Boron Nitride Nanotube (BNNT) Vibration Damping for SRF Structures

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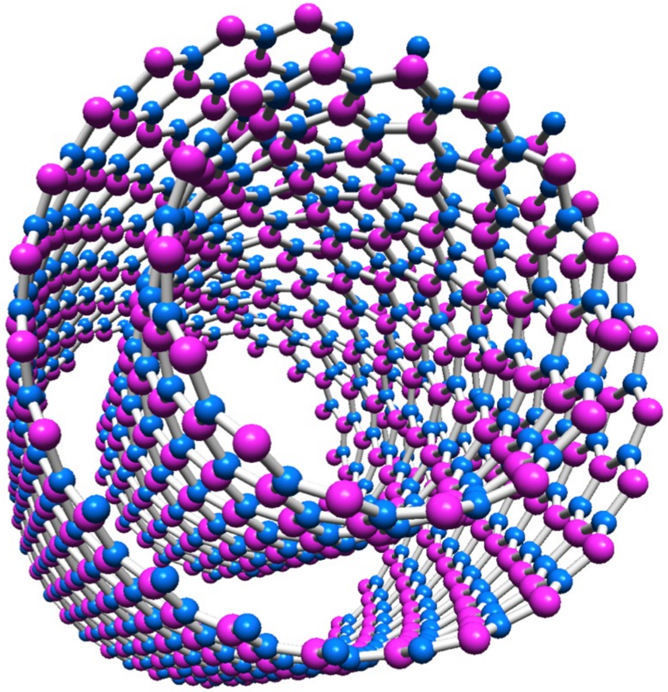
23 August 2022



Viscoelastic behavior results from BNNT molecules rubbing against one another. Boron-nitrogen bonds contain a partial dipole believed to produce nanoscale friction that generates phonons in (and between) BNNT molecules that dissipate vibrational energy as heat. Conversely, carbon nanotubes (CNTs) do not exhibit viscoelasticity because the aromatic, nonpolar carbon-carbon bonds have lubricious behavior like graphite.

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BNNT

Commercializing Revolutionary New Material

- **Commercialized high-temperature/high-pressure (HTP) method for synthesizing BNNTs**
  - Results in more highly flexible, ultra-strong, lightweight, and highly crystalline BNNTs [independently validated vs. competitors]
  - New pilot plant enables kilogram quantities while exploring automation, maintenance projections, and other economies of scale for future scale-up

- **USG work:**
  - Cryogenic vibration damping (DOE) including FNAL
  - Radome materials (Navy - Carderock, Maryland)
  - Reusable hot structures (NASA)
  - Thermal management in high power electronics (Navy)
  - CRADA w/ Navy Air (China Lake, California)
    - Very broad, even PFAS water cleanup
  - Space Act Agreement (NASA-LaRC)

- **Commercial research center endeavors (partial sampling only):**
  - Vibration damping at Helmholtz Zentrum Berlin
  - Electronics thermal management
  - Power generation

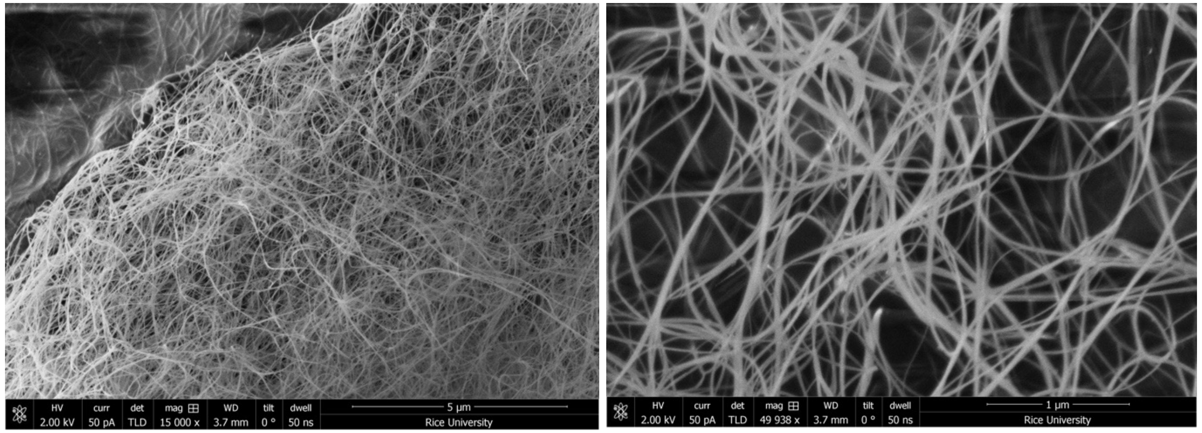
NASA Invention of the Year

Office of Naval Research ONR Science & Technology

National Institute of Aerospace

NASA

Jefferson Lab

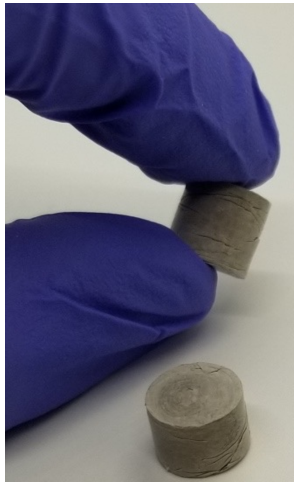


SEM micrograph of purified BNNT courtesy of M. Pasquali (Rice Univ.)

Pellets to Cartridges to Cavities

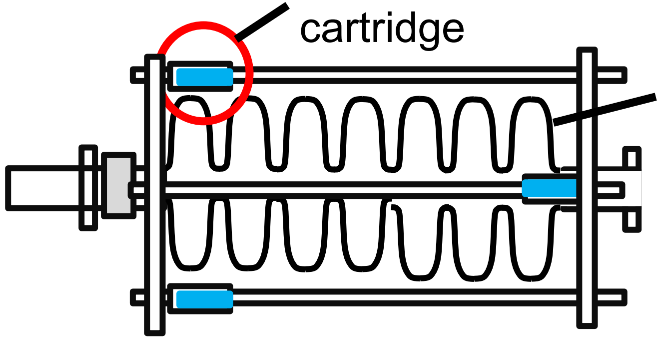
- SBIR Phase I: April 9, 2018 – April 8, 2019
    - Viscoelastic vibration damping at 2 K demonstrated in VTA
- SBIR Phase II: 28 May 2019 – 27 May 2021
    - Demonstrate vibration damping in C100 and LCLS-II SRF cavities
- SBIR Phase IIA: 18 June 2021– 17 June 2023
    - Demonstrate vibration damping in C100 and LCLS-II-HE SRF cavities and cryomodules
- CRADA: JSA-2018S005

BNNT pellets fabricated from compressed BNNTs:



Multiple BNNT pellets combined in each **cartridge** for required spring constant and compressive damping:

Four cartridges of BNNTs (three illustrated in blue) provide passive vibration damping of length oscillations of C100 SRF cavity:

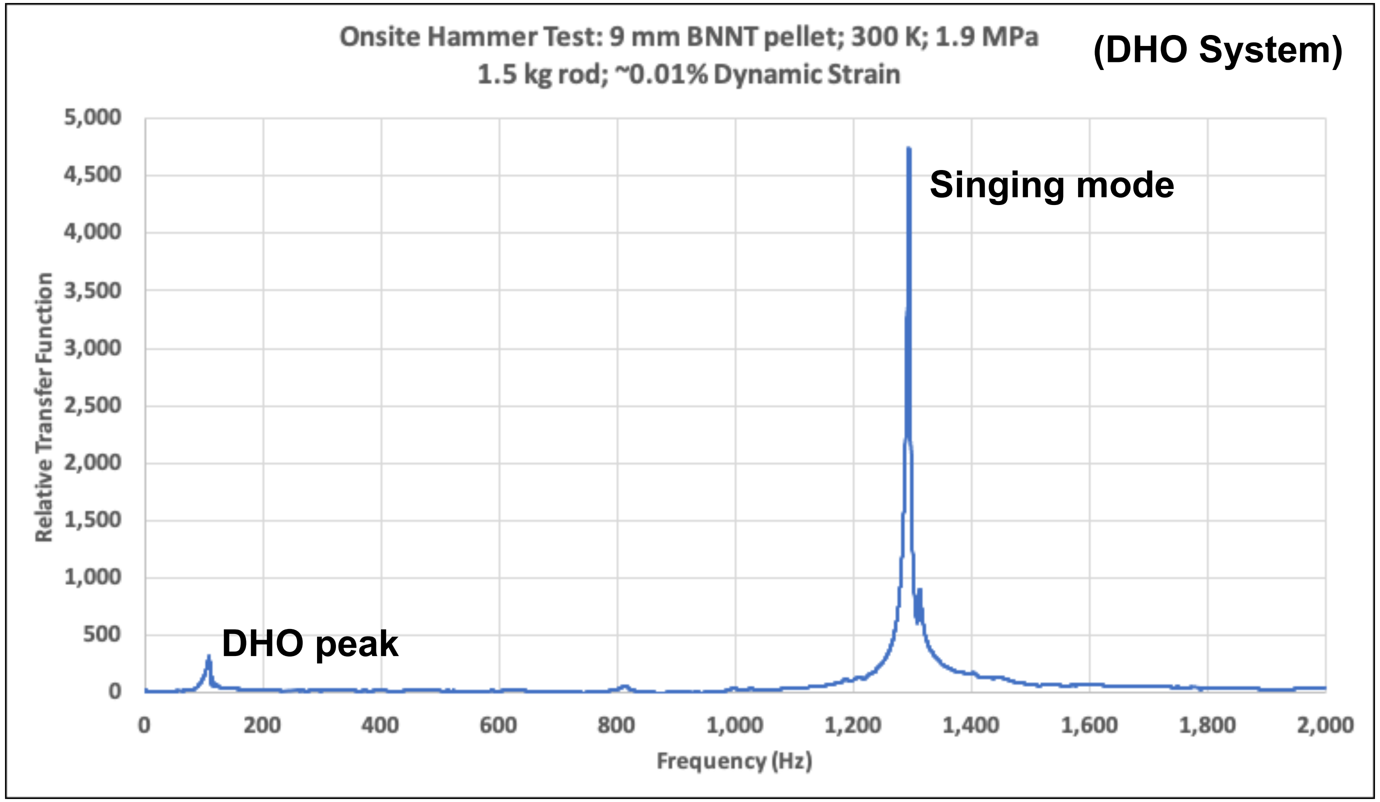


BNNT Pellets – Characterization

Two methods to characterize BNNT pellets for **elastic moduli** and **loss coefficients (tan deltas)**:

