Boron Nitride Nanotube Vibration Damping for SRF Structures

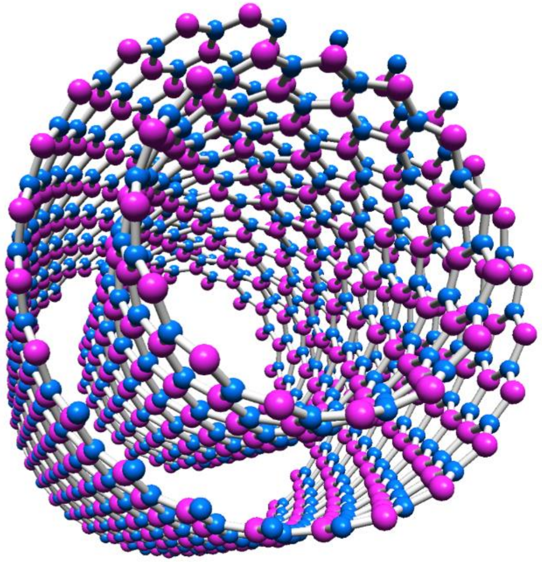
SBIR Phase II; DE-SC0018489_MOD No._0001; 5/28/2019-5/27/2021

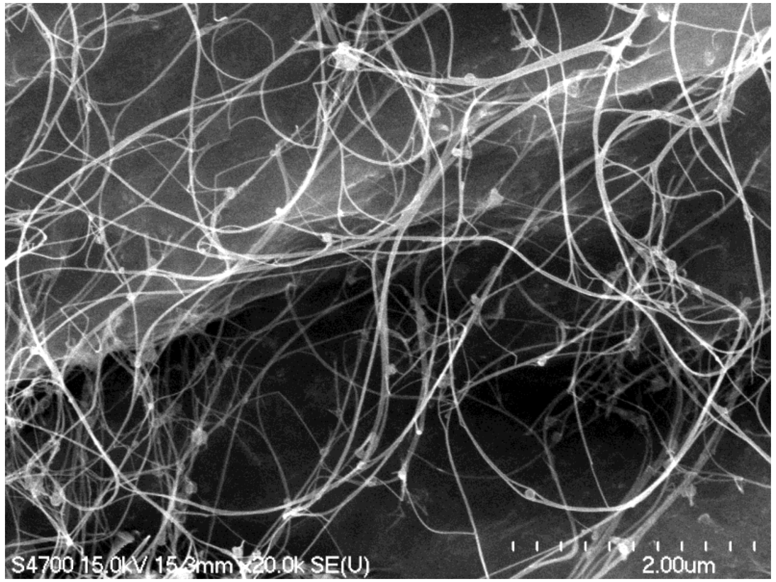
Contractor: BNNT (PI: Roy Whitney)

Subcontractor: Jefferson Lab (PI: Ed Daly)

August 14, 2020

Boron Nitride Nanotubes





As-synthesized puffball (left); refined puffball (center), powder (right); buckypaper (bottom)

BNNTs of high-quality are typically 2 and 3-wall, 2-5 nm in diameter and may exceed a 100 microns in length.

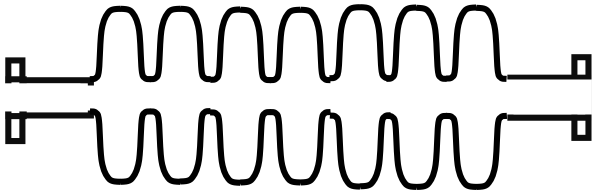
BNNT Materials LLC is the first and only commercial facility producing high-quality BNNTs. While invented at Berkeley Lab in tiny quantities, BNNTs were much more recently brought to scale by Jefferson Lab and NASA, before spinning-out into a US small business and earning NASA Invention of the Year. Our next-gen production went live in our pilot-plant recently, capable of fine-adjustments on synthesis and refinement to tailor BNNTs optimized as needed for applications.

BNNT Passive Vibration Damping

- **Goal**: Increase uptime and lower cost for SRF based cryogenic (2 K) accelerators by keeping SRF cavities on resonance under the influence of length oscillations caused by microphonics. **For the cavities $\Delta L/L \sim \Delta f/f$, this translates to managing the length of the cavities to a part in 10^7.**
  - Microphonics can create RF trips that take the accelerator offline with subsequent loss of performance.
  - Microphonics distortions are managed by a combination of mechanical vibration damping (typically passive damping and isolation elements) and real-time application of expensive (capital and operational) extra RF power.

