Boron Nitride Nanotube Vibration Damping for SRF Structures

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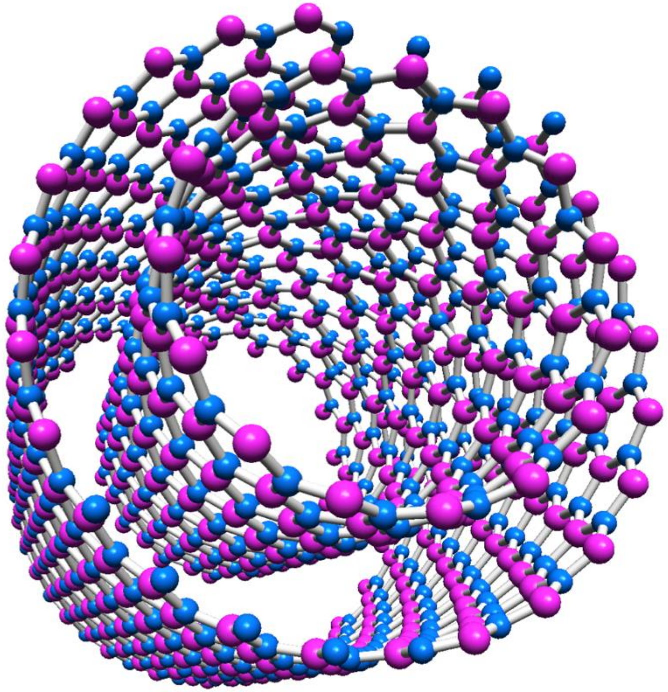
Jefferson Lab: Ed Daly, Co-PI

17-19 August 2021



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

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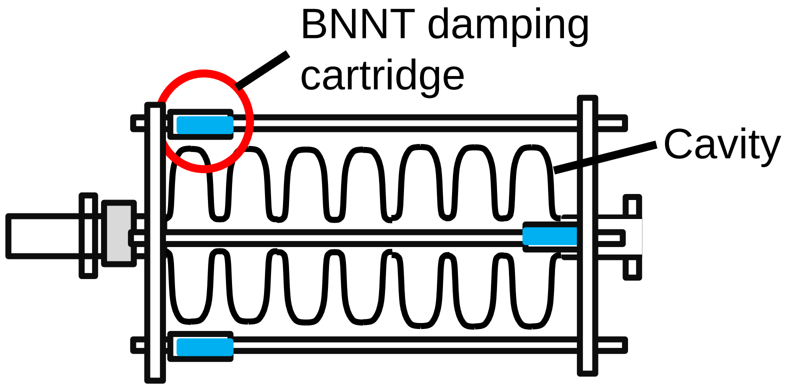
DOE SBIRs and Jefferson Lab CRADA & Pellets to Cartridges to Cavities

- 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 are fabricated from compressed BNNTs:

Multiple BNNT pellets are combined in a **cartridge** to provide required spring constant and compressive damping:

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



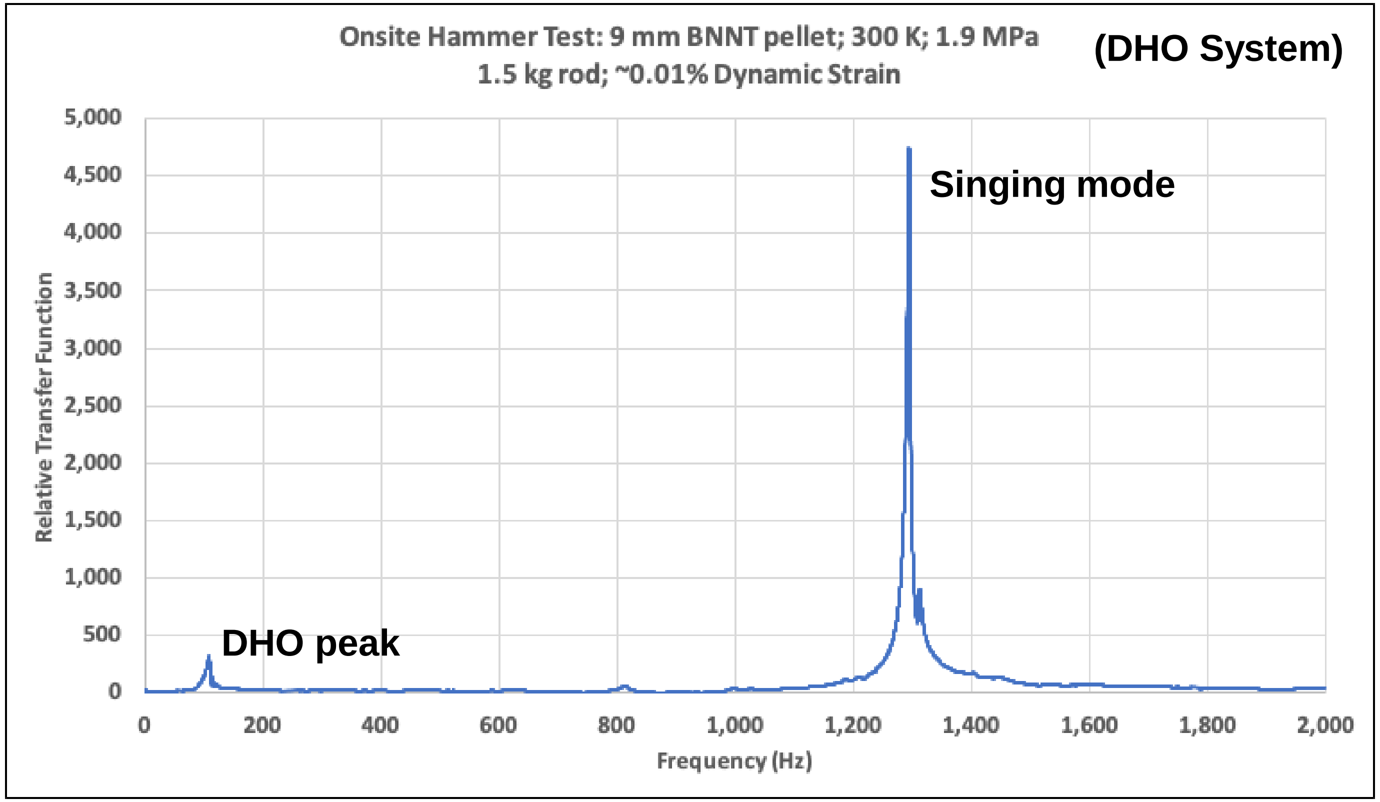
BNNT Pellets – Characterization

Two methods are typically utilized to characterize the BNNT pellets and determine their **elastic moduli and loss coefficients (tan deltas)**:

1. Damped Harmonic Oscillator (DHO) system

   Hammer testing is used onsite at BNNT LLC and can be used to measure both individual pellets and assembled cartridges. A hammer with a force transducer strikes a steel rod with an accelerometer that is under a static load on a BNNT pellet. The motions of the rod result in a relative transfer function that exhibits DHO, a “singing” mode of the rod axially vibrating, multiple harmonics, and several parasitic vibrations. **The elastic modulus and tan delta of the pellet are extracted from the position and width of the DHO peak**.

   The system operates at 77 K, 300 K and up to 700 K. The measurement system is nearly the same as utilized for the measurements at Jefferson Lab for bench testing and non-RF testing in the horizontal test bed (HTB) at 300 K.



2. Pellets have been sent to a commercial testing facility for dynamic mechanical analysis (DMA) that can test at both 300 K and 77 K.

BNNT Pellets – DHO and DMA Results

The DHO modes observed during onsite hammer testing are typically in the 40-200 Hz region, depending on the axial lengths and number of BNNT pellets tested for a given configuration.

The newly developed BNNT SP10R material is purer than RP14R and outperforms as indicated by higher tan deltas. Pellets made of both BNNT materials demonstrate a ~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

Next, 2 K measurements will be performed on C100 cartridges. A DHO system will be used for some setup test measurements at 300 K; however, the most sensitive measurements at 2 K will be made with an RF system in place. Using the RF system at JLab, the cavities' response to varying levels of compression on the BNNTs is observed 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.