1. Damped Harmonic Oscillator (DHO)

   Hammer testing onsite at BNNT LLC. The motions of the hit rod result in a relative transfer function that exhibits DHO and a “singing” mode axially vibrating. **The elastic modulus and tan delta of the pellet are extracted from the position and width of the DHO peak**.
2. Dynamic mechanical analysis (DMA) at both 300 K and 77 K (independent commercial test); results similar to DHO values, next slide.



BNNT Pellets – DHO and DMA Results

DHO modes observed during onsite hammer testing typically range from 40-200 Hz, depending on axial lengths and number of BNNT pellets tested (different configurations).

A newer BNNT variant outperforms with higher tan deltas

Pellets made of two BNNT variants demonstrate ~20% increase in elastic modulus upon cooling from 300 K to 77 K

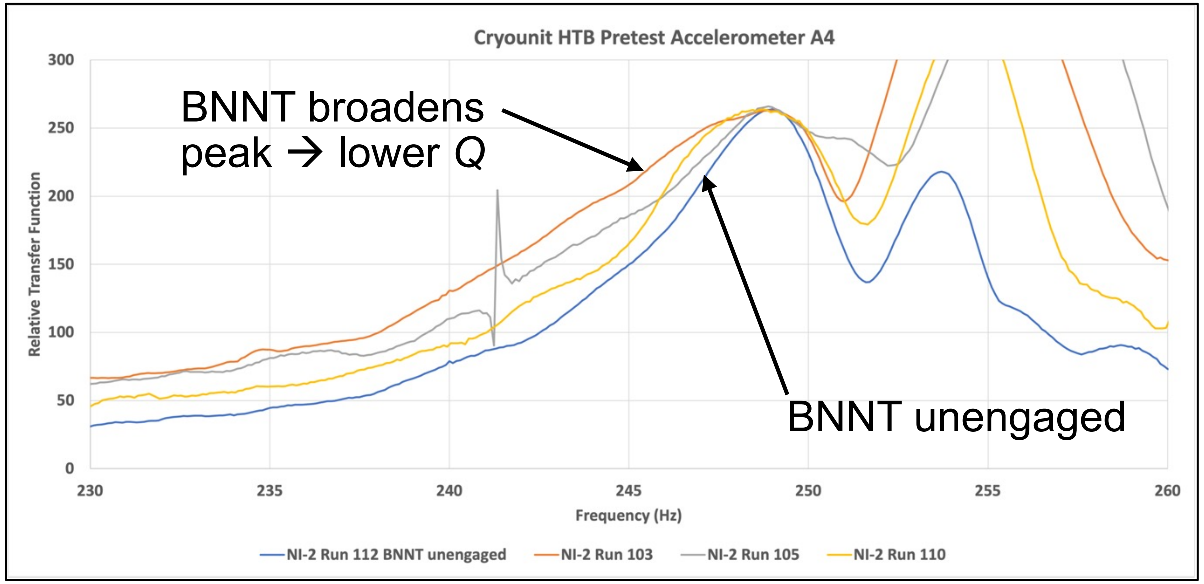
Elastic Modulus and tan delta measurements on single BNNT pellets

System and BNNT Pellet	**Temperature (K)**	**Dynamic Strain (%)**	**Elastic Modulus (MPa)**	**tan delta**
DHO – SP10R	77	0.01	105	0.10
DMA – RP14R	77	0.01	127	0.02
DHO – SP10R	300	0.01	85	0.07
DMA – RP14R	300	0.01	108	0.05

BNNT SP10R outperforms RP14R as observed from tan delta

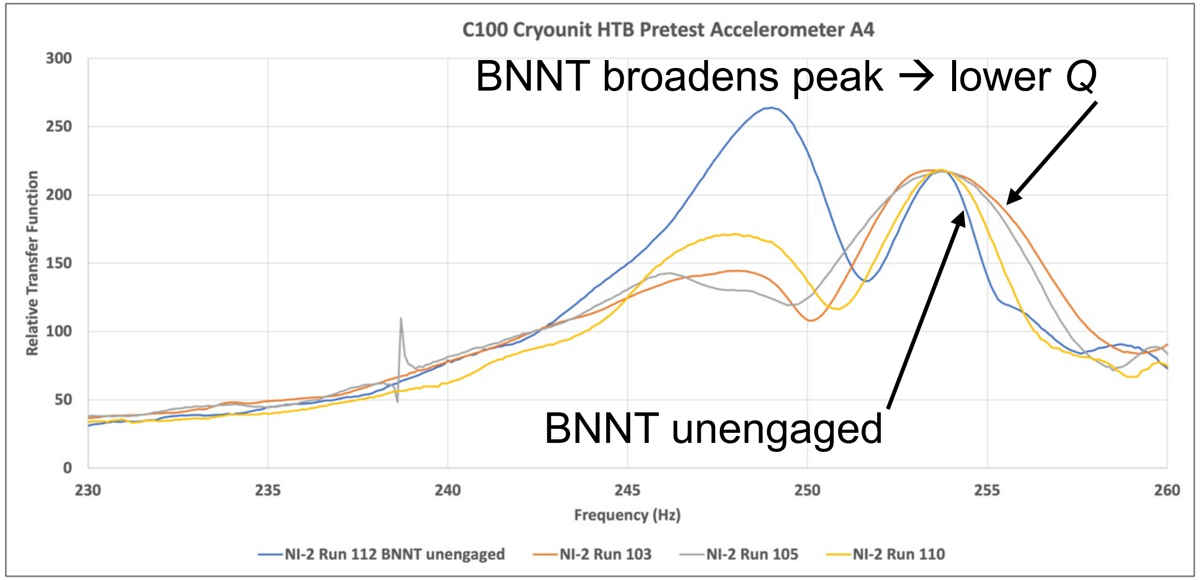
In 2 K RF measurements at JLab, the cavities' response to varying levels of compression on the BNNTs by damping of the microphonics that are typically near 0.0001% dynamic strain. This strain region also aligns the nano length scale of the friction believed to generate the viscoelastic behavior in BNNTs.

C100 Cavity Pair Peak Comparisons



BNNT broadens peak → lower *Q*

BNNT unengaged



BNNT broadens peak → lower *Q*

BNNT unengaged

Cavities' RF frequencies are adjusted to switch from BNNT engaged/unengaged.
The broader response functions with BNNT engaged demonstrate BNNT damping of cavity modes.
This detuning, lower *Q*, lowers requirements for RF power.

Representative C100 cavity pair longitudinal vibration mode Qs with BNNT unengaged/engaged at 300 K

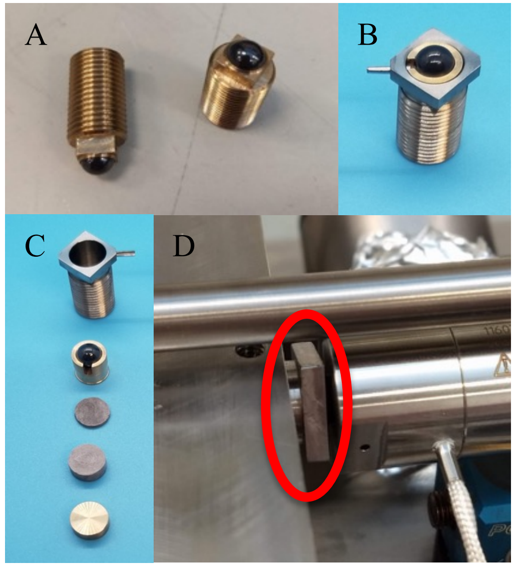
Vibration frequency (Hz)	*Q* – unengaged BNNT	*Q* – engaged BNNT	Decrease in *Q* (%)
65.7	61	29	52
78.7	54	32	41
162.6	68	44	35
248.1	59	52	12
254.8	141	72	49

