Revision History:

Revision	Date Released	Description of Change
R0	7/23/2014	Original release.

Abstract:

This note addresses the optimal setting of Q_L ($\approx Q_{ext}$) for the main linac L-band superconducting accelerator cavities. We discuss the impact on this choice of the peak excursions from the nominal resonance frequency caused by physical cavity perturbations, through which the LLRF system must maintain the accelerating gradient. Experimental data is surveyed to justify a goal amplitude for such microphonics. Nominal values based on the current linac design are tabulated, along with required RF power at different beam currents.

Introduction:

The LCLS-II superconducting cavities have an intrinsic quality factor on the order of $Q_0 \sim 10^{10}$. For power to be effectively transferred through them to the beam, the fundamental power couplers must couple to the cavity fields on a level that swamps the residual wall loss by orders of magnitude. Thus the loaded Q reflecting the total systems power losses both internal and external to the cavity (Q_L) and the external Q reflecting the power losses external to the cavity (Q_{ext}) can be treated as roughly interchangeable. For optimal, or matched, power transfer, a particular value of Q_L is called for which, particularly for the lower end of our beam current range, is still quite high. The resulting narrowness of the resonance makes it difficult to keep the cavities on tune at the fixed operation frequency and maintain accelerating gradient experienced by the beam.

A squeezing mechanism, the cavity tuner, is used as the primary means of accurately setting the resonant frequency of each cavity. External affects such as ground movements, pressure fluctuations in the liquid helium bath and microphonics – vibrations originating in various systems which find their way at some level to the cavities – disturb the cavities such that their resonant frequencies oscillate around the set point with some spectral distribution. As the major contributions to these vibrations are measurable and not random, they can to a large extent be dynamically suppressed through the use of electro-mechanical devices called piezo tuners (utilizing the piezo-electric effect). This cancellation technique is, however, imperfect, and a certain level of time varying resonance excursions remains to be dealt with. For the state-of-the-art TESLA/ILC/XFEL technology we adopt, this is expected, as discussed below, to be at the ±10 Hz level, quite a small fraction of 1.3 GHz but not negligible at the narrow operating bandwidth.

Linac Parameters and Cavity Coupling:

The LCLS-II layout and machine design parameters are by now fairly well established. For the 280 L-band superconducting cavities in the 35 cryomodules of L_0 – L_f, we can summarize parameters relevant to the RF system as shown in Table 1. These have been evolving slightly and may change again.

Table 1. LCLS-II main linac RF parameters (current).

Fixed Parameters:	
RF frequency:	$f = 1.3\times10^9$ Hz
cavity length:	$L = 1.038$ m
cavity R/Q:	$R/Q = 1{,}036\ \Omega$
Variable Design Parameters:	
cavity gradient range:	$G = 3.4$–16.3 MV/m
$\rightarrow$ cavity voltage range:	$V_c = 3.55$–16.9 MV
beam current range:	$I_b = 0$–0.3 mA
beam phase:	$\phi_b = -21$–$34°$
Uncontrolled Parameter:	
microphonic tuning error:	$\delta f(t) = -10$–10 Hz (goal)
Controlled Parameters:	
cavity loaded quality factor:	$Q_L = 1.16$–4.26×10^7
cavity deliberate detuning:	$\Delta f_0 = -8.3$–4.5 Hz
Instantaneous cavity resonant frequency:	$f_c(t) = f + \Delta f_c(t) = f + \Delta f_0 + \delta f(t)$

Note that the variance of cavity resonant frequency from $f = 1.3$ GHz is shown to have two parts, an intentional constant detuning Δf_0 to accommodate steady-state operation with the beam riding off-crest by ϕ_b (e.g. -21° in L_2), and the time varying microphonics induced error $\delta f(t)$.

