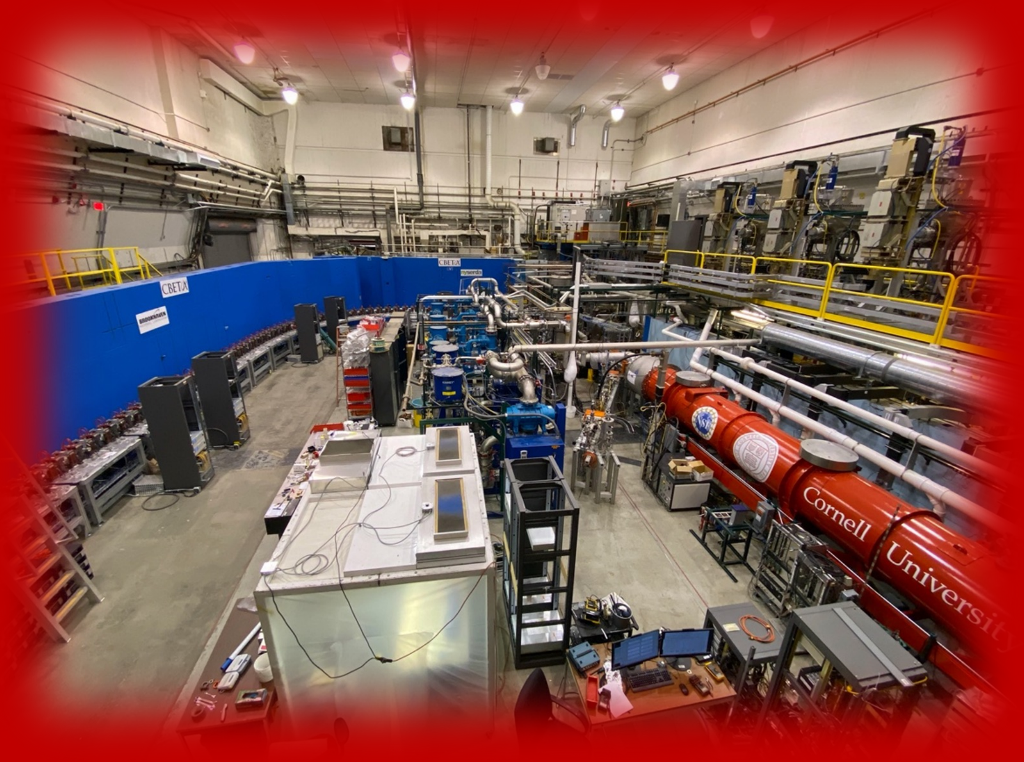

SRF Operations, microphonic control at CBETA

Nilanjan Banerjee

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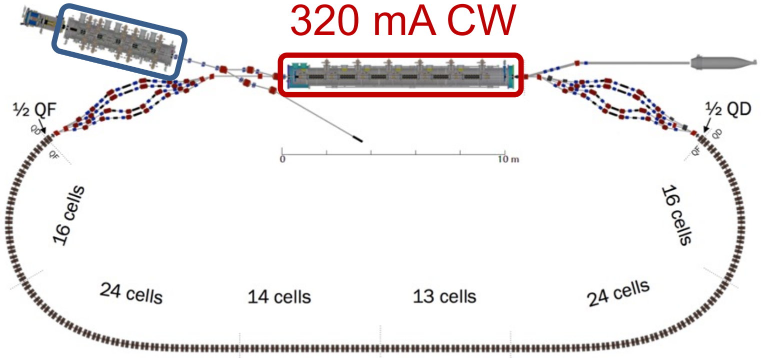
Overview

- Introduction
- Suppression of Microphonics Detuning
- Field Stability
- Beam Loading

Introduction

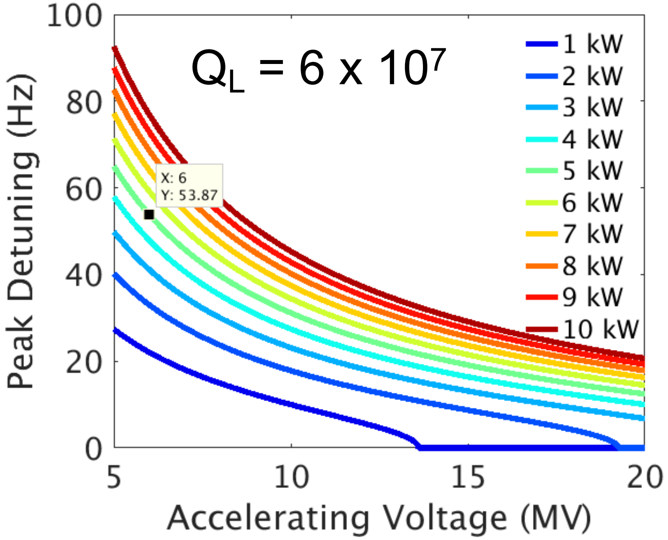
Injector Linac
40 mA CW

Main Linac
320 mA CW



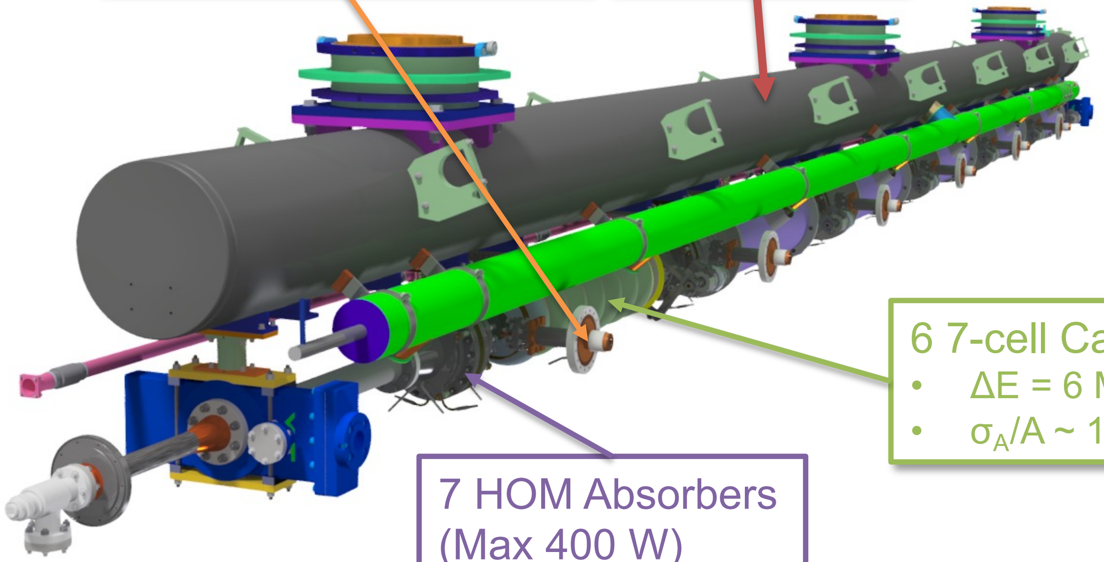
Cornell-BNL ERL Test Accelerator

Bartnik et al., Phys. Rev. Lett. **125**, 044803, 2020



Input Power Coupler
(Max 10 kW)

