Boron Nitride Nanotube (BNNT) Vibration Damping for SRF Structures

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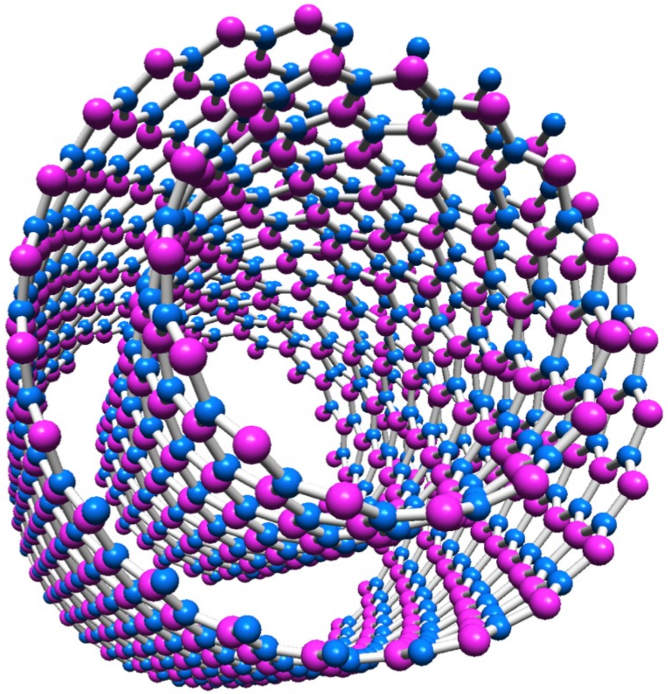

Viscoelastic behavior results from BNNT molecules rubbing against one another. Boron-nitrogen bonds contain a partial dipole believed to produce nanoscale friction that generates phonons in (and between) BNNT molecules that dissipate vibrational energy as heat. Conversely, carbon nanotubes (CNTs) do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

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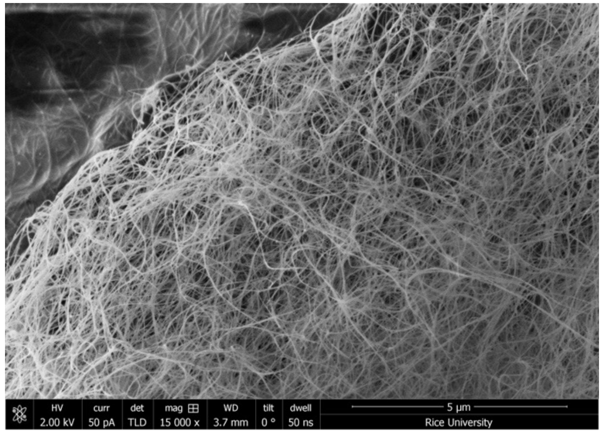
Commercializing Revolutionary New Material

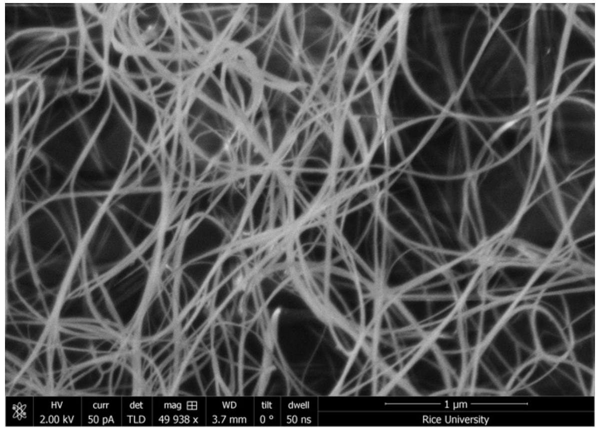
- **Commercialized high-temperature/high-pressure (HTP) method for synthesizing BNNTs**
  - Results in more highly flexible, ultra-strong, lightweight, and highly crystalline BNNTs [independently validated vs. competitors]
  - New pilot plant enables kilogram quantities while exploring automation, maintenance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



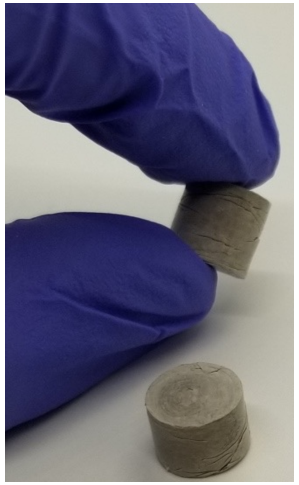


SEM micrograph of purified BNNT courtesy of M. Pasquali (Rice Univ.)

Pellets to Cartridges to Cavities

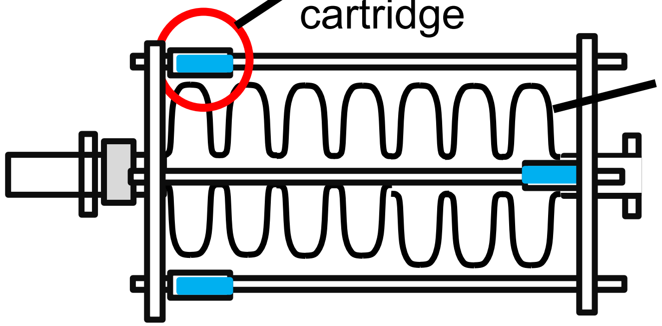
- SBIR Phase I: April 9, 2018 – April 8, 2019
  - Viscoelastic vibration damping at 2 K demonstrated in VTA
- SBIR Phase II: 28 May 2019 – 27 May 2021
  - Demonstrate vibration damping in C100 and LCLS-II SRF cavities
- SBIR Phase IIA: 18 June 2021– 31 December 2023
  - Demonstrate vibration damping 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:



