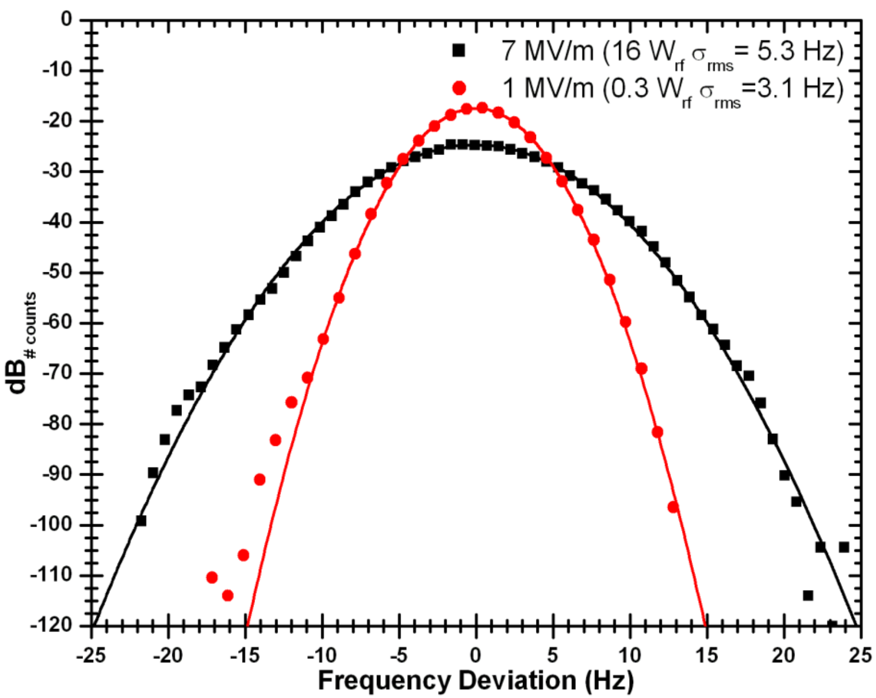
NON-OPTIMIZED EXAMPLE

Helium Bath Boiling

- **345 MHz, β = 0.40 double spoke resonator:**
  - **$\Delta f / \Delta P$ = + 49 Hz/mbar**
- **The double spoke cavity microphonic noise driven by low frequency helium bath boiling**