Now, the RF power required into a cavity with a given beam current to maintain the desired gradient and phase offset at steady state is given as a function of coupling and tune by (see [1], Eq. 3.46):

(1) $$P_i(Q_L,\Delta f_c) = \frac{V_c^2}{4(R/Q)Q_L}\left[\left(1+\frac{I_b}{V_c}\frac{R}{Q}Q_L\cos\phi_b\right)^2+\left(2Q_L\frac{\Delta f_c}{f}+\frac{I_b}{V_c}\frac{R}{Q}Q_L\sin\phi_b\right)^2\right]$$

The nominal cavity tunings are deliberately offset from the drive frequency by

(2) $$\Delta f_0 = -\frac{I_b}{V_c}\frac{R}{Q}\frac{f}{2}\sin\phi_b,$$

At which detuning the second term in the square parentheses vanishes. The required power is then a minimum when $Q_L = \dfrac{V_c}{I_b (R/Q)\cos\phi_b}$, yielding $P_i(Q_L) = \dfrac{V_c^2}{(R/Q)Q_L} = I_b V_c \cos\phi_b$, a perfect match into the beam.

However, since Δf_c is not fully controllable, a perfect match cannot be maintained, and the LLRF will have to modulate the RF power in reaction to the microphonics driven variations around the tuning goal value. The frequency offset (2) is still useful, as it reduces Eq. (1) to Eq. (3), symmetrizing the power requirement which would otherwise rise more steeply and reach a higher maximum for perturbations in one direction.

(3) $$P_i(Q_L, \delta f) = \frac{V_c^2}{4(R/Q)Q_L}\left[\left(1 + \frac{I_b}{V_c}\frac{R}{Q}Q_L\cos\phi_b\right)^2 + \left(2Q_L\frac{\delta f}{f}\right)^2\right]$$

To further reduce the maximum power needed over the expected tune range, minimizing Eq. (3) at the edges suggests that we should compromise the center match and set the coupling instead for

(4) $$Q_L = \left[\left(\frac{I_b}{V_c}\frac{R}{Q}\cos\phi_b\right)^2 + \left(2\frac{f_m}{f}\right)^2\right]^{-1/2},$$

where f_m is the magnitude of the largest perturbation, i.e. $|\delta f(t)| \le f_m$. In addition to slightly lowering the installed power requirement, this broadens the resonance, which helps the LLRF controls. These effects of tune offset and coupling adjustment on RF power are illustrated in Fig. 1, for which f_m = ~10 Hz is assumed.

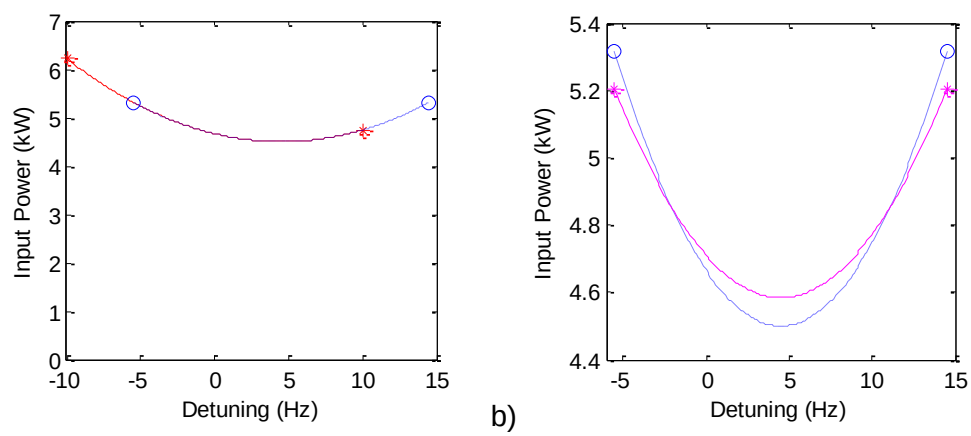

Figure 1. Input power *vs.* cavity detuning required to maintain 15.48 MV/m with 0.3 mA at -21° in an L_2 cavity over a ±10 Hz microphonics range. a) The effect of deliberately detuning the center cavity frequency is to shift from the red curve bounded by asterisks to the blue dashed curve bounded by circles. b) Peak power is further reduced by adjusting Q_L from the center-matched value (5.15×10^7) to the end-minimizing value (4.22×10^7), moving from the blue dashed curve to the magenta curve.