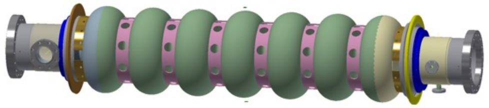
Helium Gas
Return Pipe



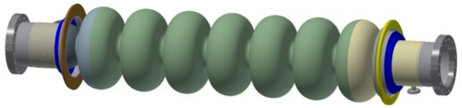
6 7-cell Cavities
- ΔE = 6 MeV
- $\sigma_A/A \sim 10^{-4}$, $\sigma_\varphi \sim 0.1°$

7 HOM Absorbers
(Max 400 W)

The peak detuning of the cavity must be less than **54 Hz** in order to sustain a cavity voltage of 6 MV using a power amplifier capable of delivering **5 kW**.



x 3



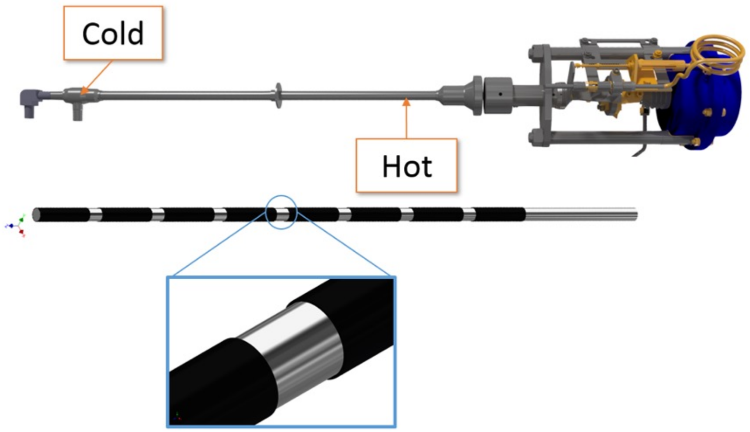
x 3

Vibration Sources

Vibrations of the cavity may arise from pressure waves in the cryogenic system or get coupled in from external sources.

Needle Valves

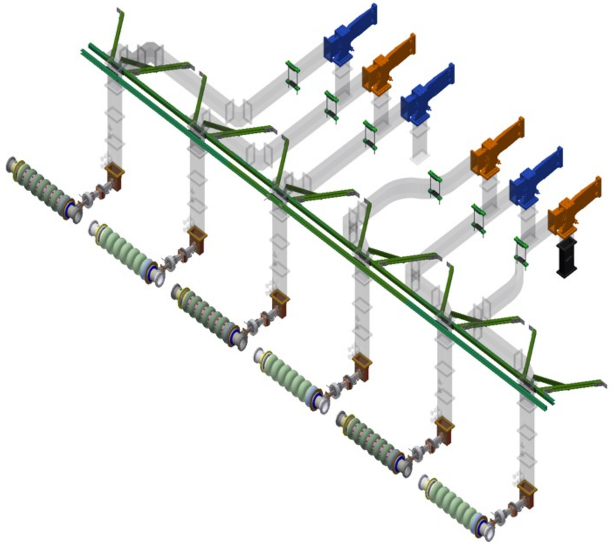
- Thermo-acoustic Oscillations (TAO)
  - Caused large steady state oscillations with RMS ~15 Hz
  - Insert sleeves to stop mass transport.
- Valve transients
  - Caused peak detuning up to 200 Hz.
  - Reduce valve actuation.

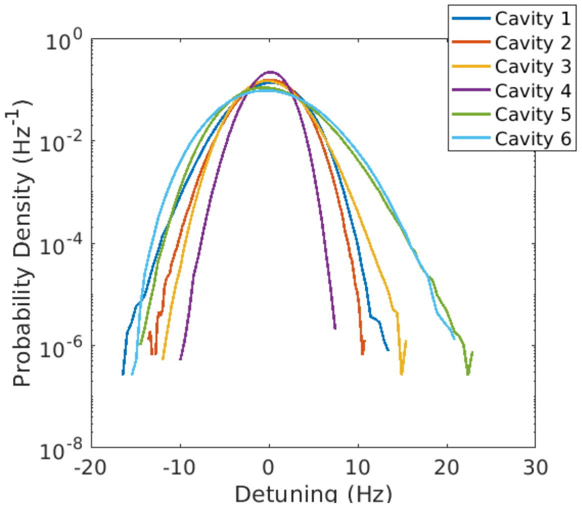


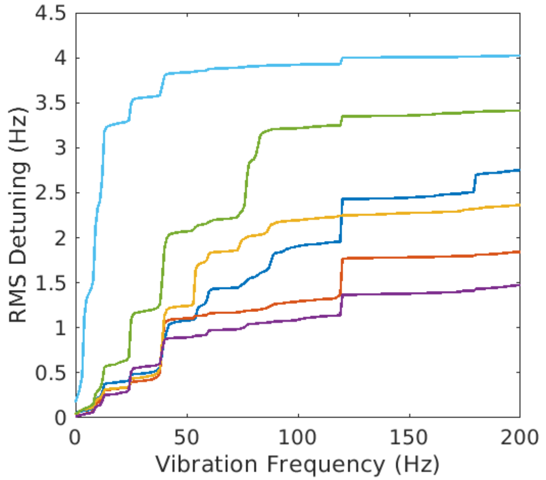
B J Hansen et al 2017 IOP Conf. Ser.: Mater. Sci. Eng. 278 012188

Coupled Vibrations

- Input Coupler
  - Mostly coupled 60 Hz vibrations.
  - Put damping material and bracing on waveguide supports.
- Cryogenic Pipes