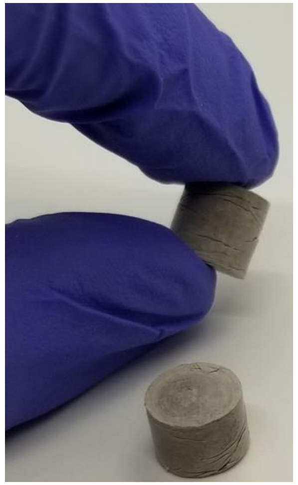
- **BNNT**: Boron nitride nanotubes demonstrate viscoelastic behavior that can be utilized for passive vibration damping from 2 K to 700 K (-271°C to 427°C). Results from DOE/NP Phase I SBIR.

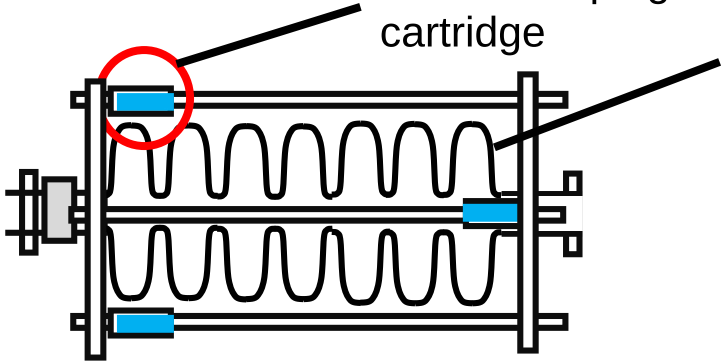
- **Target**: Damp microphonics in Jefferson Lab CEBAF C100 cavities that currently have high microphonics at 2 K.



Cavity frequency is proportional to length.

Year 1 – Pellets to Cartridges to Cavities



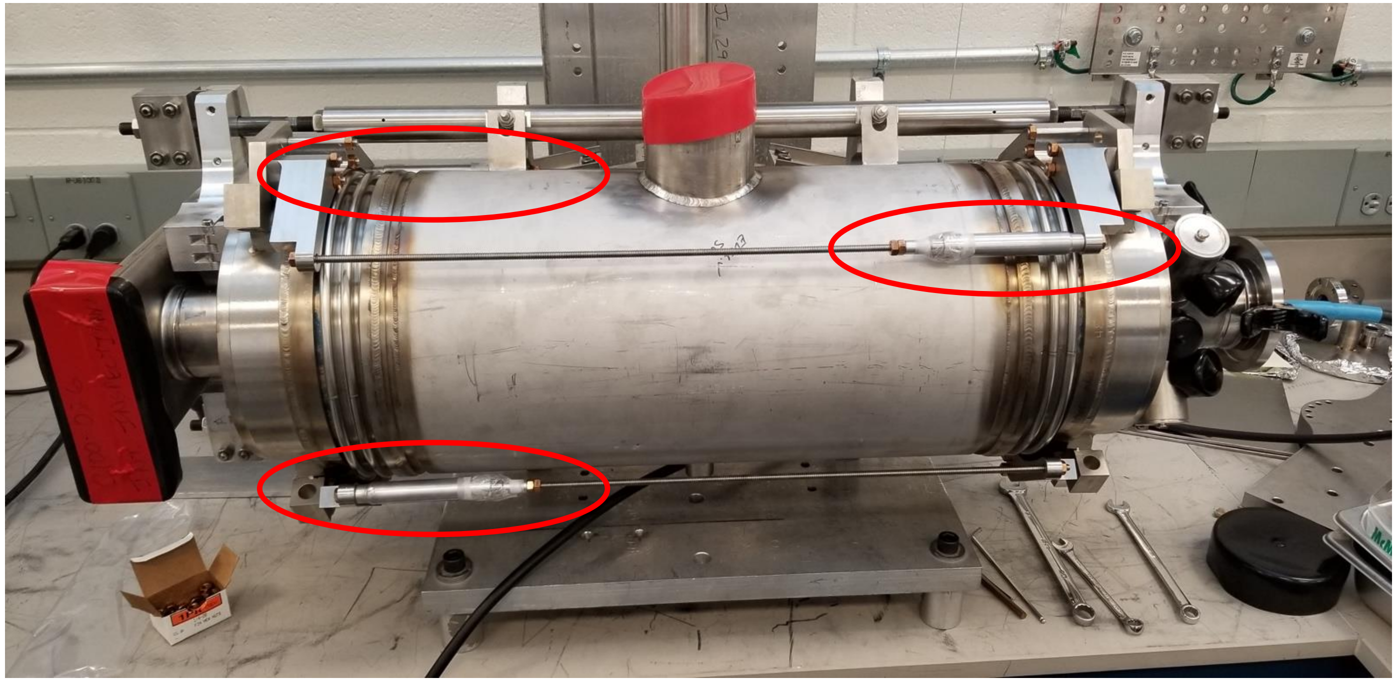


BNNT pellets are fabricated from compressed refined BNNT material.

