MICROPHONICS IN THE ATLAS UPGRADE CRYOMODULE

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Abstract

Microphonics measurements have been performed on the recently commissioned ATLAS upgrade cryomodule which holds seven new β=0.145 quarter-wave cavities operating at 109 MHz. Tests have been performed at the full operational fields with an average gradient E_{ACC}=8.3 MV/m and V_{ACC}=2.1 MV/cavity, a record for cavities in this range of beta. In the commissioning run of the cryomodule with cavities at full gradient, RMS frequency jitter ranged from 1-2 Hz RMS. With a VCX fast tuner on each cavity configured for a tuning window of 40 Hz there is no "out-of-lock" due to microphonics. Measurements were performed with the cryostat attached to the ATLAS 4.5 Kelvin liquid helium refrigeration system. The quarter-wave cavities themselves are equipped with a passive mechanical vibration damper so that low-lying intrinsic mechanical modes which couple to the cavity RF fields contribute little to the total microphonics. Rather, at useful accelerating fields most of the modest frequency jitter is due to relatively low frequency pressure oscillations in the helium bath due to pool boiling. Future plans for fast tuning on the next ATLAS upgrade cryomodule are discussed.

INTRODUCTION

The narrow frequency bandwidth, ~1 Hz or less, of superconducting (SC) cavities is simultaneously a virtue and a challenge for the operation of a large phased array of superconducting cavities. The narrow bandwidth, a direct result of the very low rf losses achievable with SC technology, also typically implies a sophisticated tuning system in order to precisely control the resonator frequency and phase. For today's SC cavities this tuning is carried out at several levels of increasing precision. Today the initial determination of the cavity frequency can be modeled using full 3-D electromagnetic simulations of the cavity rf volume with a relative accuracy that is approximately 1% [1]. The frequency stability of the cavity with respect to environmental perturbations is also considered during the design. Details are application dependent (*e.g.* cw vs. pulsed, high-current vs. low-current) Precise machining and 'one-shot' mechanical squeezing are then performed to bring the cavity within the range of the active tuning system [2]. Here, final one-shot tuning represents a tuning accuracy of one part in 10^4-10^5. Finally, a robust dynamic tuning system with conservatively chosen parameters is used to control the cavity frequency and phase during operations. We discuss a system for the ATLAS upgrade cryomodule and its operation in the ATLAS accelerator tunnel.

Figure 1: Complete ATLAS upgrade 7-cavity string.

CAVITY/MODULE DESIGN

In order to ensure that the probability of out-of-lock is sufficiently small [3], (1) the cavities have been designed to reduce the frequency response to vibrations and/or helium pressure changes and (2) a tuning system that is both sensitive to small cavity eigenfrequency deviations and has sufficient range to accommodate the largest anticipated frequency excursions has been built. The result is good cavity frequency and phase stability, as shown for example in Figure 2. Essentially no out-of-lock due to microphonics has been observed during the first several weeks of operations in ATLAS. However, the cavities field performance, quench limited as high as E_{ACC}=15 MV/m (3.75 MV/cavity) in the module, now exceeds the

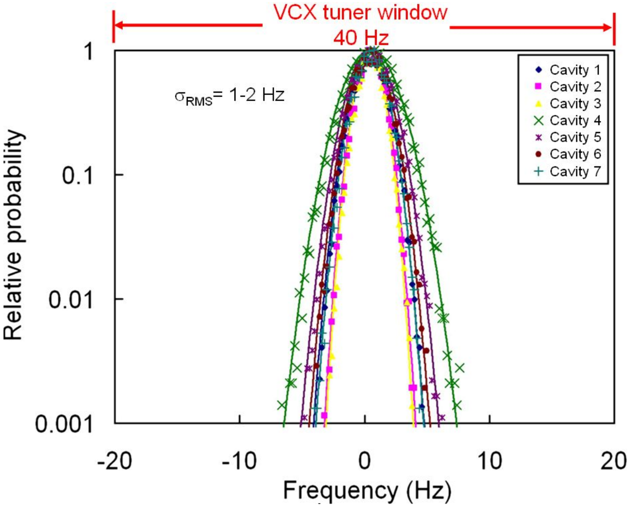
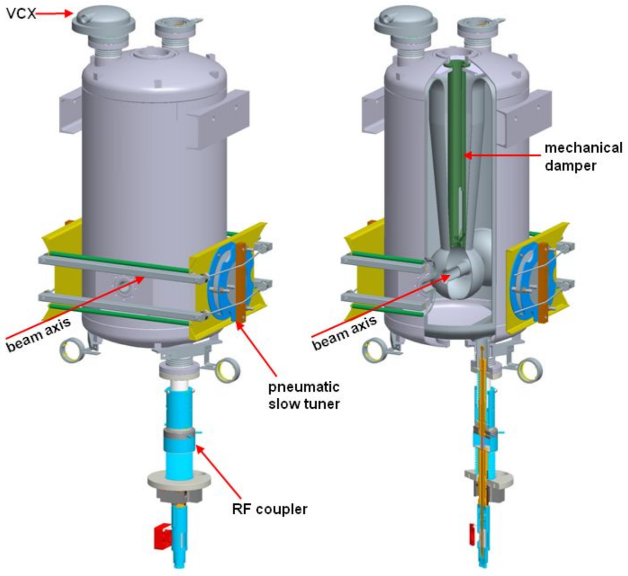