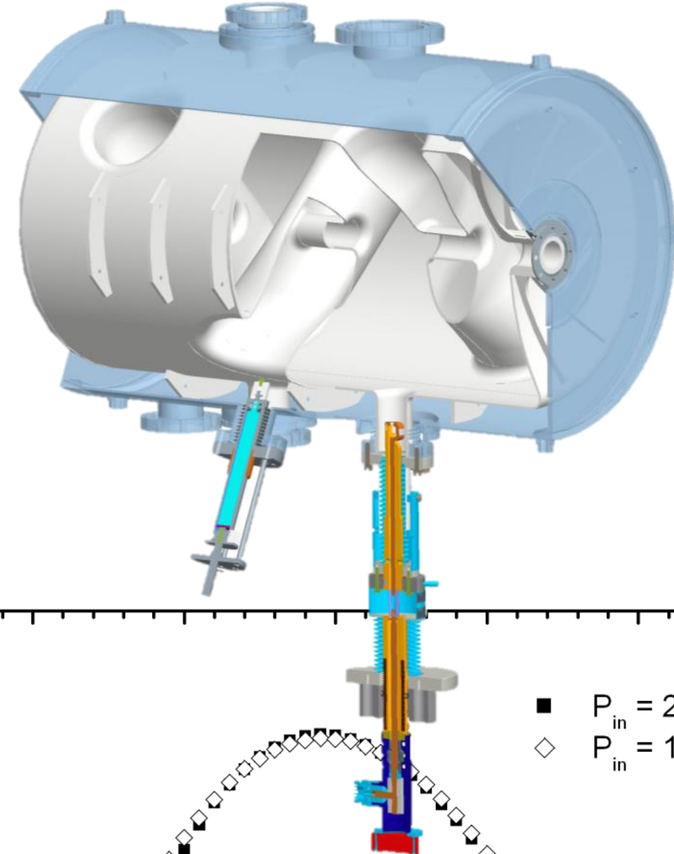


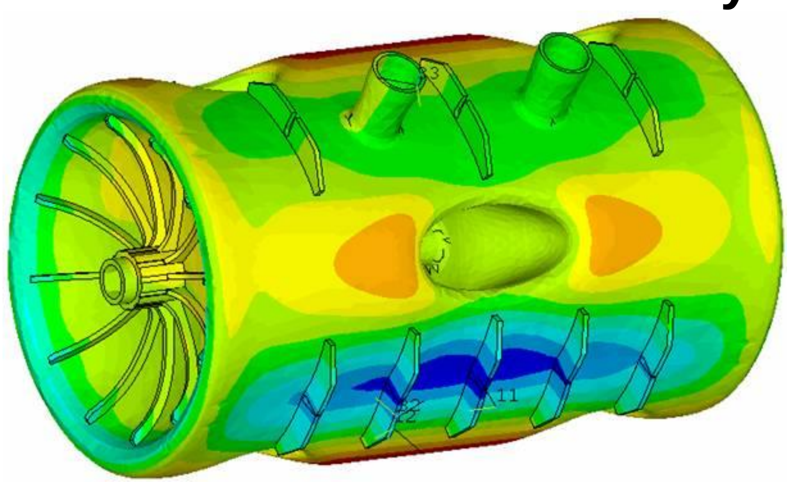


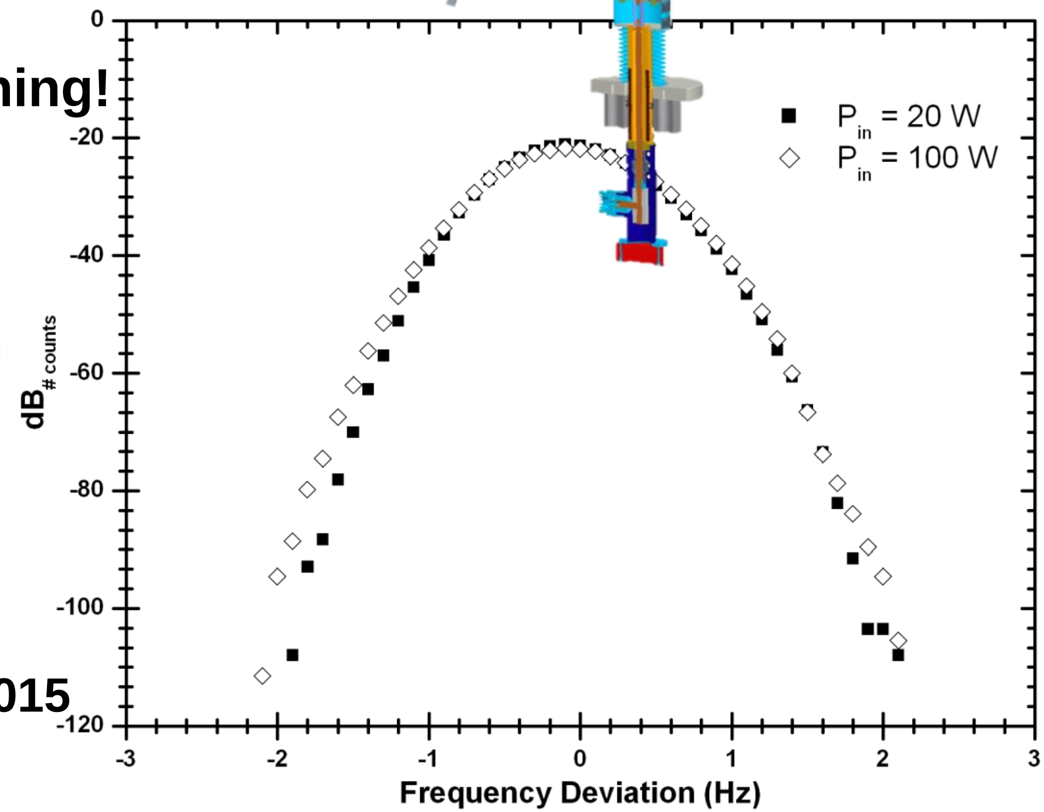
OPTIMIZED EXAMPLE

Helium Bath Boiling

- **A triple spoke resonator was built after the double spoke.**
- **Designed to de-couple the cavity RF from low-frequency helium pressure fluctuations.**
  - **TSR $\Delta f/\Delta P$ = -1.9 Hz/mbar**
  - **Cannot do this for everything!**