This assumed peak detuning of about 10 Hz appears to be a reasonable design target, as justified by the discussion below. The mean loaded quality factor for our parameters is then Q_L = ~4.12×10^7. As this is above the tuning range of the TTF-III couplers (10^6–2×10^7), LCLS-II couplers will feature a modified antenna, cut back several millimeters, as illustrated in Fig. 2. For operation at beam currents lower than the 0.3 mA upgrade limit, it is not practical for the cavity Q_Ls to be adjusted accordingly; they would become too high, making it more difficult to stay within the bandwidth and slowing the response time of the RF system. Instead, the peak current coupling values (or a uniformly set ~4.12×10^7) will be maintained, and mismatched excess input power will be reflected into the feed waveguide, to be absorbed in the isolator load. Should we have to deal with a higher value of f_m the RF power requirement would increase, with a further reduction of Q_L. f_m = 20 Hz, for example, pushes the typical Q_L down to ~2.8×10^7 and the required input power up by ~26%. If power limitations require some cavities to be run below design gradient due to excess microphonics, the beam energy feedback system will correct for the difference elsewhere.

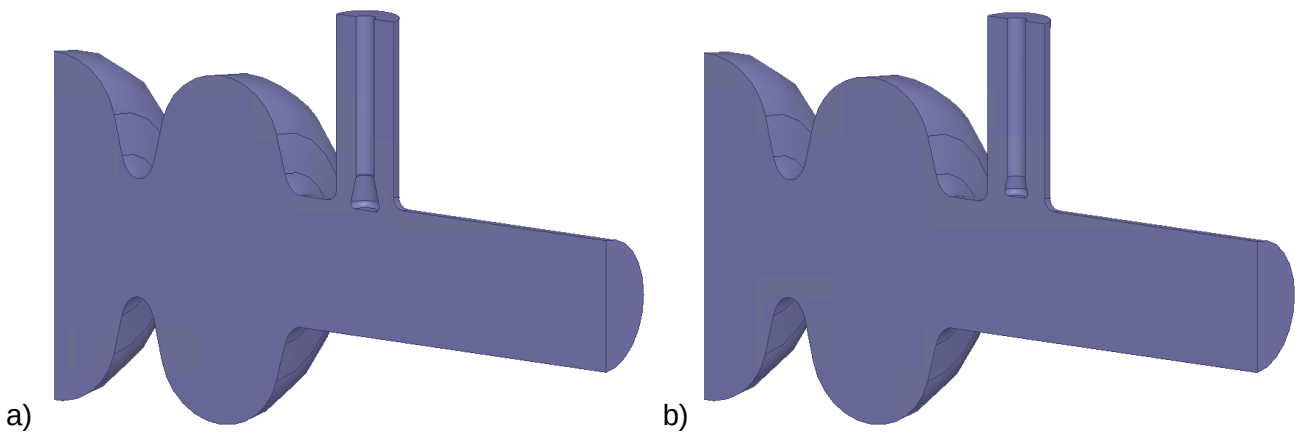

Figure 2. a) Original TTF-III fundamental power coupler coaxial antenna design and b) modified design, truncated 8.5 mm for higher Q_L range to accommodate lower beam current in LCLS-II.

Maximal Cavity Tuning Perturbations:

Mechanical vibrations of the cavity cause fluctuations $\delta f(t)$ in its resonant frequency from the fixed desired value. LCLS-II cavities will operate with much narrower bandwidths (~30 Hz, determined by the cavity loaded quality factor Q_L) than the typical values used in pulsed linacs such as FLASH (approximately 200 Hz). The narrower bandwidths make the LCLS-II cavities more susceptible to detuning than their pulsed counterparts. Microphonics levels measured at various machines are summarized in Table 2. As described in reference [2], the peak cavity detuning is estimated at 6σ. It is important to note, however, that even larger detuning has been observed occasionally. Detuning levels range between 0.6 Hz and 7 Hz RMS (4 to 40 Hz 6σ peak) and significant differences are commonly seen from cavity to cavity, even within the same cryomodule, although this phenomenon is not yet well understood. Note that this data is from systems not employing piezo tuners to suppress vibrations. Typically, the dominant part of the microphonics spectrum occurs at vibration frequencies of several tens to a few hundred hertz (see Fig. 3).