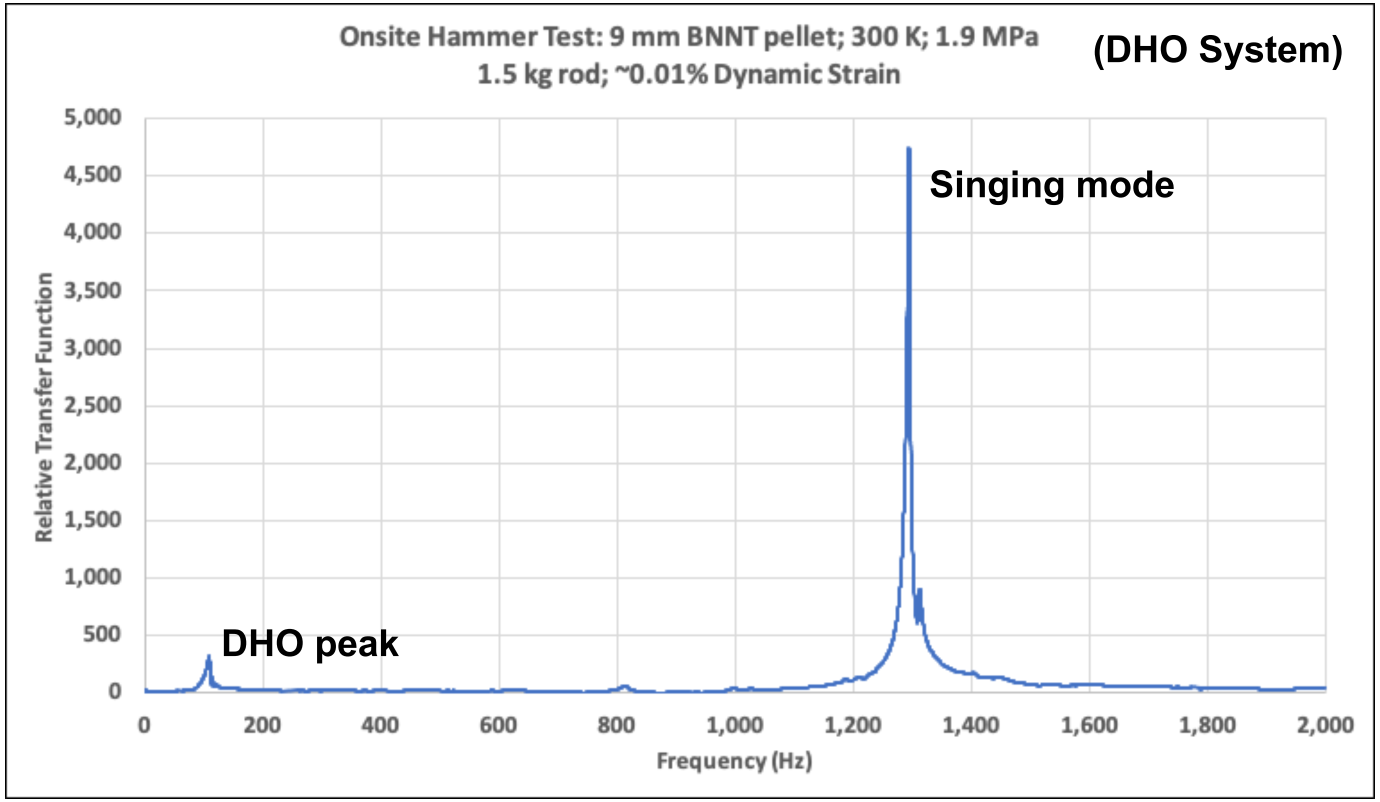
BNNT Pellets – Characterization

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

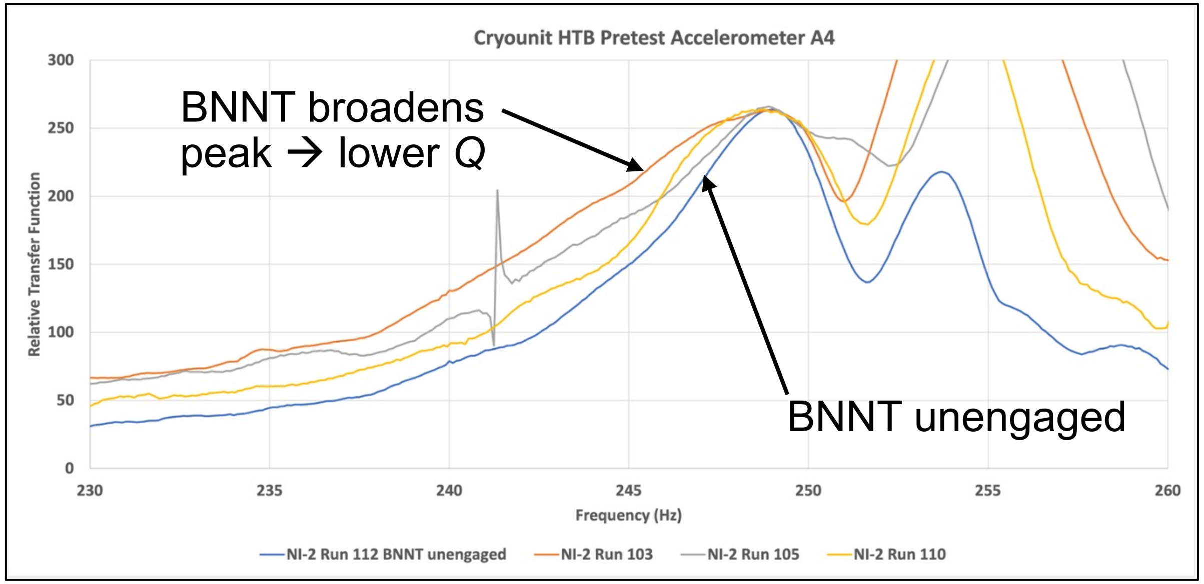
1. Damped Harmonic Oscillator (DHO)