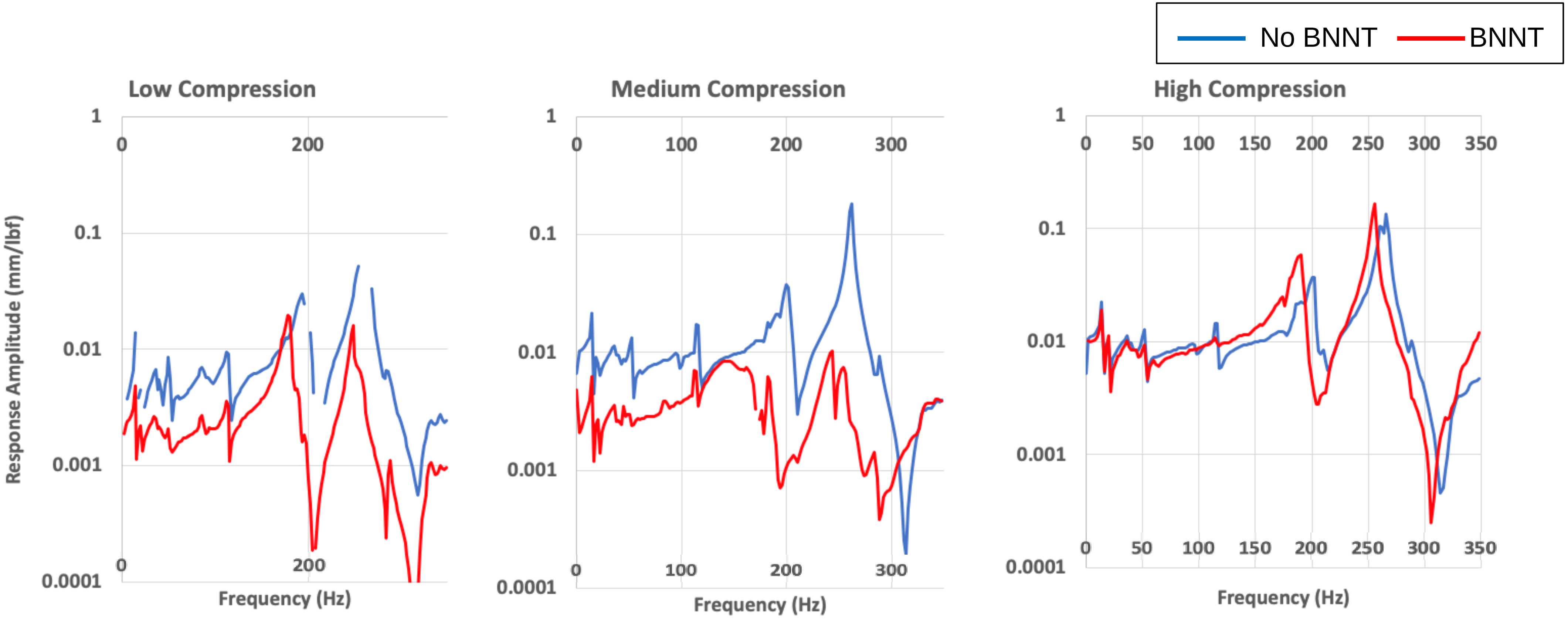
C100 Cavity 300 K Bench Test Setup

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

C100 cavity tuner drive mechanism behind and above cavity.

C100 Cavity 300 K Bench Test Results

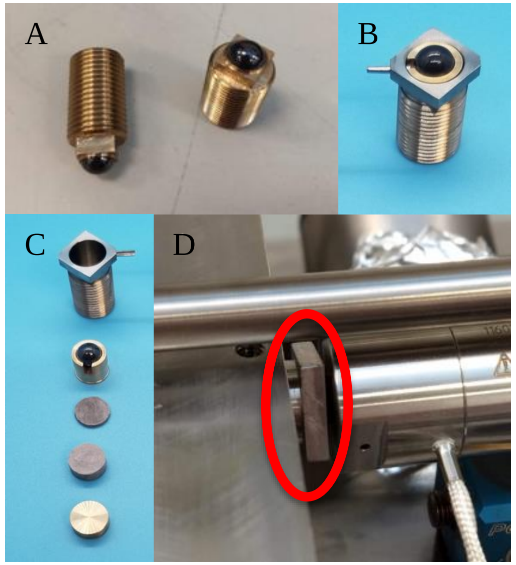
Preliminary results demonstrate passive vibration damping by BNNTs in the frequency range of interest. The cavities are in tension to tune them to the operating frequency of the accelerator. Best results, as determined by the heights of the peaks, are at low and medium compression of the cavity which is where the cavities typically operate. The level of compression on the BNNT pellets in the cartridges can be tuned to take advantage of this effect.