Z. Conway, SRF 2005
Posen & Liepe, PRST-AB 02202 2015

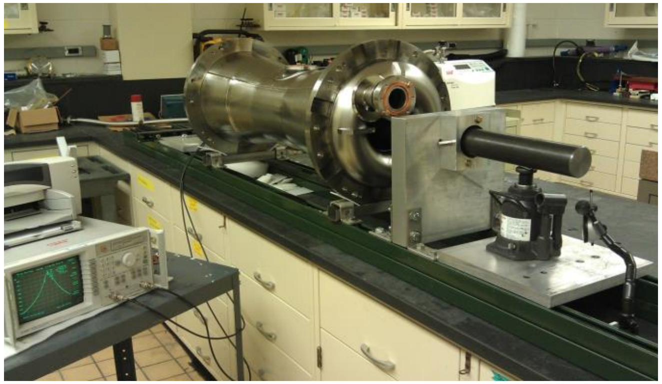
MICROPHONIC CENTERING

Balance Cell-to-Cell Reactance

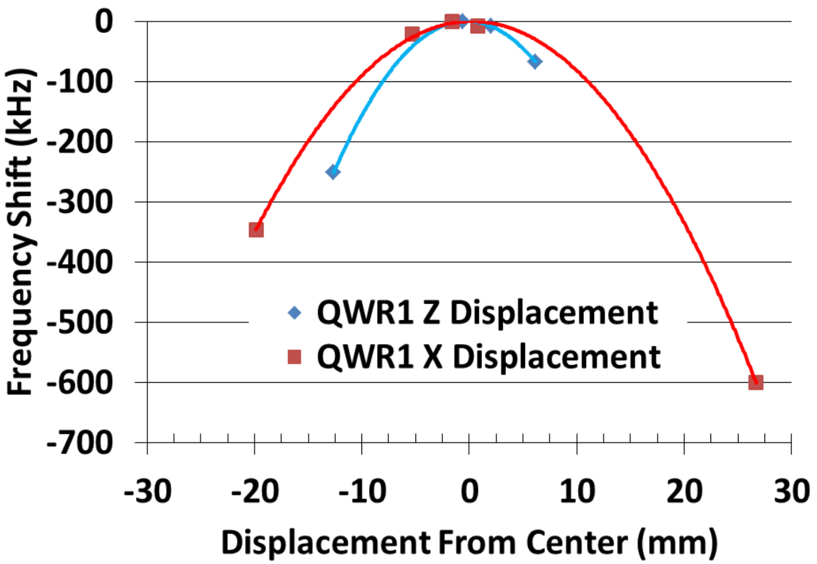
72 MHz QWR

Center Conductor

- **Possible to reduce microphonic frequency variations due to pendulum-like motion of inner conductor.**
  - **J.R. Delayen, NIMA A259 (1987) 341-357.**
- **Practically accomplished by electromagnetic centering of the inner conductor.**
  - **Maximize the cavity frequency – No position measurements required.**
  - **Frequency perturbations are 2nd order with respect to inner conductor position – Eliminates microphonics due to pendulum-like motion.**



HWR Being Tuned

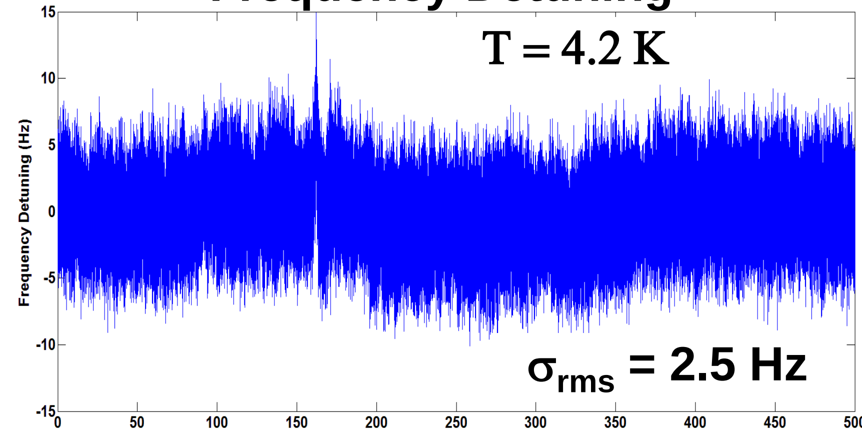


HWR POWER REQUIREMENTS

Half-Wave Resonator Electro-Mechanical Interactions

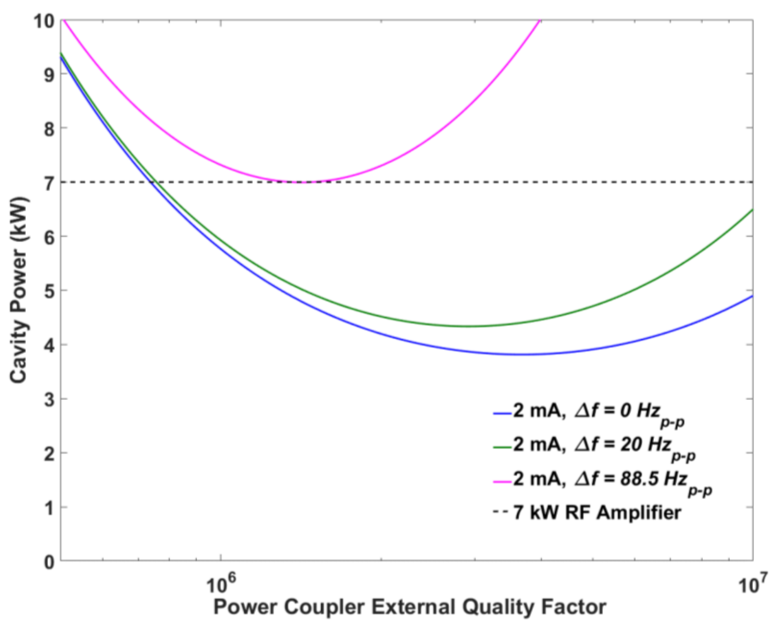
- **All HWR tested have a *df/dP* ~ 11 Hz/mbar.**
- **With a helium pressure stability of 0.1 mbar → $\Delta f = 1.1$ Hz.**