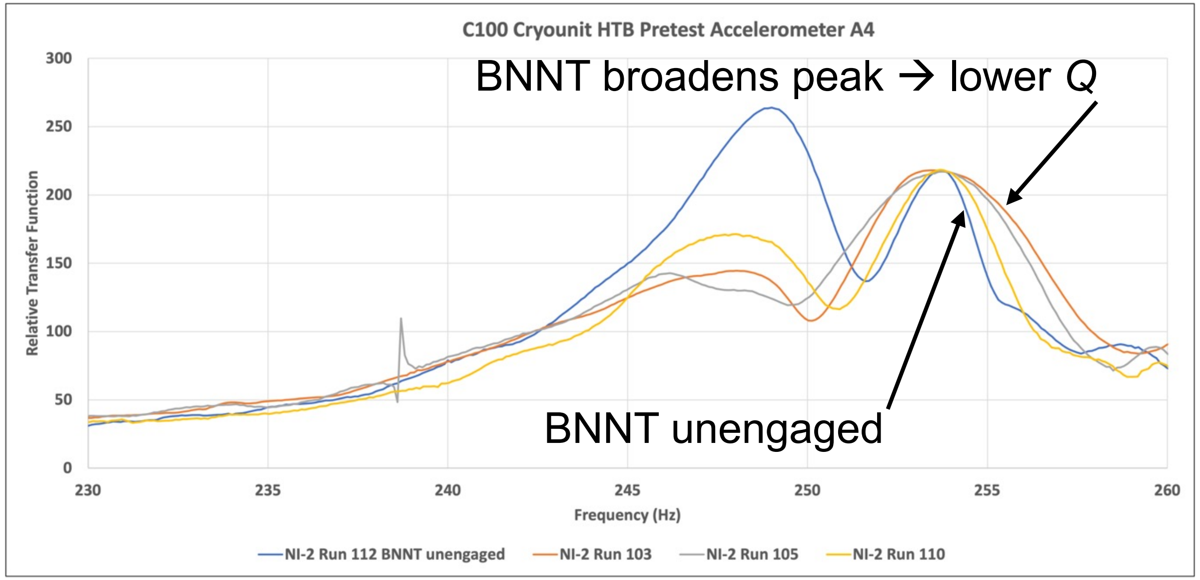
   Hammer testing onsite at BNNT LLC. The motions of the hit rod result in a relative transfer function that exhibits DHO and a “singing” mode axially vibrating. **The elastic modulus and tan delta of the pellet are extracted from the position and width of the DHO peak**.

2. Dynamic mechanical analysis (DMA) at both 300 K and 77 K (independent commercial test); results similar to DHO values, next slide.



C100 Cavity Pair Peak Comparisons





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

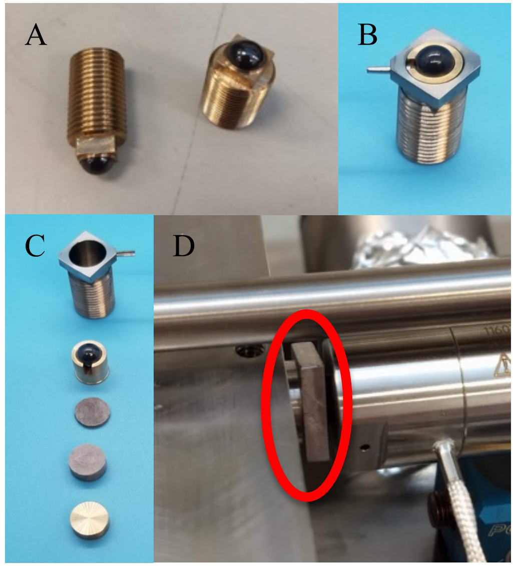
BNNT pellets provide significant longitudinal-mode vibration damping in the C100 cryounit cavities

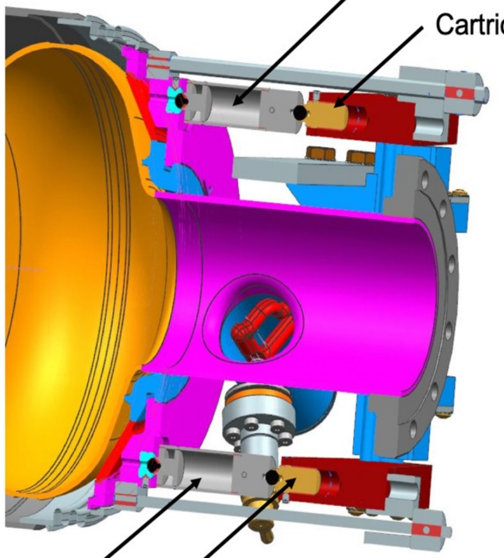
LCLS-II Opportunity

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

These are now in LCLS-II for operations

LCLS-II CM-20 testing in LERF at 2 K – Peter Owen
(Photo courtesy of Jefferson Lab)





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.