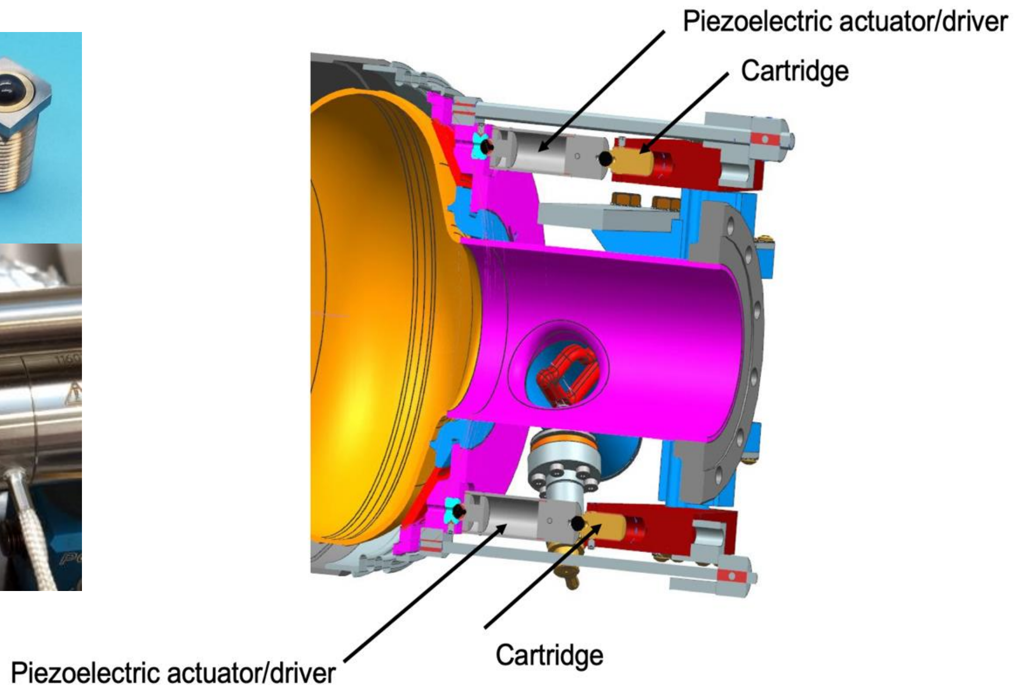


BNNT

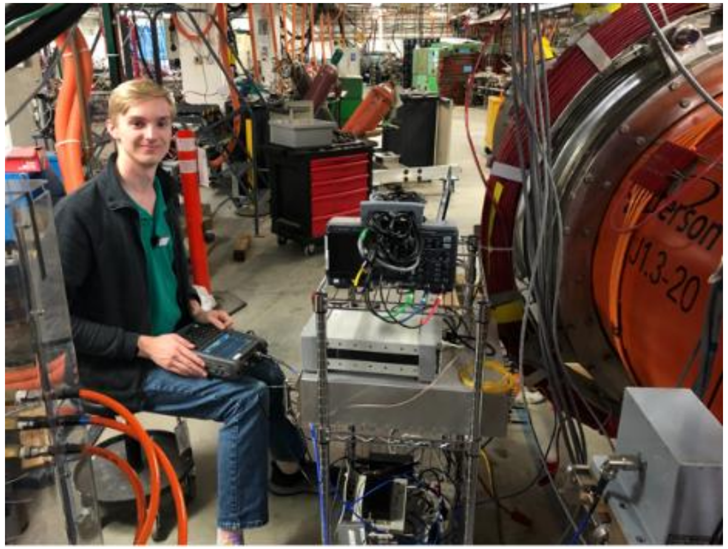
LCLS-II Opportunity

An LCLS-II cryomodule was being set up in the Jefferson Lab LERF and we achieved approval to put BNNT vibration damping in two of the eight cavities for testing at 2 K. LCLS-II cavities and cryomodules are very different from C100 systems and to achieve timelines LCLS-II BNNT cartridges had to exactly match standard parts.



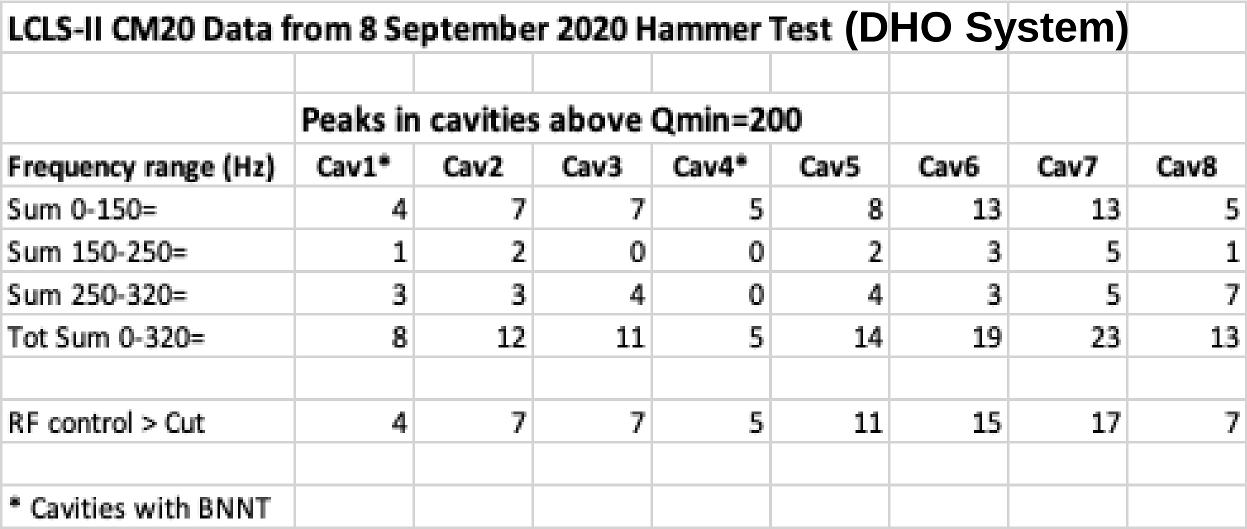


BNNT pellet installed onto an LCLS-II cavity. Standard parts (A) are readily exchanged for BNNT cartridge holders (B). BNNT cartridge holder components (C) prior to assembly. BNNT cartridge (D) is circled in red installed on a LCLS-II cavity between the tuner plate and piezoelectric actuator.



LCLS-II CM-20 testing in LERF at 2 K

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

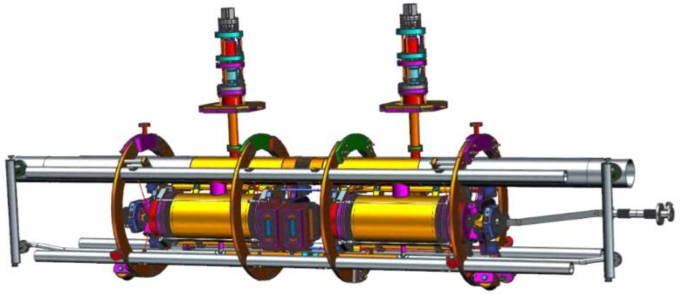
	Peaks in cavities above Qmin=200							
F(Hz)	Cav1*	Cav2	Cav3	Cav4*	Cav5	Cav6	Cav7	Cav8
Sum 10-80=	3	2	5	1	3	3	2	2
Tot Sum 60-160=	2	3	1	2	3	0	3	2
Tot Sum 120-320=	11	13	15	15	10	11	19	8
RF control > Cut								
Sum 10-80=	3	2	5	1	3	3	2	2
Sum 60-160=	2	3	1	1	2	0	2	1
Sum 120-320=	0	0	0	0	1	0	1	0
* Cavities 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 the BNNT vibration damping show less microphonics than the other six cavities for a range of parameters for the selection of peaks.
- **From PZT Chirp test:** Energy is being 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 do not show vibrations in the other cavities.