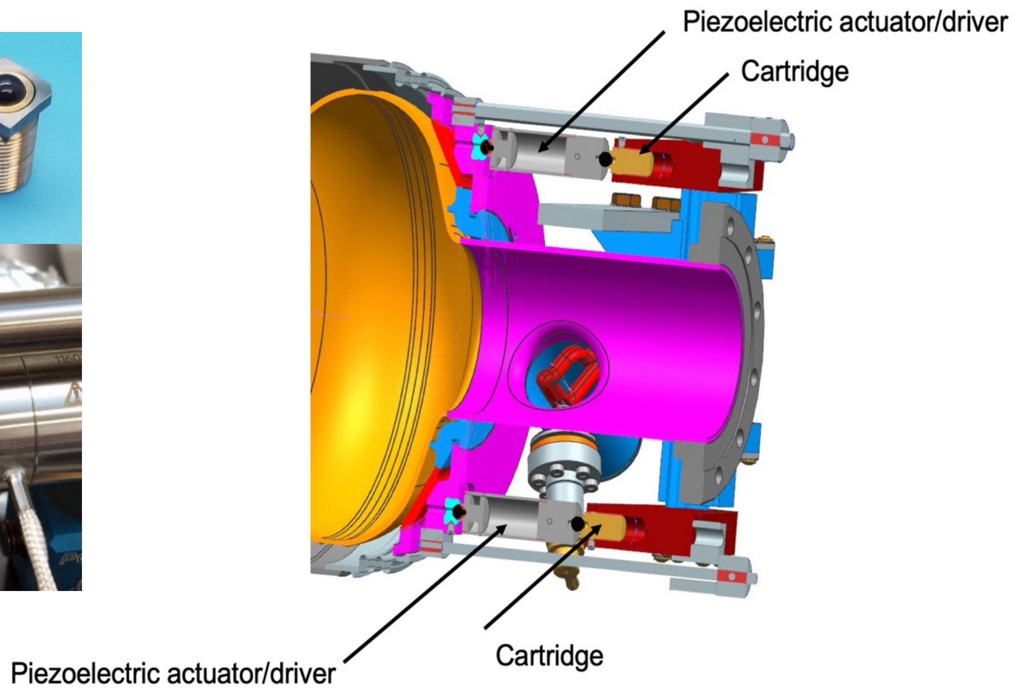
BNNT pellets provide significant longitudinal-mode vibration damping in the C100 cryounit cavities

LCLS-II Opportunity

Two of eight cavities in an LCLS-II cryomodule in Jefferson Lab’s LERF had BNNT vibration damping installed and tested at 2 K.

LCLS-II CM-20 testing in LERF at 2 K – Peter Owen





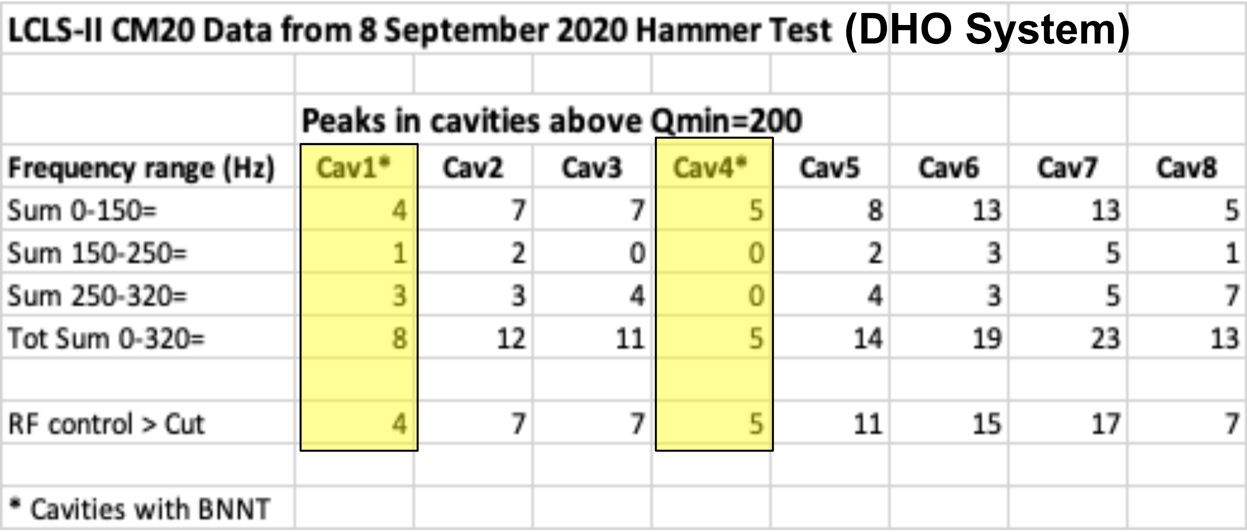
BNNT pellet installed on LCLS-II cavity:

Standard parts (A) are readily exchanged for BNNT cartridge holders (B).

BNNT cartridge holder components (C) prior to assembly.

BNNT cartridge (D) circled in red installed on LCLS-II cavity between tuner plate and piezoelectric actuator.

LCLS-II CM 20 Results



LCLS-II CM20 Data from 8 September 2020 Hammer Test (DHO System)

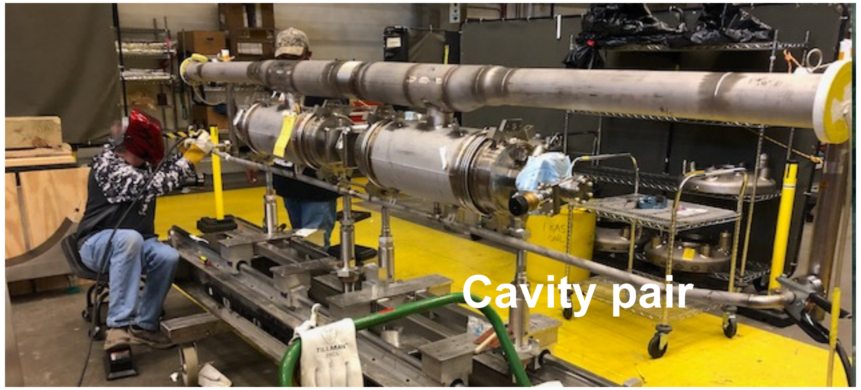
	Peaks in cavities above Qmin=200							
Frequency range (Hz)	**Cav1***	**Cav2**	**Cav3**	**Cav4***	**Cav5**	**Cav6**	**Cav7**	**Cav8**
Sum 0-150=	4	7	7	5	8	13	13	5
Sum 150-250=	1	2	0	0	2	3	5	1
Sum 250-320=	3	3	4	0	4	3	5	7
Tot Sum 0-320=	8	12	11	5	14	19	23	13
RF control > Cut	4	7	7	5	11	15	17	7
* Cavities with BNNT								

LCLS-II CM20 Data from September 2020 PZT Chirp Test

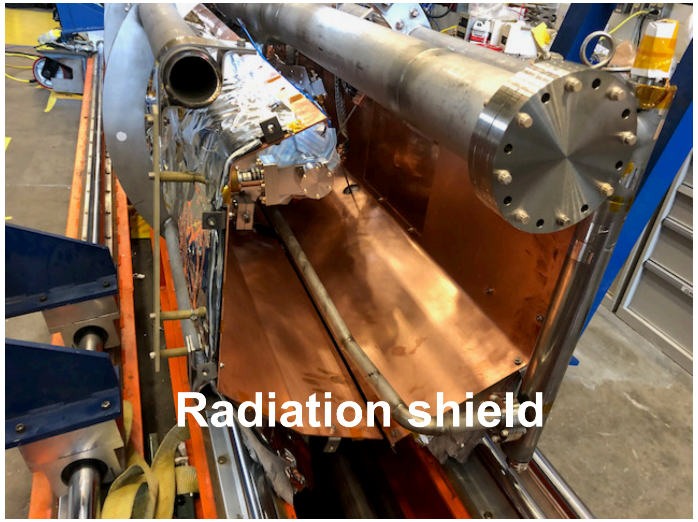
	Peaks in cavities above Qmin=200							
F(Hz)	**Cav1***	**Cav2**	**Cav3**	**Cav4***	**Cav5**	**Cav6**	**Cav7**	**Cav8**
Sum 10-80=	3	2	5	1	3	3	2	2
Tot Sum 60-160=	2	3	1	2	3	0	3	2
Tot Sum 120-320=	11	13	15	15	10	11	19	8
RF control > Cut								
Sum 10-80=	3	2	5	1	3	3	2	2
Sum 60-160=	2	3	1	1	2	0	2	1
Sum 120-320=	0	0	0	0	1	0	1	0
* Cavities with BNNT								

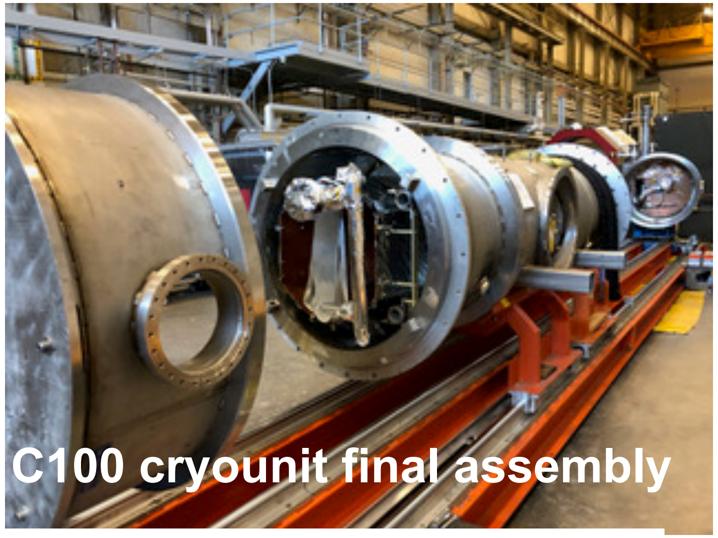
- **From DHO System (Hammer) test:** Energy is put into many components of the cryomodule including all of the cavities. 3 dB Q values of hammer test peaks show that **cavities 1 and 4, with BNNT vibration damping, show less microphonics than the other six cavities, without BNNT vibration damping**, for a range of parameters for the selection of peaks.
- **From PZT Chirp test:** Energy is put into a single cavity from a pulse (chirp) induced on an individual PZT actuator.
  The BNNT is between the actuator and the cavity. Measurements do not show cavities with BNNT vibration damping (cavities 1 and 4) to have significantly better/worse performance compared to the other cavities. PZT single cavity chirp test pulses were not expected to be damped by the BNNT, rather the chirp pulses were expected to be attenuated (see slide 14 results). Additionally, putting chirp pulses into one cavity does not show vibrations in the other cavities.