Figure 2: Microphonics probability distribution with seven cavities at full gradient in the ATLAS tunnel.



Outside View **Same cavity - Sectioned View**

Figure 3: Quarter- wave cavities with coupler and tuner

power handling capability of the VCX (voltage-controlled-reactance) fast tuner and restricts operational field levels to an average of E_{ACC}=8.3 MV/m (2.1 MV/cavity).

Cavities

The seven upgrade cavities (1 prototype + 6 production) were all fabricated from 3 mm RRR~250 niobium sheet die hydroformed by Advanced Energy Systems Inc. In order to perform the initial coarse tuning of the cavity frequency, the three subassemblies were clamped together and the frequency was measured. The cavity housing and center conductor were trimmed iteratively using an initial course and then a final fine wire EDM cut. See Ref. [2,4] for additional details on the fabrication and tuning techniques. The completed niobium sub-assemblies were electron beam welded at Sciaky Inc. and housed in an integral stainless steel helium vessel [5].

A passive mechanical vibration damper based on the design developed at Legnaro [6] is installed in each quarter-wave loading element as shown in Figure 3. A substantial reduction in vibrations was verified in room temperature measurements as shown in Figure 4. The decay time for mechanical vibrations including the 'pendulum mode' at just over 50 Hz, is reduced by ~4X. Additional optimization could likely be achieved with more development.

The mechanical design with mostly cylindrical cross sections along the length of the cavity is intrinsically stable with respect to pressure fluctuations. Additional mechanical ribs near the intersection of the center conductor and the cavity housing are bridged by a titanium plate and further reduce pressure sensitivity and increase stiffness. The four cavities for which $\Delta f/\Delta p$ was measured have values in the range of -12 to +5 Hz/torr.

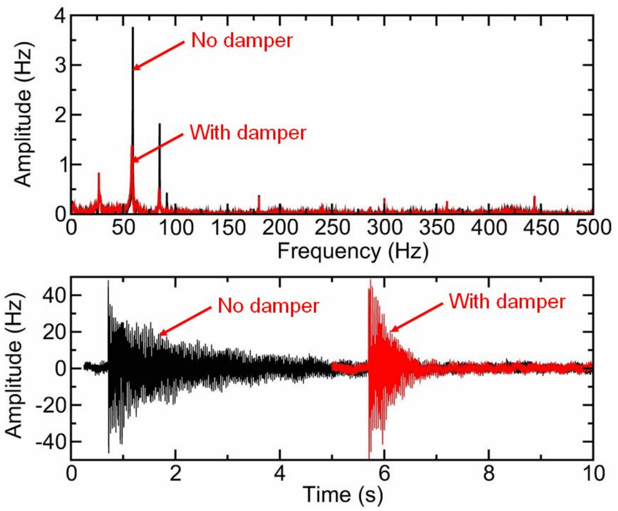


Figure 4: Room temperature cavity vibration data in a 'hammer test' with and without a passive mechanical damper.

Cryomodule

The cavity string is supported on a pair of aluminum beams 4.5 meters long by 0.3 meters high by 0.05 meters thick. The beams are in turn suspending from the lid of the cryostat by four vertical invar beams and an additional two diagonal invar members to prevent swinging. Two of the vertical members and the two diagonal members are visible in Figure 1. The only rigid mechanical connection from the outside of the cryomodule directly to the cavities is through the power coupler.