Table 2. Measured cavity microphonic frequency deviations [3].

Machine	σ [Hz]	6σ [Hz]	Comments
CEBAF	2.5 (average)	15 (average)	Significant fluctuations between cavities
ELBE	1 (average)	6 (average)	
SNS	1 to 6	6 to 36	Significant fluctuations between cavities
TJNAF FEL	0.6 to 1.3	3.6 to 7.8	Center cavities more quiet
TTF	2 to 7	12 to 42	Pulsed. Significant fluctuations between cavities

For a fixed cavity bandwidth, an additional term in the RF power required to maintain a stable cavity field increases with the square of the ratio of the peak detuning to the cavity half-bandwidth (Eq. 3). To limit the capital and operating RF costs, peak detuning levels must be kept low (approximately cavity half-bandwidth or less). The narrow bandwidths planned for the LCLS-II cavities make achieving low microphonics levels an important objective in the designs of the cavity, frequency tuner and cryomodule. In addition to designing the cryomodule for minimal microphonics, a further reduction in microphonics amplitude can be achieved with active control schemes, making use of a fast frequency (piezo) tuner. Active resonance stabilization is an area of active research in laboratories around the world, and initial studies have shown some promising results, as presented below. The success of such active, fast frequency control, however, strongly depends on the mechanical properties of the cavities and their environment, especially mechanical resonances and the local noise spectrum that may excite these. In general, feedback control bandwidths of a few hertz have been achieved; they are limited by mechanical resonances, allowing reliable compensation of slower frequency modulations and drifts. Adaptive feedforward can be used to compensate for individual, strong lines in the microphonics spectrum [4], unless several strong spectral lines are close to each other.

Extensive studies have been performed in the HoBiCaT test stand at HZB in Berlin using 9-cell 1.3 GHz TESLA style cavities operating at 2 K, with bandwidths between 20 and 40 Hz [4]. As shown in Fig. 4, in the absence of active stabilization of the resonance frequency, variations of 12 Hz peak over periods as short as 10 seconds were measured [9]. With piezo feedback, the resonant frequency of the same cavity varied by less than 2 Hz peak over an equal measurement interval. During an extended test lasting 48 hours, the HoBiCaT piezo control system was able to stabilize the resonance frequency to better than 1 Hz RMS, but peak excursions of up to 15 Hz still were observed (see Fig. 5) [4,10]. These tails are speculated to be an artefact of the experimental setup, due perhaps to the cryo system, their analog RF system, or piezo amplifier noise.