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

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

C100 Cavity Bench Test

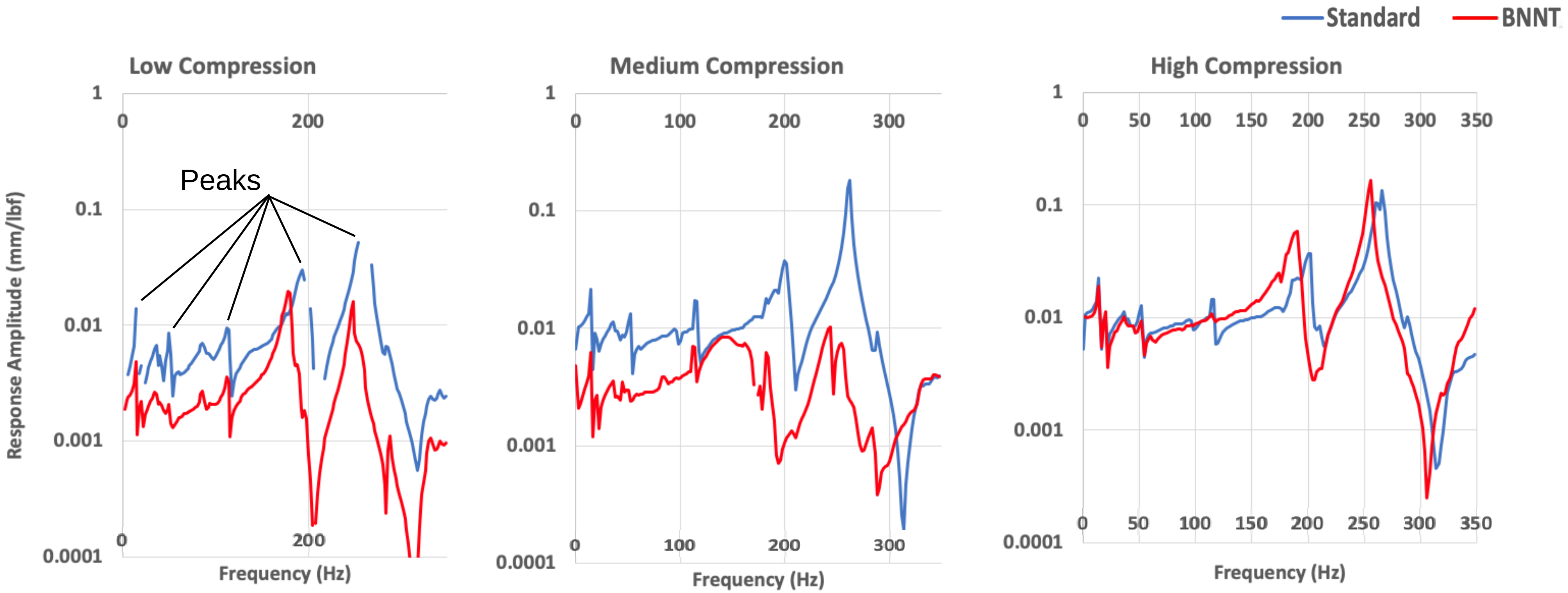


C100 cavity bench test at 300 K at Jefferson Lab.

Two of four BNNT C100 cartridges are shown during test assembly with location of third cartridge indicated.

C100 cavity tuner drive mechanism behind and above cavity used to compress the cavity to achieve resonance frequency.

C100 Cavity Preliminary Results



The horizontal axes have been adjusted to track the resonances.