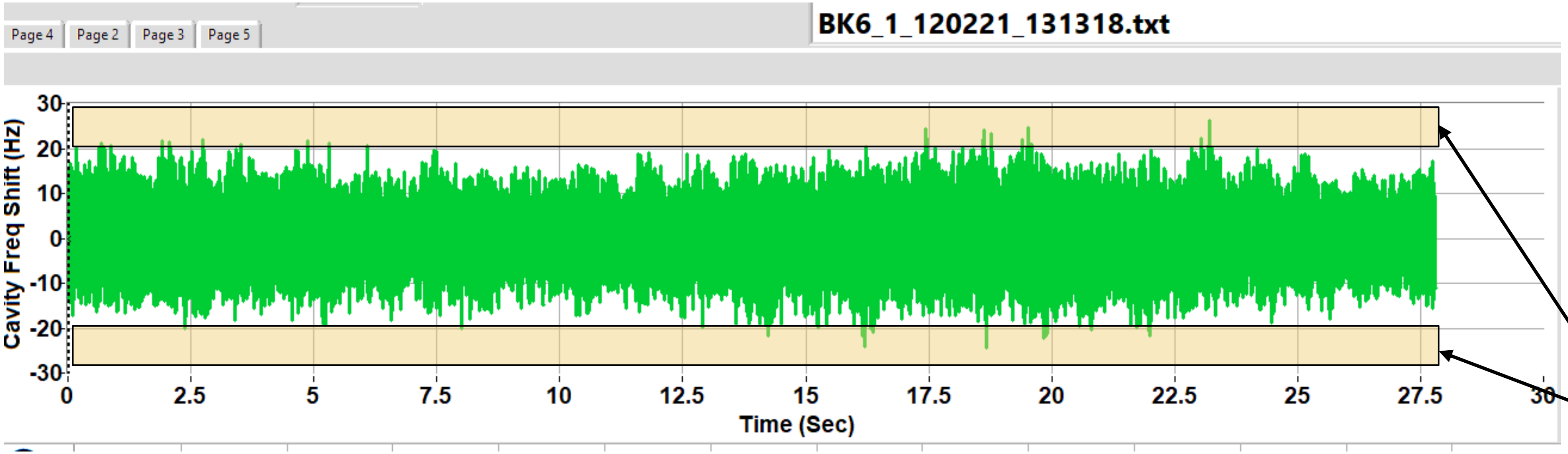
LCLS-II CM 20 Results

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.

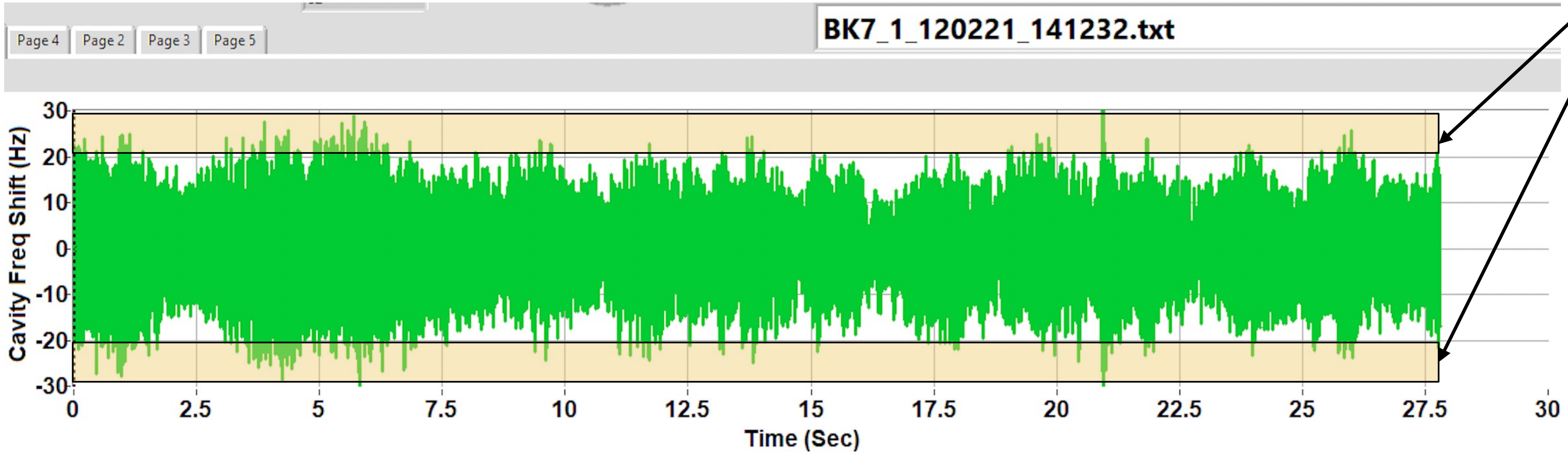
2 K HTB C100 Style Cavity 1 Background-Generated Frequency Shifts