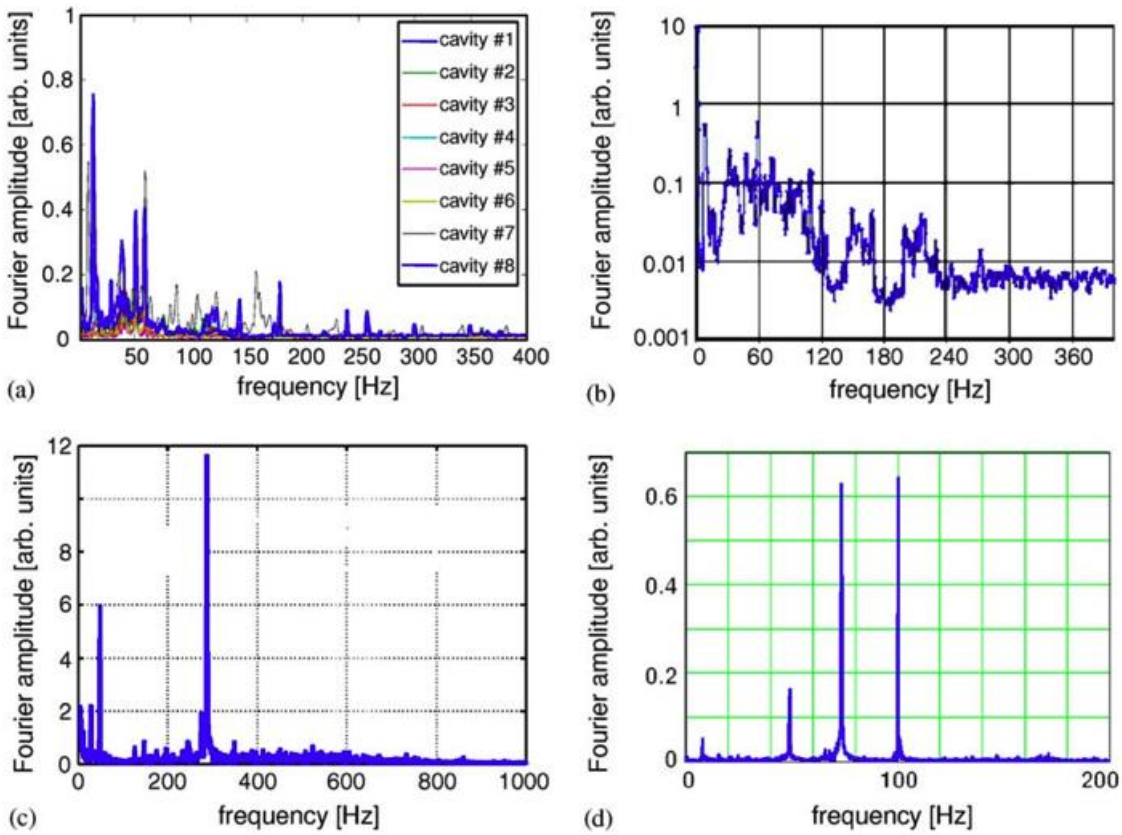

Figure 3. Examples of microphonics spectra. a) TJNAF FEL (CEBAF upgrade module) [5]; b) SNS module [6]; c) TTF test cryostat (CHECHIA) [7]; d) ELBE module [8].

While no active cavity tuning control systems currently operate in existing accelerators, the results from HZB and other laboratories suggest it is reasonable to expect that an active microphonics control system based on existing technology can be deployed to help stabilize the resonance frequency of each LCLS-II cavity. Compensating for slower frequency variations (modulation frequencies below a few hertz) and active compensation of Lorentz-force detuning has been demonstrated to work reliably at HZB, Cornell and elsewhere. Fig. 6 shows an example of active Lorentz-force detuning compensation. Also notice that the peak microphonics detuning is kept below 20 Hz. Based on the information currently available on microphonics and its compensation, a peak detuning of less than or equal to 10 Hz appears to be a realistic target for LCLS-II. Measurements on LCLS-II prototype cryomodules and additional cavity resonant frequency control studies will confirm this value. As noted above, larger cavity detuning can be accommodated with additional RF power.

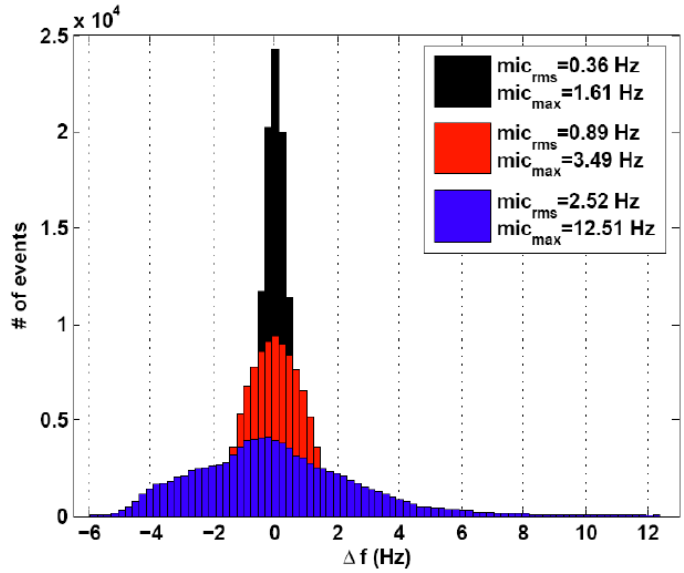

Figure 4. Microphonics distributions measured at HoBiCaT, using a combined detuning controller made up of a low-frequency proportional-integral feedback loop and an adaptive least-mean-square based FIR filter feedforward system. Detuning is measured over 100 s for open loop (blue), feedback control only (red) and the combined controller (black).