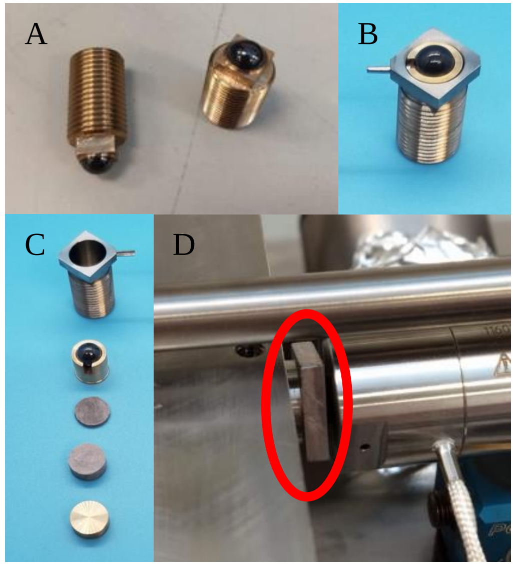
Preliminary 300 K results showing BNNT passive vibration damping in the frequency range of interest. The cavities are compressed to tune them to the operating frequency of the accelerator. Best results, as determined by the heights of the peaks, are at low and medium compression of the cavity which is where the cavities typically operate.

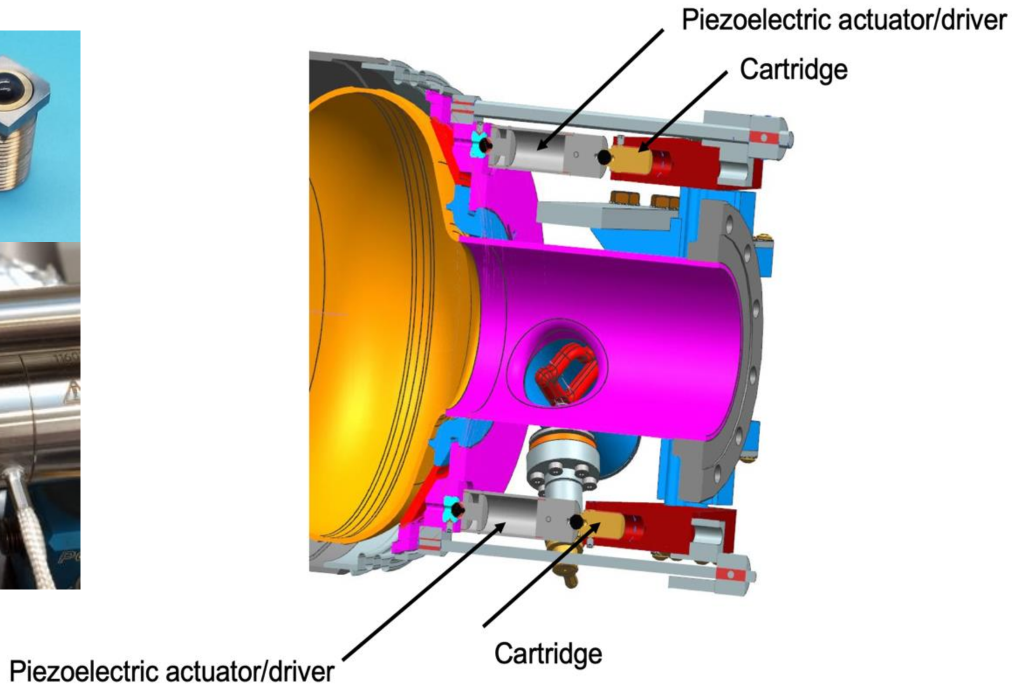
Testing was interrupted by the pandemic but has just resumed.

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.

Preliminary results appeared positive, but testing was interrupted by the pandemic. Testing has just resumed.