120 Hz driven mode removed

Cartridges Engaged
RMS = 6.1 Hz

Transient peaks reduced

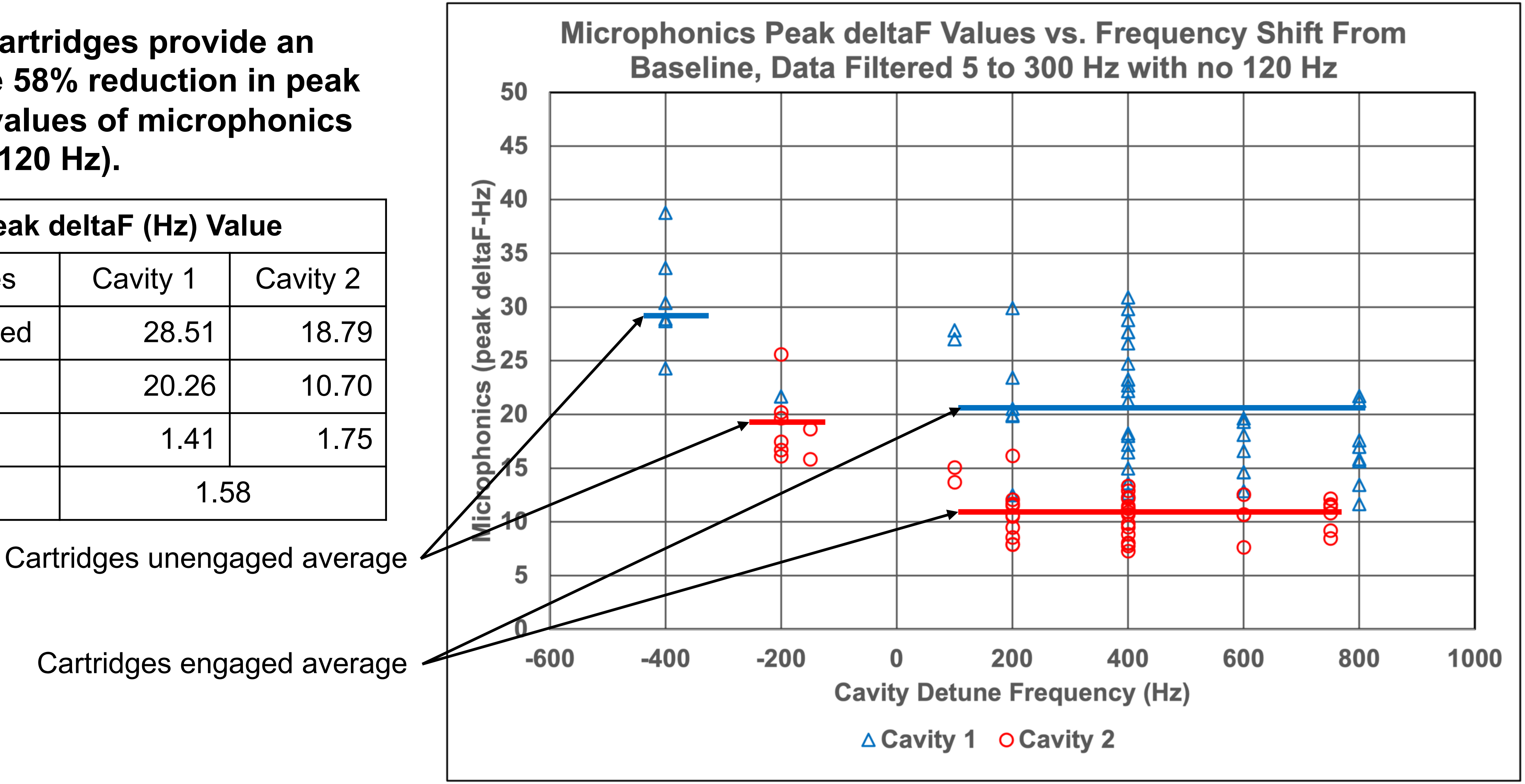


Cartridges Unengaged
RMS = 8.6 Hz

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).

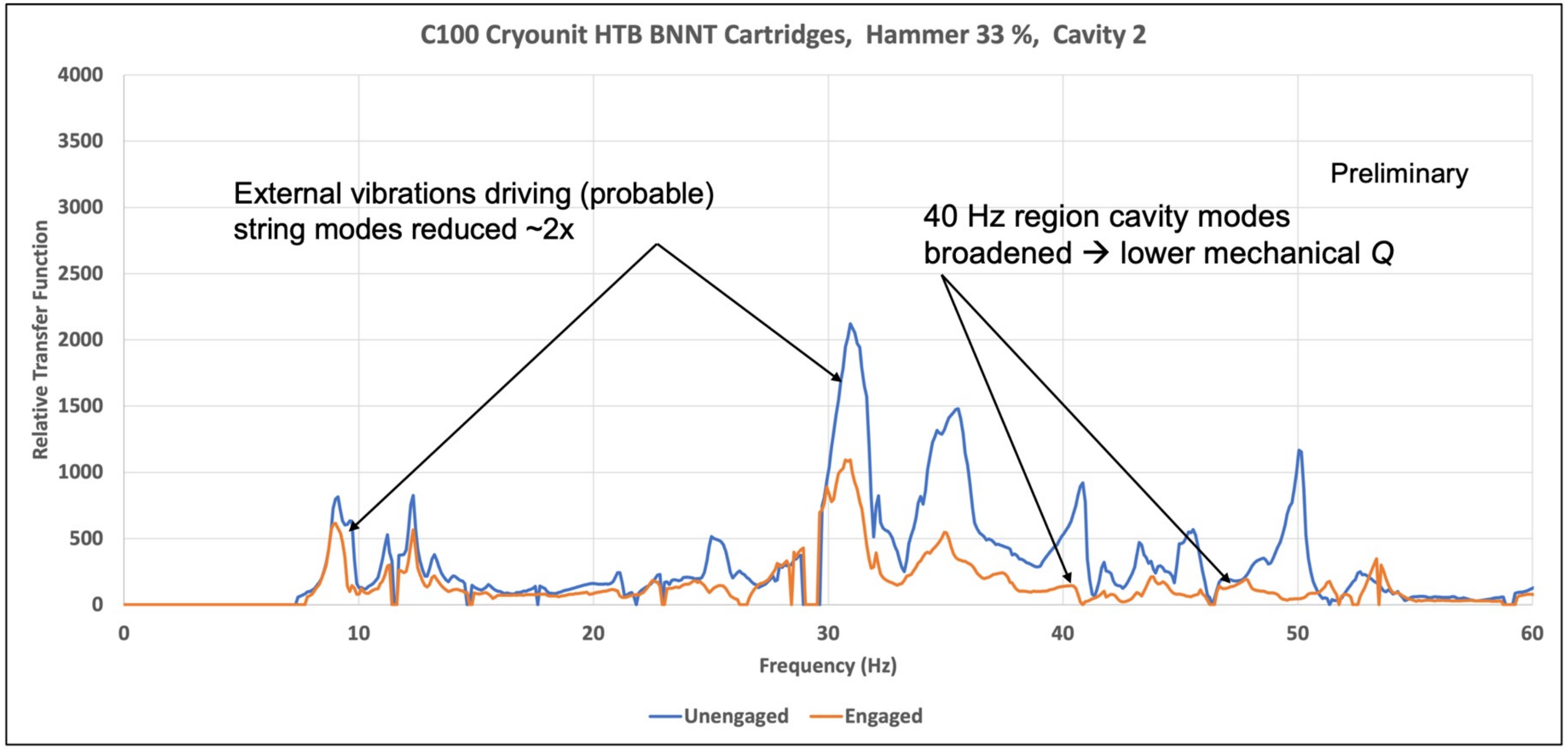
Peak deltaF (Hz) Value		
Cartridges	Cavity 1	Cavity 2
Unengaged	28.51	18.79
Engaged	20.26	10.70
Ratio	1.41	1.75
Average	1.58	



