Q MEASUREMENT OF THE COUPLED CAVITY LINAC AT LANSCE, AFTER 50 YEARS

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Abstract

This paper shows the results of measurement on the 805 MHz Couple Cavity LINAC (CCL) at the Los Alamos Neutron Science Center (LANSCE). The CCL was installed and commissioned in 1972, and it has been in operation with regular yearly operations cycles for over half a century. This test was done with a Vector Network Analyzer (VNA), the results of the measurement are presented in the form of S-parameters. The resulting S-parameters were then projected into the Smith-chart for computation of the cavity Q_0. Additionally, the Stopband is also computed from the nearest resonant modes. The results are also compared with Q measurement at the time of installation, this serves to draw an estimate of the change in the cavity performance over 50 years after installation.

INTRODUCTION

As the linac at the Los Alamos Neutron Science Center (LANSCE) facility enters its sixth decade of operation, there is a question of how the normal conducting copper accelerating structures are ageing. In 2019, the 100 MeV, 201 MHz Alverez linac at the front of LANSCE experienced cracking of the copper plating that interfered with operations [1]. This failure was repairable, but concerns of future failures led to plans to replace this portion of LANSCE with new Alverez accelerating cavities [2] powered by a reconfigured RF system [3]. The 805 `MHz Side Coupled Cavity Linac that takes the beam from 100 to 800 MeV has not yet had a problem of this magnitude, but we are now focused on evaluating the health of these accelerating structures.

SIDE COUPLED CAVITY LINAC

The LANSCE 805 MHz Side Coupled Linac was originally developed for the Los Alamos Meson Physics Facility (LAMPF) and was first side-coupled standing-wave linac ever built for protons [4]. The 805 MHz linac is comprised of 44 modules, numbered 5-48, because the first four module numbers apply to the first four 201 MHz Alvarez cavities. Each of the 44 805 MHz modules is made up of four "tanks", which are sets of accelerating and axially offset side coupling cavities. The four tanks form a module when connected together by elongated and further offset cells called bridge couplers. The purpose of the bridge couplers is to allow for room on the beam axis for required focusing quadrupole doublets between the tanks, as shown in Figure 1 [5], while still maintaining all four tanks as a single standing wave structure. The linac operates in pulsed mode with a duty factor that can vary between 1 and 12% depending on the needs of users and accelerator tuning.

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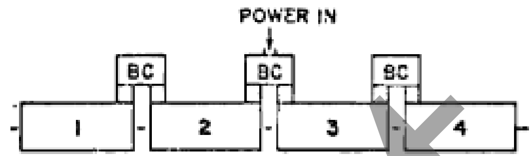

Figure 1: Module Tanks and Bridge Couplers [5].

STRUCTURE HEALTH EVALUATION

Motivation for Health Evaluation

The physical structure of the Side Coupled Cavity linac (CCL) at LANL has been remarkably durable. Most repairs have been related to vacuum leaks in the bellows connections to the cavities, and only a few H field monitor loops and RF windows at the bridge coupler inputs have required replacement.

Fifty years after startup of the 201 MHz Alvarez Drift Tube cavities at LANL, the appearance of a crack in the copper plating inside one of the four Alvarez structures caused the LANSCE facility to reduce average beam current and eventually shutdown for repairs [1]. As plans are being developed to replace these 201 MHz Alvarez structures [2], it makes sense to evaluate the health of the 805 MHz structures as they are nearly the same age.

Quality Factor as a Measure of Health

The unloaded quality factor (Q_o) of each tank was measured before final assembly into modules and these measurements were published [4]. This serves as one baseline that we compare our recent measurements against. A reduction in Q_o can indicate surface degradation or cavity braze joint quality. Measurements of Q were also made at each module's waveguide to bridge coupler iris after each set of four tanks were fully assembled with bridge coupling cavities, but after five decades not all of these values are available.