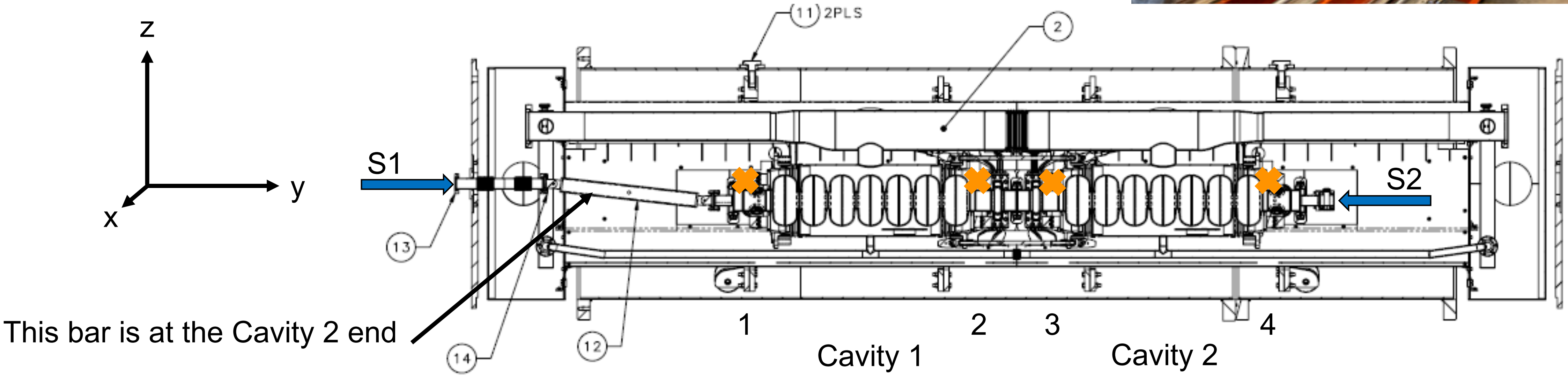
C100 HTB Test Assembly



Jefferson Lab SRF facility





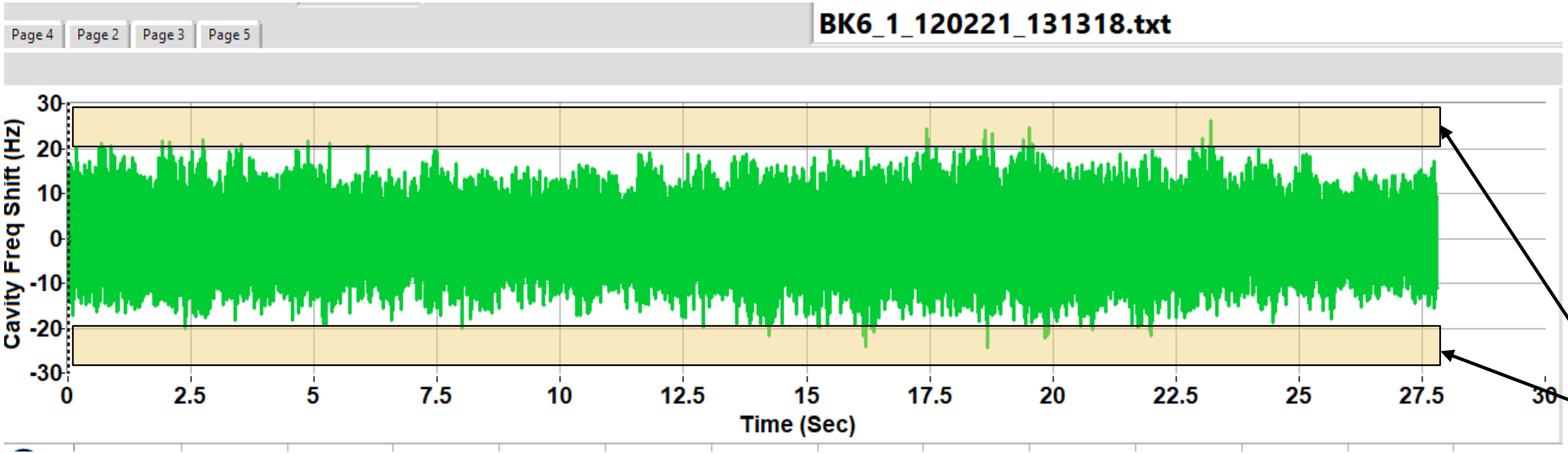


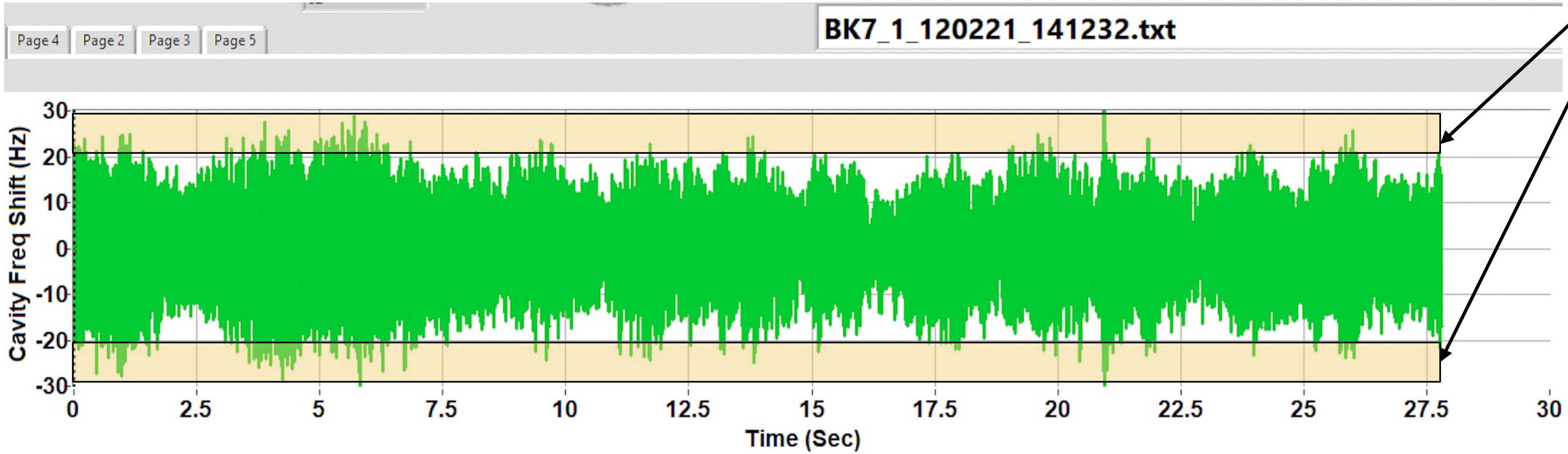
This bar is at the Cavity 2 end

Accelerometer ✖

Strike Location →

2 K HTB Cavity 1
Background-Generated Frequency Shifts





120 Hz driven mode removed

Cartridges Engaged

RMS = 6.1 Hz

Transient peaks reduced

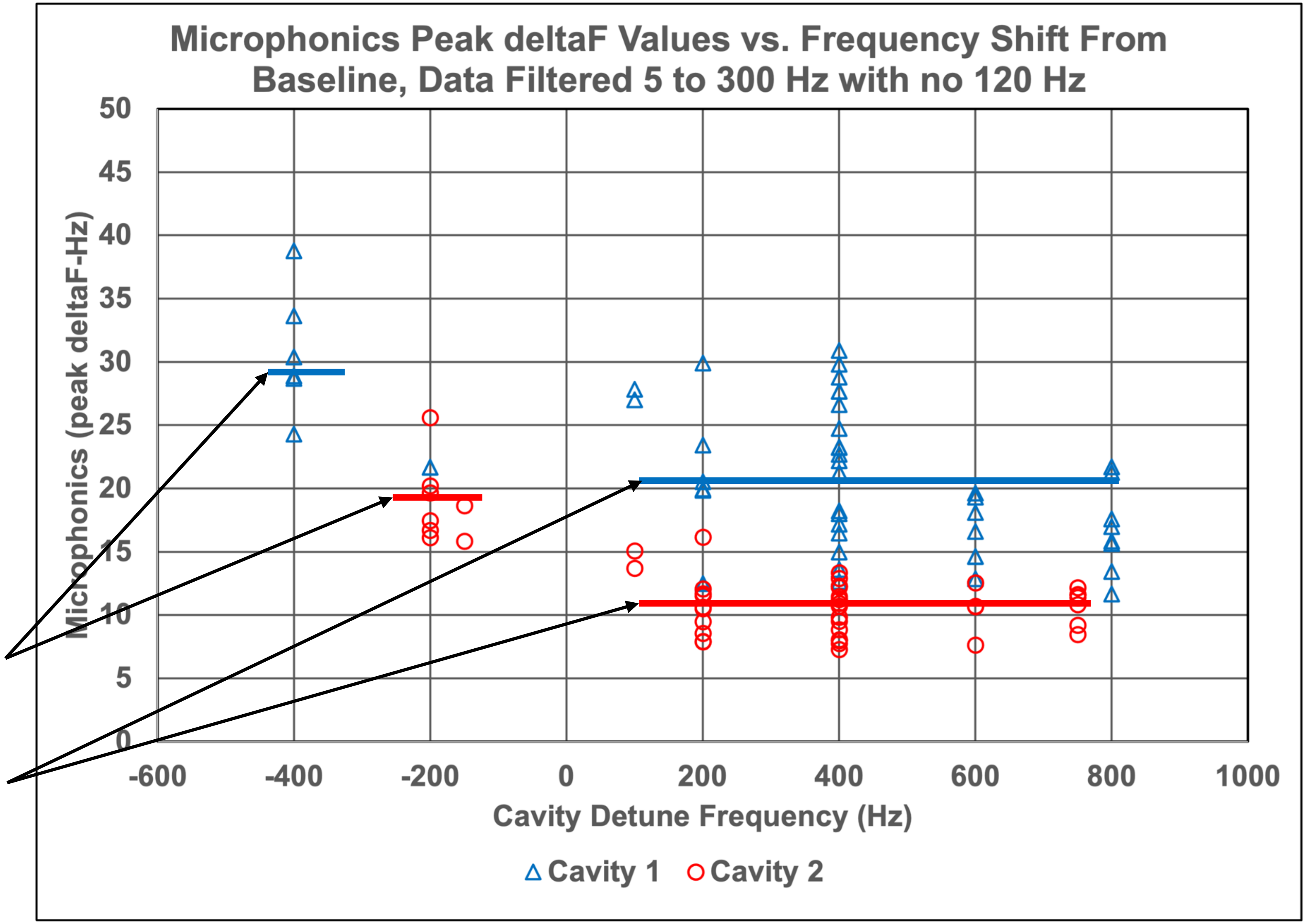
Cartridges Unengaged

RMS = 8.6 Hz

2 K HTB
Background Peak deltaF (minus 120 Hz)

BNNT cartridges provide an average 58% reduction in peak deltaF values of microphonics (minus 120 Hz).