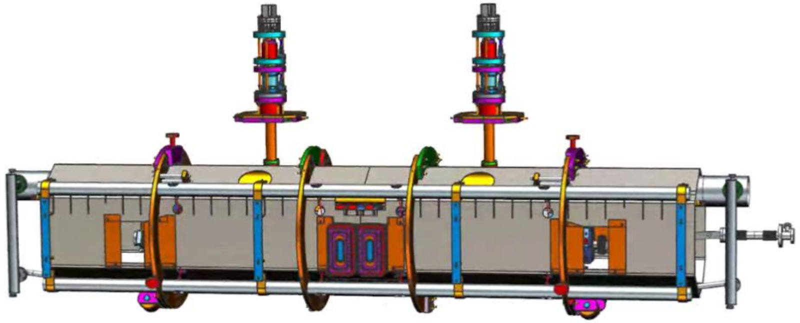
C100 Horizontal Test Bed Test

With the CEBAF schedule for C100 upgrades, it was worked out to do a test of two BNNT damped C100 cavities in the HTB facility at Jefferson Lab.

This will reduce risk when going to a full C100 cryomodule with eight cavities because if any issues arise, C100s take nearly a year to disassemble, rework and reassemble. The HTB C100 style cryounit can be disassembled, reworked and reassembled in a few weeks.



C100 cavities in space frame

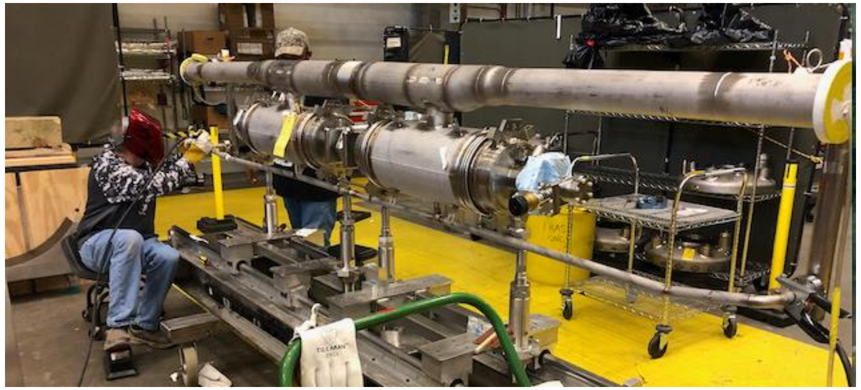


C100 cavities with thermal shield

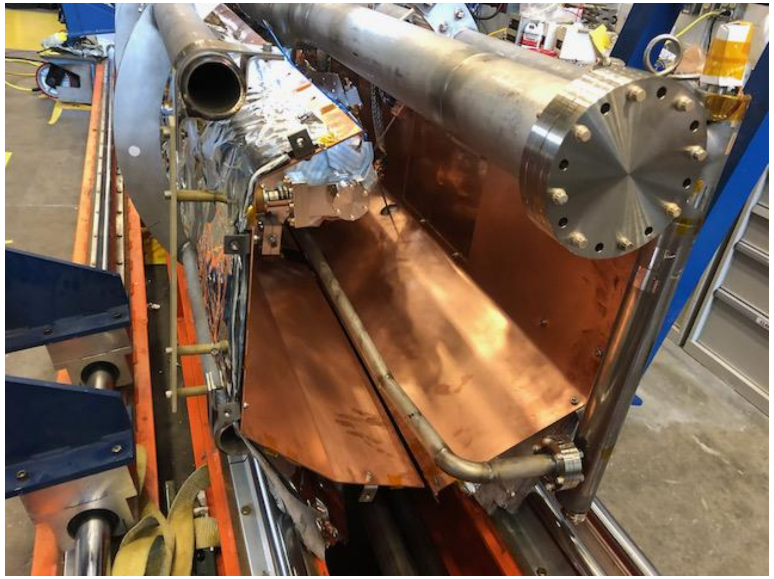
C100 cryounit vacuum containment

Vibrations enter via the tuners (sticking up), RF waveguides, liquid helium feeds, beam lines at ends, vacuum system, ground supports and nearby RF events.