Stopband as a Measure of Health

When the module resonances are measured with electric field probes in the end accelerating cells, the biperiodic nature of the Side Coupled Cavity design leads to a discontinuity in the dispersion curve; with upper and lower branches around the $\pi/2$ mode. Closing the gap between the upper dispersion curve and lower dispersion curve is essential for operation of the accelerating coupled cavity structure [6], but details of how close to bring them were initially unclear. When the two curves are widely separated (as is the case when the accelerating and coupling cavity frequencies are significantly different), the term stopband refers the frequency difference between the two separate dispersion curves. In the case where this frequency difference is small relative the mode separation, the term "stopband" was defined to be the difference between the spacing between the π/2 mode frequency and the next resonances above and below (π/2±1, modes) as given in equation 1 [4].

$$\text{stopband} = \left(f_{\frac{\pi}{2}+1} - f_{\frac{\pi}{2}}\right) - \left(f_{\frac{\pi}{2}} - f_{\frac{\pi}{2}-1}\right) \quad (1)$$

Here, a positive stopband indicates that the π/2 resonance frequency and is closer to the frequencies of the lower branch of the dispersion curve, and a negative stopband indicates the π/2 mode is closer to the frequencies of the upper branch of the dispersion curve.

A critical factor in the successful operation of the Side Coupled Cavity Linac is maintaining the distribution of accelerating fields along the length of the structure as the average power into the structure is varied with changing RF duty factor. When side coupled cavity structures were being developed in the 1960s and 1970s, the first tank constructed displayed a runaway end-to-end axial field tilt as the average RF power into the was increased with increasing the duty factor. The proper setting of the stopband was found to be essential to keep the field distributions stable and prevent the runaway condition. A negative value of the stopband was correlated with field tilt and thermal runaway when the RF duty factor (proportional to average power into the structure) was increased from 6% to 12%. A positive (between 0 and +110 kHz) stopband was correlated with stable operation at RF duty factors up to 12% [7]. For this reason, we chose the stability of the stopband as a second measure of cavity health.

Measurement Method

The impedance method used for measuring the unloaded Q of the cavity (Q_o) cavity is described in Ginzton [8]. The data resolution was set as to obtain at least 1% resolution on the resonant modes around the π/2 mode. Figure 2 shows the $|S_{11}|$ data for the π/2-2, π/2, and π/2+2 modes for module 5. Figure 3 shows the S_{11} data for module 5 projected onto the Impedance Smith Chart where the $\pi/2$ mode of resonance intersects with the constant unity Q contour (red). The resonance of the π/2 mode and next nearest modes are shown as blue circles.

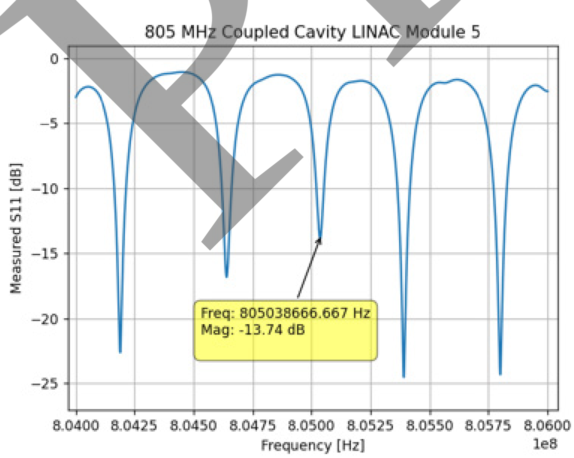

Figure 2: Module 5 $|S_{11}|$ data.

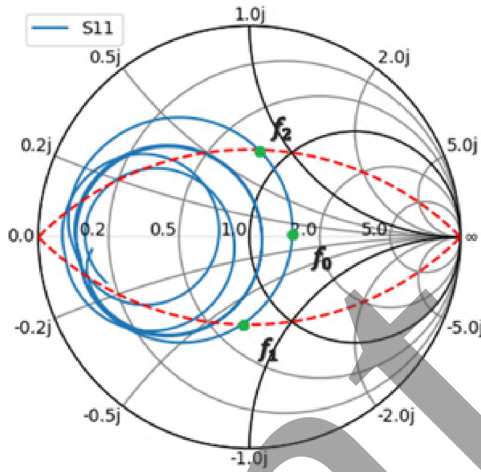

Figure 3: Module 5 S_{11} data projected on Smith chart.

The corresponding frequency points $f_0, f_1, and\ f_2$, are on the circle mapped out for the accelerating frequency π/2 mode, and the two half-power points of this mode, respectively. The process for computing the unloaded Q_0 then is the familiar process for lumped element analysis. The unloaded quality factor in this case is measured to be 16100. This method was repeated for the other modules.