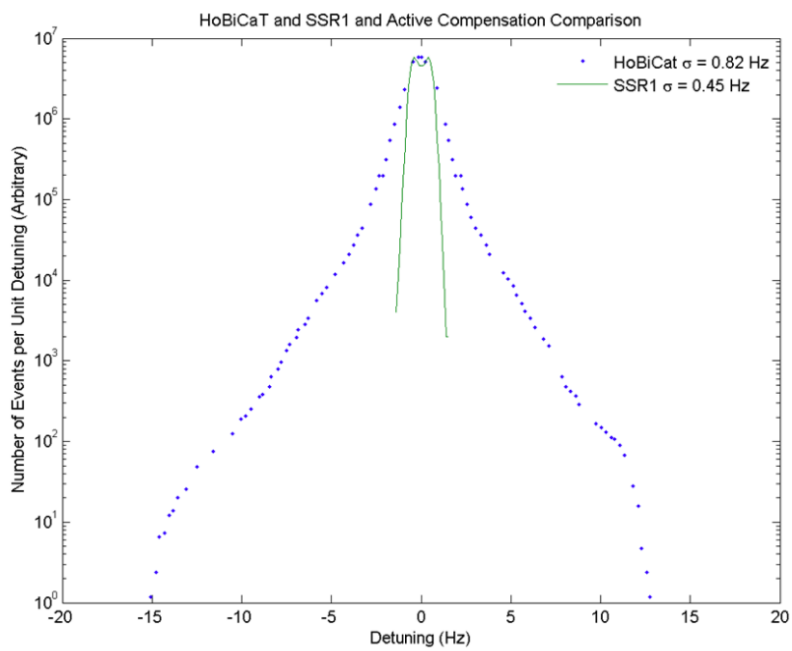

Figure 5. A comparison of the microphonics distributions measured at HoBiCaT and FNAL over a period of 48 hours. The variance of the HoBiCaT microphonics distribution was less than 1 Hz. The non-Gaussian drop-off measured out to several times this may be a result of electronics limitations.

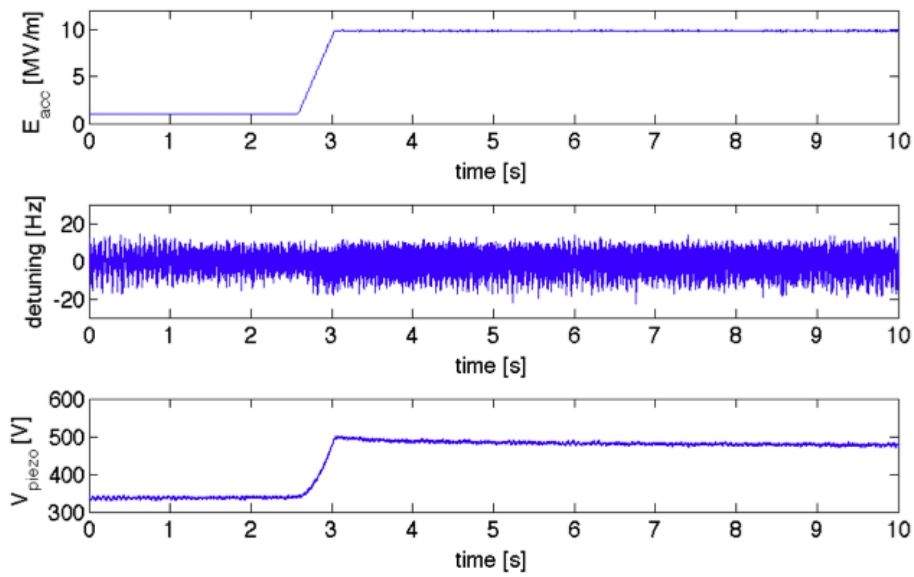

Figure 6. Example of active Lorentz-force detuning compensation by a piezo-tuner during field ramp-up of a 9-cell cavity with high loaded Q. Without compensation, the cavity would detune by more than 100 Hz (i.e., many bandwidths). The measurement was done at HoBiCaT with the Cornell LLRF control system [11, 12].