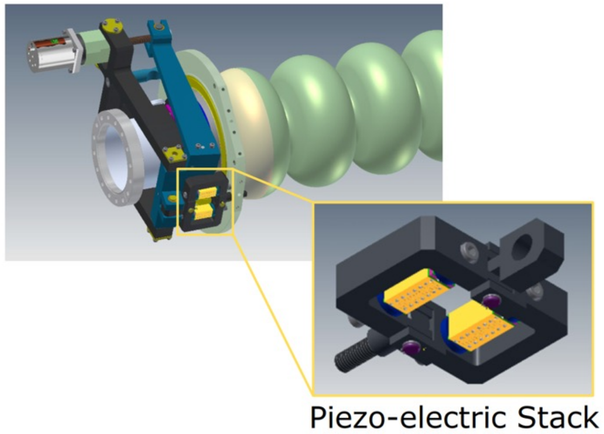


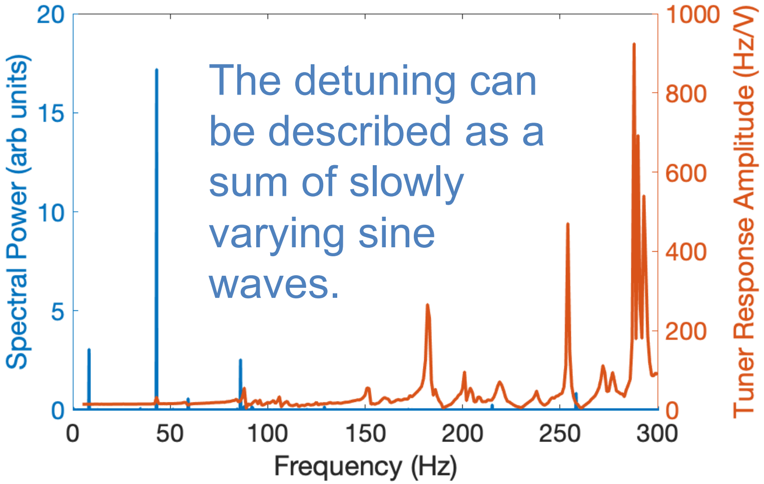


After mitigating vibration sources, the peak detuning was 23 Hz among all cavities.

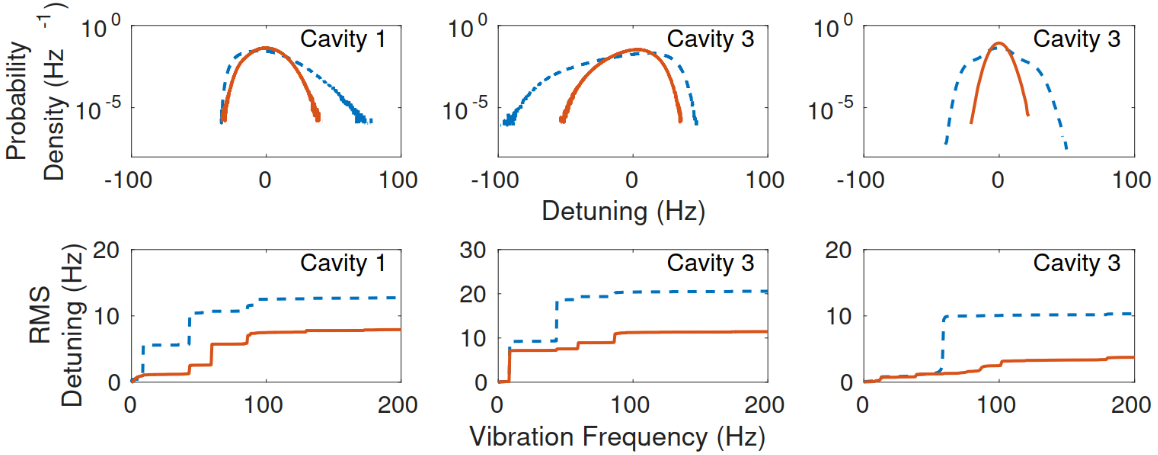
Active Suppression

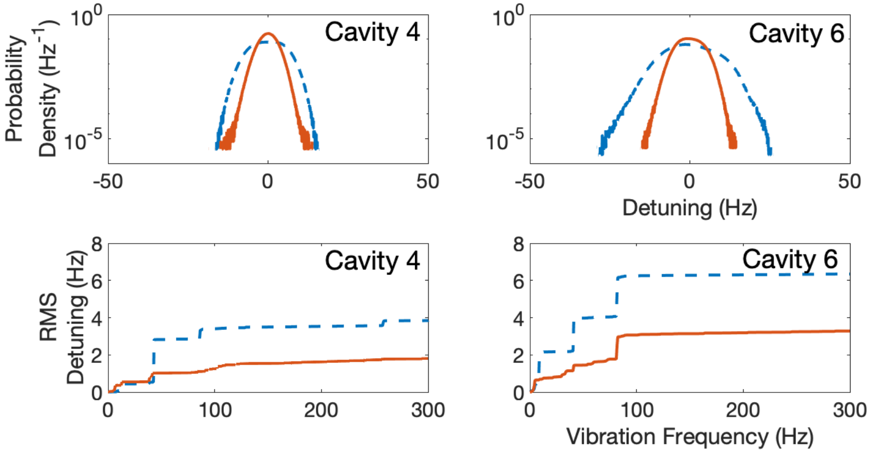
Mitigation of vibration sources is the preferred method of reducing peak microphonics detuning but having an active control system is also necessary!





Developed a modified narrowband Active Noise Control (ANC) algorithm to compensate for microphonics detuning by applying a sum of sine waves on the actuator.