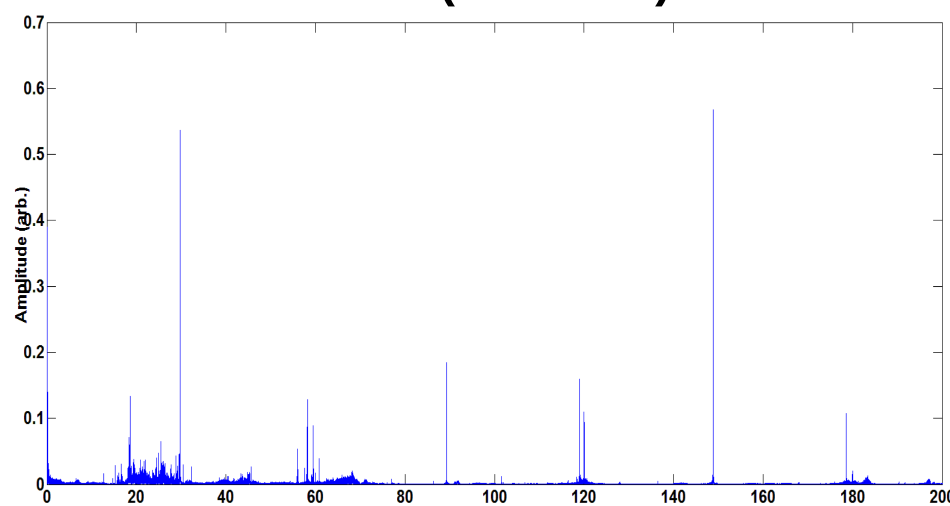
Measured HWR1 Microphonic Frequency Detuning



Time (Seconds)