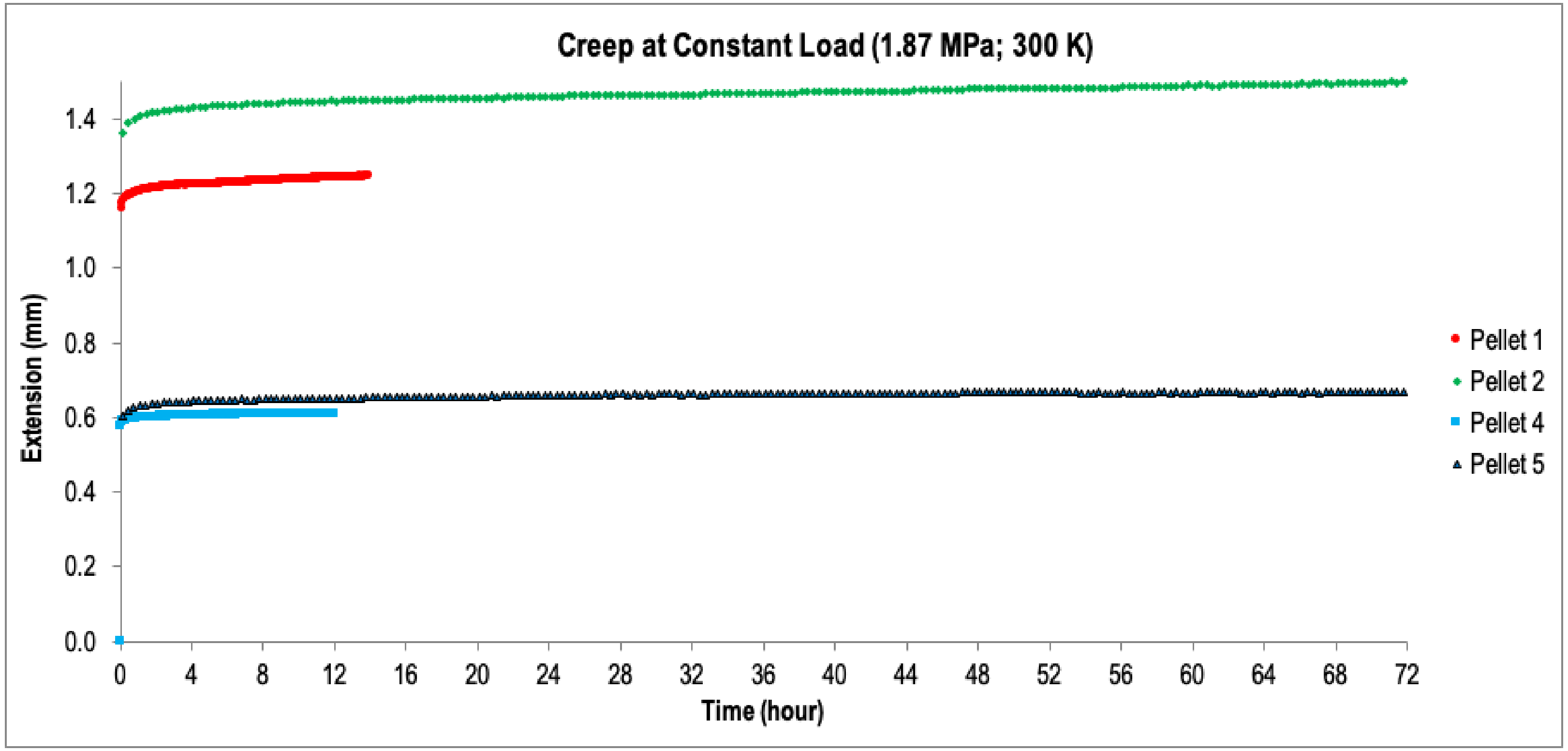
BNNT pellet installed onto an LCLS-II cavity. Standard parts (A) are readily exchanged for BNNT cartridge holders (B). BNNT cartridge holder components (C) prior to assembly. BNNT cartridge (D) is circled in red installed on a LCLS-II cavity between the tuner plate and piezoelectric actuator.

BNNT Pellets – Synthesis and Creep

Advances in BNNT synthesis and BNNT pellet characterization are furthering understanding and optimization of designs for passive vibration damping.

Comparisons are now underway for measuring the creep, elastic/storage modulus, and loss coefficient (tan delta) of the BNNT material synthesized and refined with different parameters.

Installation planning addresses the initial few hour creep, the following slow creep and the temperature cycling creep.