C100 HTB Test Assembly



Cavity pair



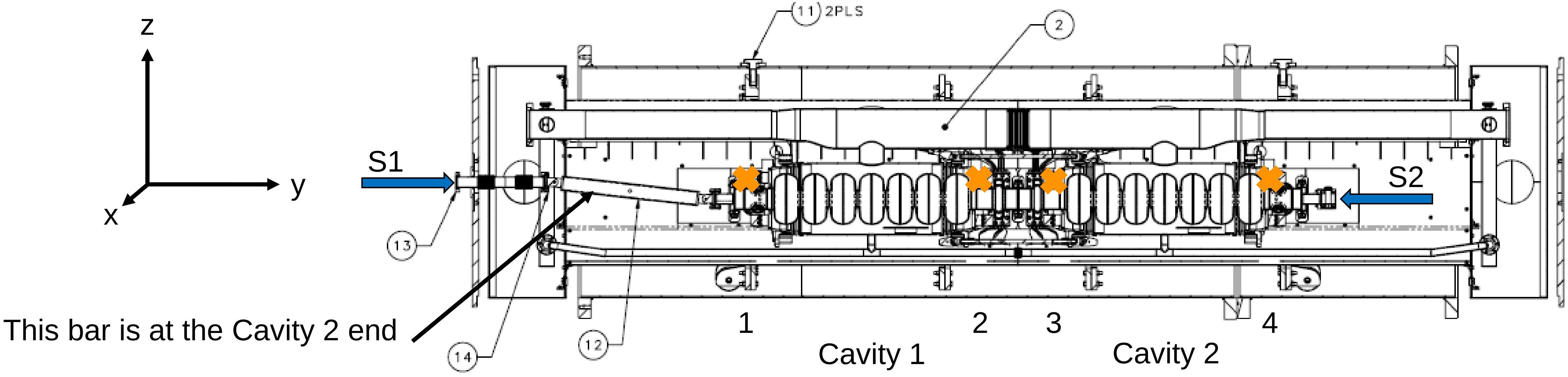
Radiation shield

Assembled into space frame

C100 cryounit final assembly

Jefferson Lab SRF facility

C100 HTB Test Arrangement



This bar is at the Cavity 2 end

Accelerometer ✖

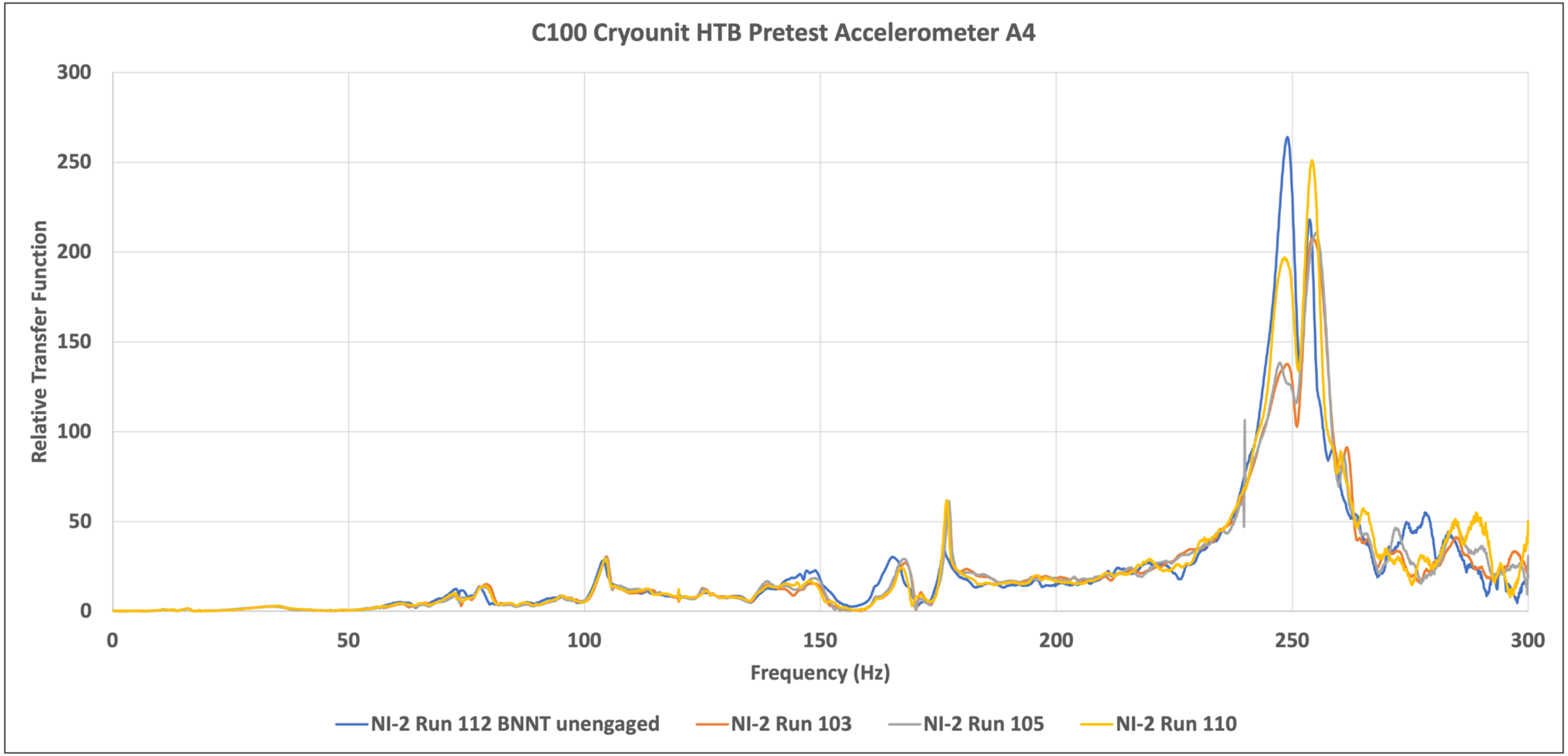
Strike Location →

Room temperature C100 cryounit setup

- Accelerometers are placed at the four locations indicated, plus one is on the tuner stack.
- Hammer impacts take place on the two ends of the cryounit.

