MEASUREMENT AND CONTROL OF MICROPHONICS IN HIGH LOADED-Q SUPERCONDUCTING RF CAVITIES*

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INTRODUCTION

Superconducting radio frequency (SRF) linacs with light beam loading, such as the Rare Isotope Accelerator (RIA), S-DALINAC, CEBAF upgrade, and energy recovery linacs, operate more efficiently with loaded-Q, Q_L, values greater than 10^7. The resulting narrow bandwidth puts stringent limits on acceptable levels of vibration, also called microphonics, which detune the SRF cavities and require additional rf power to maintain amplitude and phase.

RIA will use six-cell 805 MHz elliptical cavities for acceleration of uranium from 88 MeV/u to 400 MeV/u (β=v/c=0.41 to 0.72) with a final beam power of 400 kW [1]. To cover this velocity range, three geometric β, β_g, values of 0.47, 0.61 and 0.81 are used [2,3]. A multi-charge state uranium beam with three charge states centered on $^{238}U^{89+}$ and a total beam current, I_{beam}, of 0.37 mA are accelerated in the elliptical cavity section of RIA.

A prototype RIA 805 MHz β_g=0.47 cryomodule has been tested in realistic operating conditions [4]. For Q_L~10^7 operation of RIA, rf power requirements are determined, and measurement and control of microphonics have been demonstrated.

BEAM LOADING & RF REQUIREMENTS

Superconducting cavities require very little rf power to generate the accelerating gradient, and therefore, have intrinsic quality factors, Q_o, greater than 10^8. Additional rf power is required for beam acceleration and control of microphonics. If the beam current is high, beam loading is large enough so that the system bandwidth is much larger than any microphonics detuning. Under these circumstances, the rf generator power (P_g) equals the beam power (P_{beam}). But, if the cavity resonant frequency is shifted, then additional rf power is required to maintain amplitude and phase. The required P_g for a given beam loading, coupler strength ($Q_{ext}\cong Q_L$), and maximum detuning ($\pm\delta f$) is given by [5]

$$\frac{P_g}{P_{beam}} = \frac{1}{4}\frac{Q_{beam}}{Q_L}\left[\left(1+\frac{Q_L}{Q_{beam}}\right)^2 + \left(\frac{\delta f}{\Delta_{beam}}\frac{Q_L}{Q_{beam}}\right)^2\right]$$

$$Q_{beam} = \frac{2\pi f U}{I_{beam} V_a \cos\phi_s} = Q_o \frac{P_o}{P_{beam}}$$

$$\Delta_{beam} = half\ \ beam\ bandwidth = \frac{f}{2Q_{beam}}$$

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Table 1: Beam loading requirements for 400 kW, 400 MeV/u uranium in RIA elliptical cavities

Type	6-cell	6-cell	6-cell
β_g	0.47	0.61	0.81
V_a(MV)	5.12	8.17	13.46
P_{beam}(W)	1660	2640	2600*
Q_{beam}	9.1x10^7	9.1x10^7	1.4x10^8
P_g(W)	3320	5280	5200
Q_L	3.0x10^7	3.0x10^7	4.7x10^7
$\Delta_{allowed}$(Hz)	25	25	16

*β_g=0.81 decreased from the maximum value due to transit time factor

For RIA, the rf generator requirements are chosen to be twice the maximum beam power. From the previous equation it can be shown that the maximum allowable detuning occurs when Q_L/Q_{beam}=0.33 for these conditions. The maximum allowable detuning for which amplitude and phase can be maintained is then $\delta f=2.8\Delta_{beam}$. Therefore, the microphonics can detune the cavity over a full bandwidth, $\Delta_{allowed}=2\delta f=5.6\Delta_{beam}$, and the amplitude and phase can still be maintained. The control bandwidth is slightly smaller than the Q_L bandwidth (f/Q_L) due to the generator requirements.

The design beam for the driver linac is 400 MeV/u uranium with a total power of 400 kW. For this case, the beam loading values are shown in Table 1 for a synchronous phase, ϕ_s, of -30º. The accelerating voltages, V_a, correspond to peak surface electric fields of 32.5 MV/m and accelerating gradients of 10-15 MV/m. Because the β_g=0.81 cavity does not accelerate uranium at the peak of its transit time curve, the maximum beam power is nearly the same as the maximum value for the β_g=0.61 cavity. The allowable detuning for RIA, assuming a generator power that is twice the beam power, is also shown in Table 1. Due to transit time effects, most of the cavities do not supply the maximum power to the beam. Therefore, most of the cavities will be able to handle significantly higher detuning than shown here. The measured microphonics with and without passive and active damping on the prototype RIA cryomodule show that the values in Table 1 are adequate for RIA.