Each module accelerating structure is integrated into the LANSCE beamline. It is impractical to measure the modes as was done in 1971 using an electric field probe inserted into the beam aperture at one end of the module, so during the 2026 LANSCE Maintenance period a calibrated Vector Network Analyzer (VNA) was used to record S_{11} values at the input iris of the waveguide feed to the central bridge coupler of modules 5, 6 and 28. When the resonance is measured at the input iris on the bridge coupler by the S_{11} parameter, only the even resonances are detected, so the adjacent modes are the π/2 ±2 modes and the stopband as measured at the iris ($\text{stopband}|_{\text{iris}}$) is given by equation 2.

$$\text{stopband}|_{\text{iris}} = \left(f_{\frac{\pi}{2}+2} - f_{\frac{\pi}{2}}\right) - \left(f_{\frac{\pi}{2}} - f_{\frac{\pi}{2}-2}\right) \quad (2)$$

Because the spacing between modes on each dispersion curve branch is roughly constant due to the large number of modes in a module (287 in module 5), we assumed that the stopband as measured at the iris ($\text{stopband}|_{\text{iris}}$) is the same sign and roughly twice the magnitude of the stopband measured using equation 1. In 2026 the module 5 $\text{stopband}|_{\text{iris}}$ value was measured to be -43 kHz, indicating a ($\text{stopband}|_{\text{iris}}$ /2) equivalent stopband value of -22 kHz to compare to the value of +19 kHz measured in 1971 [4].

Measurement Results

The measured Q_o of the fully assembled modules in 1971 was assumed to be the average of the 1971 measured Q_o for each of the four tanks in a module because the original data for the fully assembled module was no longer available [4]. The change in unloaded quality factors is shown in Table 1.

Table 1: Quality Factor Change

Module	Unloaded Q (4 tank ave.) circa 1971 [4]	Unloaded Q circa 2026
Module 5	16200	16100
Module 6	17800	16888
Module 28	22100	21955

The stopband for each the fully assembled module in 1971 was assumed to be the average of the 1971 measured stopbands for each of the four tanks in a module [4]. Based on the assumption that the average of the tank values represents what is measured at the coupling iris, the change in stopbands from 1971 to 2026 is shown in Table 2.

Table 2: Stopband Change

Module	1971 Stopband (4 tank ave.) [kHz]	2026 Stop-band$\|_{iris}$ / 2 [kHz]
Module 5	+19	-22
Module 6	+15	-32
Module 28	+22	-15

In 1980, module 5 was physically relocated downstream approximately 1 m to make room for a redesigned transition region between Alvarez and Side Coupled Cavity sections of the linac. Notebooks show that stopband measurements at the bridge coupler iris were performed both before and after the move. The results of these measurements are shown in Table 3.

Table 3: Module 5 Stopband Changes Over Time

Year and Method of Module 5 Stopband Measurement	Stopband [kHz]
1970 Ave. stopband of four tanks	+19
1980 stopband$\|_{iris}$ / 2 before move	+20
1980 stopband$\|_{iris}$ / 2 after move	-4
2026 stopband$\|_{iris}$ / 2	-22

The agreement between the average stopband of the four tanks that make up module 5 and the stopband$|_{iris}$ / 2 value measured in 1980 suggest our assumption that the stopband ≈ stopband$|_{iris}$ / 2 is reasonable. The present measurement of the module 5 stopband$|_{iris}$ / 2 is -22 kHz, which differs from the value of -4 kHz as measured after the 1980 move.

ANALYSIS OF RESULTS

The change in quality factor values in all three modules is less than 1% and is not considered to be a concern.

When the module 5 accelerator structure was first being tuned in 1970, a stopband value of -75 kHz and operation between 6 and 12% duty factor was associated with increasing fields in the coupling cavities and increasing end-to-end field tilt. Operation with stopband values of 0, +40 and +110 kHz were associated with stable operation over the same duty factor range [7].

Our estimates for the stopbands of modules 5 and 6 indicate that they are outside the acceptable range established when the structures were first assembled [4]. The peak RF power required by modules 5 and 6 has increased over the past decade of operations at 9.5% RF duty factor. This increase had been attributed to changes in tuning choices by the accelerator operators in an effort to capture more beam at the entrance to the 805 MHz section of the linac. The decrease in stop band value indicates that at least part of the increase in required RF power in modules 5 and 6 could be due to additional RF losses in the coupling cells and field tilt caused by detuning of this module.