Nominal Settings:

The cavities in the five regions of the LCLS-II linac, L_0-L_3, &L_f, have different gradients and RF-to-beam phases. At the sensitive low-energy end, the L_0 cryomodule has individual parameters specified for each cavity. Table 3 lists design values for these parameters and the calculated optimal Q_L settings for 0.3 mA beam acceleration with microphonics at the 10 Hz level. Required powers at the cavity inputs are also shown for various currents. Note that with the couplings fixed, RF power does not drop as beam power. Reflected power increases with dropping current, approaching the input power levels given for no beam. At turn on, power must jump from the no beam value to the operating value. With the initial installation, I_b will be limited to 0.1 mA. RF source requirements are somewhat higher than the powers shown here, due to system losses and overhead.

Table 3. Linac region design parameters (subject to further modification), loaded quality factors and cavity input power requirements for different beam currents.

Region (cavity)	**Gradient** (MV/m)	**Phase** (degrees)	**$Q_L/10^7$** (δf_m=10Hz)	**P (kW)** (I_b=300 μA)	**P (kW)** (I_b=100 μA)	**P (kW)** (I_b=10 μA)	**P (kW)** (I_b=0)
L_{0_1}	11.40	3	3.29	3.83	1.97	1.35	1.29
L_{0_2}	3.42	-15	1.16	1.03	0.463	0.287	0.270
L_{0_3}	16.30	0	4.17	5.85	3.29	2.42	2.34
L_{0_4}	16.30	0	4.17	5.85	3.29	2.42	2.34
L_{0_5}	16.30	0	4.17	5.85	3.29	2.42	2.34
L_{0_6}	16.30	0	4.17	5.85	3.29	2.42	2.34
$L_{0_7,8}$	15.74	15	4.26	5.69	3.24	2.40	2.32
L_1	13.56	-12.7	3.78	4.59	2.47	1.76	1.69
L_2	15.48	-21	4.22	5.21	2.95	2.18	2.10
L_3	15.68	0	4.08	5.58	3.11	2.27	2.19
L_f	15.68	±34	4.08	4.86	2.93	2.25	2.19

References:

[1] Thomas Schilcher, “Vector Sum Control of Pulsed Accelerating Fields in Lorentz Force Detuned Superconducting Cavities,” doctoral thesis, Hamburg University, 1998.

[2] M.K. Kelly *et al.*, in: Proceedings of the 2003 Particle Accelerator Conference, Portland, OR, 2003.

[3] M. Liepe and J. Knobloch, “Superconducting RF for energy-recovery linacs, Nuclear Instruments and Methods in Physics Research,” A 557 (2006) 354–369.

[4] A. Neumann *et al.*, Phys. Rev. ST Accel. Beams 13, 082001 (2010).

[5] G. Davis *et al.*, "Microphonics Testing of the CEBAF Upgrade 7-Cell Cavity," PAC2001.

[6] J.R. Delayen, *et al.*, "Microphonics and Lorentz Transfer Function Measurements on the SNS Cryomodules," SRF 2003.

[7] M. Liepe, "Experience with Microphonics," ERL 2005.

[8] G. Staats, *et al.*, "Microphonics Measurements at ELBE," ERL 2007.

[9] A. Neumann, W. Anders, J. Knobloch and O. Kugeler, "Microphonics in CW TESLA cavities and their compensation with fast tuners," Proceedings of SRF2007, Peking Univ., Beijing, China.

[10] Y. Pischalnikov *et al.*, "Tests of a Tuner for a 325 MHz Spoke Resonator," PAC2011.

[11] A. Neumann *et al.*, "CW Measurements of Cornell LLRF System at HoBiCaT," SRF 2011.

[12] S. Belomestnykh, "Cornell LLRF Digital System," LLRF05.