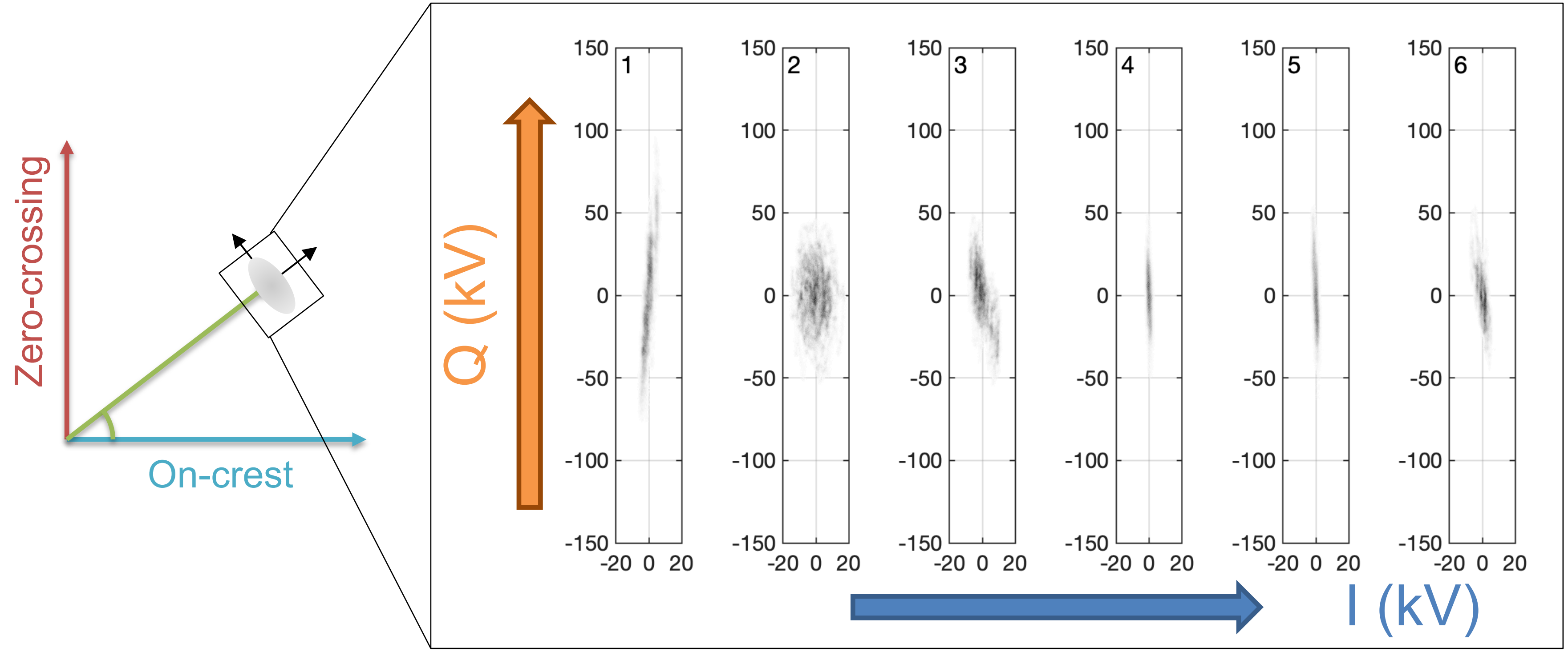




Nilanjan Banerjee et al. Phys. Rev. Accel. Beams 22, 052002, 2019

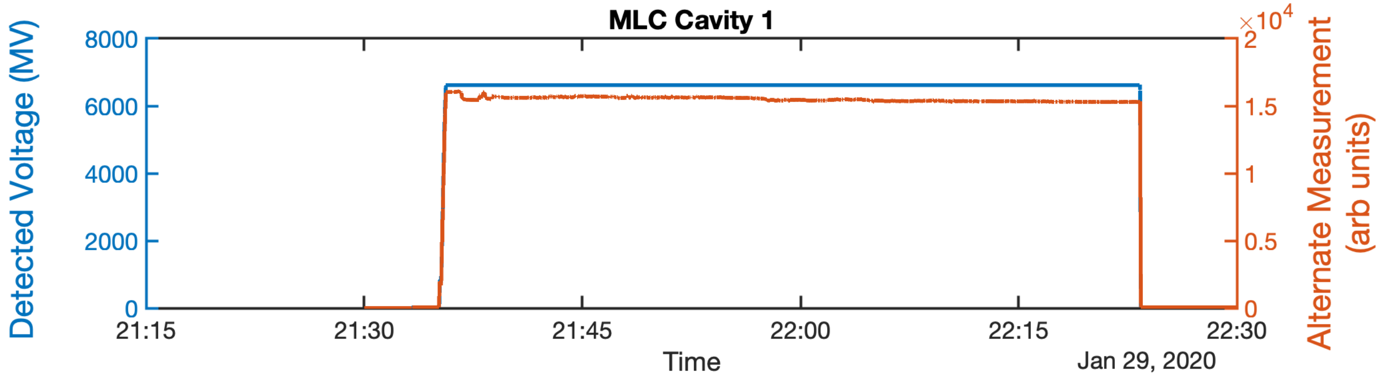
Field Stability

The goal of RF commissioning is to operate the accelerating cavities with stable fields.



Cavity	σ_V/V	σ_φ (deg)
1	3.9×10^{-4}	0.26
2	1.0×10^{-3}	0.16
3	8.0×10^{-4}	0.18
4	1.7×10^{-4}	0.15
5	1.8×10^{-4}	0.17
6	4.5×10^{-4}	0.15

Short term probability distributions of phasors can be used to characterize the source of noise. Long term measurements can show drifts.



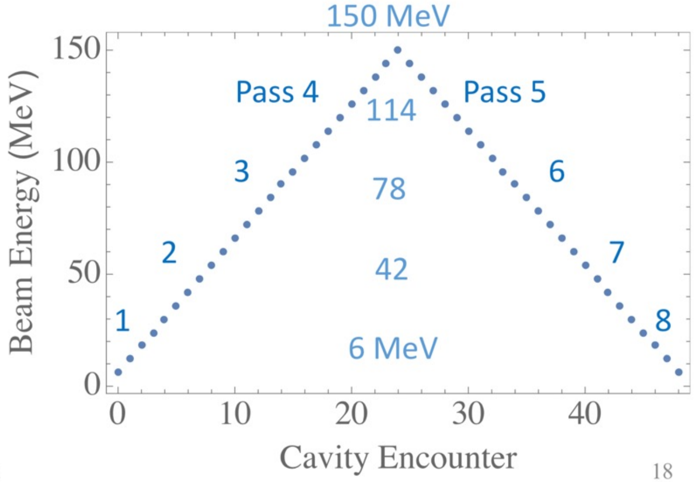
Average Beam Loading

We can only deliver limited RF power to the beam in the main linac, about 1 - 2 kW in each cavity.