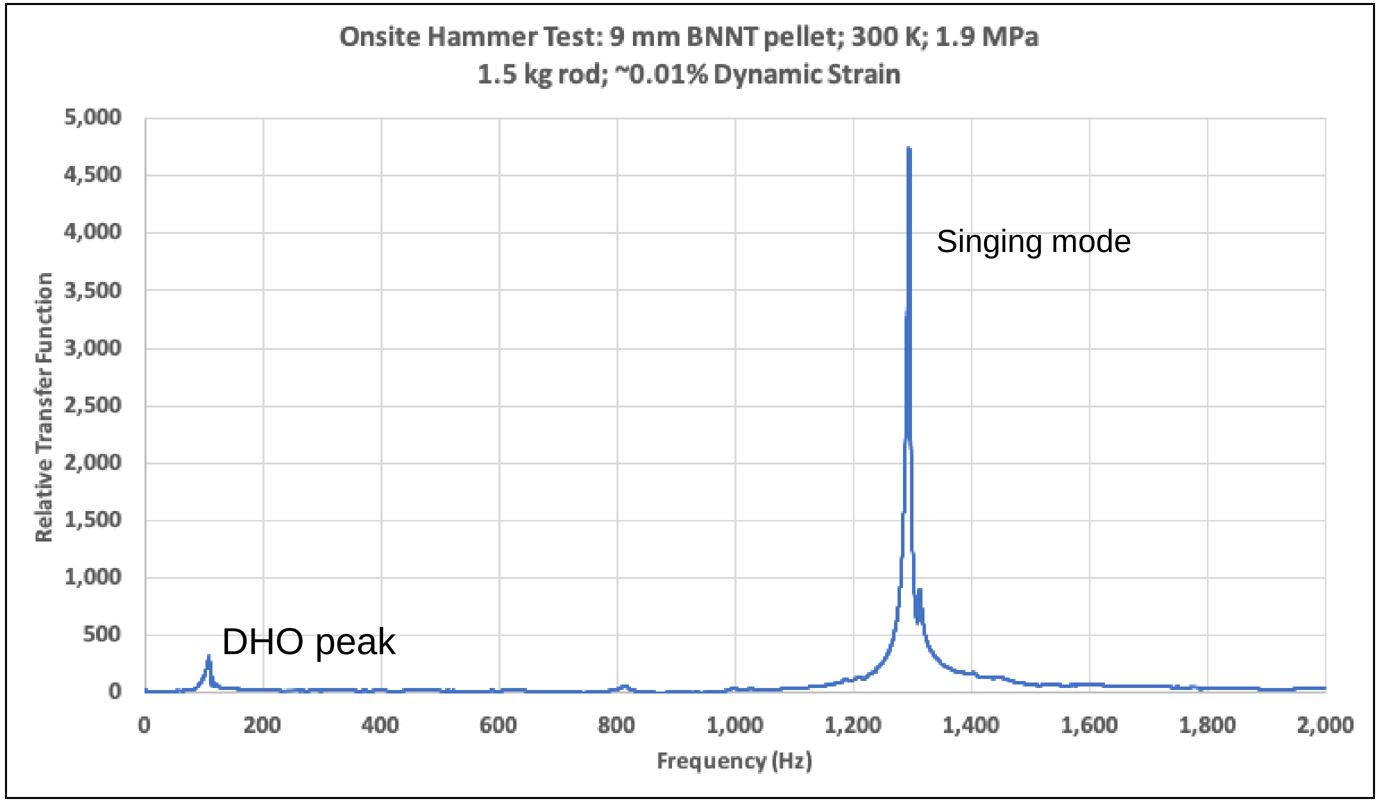


Preliminary creep measurements show that most of the BNNT pellet creep is within 4 hours but there is a tail in the creep that extends for several days. Additionally, cycling average pressure and temperature on the pellets introduces some creep. Current measurements are investigating temperature and pressure cycling.

BNNT Pellets – Characterization

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

- Hammer testing is used onsite. A hammer with a force transducer hits a steel rod with an accelerometer that is under a static load on a BNNT pellet. The motions of the rod exhibit damped harmonic oscillations (DHO), a "singing" mode of the rod axially vibrating, multiple harmonics and a number of parasitic vibrations. The elastic modulus and tan delta of the pellet are extracted from the position and width of the DHO peak.