The importance of the stop band being strictly positive has been debated. Early work highlighted the danger of any negative value for the stop band [7]. However, the final assembly procedures stated an allowable stop band range of –15 kHz to +30 kHz [4], and more recent publications state that "thermal stability can often be achieved even the presence of a small negative stopband" [6].

The module 5 stopband measurements taken in 1980 showed a decrease in the stop band from before the move to after the move, but the final value was within the acceptable range of – 15 kHz to +30 kHz [4]. Notebooks from that time state that this was a concern, so the module was tested to full peak and full average RF power and determined to be operating correctly after showing no signs of the instability.

CONCLUSION

Determination of the health of the now 54-year-old Side Coupled Cavity Linac accelerating structures at LANSCE is becoming more important as the facility enters its sixth decade of operations. Two measures of this health are changes in the unloaded quality factor and stopband of these structures. Three modules were chosen for a check of their quality factor and stopband measurements during the 2026 maintenance period. The 1971 measurements of Q_o of the fully assembled modules were not available, so the average of the four tank Q_o values that make up each module was used as baseline for each fully assembled module. The Q_o values measured for the modules showed no significant change, indicating no surface nor cavity braze joint degradation.

When the module 5 was first tuned in 1971, increasing unacceptable field tilt was observed as the RF duty factor was increased into the range of 6%-12% [7]. This problem was solved by increasing the module stopband value into the range between -15 kHz and +30 kHz [4]. The measurements made in 2026 indicate that the stopband of modules 5 and 6 are now below the lower recommended limit established when the accelerator was constructed. The RF duty factor for the 805 MHz linac is presently 9.4%. The combination of the lower stopband and duty factor could be causing an increase in power lost in the coupling cells and creating field tilt, both of which could explain the increase the required peak RF power in modules 5 and 6 over the past decade.

Based on these results, a complete set of Q_o and stopband measurements is being planned for additional 805 MHz modules during the coming 2027 maintenance period.

REFERENCES

[1] W. C. Barkley *et al.*, "Diagnoses and repair of a crack in the drift tube linac accelerating structure at LANSCE", in *Proc. NAPAC'22*, Albuquerque, NM, USA, Aug. 2022, pp. 19-21. doi:10.18429/JACoW-NAPAC2022-MOYE4

[2] K. Bishofberger *et al.*, "An overview of the LAMP front-end upgrade at LANSCE", in Proc. IPAC'24, Nashville, TN, USA, May 2024, pp. 1677-1679. doi:10.18429/JACoW-IPAC2024-TUPS18

[3] M. Sanchez Barrueta, R. Bratton, J. Lyles, W. Hall, and H. Xu, "RF amplifier system reconfiguration plans for new DTL and RFQ", in *Proc. NAPAC'25*, Sacramento, California, USA, Aug. 2025, pp. 843-847. doi:10.18429/JACoW-NAPAC2025-WEP078

[4] G. R. Swain, *LAMPF 805-MHz Accelerator Structure Tuning and Its Relation to Fabrication and Installation*, Los Alamos National Laboratory, Los Alamos, NM, USA LA-7915-MS, 1979.

[5] J. M. Potter and E. A. Knapp, "Bridge Coupler Design and Tuning Experience at Los Alamos", in *Proc. LINAC'72*, Los Alamos, NM, USA, Oct. 1972, paper I06, pp. 250-255.

[6] T. P. Wangler, *RF Linear Accelerators*, 2nd ed., WILEY-VCH Verlag GmbH & Co. KGaA, Weinhelm, Darmstadt, Germany, pp 113.

[7] R. A. Jameson, R. L. Cady, D. J. Liska, J. B. Sharp, G. R. Swain, and J. D. Wallace, "Full power operation of the LAMPF 805 MHz system", in *Proc. LINAC'70*, Batavia, IL, USA, Sep.-Oct. 1970, paper F-2, pp. 483-504.

[8] E. L. Ginzton, *Microwave Measurements*, 1st ed., The Maple Press Co., York, PA, USA, pp 413-417.