Peak deltaF (Hz) Value		
Cartridges	Cavity 1	Cavity 2
Unengaged	28.51	18.79
Engaged	20.26	10.70
Ratio	1.41	1.75
Average	1.58	



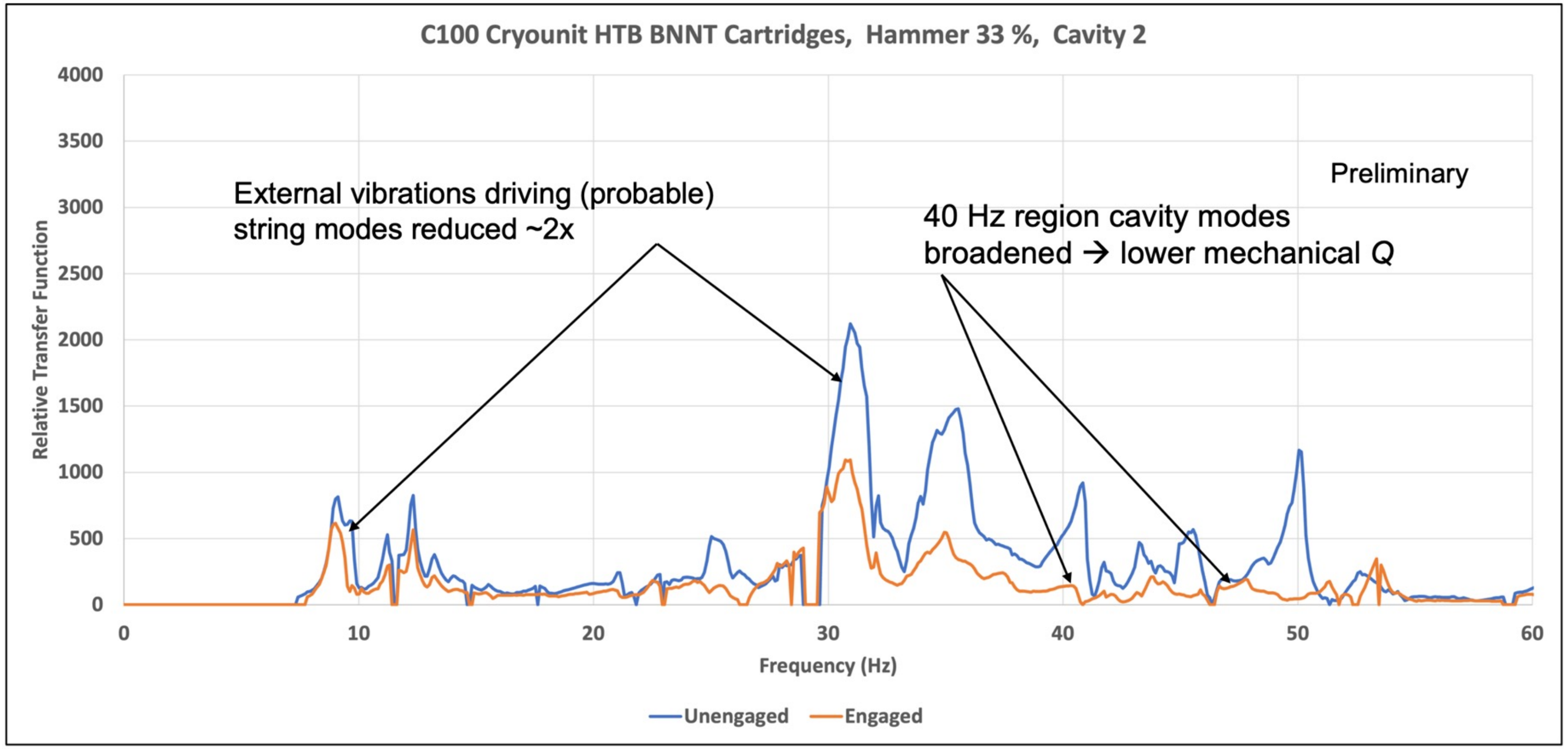
Cartridges unengaged average

Cartridges engaged average

2 K HTB
Background Peak deltaF (minus 120 Hz)

Attenuation/damping reductions in trip generating microphonics:

1. deltaF peak and RMS (no 120 Hz) microphonics reductions:
   - 58% lower in background peak values
   - 52% lower in RMS values
2. 2x typical reductions in transfer function mode amplitudes