ERL optimization goals

- Full energy recovery in each cavity (load → 0)
- Correct pass energy

Koscica et al., Phys. Rev. Accel. Beams **22**, 091602, 2019



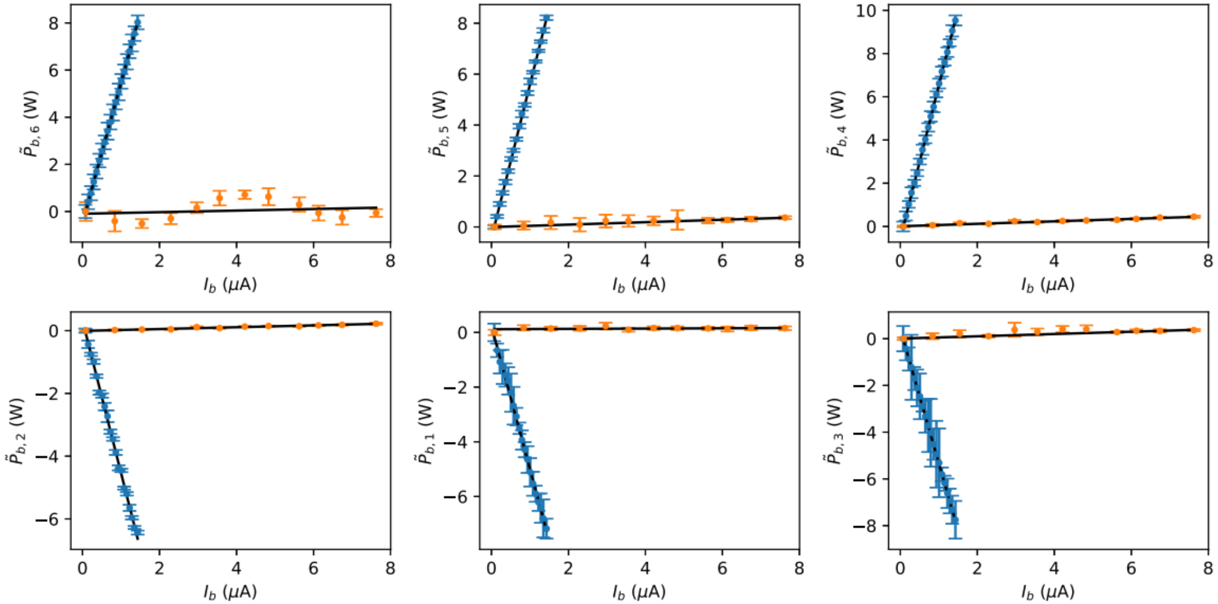
ERL symmetry reduces optimization system size.

- Cavities are paired.
- The beam energies are symmetric.

Net efficiency: **99.4 ± 0.1 %**

Reached 70 μA!

Gulliford et al., Phys. Rev. Accel. Beams **24**, 010101, 2021



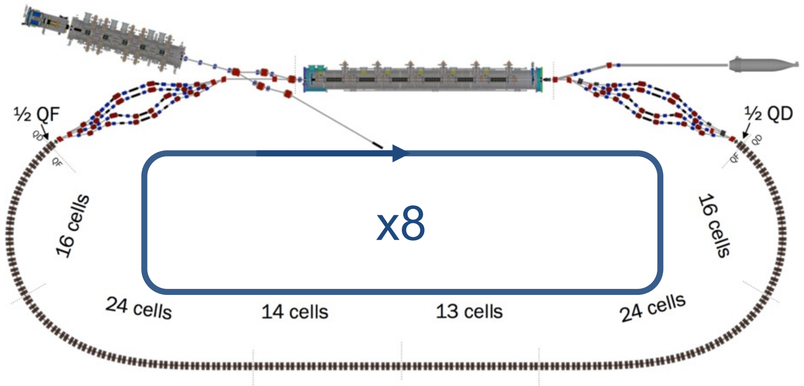
However, beam loading does not reach equilibrium, when we are just turning on or off!

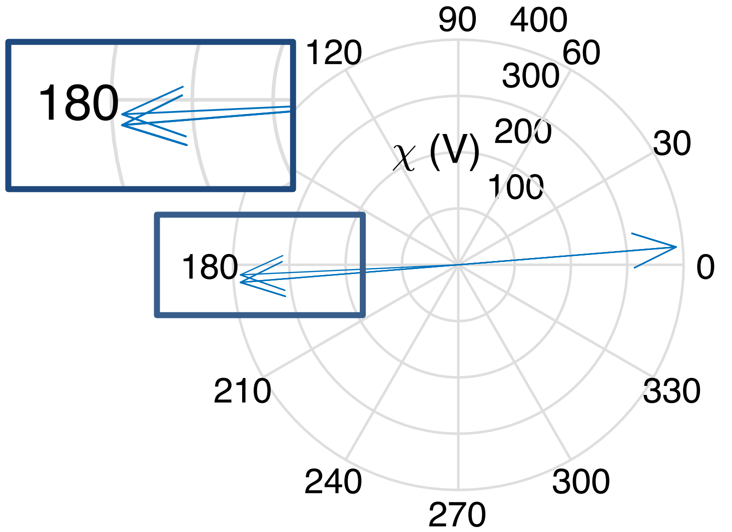
Transient Beam Loading

When starting up the ERL we need to provide enough RF energy to accelerate 8 passes full of beam to reach equilibrium.

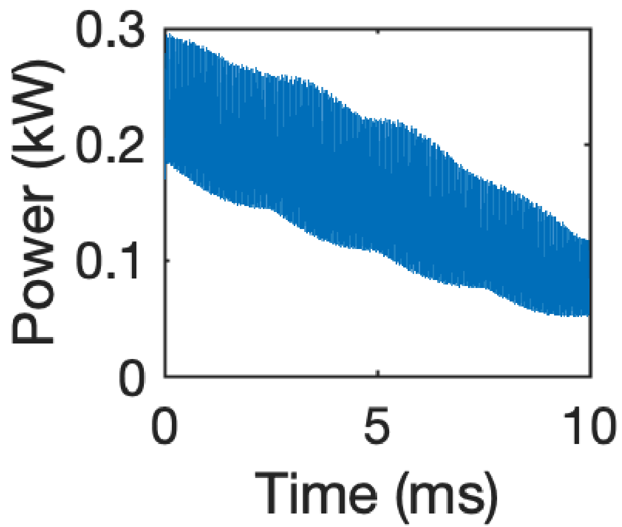
$$\varepsilon_{beam} = 16\, I\, V_C\, T_p = 1\ \text{J}$$

8 passes, average current 2 I
Design injection current is I = 40 mA
Nominal cavity voltage is V_c = 6 MV
Nominal path length T_p = 0.262 μs





The bunch slips with respect to the phase velocity of the accelerating field which generates reactive beam loading specifically at low energies.



Solution: Detune cavities as a function of beam current to compensate for reactive beam loading.

Example: The reactive beam loading from the 40 mA injected beam (325 MHz) should be compensated by detuning the cavity by -125 Hz in this configuration otherwise it will lead to a 36-kW power requirement!

Conclusion

Vibrations

Primary Sources: Cryogenic needle valve, mechanical coupling through waveguides. After mitigation, maximum detuning is 23 Hz compared to the 54 Hz requirement.

Active Suppression

Stop-gap measure. Modified narrowband Active Noise Control (ANC) algorithm is effective and stable over hours of operation.

Field Stability

Mostly dominated by microphonics detuning on most cavities. Two cavities have lots of amplitude noise. Some cavities have long term stability issues.

Energy Recovery

Measured an energy recovery efficiency of 99.4±0.1% for 1-turn operations at 70 µA. High-current multi-turn operations require consideration of reactive beam loading due to relativistic effects.

Acknowledgements

The entire CBETA team and the Cornell SRF group.

The work on CBETA was supported by New York State Energy Research and Development Authority and Brookhaven National Laboratory. The main linac cryomodule was designed and constructed using funds from the National Science Foundation.