Operation of SRF cavities with Q_L=3x10^7 is done at the S-DALINAC in Darmstadt [6], and a Q_L in the low 10^7 range is proposed for the CEBAF upgrade [7]. Energy recovery linacs would benefit from Q_L in the 10^8 range. Therefore, the design bandwidth values proposed here for RIA are consistent with the goals of other projects and will be able to capitalize on the advances made for other accelerators.

Finally, Lorentz detuning which is a shift in the cavity frequency due to radiation pressure of the electromagnetic field must be compensated for during rf turn on. For RIA, a cw linac, this can be done slowly using the tuner and will not be a critical issue.

METHODS OF MITIGATION

Vibrations and pressure fluctuations cause the cavity frequency to shift (detune) only if the forces distort the cavity walls. Typical sources of vibration are rotating machinery, fluid fluctuations, and ground motion. Motors will generate discrete vibration frequencies at harmonics of their revolution rate. Fluid fluctuations such as boiling, cavitation, and turbulent flow, and ground motion will generate a broadband vibration spectrum.

There are many techniques to reduce microphonics or otherwise mitigate their effect on an SRF cavity. The mechanical frequencies of concern are usually low (less than 200 Hz). A proper cavity and cryomodule design can significantly reduce the microphonics problem. The cavity can be made more rigid with thicker material and gussets to reduce distortions, but the tuner will become more complicated and heat transfer from the rf surface to the helium bath may be degraded. Structural resonances should be eliminated or shifted to higher frequency. As an example, the lowest frequency transverse mechanical mode of the 805 MHz cavities was removed with a support at the center of the six-cell structure. Designing the cavity and helium vessel so that distortions in regions of high electric field are canceled by distortions in high magnetic field regions can reduce the frequency shift due to pressure fluctuations in the helium bath. Passive mechanical dampers can be integrated into the cavity as has become standard for quarter-wave resonators [8].

The choice of operating temperature can have a large influence on microphonics excitation. Operation at 4 K results in helium at atmospheric pressure with fluctuations from the plant and pool boiling heat transfer with its concomitant broadband vibration. Operation at 2 K has sub-atmospheric liquid helium with lower disturbances from the cryoplant, and heat transfer via conduction is enhanced due to the unique properties of superfluid.

Another system design issue is cw versus pulsed operation. Pulsed operation must deal with the transient Lorentz force detuning, which is likely to dominate all other microphonic sources.

Sources of vibration should be eliminated when possible or isolated from the cryomodule. Vibrations will be transmitted through the ground, pipes and fluids. Passive and active absorbers can reduce the amplitude before the vibrations reach the cryomodule and cavity. Examples from other disciplines are optical benches, telescopes, automobile suspension systems, and sound cancellation [9]. Vibrations that reach the cryomodule can be actively and passively damped before that motion affects the cavity.

Even with the damping and isolation techniques listed above, there will likely still be some cavity vibration. There are several methods available to compensate the microphonics. A fast mechanical tuner can distort the cavity shape and cancel the frequency shift induced by the microphonics. Another way to apply a force on the cavity is to vary the accelerating gradient by a small but acceptable amount and use the Lorentz force [10]. The cavity frequency can also be shifted using a tunable reactive element that is coupled through the input power coupler or a dedicated fast tuner coupler [11,12].

Finally, small changes in the synchronous phase can accommodate the microphonics by allowing the rf drive frequency to remain on resonance, as is done with the VCX tuner [12], with an additional correction to the voltage amplitude given the known phase error.

MEASUREMENTS

The prototype RIA 805 MHz β_g=0.47 cryomodule has two multi-cell cavities with fixed input power couplers and external tuners actuated by a room temperature piezoelectric actuator [4]. The cavities are cooled by 2 K superfluid with cryoplant temperature regulation. The coupler strength, Q_{ext}, is varied from $6x10^4$ to $6x10^9$ using an external transmission line transformer. Figure 1 shows a cross section of the cavity with tuner and coupler.

Real-time frequency detuning measurements were made for modulation rates from dc to greater than 1 kHz. Figure 2 shows the microphonics measurement technique. A stable signal generator in open loop mode is used to drive the rf cavity, and a pickup from the cavity is mixed with the input to generate an error signal that is proportional to the cavity detuning. Since Q_L is adjustable, the system bandwidth is set so the peak detuning is within the system bandwidth and generates linear error signals. This technique gives real-time error signals that can be analyzed or used for feedback/feedforward. Other methods give similar results, but require a longer acquisition time, more stable signal generator, and cannot be used for feedback [13].