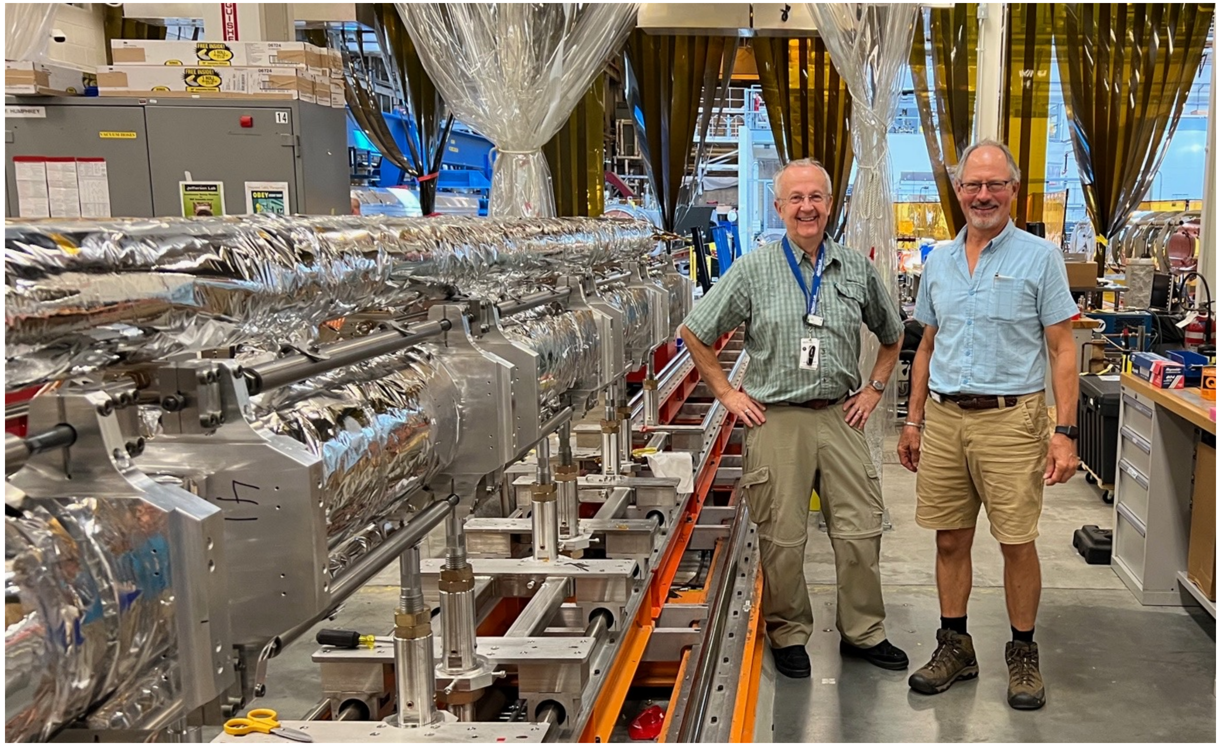


Preliminary

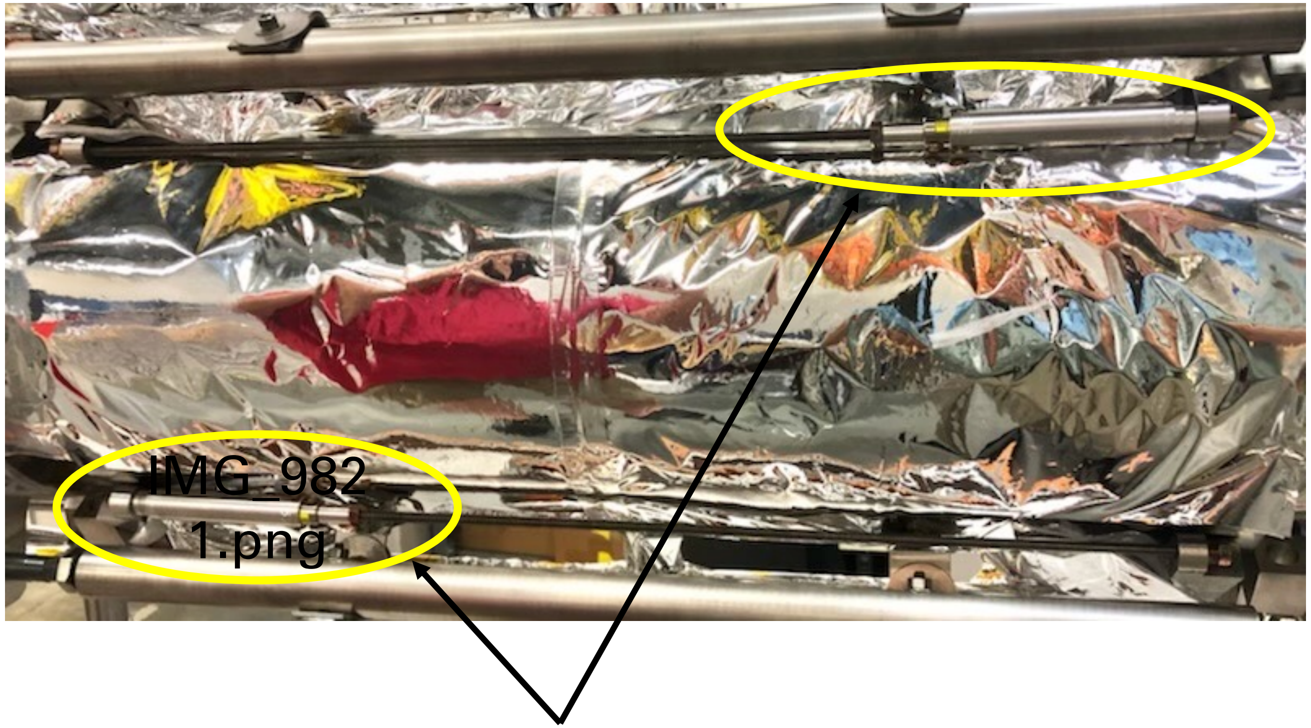
External vibrations driving (probable) string modes reduced ~2x

40 Hz region cavity modes broadened → lower mechanical *Q*

This week – C100 Cryomodule BNNT Cartridge Installation



George Biallas and Kevin Jordan setting up for installation in full C100 cryomodule



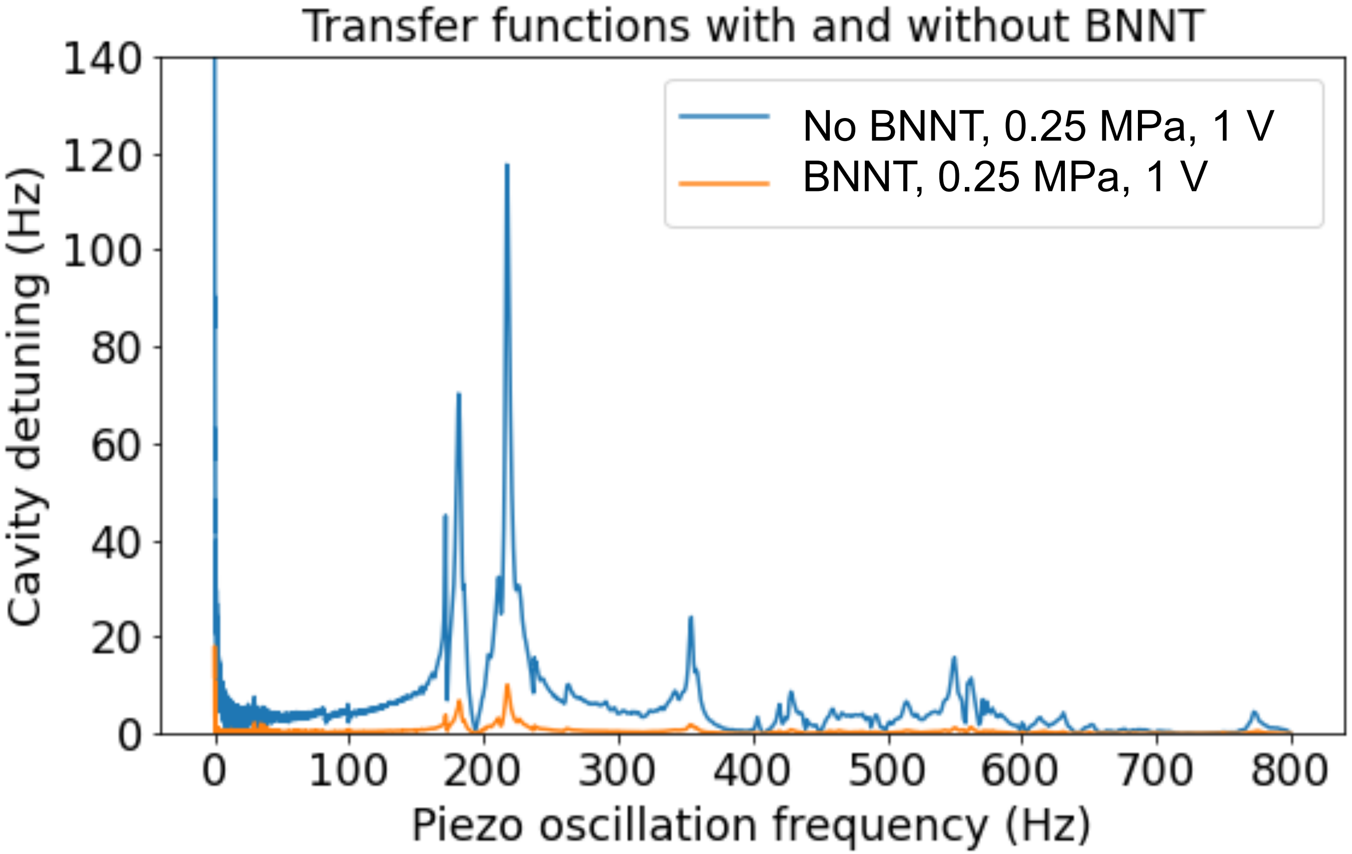
Cartridges

Mockup for assembling BNNT cartridges in full C100 cryomodule

Int’l Tech Transition: Vibration Attenuation

Helmholtz Zentrum Berlin (HZB) made measurements* using a TESLA type cavity equipped with a Saclay-I type tuner featuring twin parallel piezo drivers, with one piezo in series with BNNT pellet.

Results: 10x attenuation of external mechanical excitation, which makes BNNT a most promising candidate for mechanical dampening at cryogenic temperatures



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* Measurement of the Mechanical Dampening [attenuation] Properties of Few-walled Boron Nitride Nanotube Material at Cryogenic Temperatures; Oliver Kugeler, Helmholtz Zentrum Berlin, Tom Powers, Jefferson Lab, R. Roy Whitney, BNNT LLC, George Herman Biallas, Hyperboloid LLC; presented as a poster at: 2021 International Conference on RF Superconductivity (SRF ’21).

BNNT Vibration Damping Works!
Thank You for the Support!