2 K HTB
Background Peak deltaF (minus 120 Hz)

Attenuation/damping reductions in trip generating microphonics:

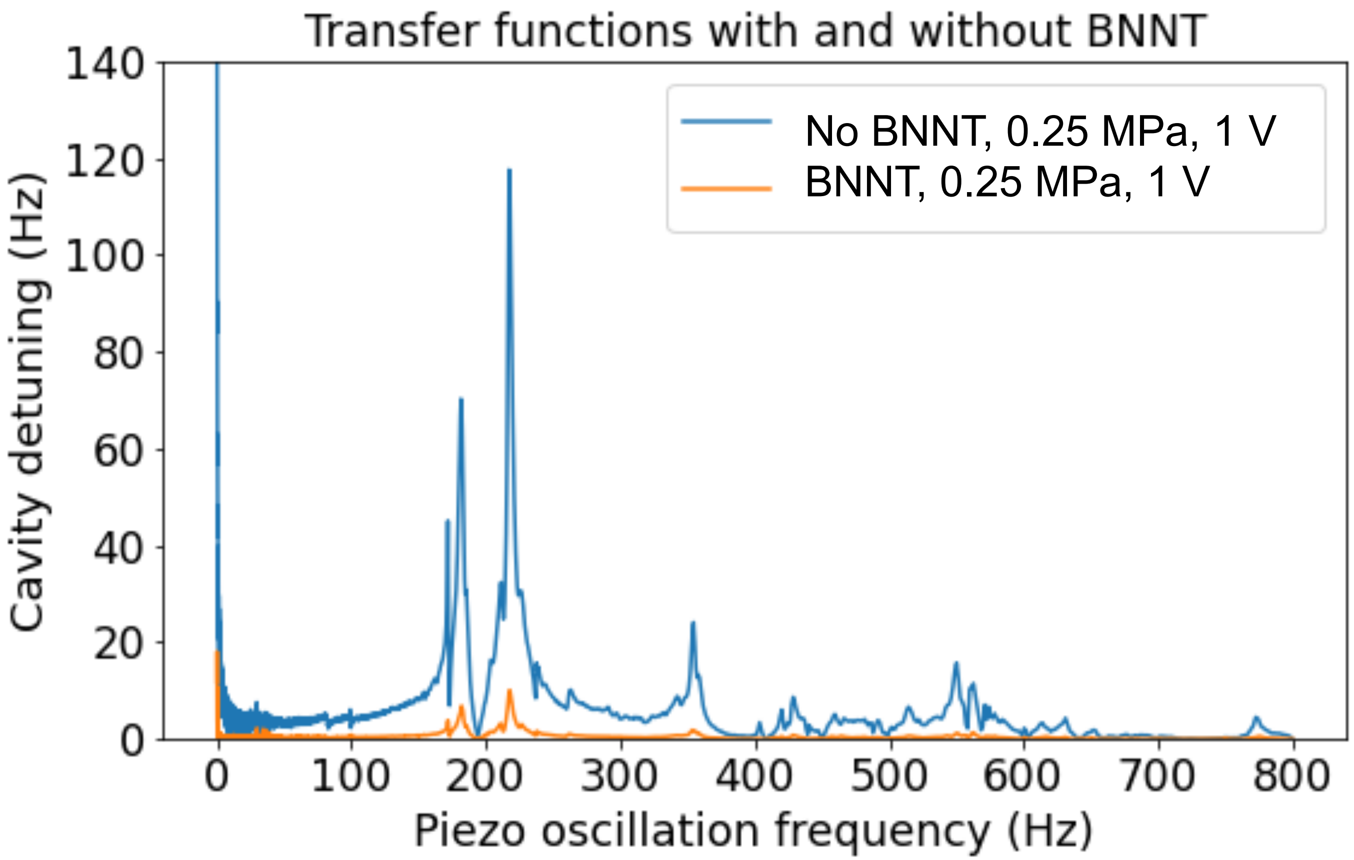
1. **deltaF peak and RMS (no 120 Hz) microphonics reductions:**
   - **58% lower in background peak values**
   - **52% lower in RMS values**
2. **2x typical reductions in transfer function mode amplitudes**