Couplers and Tuners

Three variations on the ANL rf power coupler are installed on the upgrade cryomodule cavities. Two use an inductive 'magnetic loop' probe and differ only in the loop area. The third is a capacitive probe adapted from the inductive design by removing both the loop and a section of the outer conductor and then welding a 1.3 cm copper sphere to the end of the center conductor. Each probe has a single warm vacuum window, is ~60 cm long and variable over 70 mm or about 50 dB in coupling strength. The coupler penetrates up through the bottom of the cryostat with a room temperature worm gear motor drive located just below the under side of the cryomodule. The coupler is the only rigid linkage going directly from the outside of the cryomodule to the cavities. In room temperature tests where the coupler was not necessarily rigidly fixed it was observed that coupler vibrations could couple to the cavity rf frequency. In operations, with the coupler well constrained at the bottom of the module, coupler vibrations do not seem to contribute measurably to cavity frequency shifts.

Compensation of slow time varying frequency shifts (~1 Hz or slower) is done by deforming the cavities along the beam axis using a pneumatically operated stainless steel bellows (see Figure 3). The bellows are pressurized using helium gas at 77 K and a maximum pressure of 0.6 bar. The 30 kHz tuning range corresponds to a 2.5 cm bellows stroke and a 4 mm cavity length change along the beam axis.

Fast tuning is performed using a voltage controlled reactance (VCX) fast tuner to rapidly modulate the cavity frequency between two different states such that the time average cavity frequency matches the master oscillator. The tuning window is set during assembly by choice of the length of the VCX inductive loop projecting into a port on top of the cavity. The 40 Hz window for the upgrade cryomodule cavities is more than sufficient to compensate for the 1-2 Hz RMS frequency jitter observed during operations.

Though the VCX tuner system is highly reliable, it does have a drawback when used with today's high-gradient (high stored energy) cavities. Namely, the power handling is limited due to losses and heating in the PIN diodes as they are cycled on and off. Practically, this limits cavity operation to E_{ACC}=8-9 MV/m. Additional modest changes underway to the PIN diode driver circuit will extend this range somewhat, however, the next upgrade of ATLAS, including another cavity cryomodule, will replace the VCX with a fast mechanical tuner.

ONLINE MEASUREMENTS

Since the commissioning of the upgrade module online measurements of the tuning system and microphonics have been performed both to optimize current operations and as input for the next ATLAS upgrade cryomodule [7].

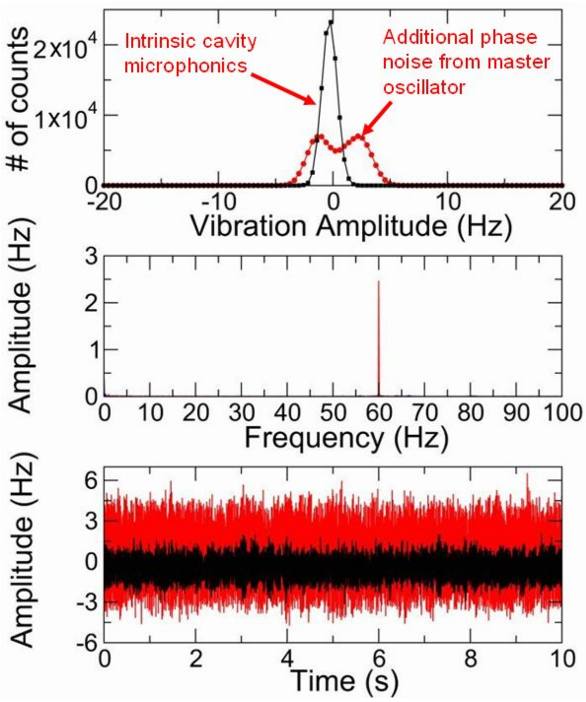


Figure 5: Frequency jitter with cavity locked to a low noise generator (black) and when locked to the ATLAS master oscillator (MO) (red). A low noise MO for ATLAS is planned.

Master Oscillator

In ATLAS each of the 68 SC cavities is phase locked to a harmonic of the 12 MHz master rf oscillator. Figure 5 shows the error signal for one of the seven ATLAS upgrade quarter-wave cavities when locked to the ATLAS master rf oscillator (red) and when locked to a low noise external signal generator (black). In the former case more than half of the frequency jitter is due to 60 Hz frequency modulation (i.e. not real microphonics) superimposed on the 109 MHz master oscillator signal. This additional frequency jitter was unimportant for split-ring cryomodules where overall jitter and fast tuning windows (~150 Hz) are large, but it is substantial here. A low phase noise master oscillator upgrade is planned for ATLAS.

Cavity-to-cavity Correlations

It has been proposed that it may be possible to reduce overall cavity microphonics in some general way if cavity microphonics where strongly correlated. Figure 6 shows Fourier amplitudes and phases of the frequency error signal for two adjacent cavities in the ATLAS upgrade cryomodule. The peak near 30 Hz appears to be phase and amplitude correlated; however, the remainder of both spectra are mostly uncorrelated. This indicates that the microphonics here are not driven by 'global' pressure fluctuations in the ATLAS refrigeration system, but by local changes specific to the individual cavities.