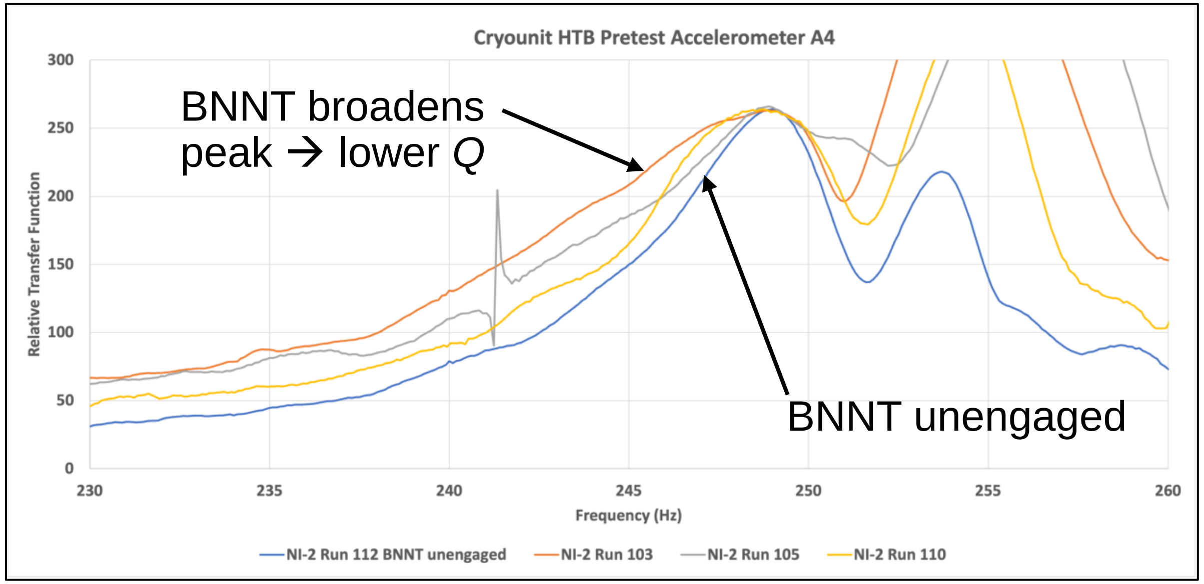
The key measurement is to observe the longitudinal/axial modes with the BNNTs engaged vs. unengaged and determine their relative *Q* values as observed with changes in the vibration response function.

Relative Transfer Function at 300 K Example



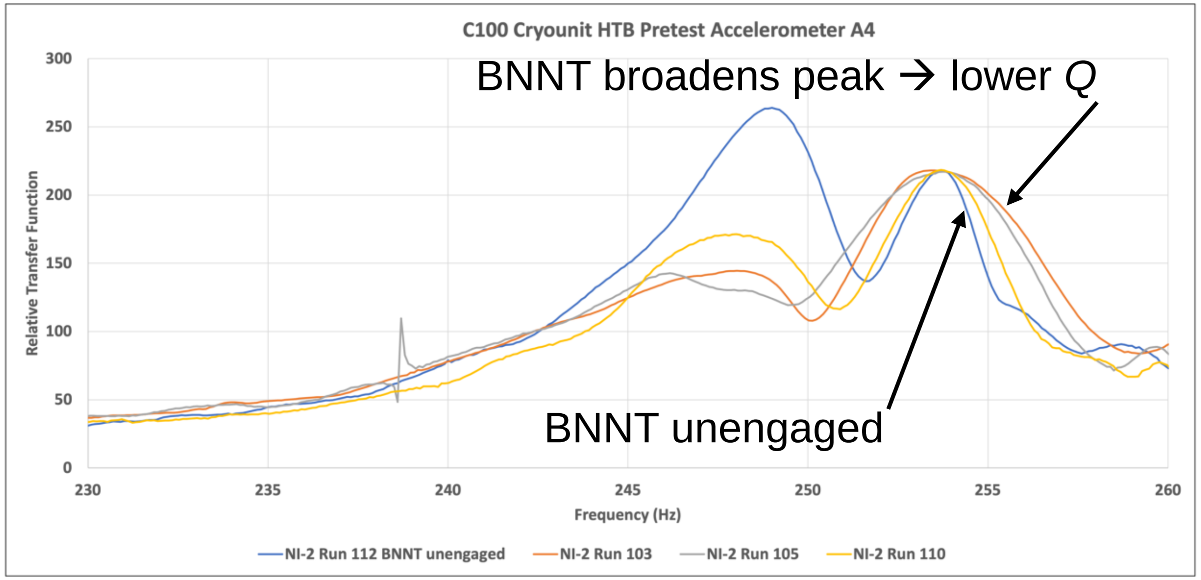
The tuner changing the cavity length (frequency) also slightly shifts the frequencies of some of the vibration modes. Accelerometer A4 is the one closest to the hammer strike in the test shown.