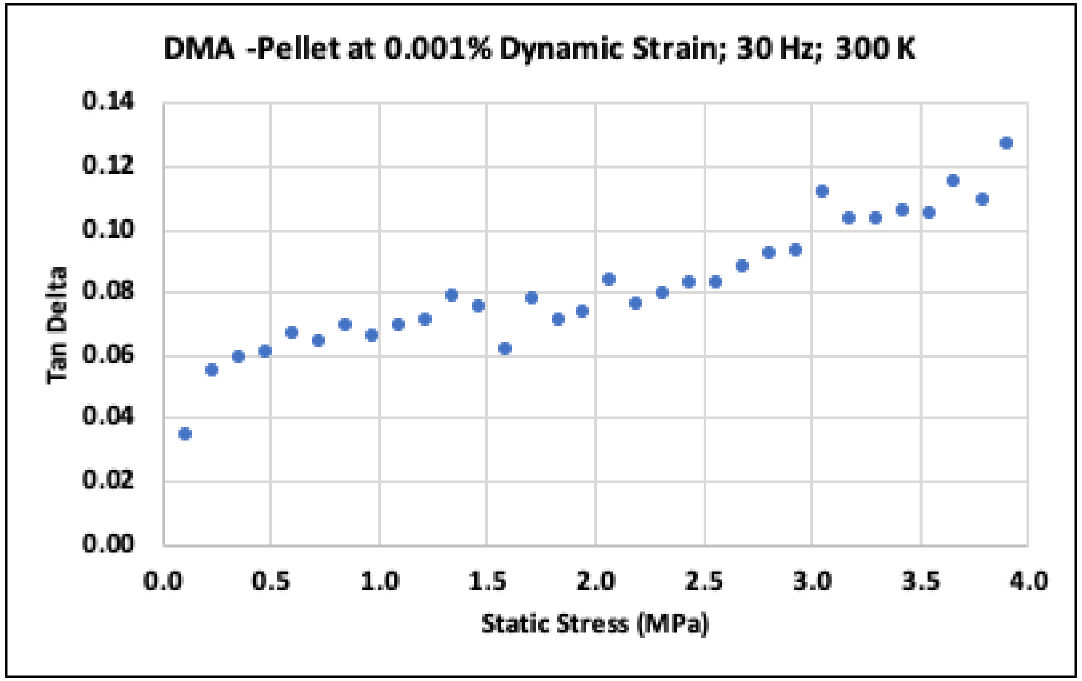


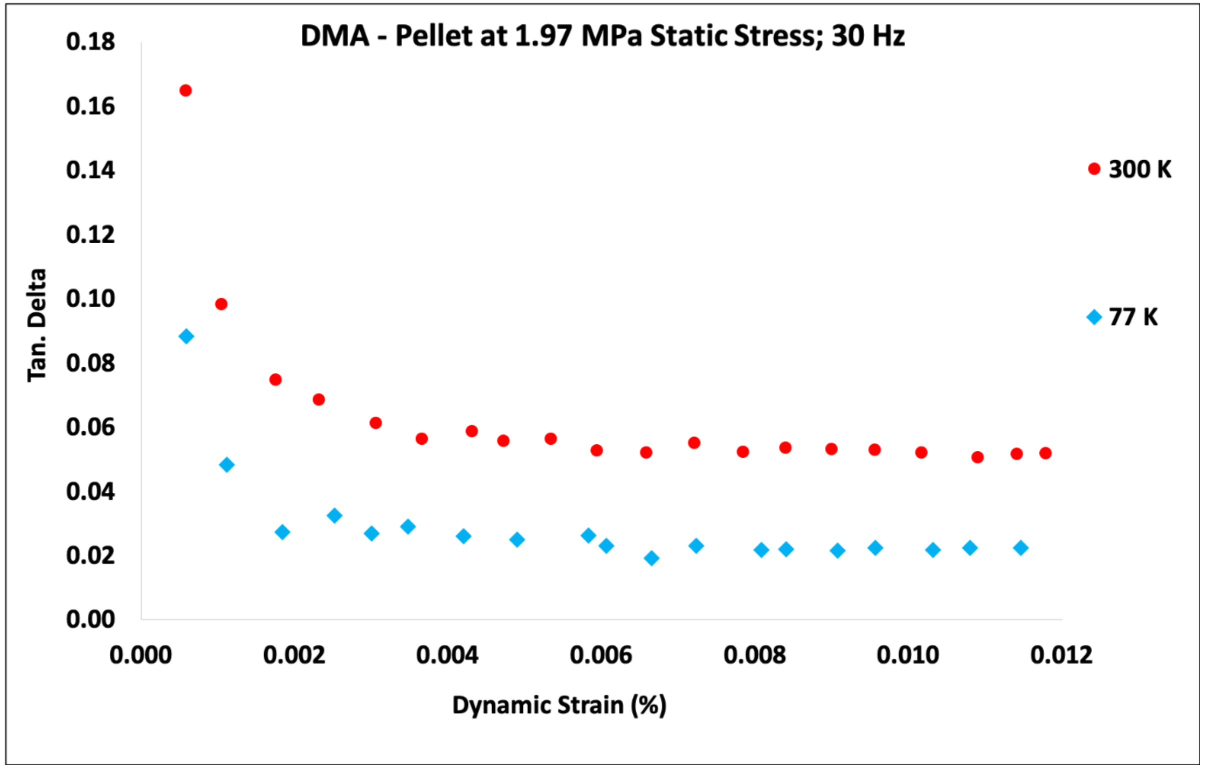
  The system operates at 77 K. K, 300 K and up to 700 K. The measurement system is nearly the same as utilized for the measurements at Jefferson Lab for bench testing and non-RF testing in the horizontal test bed (HTB) at 300 K and 2 K.