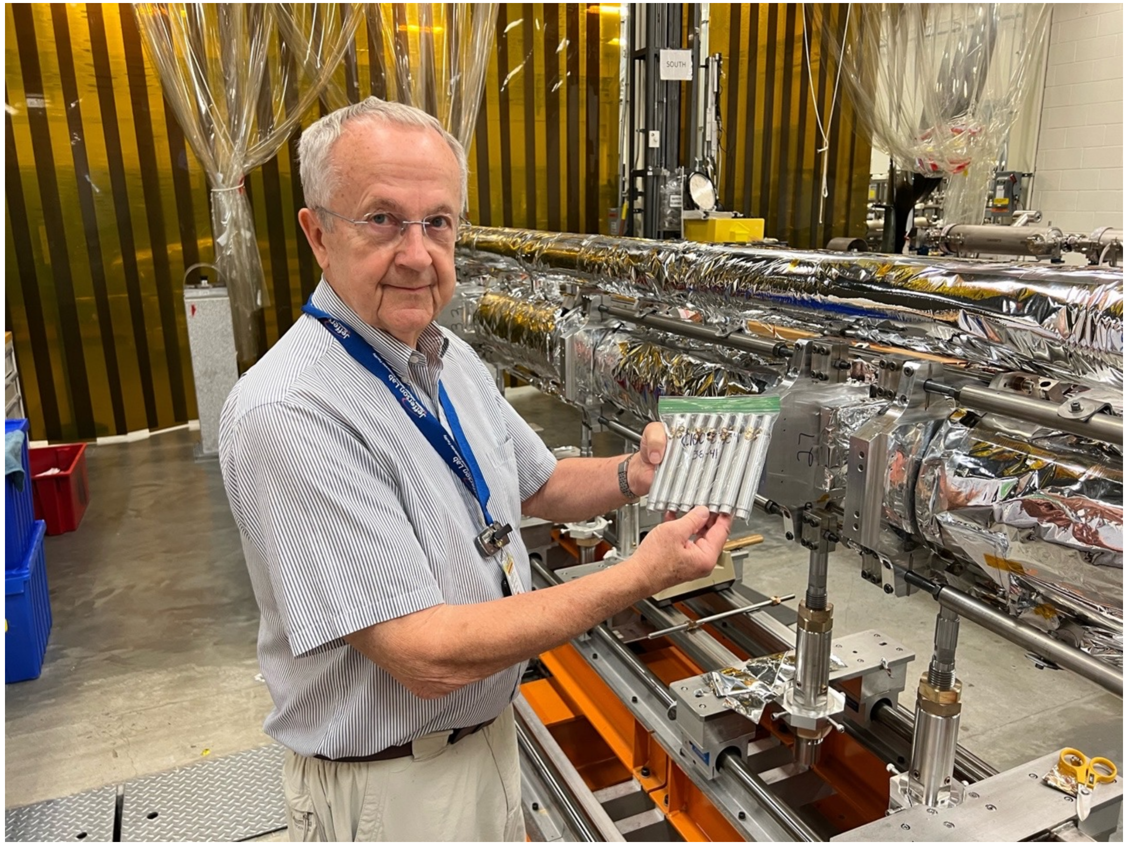
- BNNT vibration damping demonstrated at 2 Kelvin:
  - in cavity pair of a C100 cryomodule
  - in two cavities in LCLS-II cryomodule
- BNNT vibration damping cartridges are being installed in a full C100 cryomodule (8 cavities)
  - … this week!
- Components for placing BNNT vibration damping in an LCLS-II-HE cryomodule are ready.
- Transition/commercialization beyond SBIR
  - From JLab (as originally proposed) transitioned to exploration by SLAC
  - FermiLab sales and experimentation
  - International interest at Germany’s Helmholtz Zentrum Berlin

Thank you to Michelle Shinn,
DOE – Office of Science – Nuclear Physics, and
Jefferson Lab for support!

BACKUPS (time permitting)

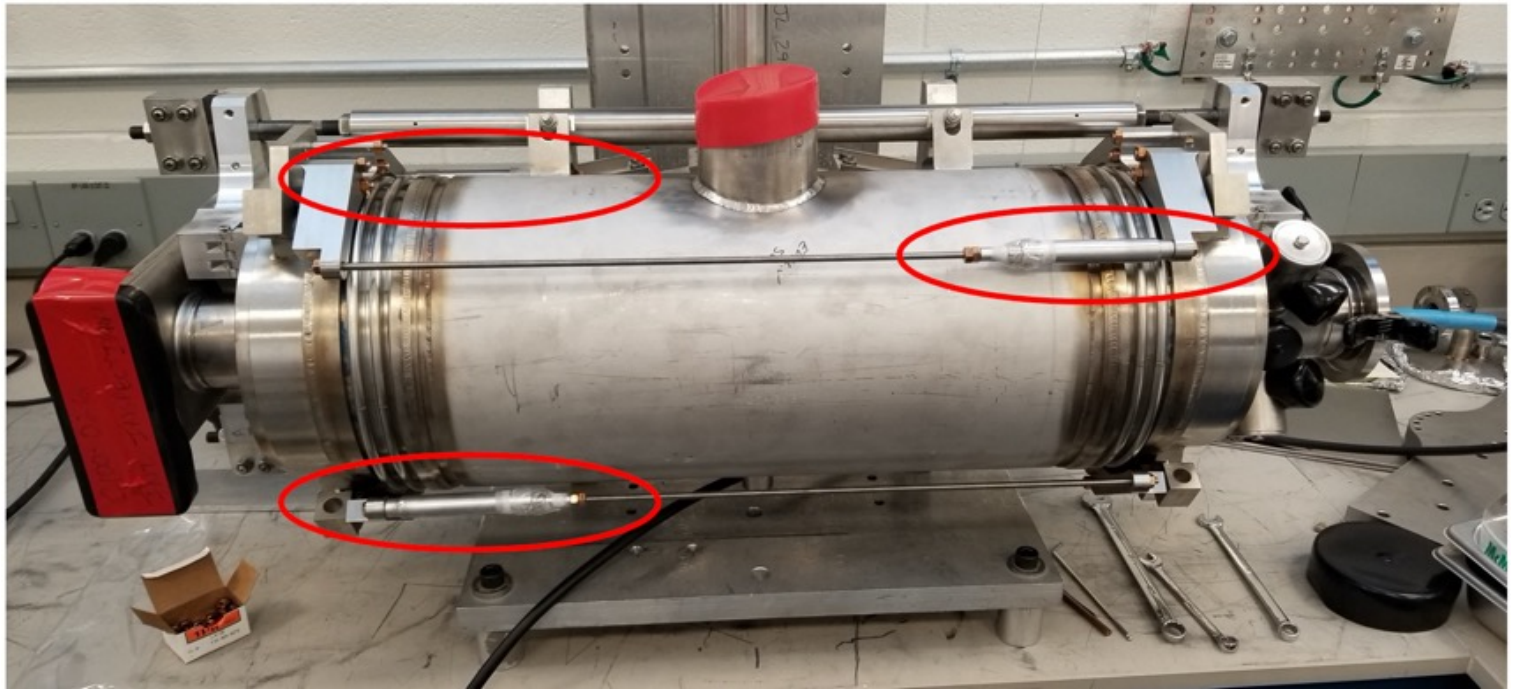
This week – C100 Cryomodule BNNT Cartridge Installation

C100 cryomodule assembly



George Biallas preping for installing
BNNT cartridges on C100 cryomodule

C100 Cavity 300 K Bench Test Setup

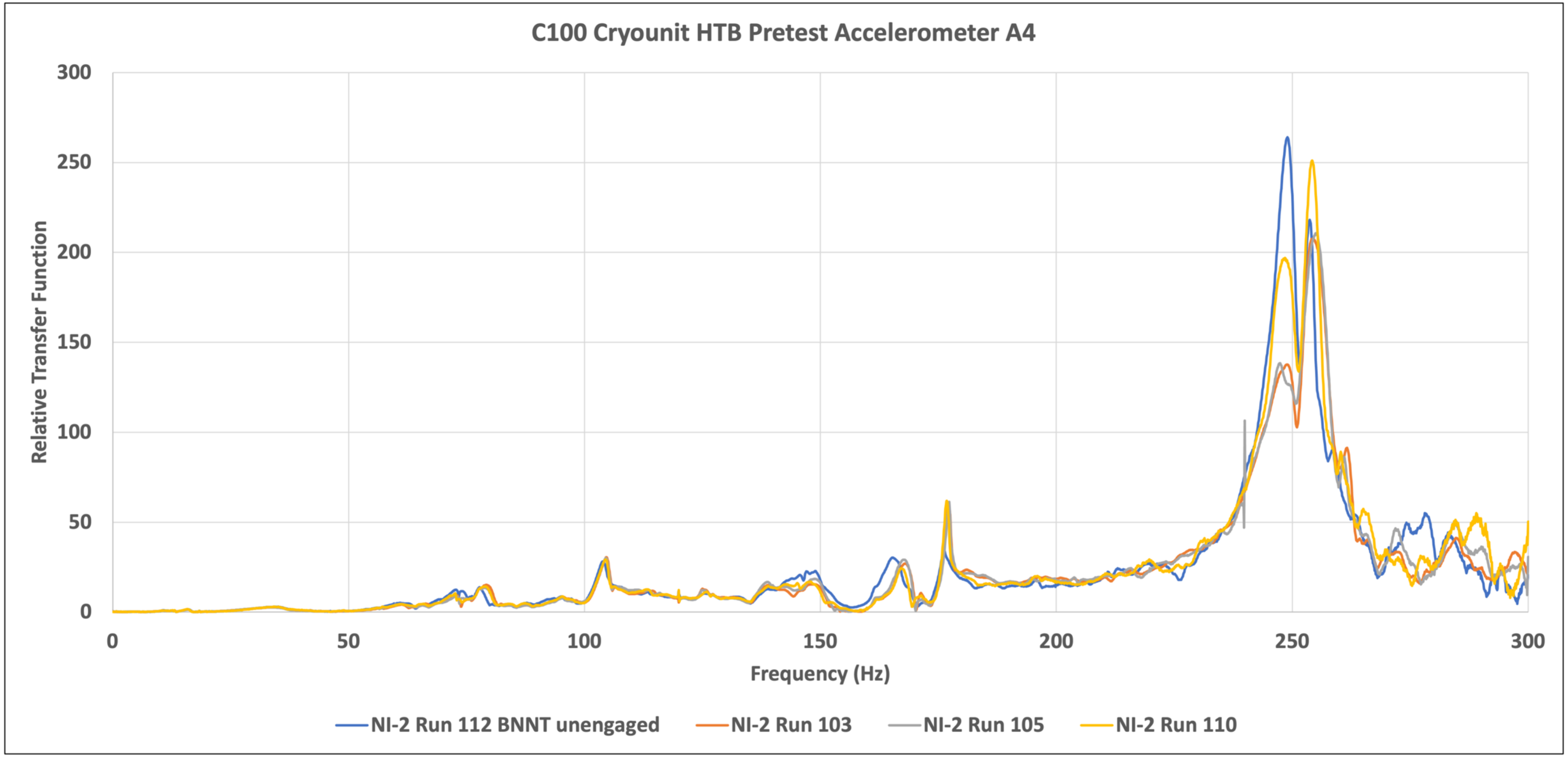


C100 cavity with two of four BNNT C100 cartridges shown during test assembly; location for third cartridge indicated.