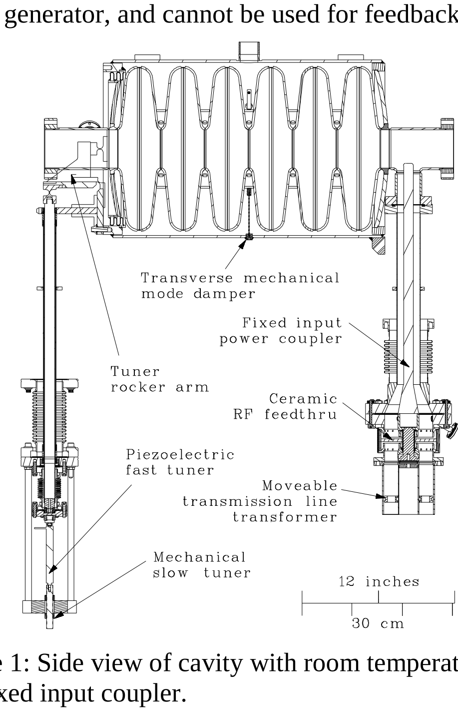

Figure 1: Side view of cavity with room temperature tuner and fixed input coupler.

At 2 K low power measurements were made with the liquid helium partially filling the distribution pipe as would be done for operation. The maximum frequency deviation using the calibrated error signal was less than 40 Hz peak-to-peak (see figure 2). The error signal was calibrated using a known frequency shift from the signal generator. The measured modulation spectrum was primarily comprised of discrete Fourier components with modulation frequencies less than 80 Hz. The main components were at 59.5 and 59.7 Hz. They could be clearly distinguished from 60 Hz electronic pickup, which was negligible in these measurements. Additional components near 54 Hz, which is the lowest frequency natural mode of the cavity, were measured and likely due to other nearby motors. Using an accelerometer, the primary sources of vibration were identified to be the two cryoplant screw compressors (rated for 1500 hp/3560 rpm and 250 hp/3550 rpm). The cryoplant was designed to cool superconducting magnets so vibration was not a consideration, and no isolation from the floor or the piping was implemented. The motors are about 20 m from the cryomodule test area. For RIA the cryoplant motors will be farther away and better isolated.

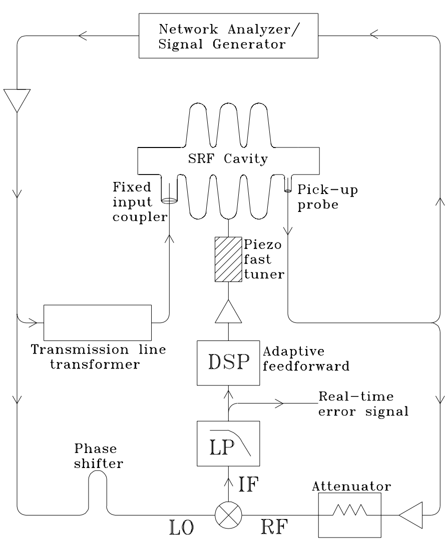

Figure 2: Microphonics measurement and control technique.

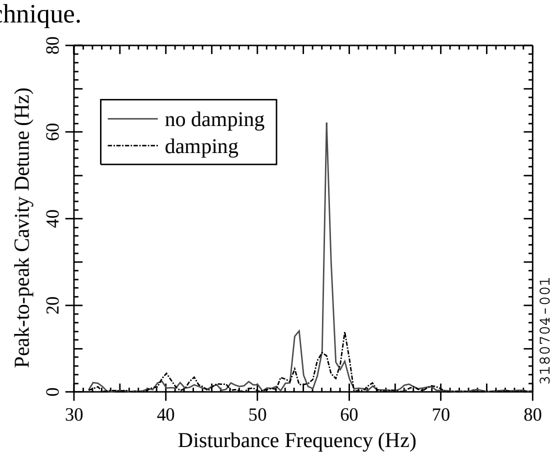

Figure 3: Fourier components of cavity detuning with and without active damping.

Since the detuning spectrum is made up primarily of discrete sinusoidal disturbances, an adaptive feedforward scheme was used to damp individual Fourier components [14]. The dominant microphonics signal was determined to consist of two closely spaced sinusoidal disturbances whose damping would be more problematic then a single peak, so for demonstration purposes a small motor with a Fourier component at about 57 Hz was placed on the cryomodule to generate a known sinusoidal disturbance. Figure 3 shows the Fourier components before and after active compensation and shows about a factor of seven damping of the 57 Hz component. The measured microphonics are near required levels for RIA without active damping, and can be brought below them using the adaptive feedforward cancellation.

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