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

BNNT Pellets – DMA Testing

DMA measurements were mostly at 0.001% dynamic strain. SRF cavity microphonics are closer to 0.0001% dynamic strain. C100 Cavities will typically have static stress on the BNNT pellets in the range between 0.3 and 3 MPa.





Values from 20 Hz to 100 Hz are close to the values shown to the left for 30 Hz and 2 MPa static stress, but the DMA was not stable for results below 20 Hz because it was being operated at the lower limit of its capabilities for dynamic strain.

BNNT Pellets –DHO and DMA Results

The DHO modes are typically in the 20-120 Hz region depending on the axial lengths and number of the BNNT pellets tested for a given configuration. The elastic modulus and storage modulus are nearly the same because the loss modulus is a small fraction of the elastic modulus.

The SP10R is a newer material and appears to perform better. Both materials show roughly a 20% increase in elastic modulus in going from 300 K to 77 K. The DMA results are roughly 20% higher for elastic modulus.

DHO tan delta values are higher than the DMA values. We are exploring if this is related to the differences in the pellets or the differences in the systems.

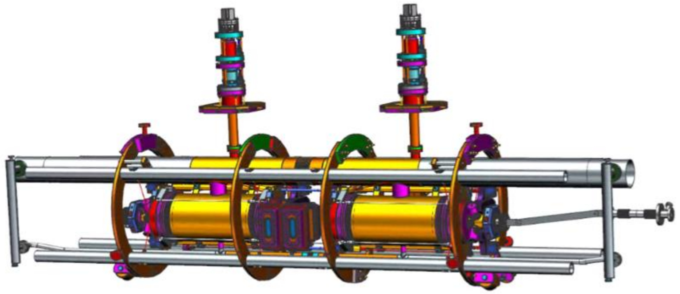
System and BNNT Pellet	Temperature (K)	Dynamic Strain (%)	Elastic Modulus (MPa)	tan delta
DHO – SP10R	77	0.01	105	0.10
DHO – SP10R	300	0.01	85	0.07
DMA – RP14R	77	0.001	117	0.05
DMA – RP14R	77	0.01	127	0.02
DMA – RP14R	300	0.001	92	0.10
DMA – RP14R	300	0.01	108	0.05

The 2 K measurements will utilize the DMO style hammer test for some measurements, but the most sensitive measurements will be made with the RF system where the cavities response to varying levels of compression on the BNNTs can be observed in the damping of the microphonics that are typically near 0.0001% dynamic strain where DMA tan delta results indicate higher values. This matches the nano length scale of the friction believed to generate the viscoelastic behavior.

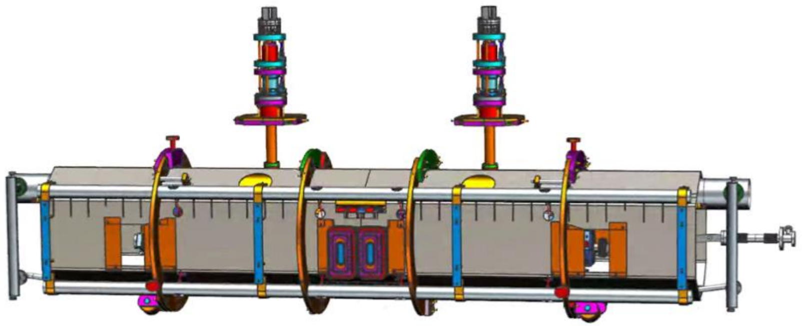
C100 Cavities in Horizontal Test Bed at 2 K

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.

Schedule and Summary

- C100 cavity benchtop testing and LCLS-II cavity testing with RF in an LCLS-II cryomodule are currently underway.
- Recent improvements in the BNNT pellet preparation will be incorporated in the HTB testing.
- Engineering, fabrication and assembly work is on track for initiating warm testing in the HTB in February and cold testing in April 2021. Testing will run for one to three months depending on the number of warmup cycles required as results are accumulated and understood.
- Project is on track to meet project goals for BNNT passive vibration damping of SRF structures.