C100 cavity tuner drive mechanism behind and above cavity.

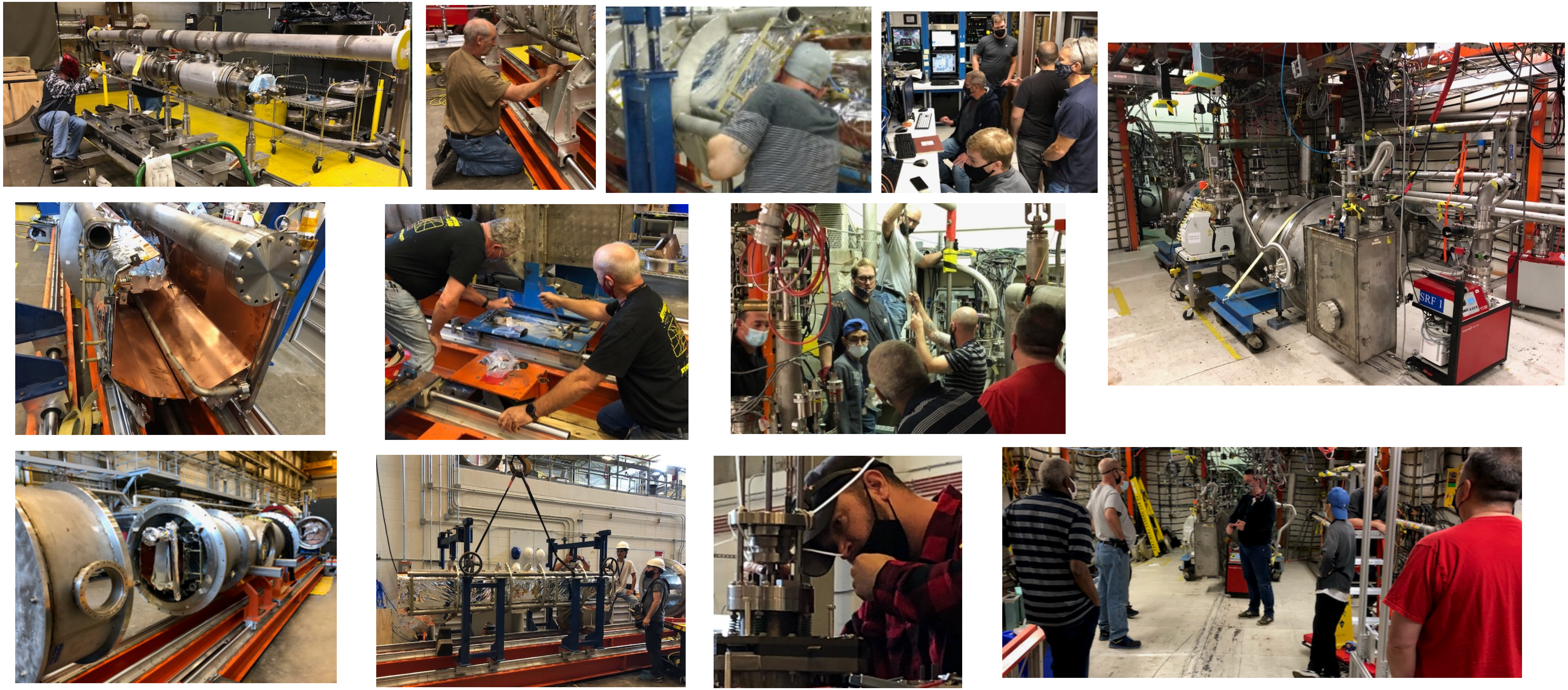
BNNT

Relative Transfer Function at 300 K Example



The tuner changing the cavity length (frequency) also slightly shifts frequencies of some vibration modes. Accelerometer A4 is closest to hammer strike in test shown.

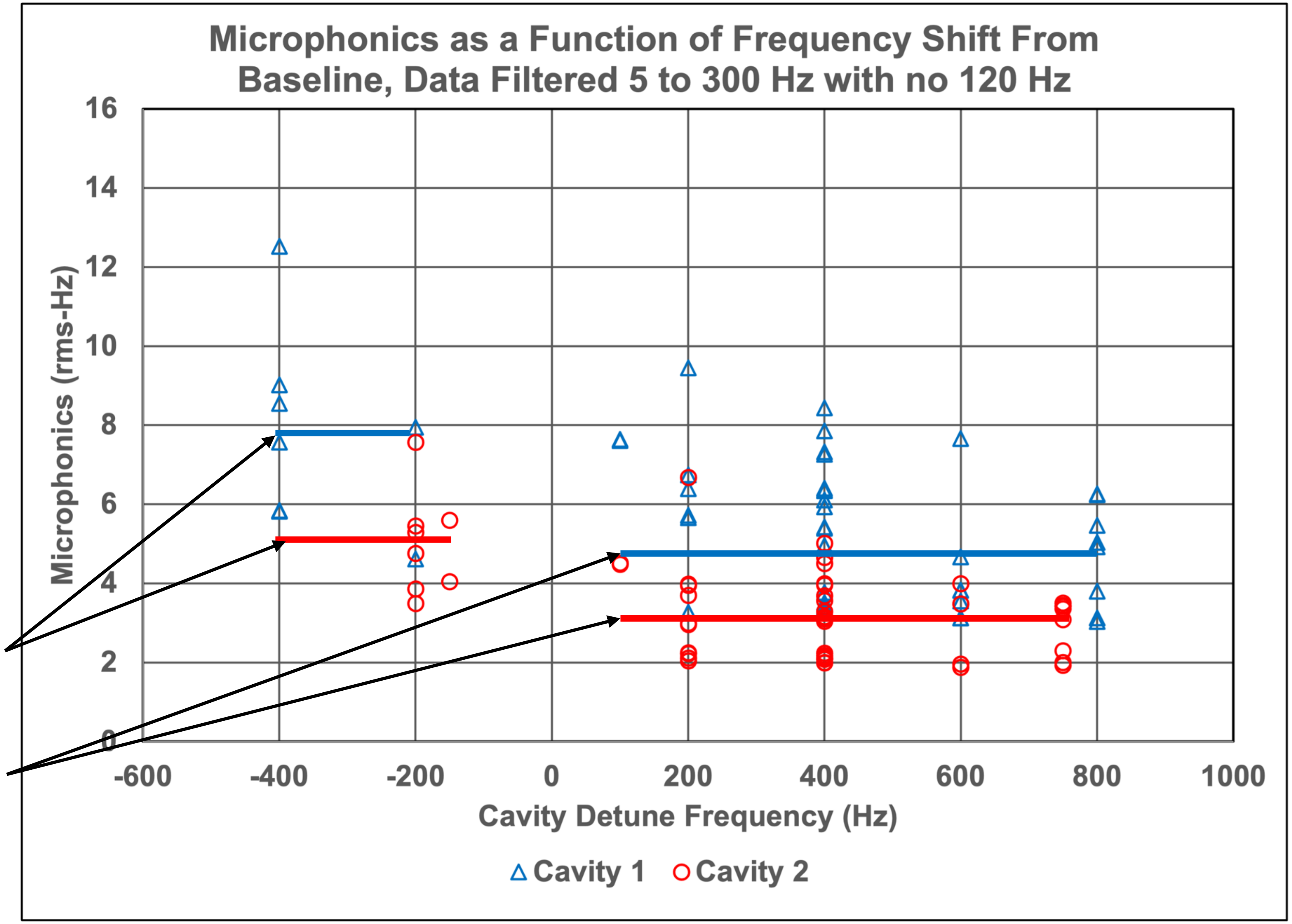
C100 Cryounit BNNT HTB



2 K HTB Background RMS (minus 120 Hz)

BNNT cartridges provide an average 52% reduction in background RMS (minus 120 Hz) of microphonics.

RMS (Hz)		
Cartridges	Cavity 1	Cavity 2
Unengaged	7.74	5.01
Engaged	5.29	3.17
Ratio	1.46	1.58
Average	1.52	



Cartridges unengaged average

Cartridges engaged average