HWR Cavity Power



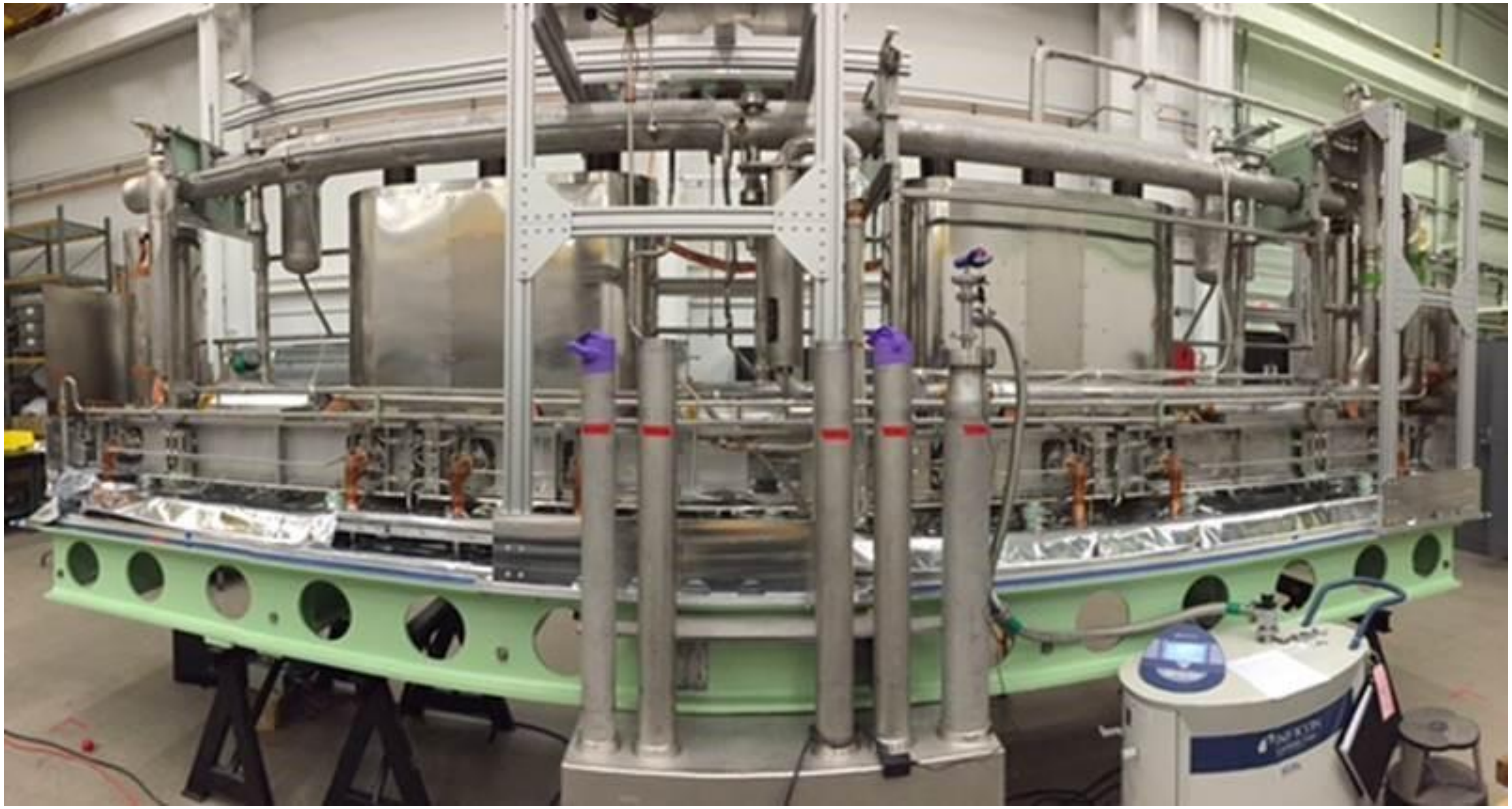


Mechanical Vibration Frequency (Hz)

CRYOMODULE DESIGN CONSIDERATIONS

Mechanically coupled to the RF system

- **Cryomodules are either the source or the coupling between mechanical vibrations and resonators.**



FRIB β = 0.085 Quarter-Wave Resonator Cryomodule
S.-h. Kim's presentation tomorrow for a good example.

THERMO-ACOUSTIC OSCILLATIONS

Good luck

- **When a gas channel is subject to large temperature gradients it may spontaneously oscillate in an undamped manner with large thermal and pressure variations.**
- **Mitigation:**
  - **Reduce the driving force:**
    - **Change temperature gradient – thermal intercepting.**
    - **Change the length to diameter ratio.**
  - **Increase viscous damping: reduce channel area.**
  - **Increase inertial damping: increase channel area, increase chamber volumes, and change the thermal gradient.**
  - **Block gas flow in the channel: check valves, filters.**
  - **Change channel coupling: ballast volume, change flow rate through the channel.**

J. Fuerst, Low Temp. Eng. & Cryo. Conf., Southampton, UK 17-19 July 1990.
Christie & Hartwig, Thermal & fluids Analysis workshop 2014.
Gupta & Rabehl, Applied Thermal Engineering, Vol. 84, 104-109 2015.

THERMO-ACOUSTIC OSCILLATION STABILITY

When and where to TAO's occur.

- **Stability mathematically calculated by N. Rott for discontinuous temperature jump.**

$$\alpha = \frac{T_{Hot}}{T_{Cold}} \qquad Y_c = r_0 \left(\frac{\omega}{\nu_c}\right)^{1/2}$$

- **Stable for small values of either a or Yc.**

- **Measured for cryogenic applications by Fuerst (1990) and then many more.**

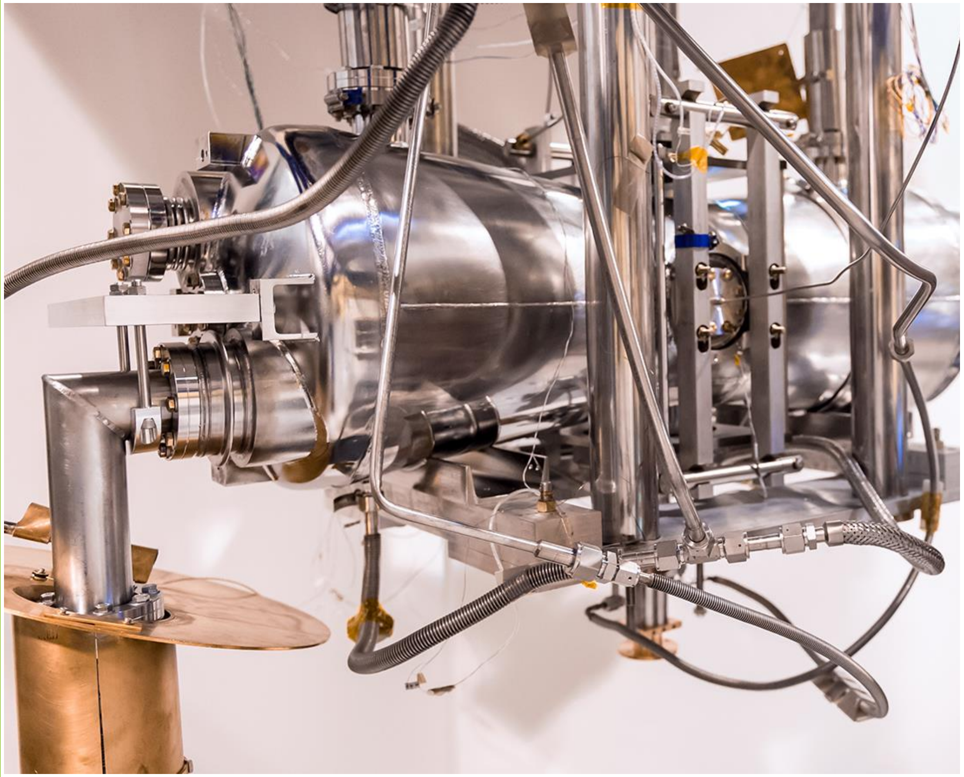
- **Reduce risk by:**
  - **Damping,**
  - **Thermal profile modifying, and**
  - **Elimination of the line containing the thermo-acoustic oscillation.**