Int’l Tech Transition: Vibration Attenuation

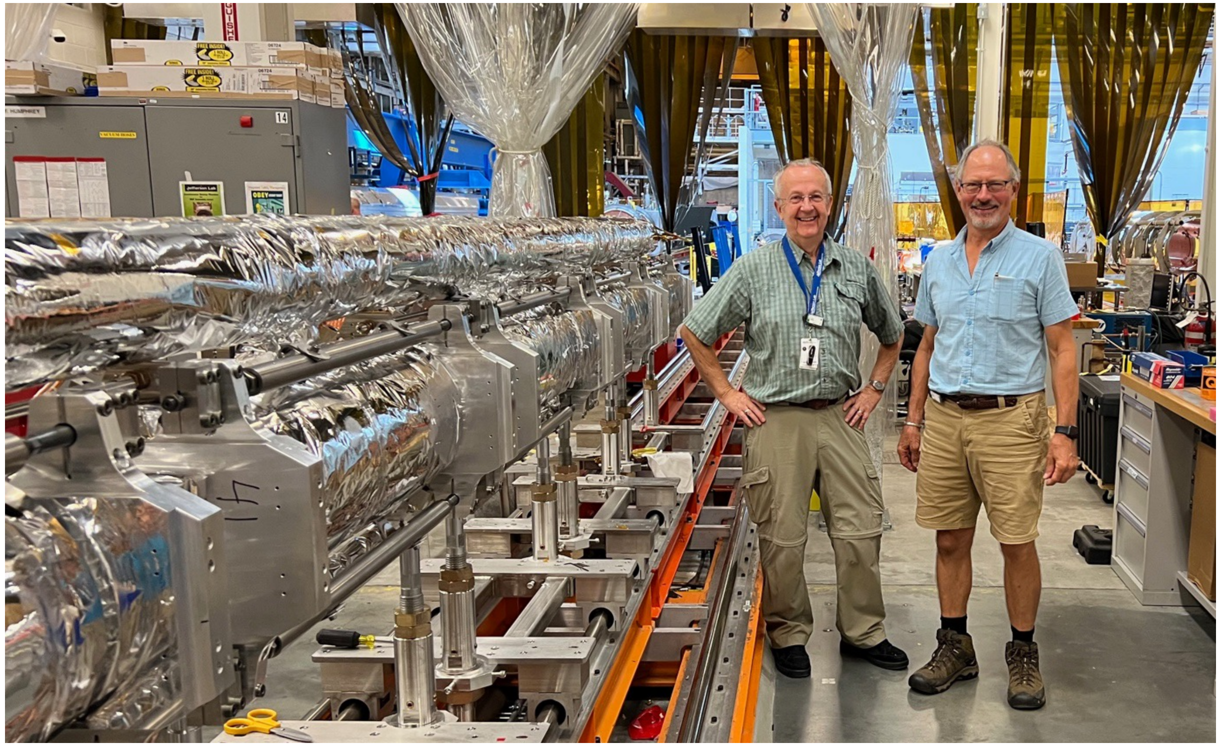
Helmholtz Zentrum Berlin (HZB) made measurements* using a TESLA type cavity equipped with a Saclay-I type tuner featuring twin parallel piezo drivers, with one piezo in series with BNNT pellet.

Results: 10x attenuation of external mechanical excitation, which makes BNNT a most promising candidate for attenuation of mechanical vibrations at cryogenic temperatures. For RF applications, the amount of attenuation can be adjusted to optimize RF control.

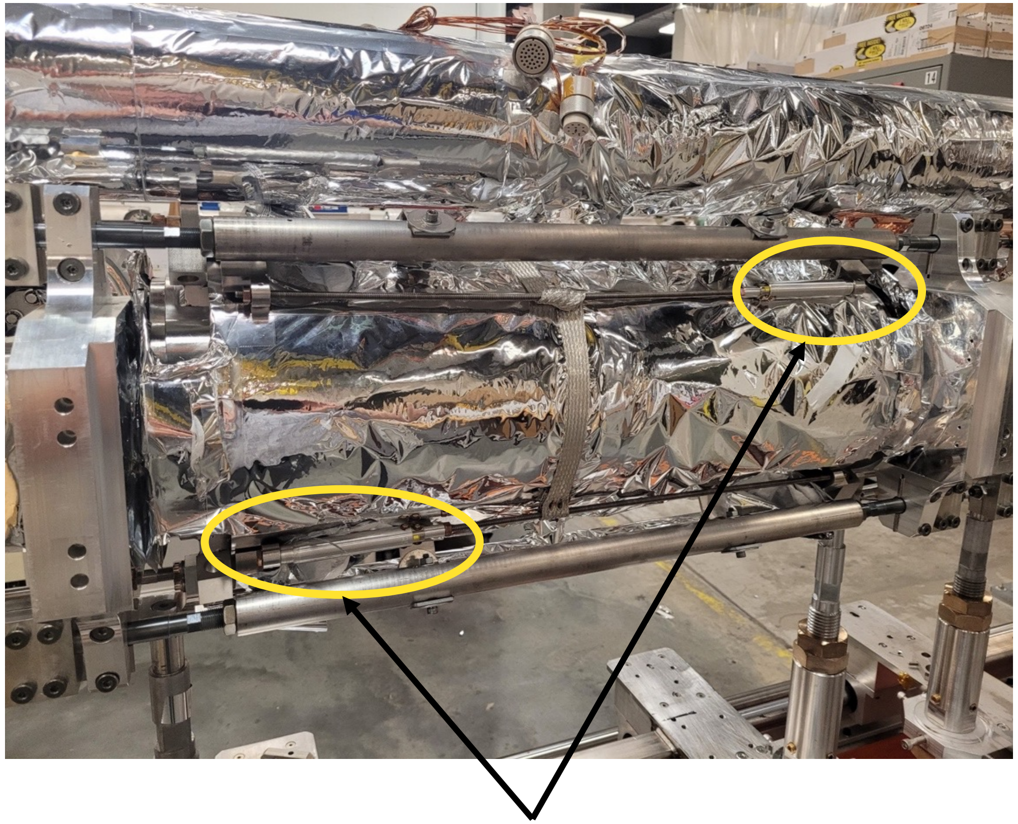


* Measurement of the Mechanical Dampening [attenuation] Properties of Few-walled Boron Nitride Nanotube Material at Cryogenic Temperatures; Oliver Kugeler, Helmholtz Zentrum Berlin, Tom Powers, Jefferson Lab, R. Roy Whitney, BNNT LLC, George Herman Biallas, Hyperboloid LLC; presented as a poster at: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