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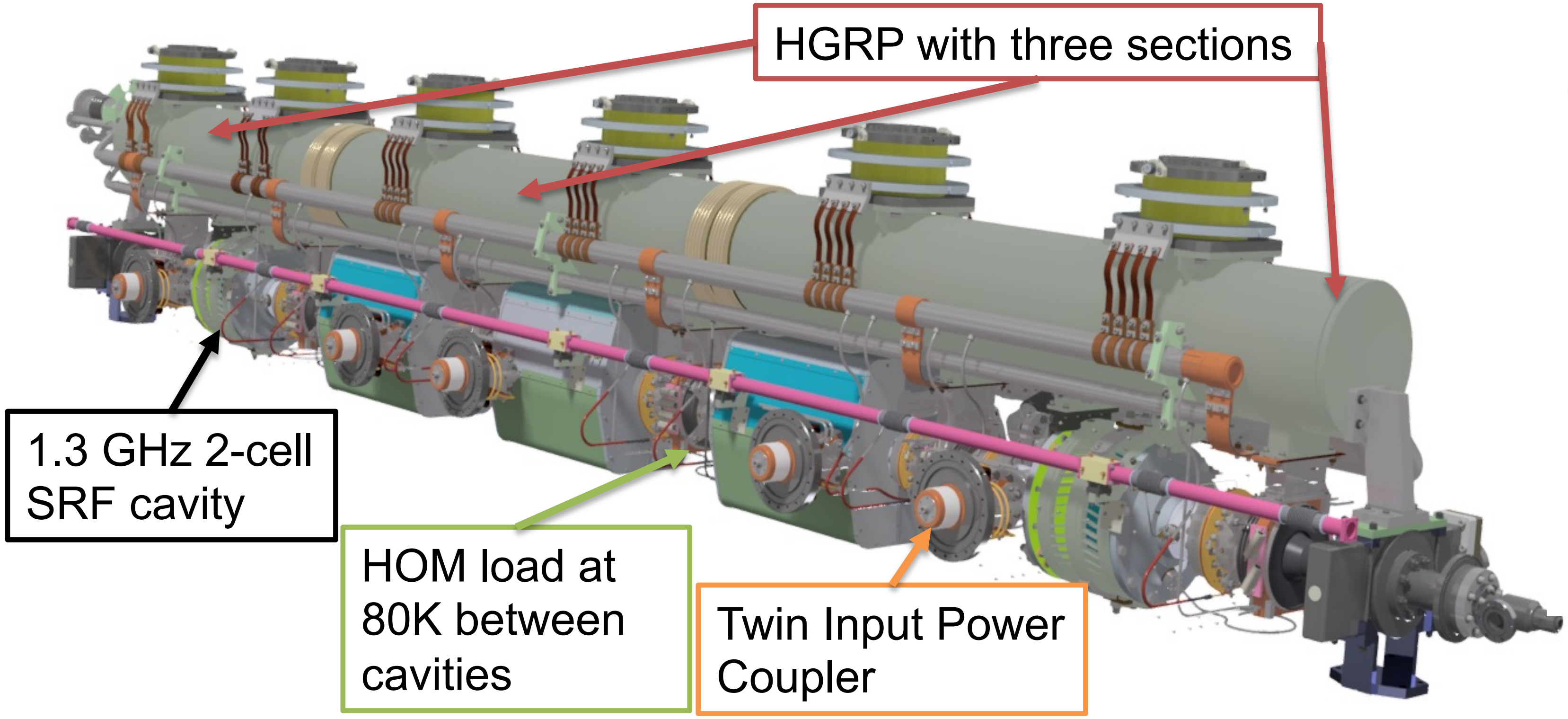
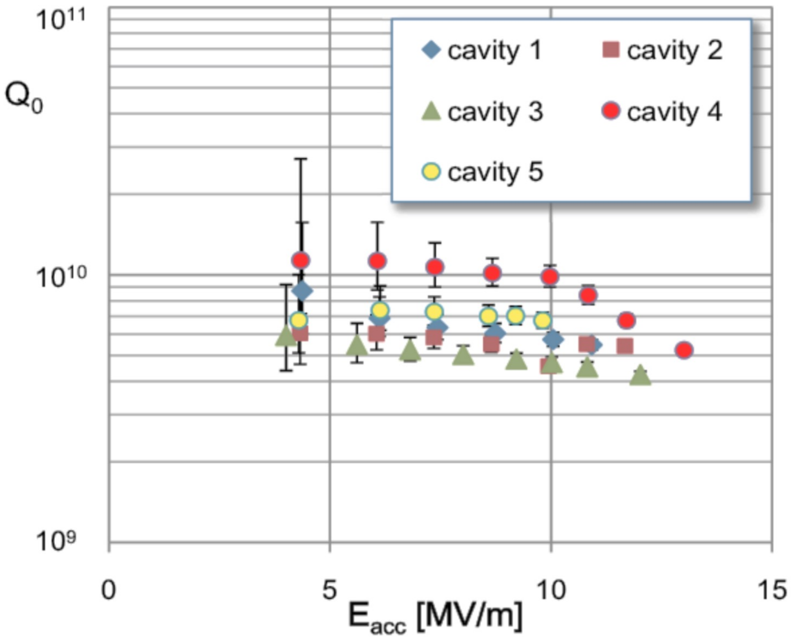
BROOKHAVEN NATIONAL LABORATORY

NSF

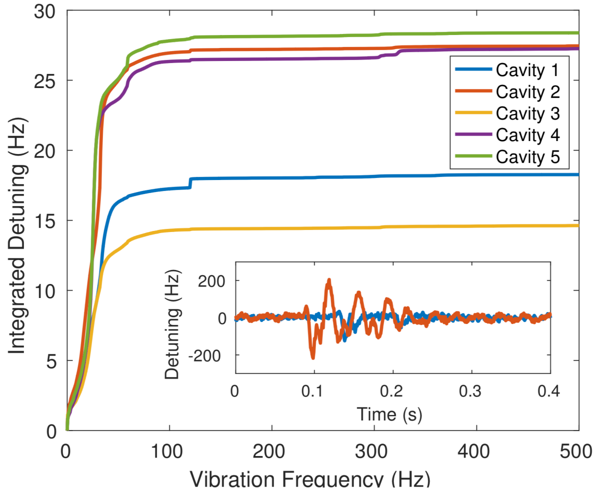
Thank you!