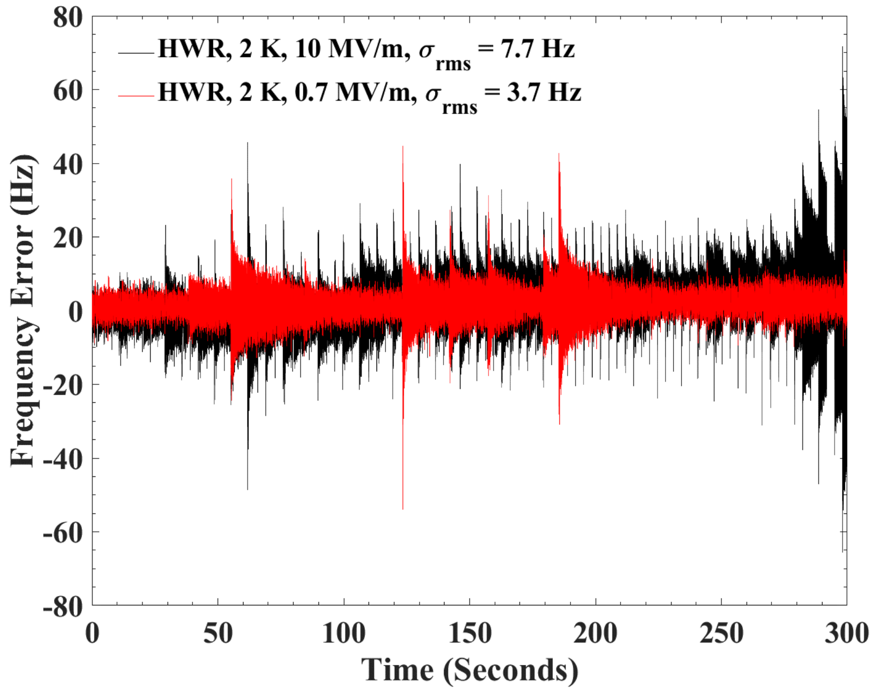
N. Rott, J. of Appl. Math. & Phys., Vol. 24, 54-72 1973.