C100 Full Cryomodule BNNT Cartridge Installation



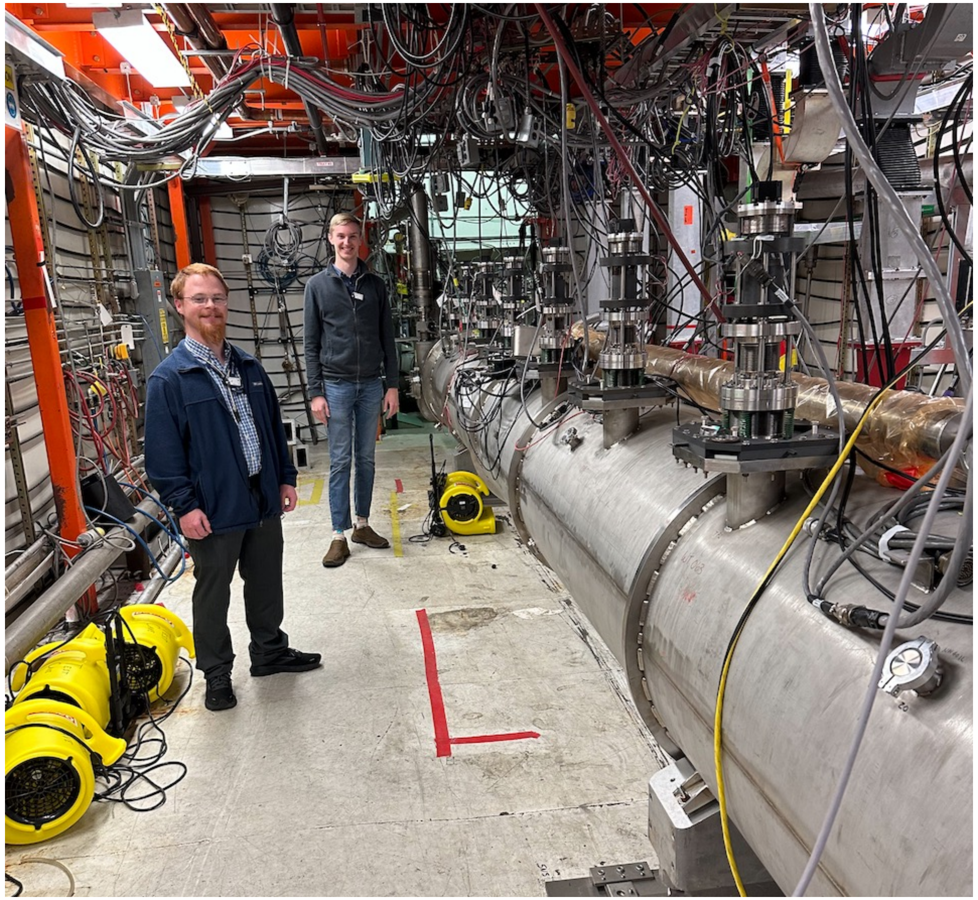
George Biallas and Kevin Jordan setting up for installation in full C100 cryomodule



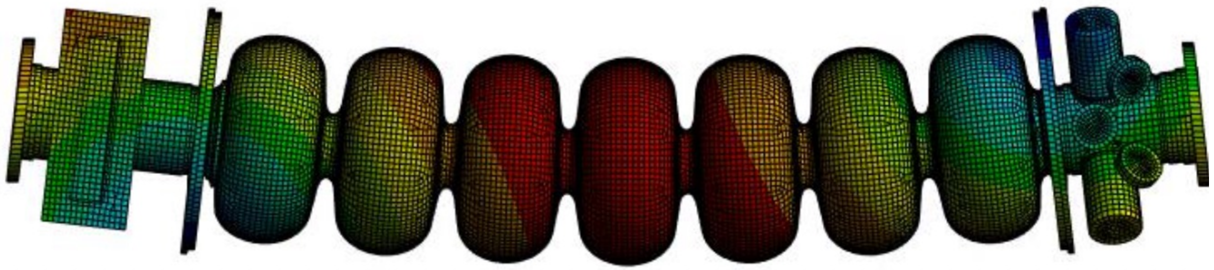
BNNT cartridges

(Photos courtesy of Jefferson Lab)

BNNT Full Cryomodule Vibration Testing in CMTF



Caleb Hull (ODU) and Peter Owen (JLab) in SRF Cryomodule Test Facility (CMTF) for BNNT vibration damping testing
(Photo courtesy of Jefferson Lab)



Caleb Hull's modeling cavity vibration modes showing a typical single cavity mode.
(Images used courtesy of ANSYS, Inc.)

BNNT C100 CMTF Test Results

Hammer test results for BNNT in all eight cavities of C100 CEBAF cryomodule in CMTF.

- All cavities performed as well or better in all frequency ranges
- Cavities with microphonics exceeding the RF control minimum criteria were reduced.

Cryomodule moved into CEBAF for:

- regular operation
- extended run testing
- further controlled testing in the operational environment

RF at 1497 MHz; BNNT engaged; *Q* > 150 Hz									
F(Hz)	Cav1	Cav2	Cav3	Cav4	Cav5	Cav6	Cav7	Cav8	All
Sum 0-150=	0	0	2	1	0	0	0	0	**3**
Sum 150-250=	1	2	1	0	1	1	1	0	**7**
Sum 250-320=	1	0	0	0	0	1	0	0	**2**
Tot Sum 0-320=	2	2	3	1	1	2	1	0	**12**
RF control > Min = *	0	0	0	1	0	0	0	0	**1**
RF at 1496.7 MHz; BNNT disengaged; *Q* > 150 Hz									
F(Hz)	Cav1	Cav2	Cav3	Cav4	Cav5	Cav6	Cav7	Cav8	All
Sum 0-150=	0	3	0	1	0	0	1	0	**5**
Sum 150-250=	2	8	3	0	2	3	2	2	**22**
Sum 250-320=	2	0	0	0	1	1	0	1	**5**
Tot Sum 0-320=	4	11	3	1	3	4	3	3	**32**
RF control > Min = *	0	2	0	1	0	0	1	0	**4**

* Exceeding a minimum value of Q/f^2 for RF control requirements

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
  - in full C100 cryomodule

- **BNNT vibration damping is in operational CEBAF C100 and LCLS-II cryomodules – results coming this fall**

- Transition/commercialization beyond SBIR
  - Operation results this fall from Jefferson Lab CEBAF and SLAC LCLS-II will be utilized generate further accelerator interest
  - Interest in Germany's Helmholtz Zentrum Berlin vibration attenuation results will be part of BNNT's potential for quantum computers

Thank you to Michelle Shinn,

DOE – Office of Science – Nuclear Physics, and

Jefferson Lab for support!