Appendix 1: Injector Cryomodule





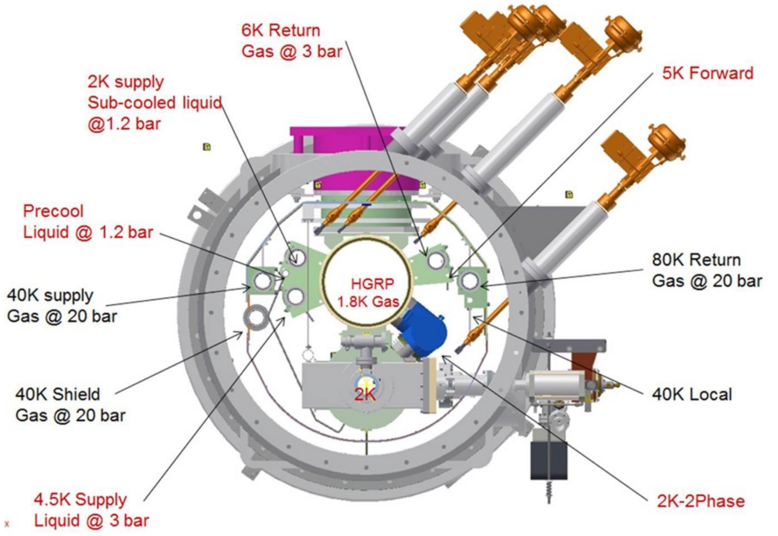
Number of 2-cell cavities	5 (Only 4 operated for CBETA)	Number of HOM loads	6
Energy gain per cavity	1 – 3 MeV	HOM Power per cavity	40 W
Gradient	4.3 – 13.0 MV/m	Couplers per cavity	2
R/Q (Linac definition)	222 Ω	RF power per cavity	120 kW
Q_{ext}	4.6×10^4 – 4.1×10^5	Amplitude/phase stability	$10^{-4}/0.1^{o}$ (rms, measured)
Total 2K / 5K/ 80K loads	30 W / 60 W / 700 W	Module Length	5 m



Appendix 2: MLC Cryogenic System

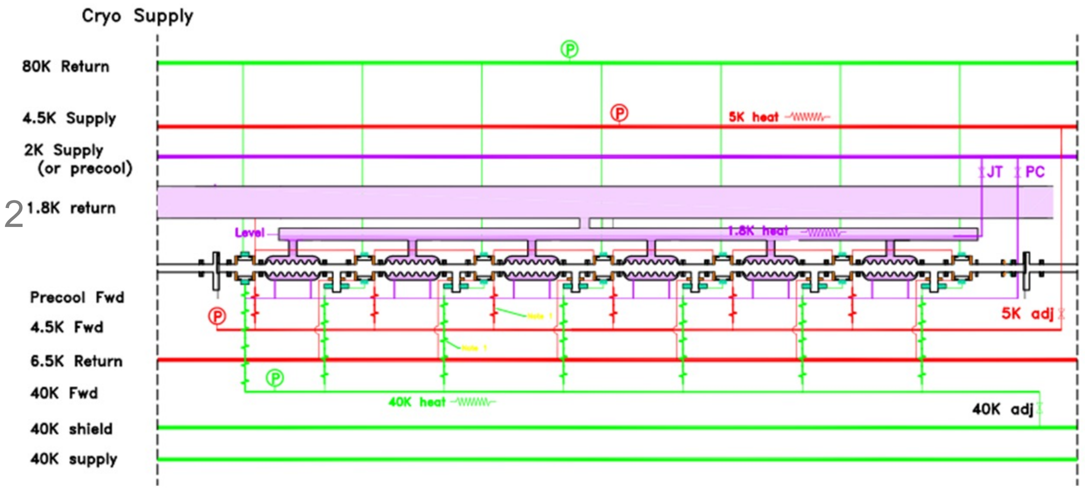
Three subsystems:

1. 40 K / 80 K
   Thermal shield, input couplers, HOM loads.
2. 4.5 K/ 6.5 K
   Input couplers, beam pipe.
3. 2 K/ 1.8 K
   Cavities.



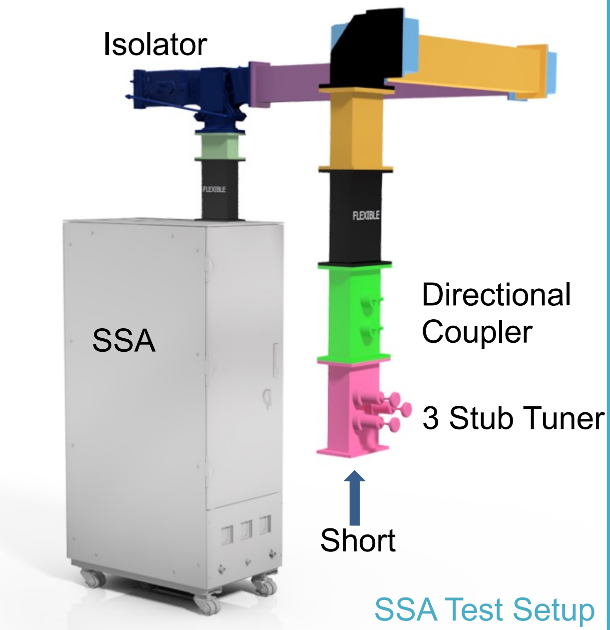
2 K liquid Helium system controlled by:

1. Pneumatic Joule-Thomson (JT) and precool valve.
   Controls amount of LHe entering the 2 K 2 phase pipe.
2. 2 K 2 Phase heater
   Adds heat load if necessary.
3. Pump Skid
   Controls vapor pressure in 2 K 2 phase pipe supplying to the Helium vessels thus controlling bath temperature.