C100 Cavity Pair Peak Comparisons



BNNT broadens peak → lower *Q*

BNNT unengaged



BNNT broadens peak → lower *Q*

BNNT unengaged

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

Representative C100 cavity pair longitudinal vibration mode *Q*s with BNNT unengaged/engaged at 300 K

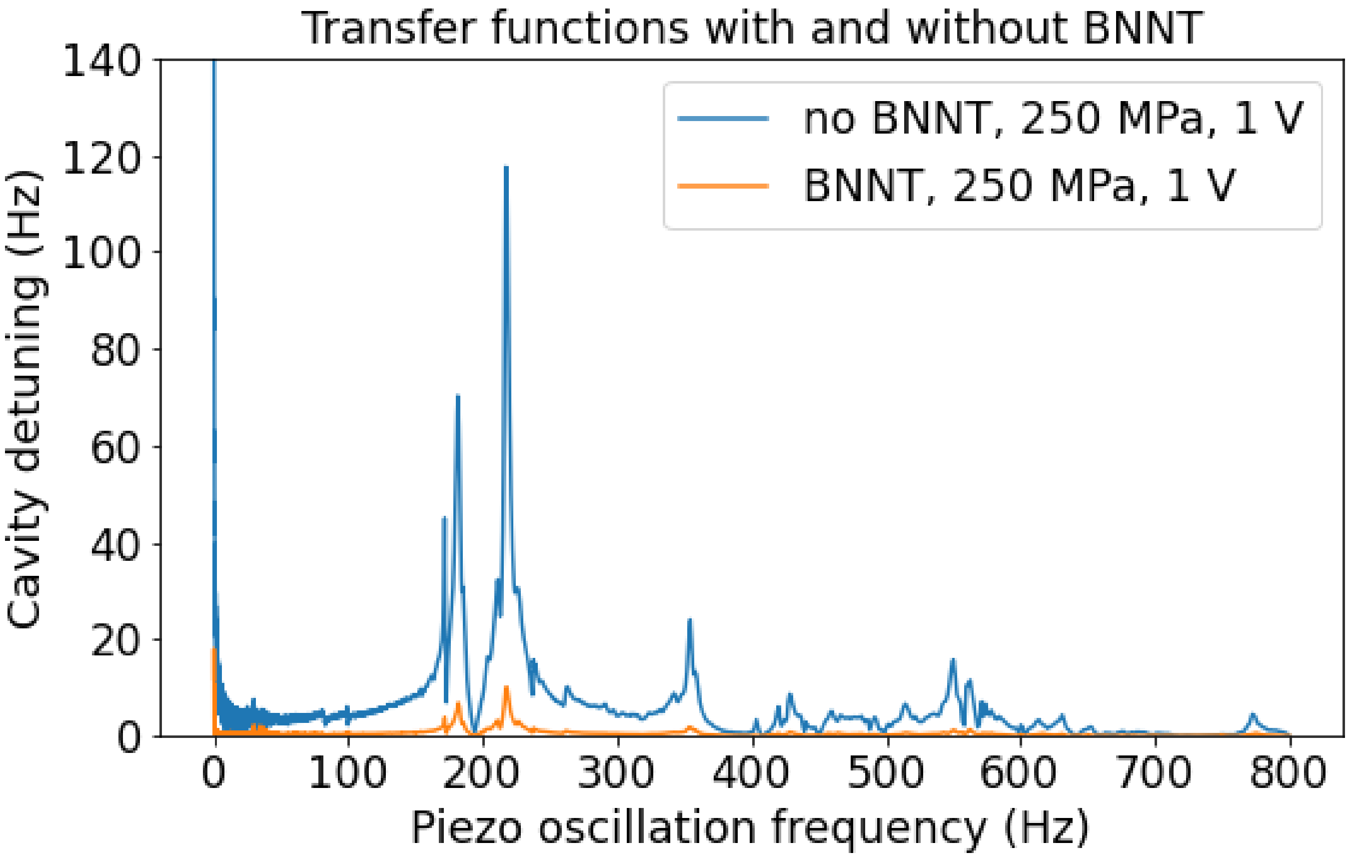
Vibration frequency (Hz)	***Q* – unengaged BNNT**	***Q* – engaged BNNT**	**Decrease in *Q* (%)**
65.7	61	29	52
78.7	54	32	41
162.6	68	44	35
248.1	59	52	12
254.8	141	72	49

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

Vibration Attenuation

Measurements* were performed at Helmholtz Zentrum Berlin (HZB) using a TESLA type cavity equipped with a Saclay-I type tuner featuring a twin set of parallel piezo drivers where one of the piezos was put in series with a BNNT pellet.

A tenfold attenuation of an external mechanical excitation was observed which makes the material a most promising candidate for applications that require 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).

Summary and Next Steps

Summary:

- BNNT vibration damping has been demonstrated in a C100 cavity pair at 300 K and in two cavities in a production LCLS-II cryomodule at 2 K.
- All of the components for the C100 and LCLS-II-HE are being manufactured.
- The project is on track for performing a test in the C100 cavity pair at 2 K, placement in a full C100 cryomodule, and placement in an LCLS-II-HE cryomodule.

Next steps:

- Perform C100 dual cavity HTB measurements at 2 K. This is planned for August/September 2021.
- Place BNNT vibration damping in full C100.
- Include BNNT damping in LCLS-II-HE as test in the verification cryomodule test and then in a portion of a production LCLS-II-HE.
- Continue working with HZB and other collaborators on incorporating BNNT vibration damping.