Pressure Sensitivity

As discussed, the quarter-wave geometry is fairly rigid with respect to pressure changes ($|\Delta f/\Delta p|$<12 Hz/torr), however it is known that thermal acoustic oscillations or He refrigerator changes can drive pressure changes of many torr. Therefore, an attempt was made to correlate pressure fluctuations in the cryomodule liquid helium bath to eigenfrequency excursions of the cavities. Fourier amplitudes and phases for a cavity phase error signal are compared with data collected at the same time using a pressure transducer mounted on cryomodule helium

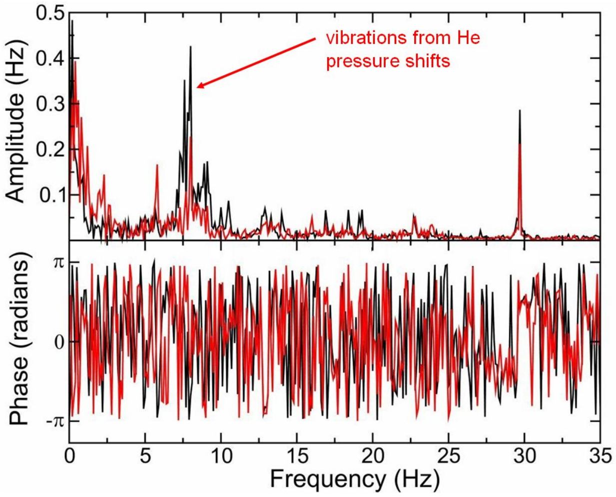


Figure 6: Cavity frequency jitter measured simultaneously in two adjacent cavities.

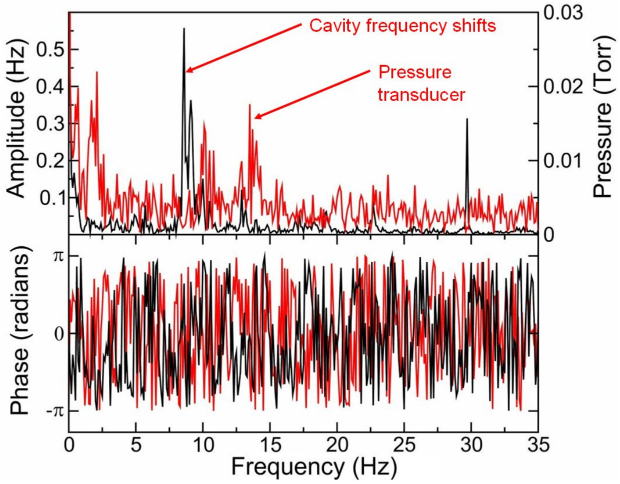


Figure 7: Fourier amplitudes and phases for a cavity phase error signal (black) and a pressure transducer (black) on the cryomodule helium tank.

system (see Fig. 2). Data are shown in Figure 7. Unlike earlier observations in the single cavity test cryostat, no clear correlations between cavity microphonics and the helium pressure in the cryomodule main storage manifold were observed.

FUTURE PLANS

A further upgrade of the ATLAS SC linac including another new cryomodule with cavities at β=0.075 is well underway. Additional improvements to the EM design such as an expanded volume in the high B-field region with lower surface fields and also final electropolishing on the *finished* niobium cavity (as for e-cell cavities) makes a goal of 3 MV/cavity plausible even at this low beta [7]. Stored energies in this case would be ~40 Joule or more requiring substantial extension of the VCX technology developed more than 30 years ago. Rather, we have decided that the next upgrade will include a combination of overcoupling using the rf power coupler and a fast mechanical tuner, likely based on a piezoelectric actuator. Development of these subsystems is also underway.

CONCLUSION

An ATLAS upgrade cryomodule housing seven 109 MHz SC quarter-wave cavities has been commissioned. The tuning system, based on a pneumatically operated bellows and a VCX fast tuner is both sensitive to small cavity eigenfrequency deviations and has sufficient range to accommodate the largest observed frequency excursions. Microphonics levels with cavities running at the full operational fields (E_{ACC}=8.3 MV/m and V_{ACC}=2.1 MV/cavity) are 1-2 Hz RMS and well within the VCX fast tuner window of 40 Hz. During the first weeks of operations there has been no “out-of-lock” due to microphonics.

ACKNOWLEDGEMENTS

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