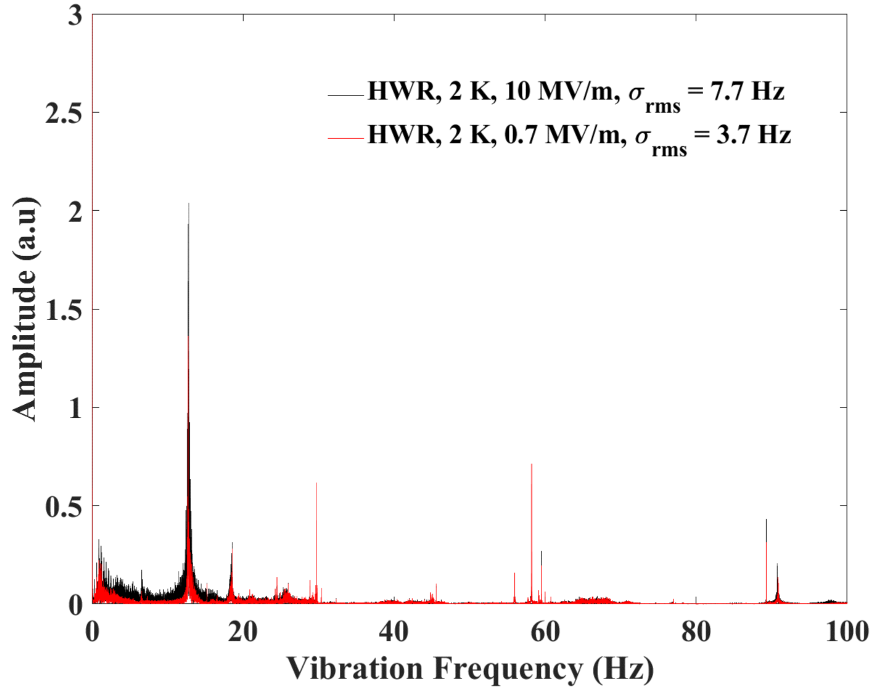
TAO EXAMPLE – PART I

Half-Wave Resonator Cool-Down Line TAO

No TAO Check Valve



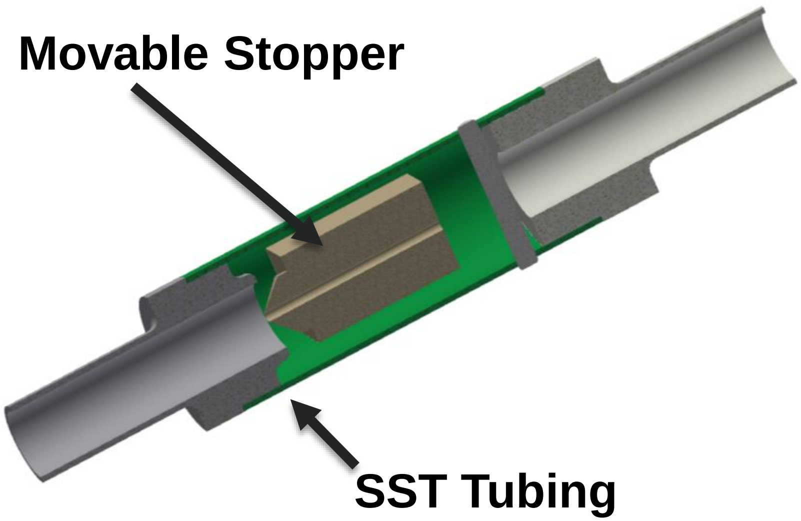




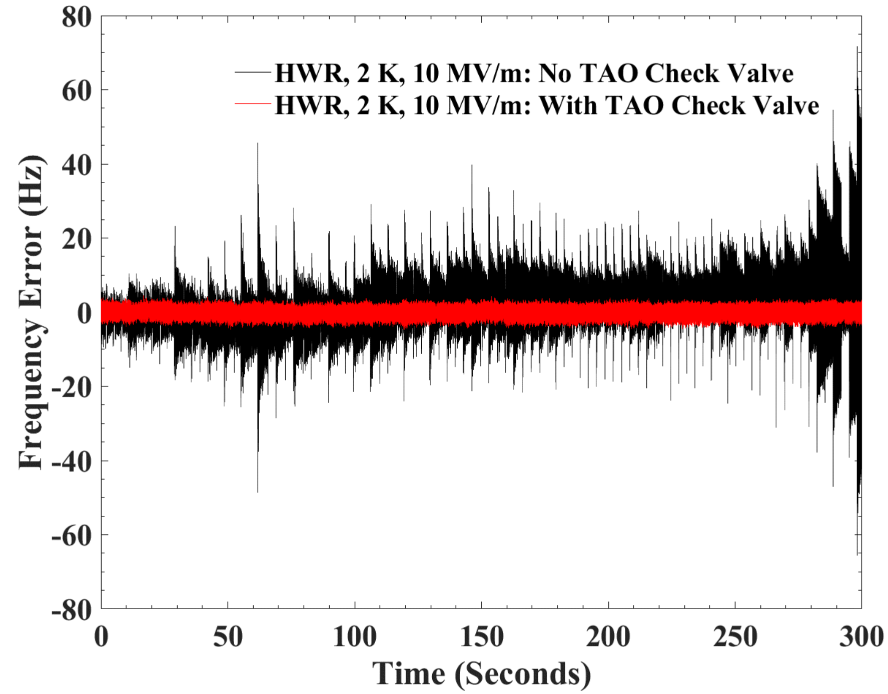
TAO EXAMPLE – PART II

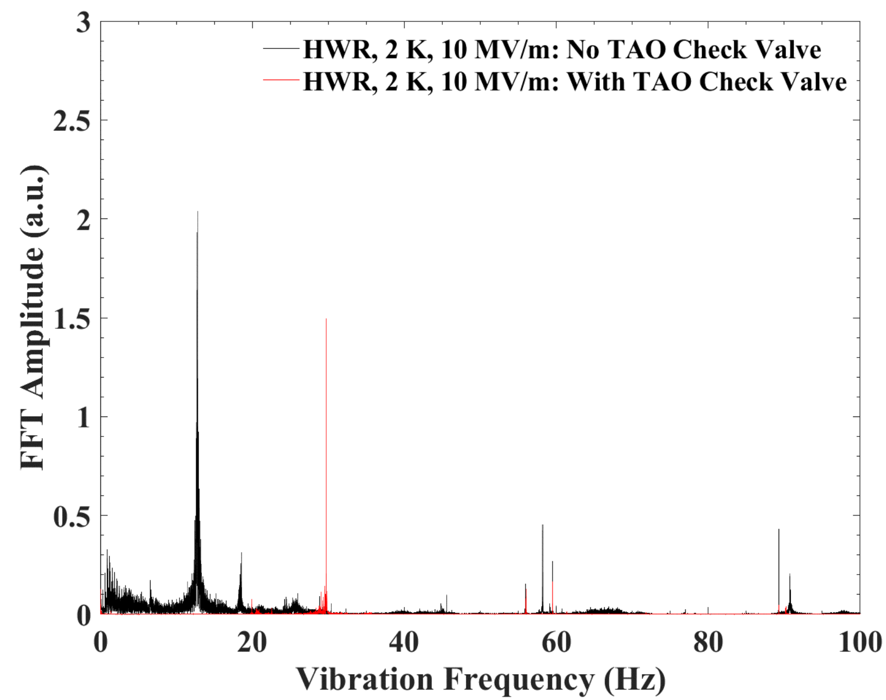
Half-Wave Resonator Cool-Down Line TAO

TAO Check Valve



TAO Check Valve Based On FNAL Design





CRYOMODULE MECHANICAL DESIGN

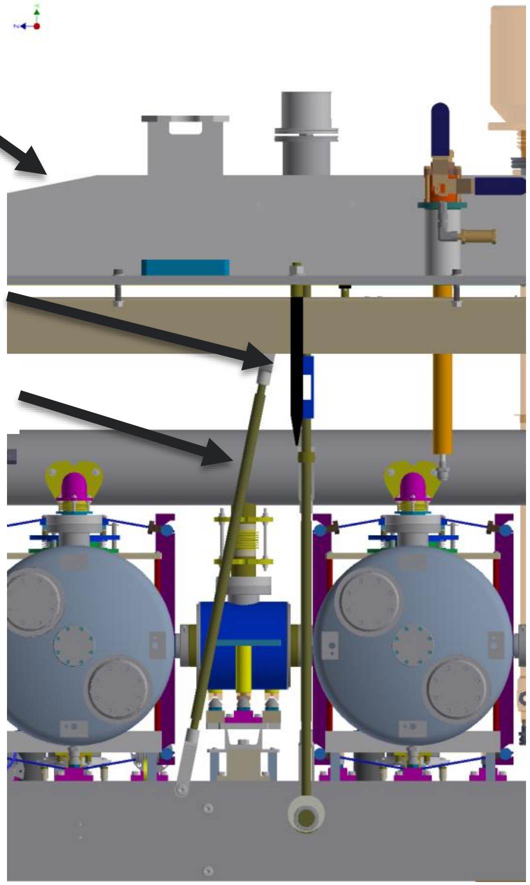
Modify coupling strengths to suit your needs

- **Oscillator frequency.**
  - **Increasing frequency can address issues.**
  - **Increase inertial mass.**

- **Coupling strength**
  - **Rigidity of coupling.**
  - **Moment of Inertia.**

$$\omega_0 = \sqrt{\frac{mgl_{c.m.}}{I_{Solid}}}$$

ANL Box Type Cryomodule Support



LINKAGE DESIGN

Acoustic Wave Transmission

- **Vibrations are mechanical waves and obey the wave equation.**
- **Take care: a wave going from a high impedance to a low impedance region increases in amplitude.**

$$R_0 = \frac{Z_2 - Z_1}{Z_2 + Z_1}$$

$$T_0 = \frac{2Z_1}{Z_2 + Z_1}$$

$$Z = \frac{Force}{Velocity} = \rho v \; (solid)$$

$$T_0(SST\ to\ Ti) = 1.26$$

Acoustic Impedance For Different Materials

Material	ρ(kg/m³)	v (m/s)	Z (MPa*s/m)
304 Stainless Steel	8,000	5,800	46
Steel	8,050	4,900	39
Titanium	4,500	6,100	27
Aluminum	2,700	6,320	17
Copper	8,930	4,600	41
Niobium	8,600	3,500	30

www.matweb.com

CLOSING REMARKS

Thank you for your attention

- **Microphonic sources are everywhere.**
- **Design your resonators and cryomodules to decouple microphonics from RF as much as practicable.**
- **Good luck.**