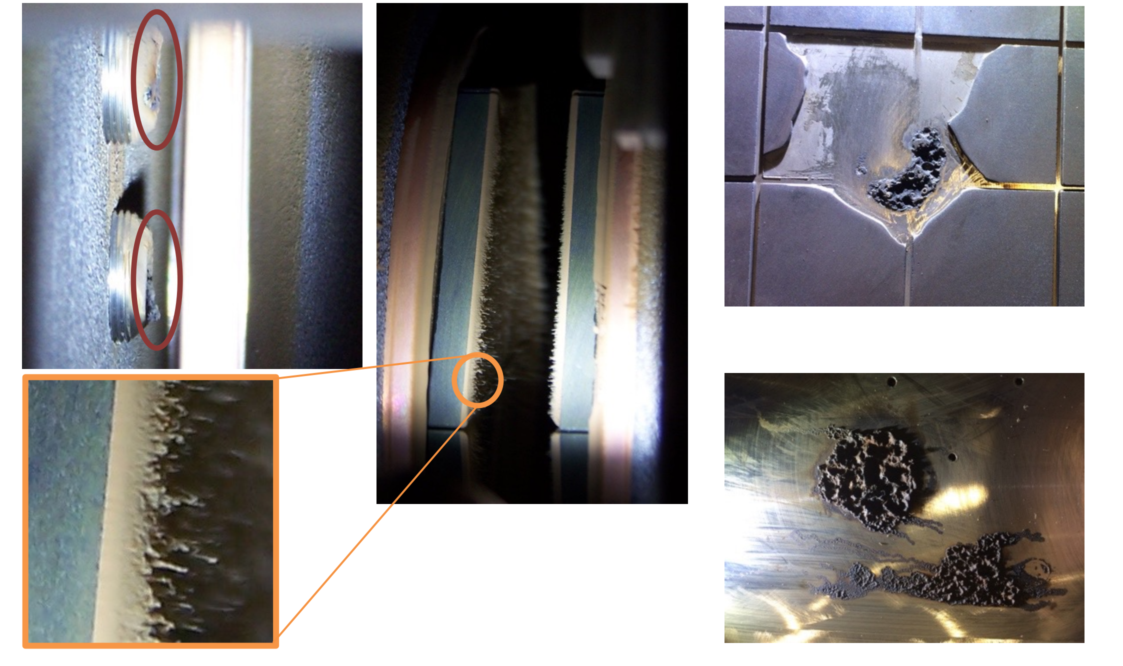


Appendix 3: MLC High Power RF

We tested each of our RF sources separately to verify operation at full power.



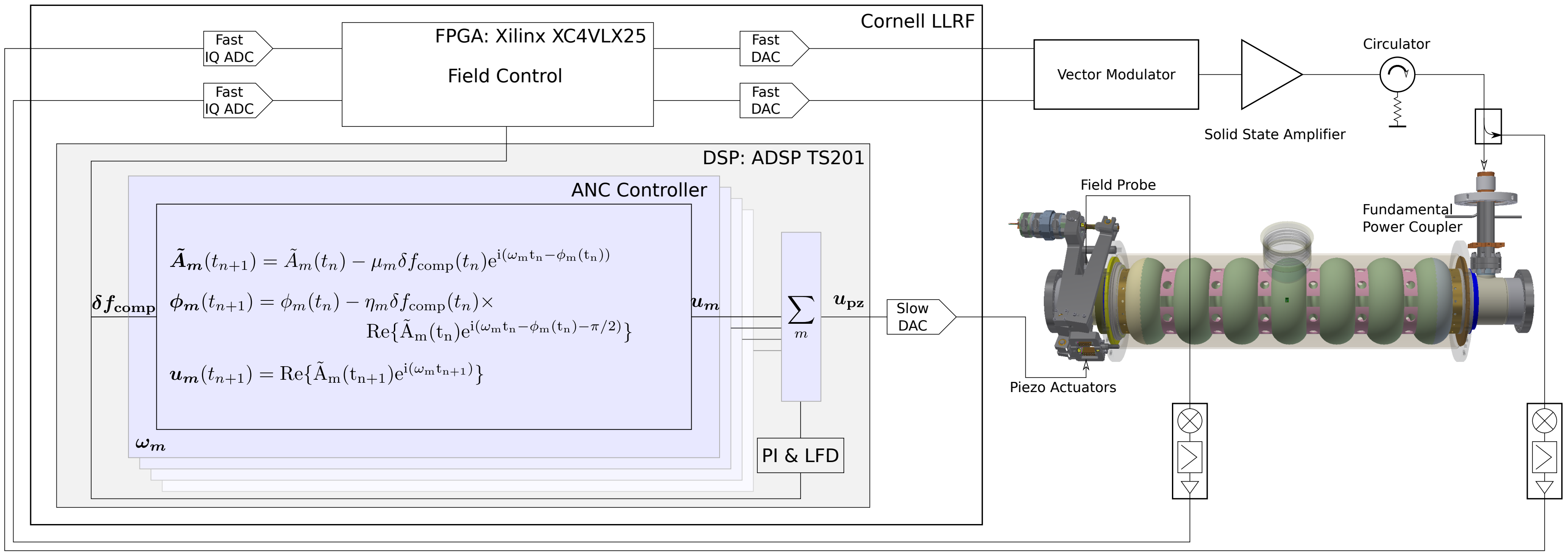
SSA Test Setup



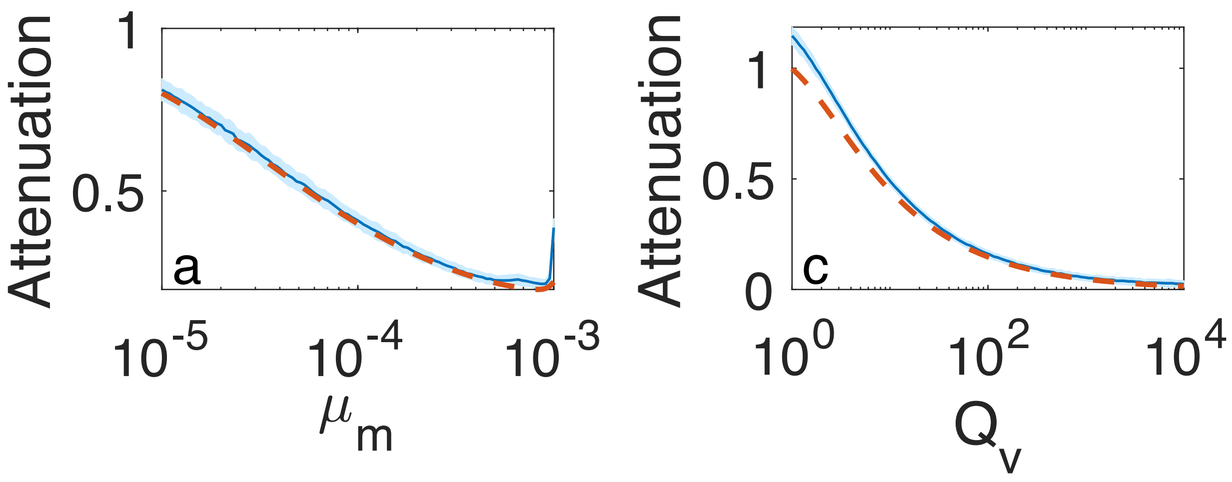
Isolators suffered catastrophic failure due to manufacturing error. Later all isolators were repaired.

Cavity #	1	2	3	4	5	6
Max P_f (kW)	10	5	10	5	10	5
Max P_r (W)	130	18	118	75	13	3.5

Appendix 4: ANC Details



Theoretical performance depends on gain and bandwidth of vibration lines.



Appendix 5: Transient Beam Loading Details

Emergence of reactive beam loading:

- Loss factor is smaller at injection energies.
- Slight difference in phasing of the beam the injected beam in the first cavity to obtain zero average real beam loading.
- Difference in phasing creates reactive beam loading