3-CELL SUPERCONDUCTING TRAVELING WAVE CAVITY TUNING AT ROOM TEMPERATURE*

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Abstract

A superconducting traveling wave (SCTW) cavity with a feedback waveguide will support a higher average acceleration gradient compared to conventional SRF standing wave cavities [1]. Euclid Techlabs, in collaboration with Fermilab, previously demonstrated a high accelerating gradient in a single cell cavity with a feedback waveguide [2], and the new waveguide design did not limit the cavity performance. The next step is high gradient traveling wave SRF cavity test. A 3-Cell SCTW cavity was designed and developed [3] to demonstrate the SRF traveling wave regime. Two Nb SCTW cavities were built, characterized and cold tested in 2016. This paper presents the results of cavity inspection, field flatness analysis, along with a discussion of the tuning procedure.

INTRODUCTION

The accelerating gradient in RF cavities plays a key role in high energy accelerators [4], since the cost of the project is highly dependent on its length. The current design of an SRF based linear collider uses superconducting Tesla type [5] accelerating cavities with accelerating gradients of 31 MV/m. The Tesla cavity length is restricted to 1 meter because of field flatness degradation and consists of only 9 cells. There is an unavoidable gap between cavities which decreases the average accelerating gradient.

A superconducting traveling wave cavity was proposed to increase the accelerating gradient [1]. However, it requires a feedback waveguide to transfer RF power from the output of the cavity back to its input section. Traveling wave (TW) cavities have lower field flatness sensitivity to the cavity length and, thus can be much longer. Our investigations showed [2] that a 10 meter long TW cavity would have a better field flatness than even a 1 meter standing wave (SW) cavity if it can be fabricated and cleaned with the required tolerances. Thus, if the technology allows building such a long cavity it might increase the accelerating gradient by 22% eliminating beam pipes empty of RF power between cavities. A TW cavity can operate at any phase advance, and, as is well known, a smaller phase advance provides a higher transit time factor. We investigated the phase advance dependence on the accelerating gradient of the SCTW cavity and it was found that 105 degrees gives an optimal accelerating gradient gain of 24% [2]. Overall, a TW cavity may increase the gradient by up to 46% compared to a conventional SW cavity.

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The first approach to a TW cavity was a single cell cavity. It was manufactured to prove the feasibility of cleaning the feedback waveguide. The cavity was cleaned at Argonne National Lab and tested at Fermilab at the vertical test stand in liquid helium. A 26 MV/m accelerating gradient was reached [2], which is comparable to Tesla single cell cavities with the same treatment. This opened the way to build a next generation TW cavity – a 3-Cell SCTW cavity [3] to demonstrate operation in the TW regime in a superconducting cavity with a high gradient. Two cavities were manufactured. Their resonant frequencies and Q factors were measured and the results are presented in this paper. Bead-pull measurements were done and are also presented here.

Tuning properties of the 3-Cell TW cavity were investigated [6, 7] and it was found that suppression of microphonics, caused by external pressure variation is possible by power redistribution in the power couplers. Also, a special 2D tuner required for Lorentz force compensation was designed, manufactured and tested [8]. Tuning studies were accomplished by a special analytic model involving S-matrix formalism which is thoroughly described in [9]. These studies provided some insight to the powering scheme which was used for cavity tuning and is presented in this paper.

CAVITY INSPECTION

Two niobium cavities were manufactured by the Spring of 2016. One of these cavities will be tested in liquid helium at Fermilab. This cavity requires additional waveguide reinforcements because of the small bandwidth during the test which will be finished by Fall 2016. The cavity with no stiffening ribs and with some of them installed is depicted in Fig. 1.

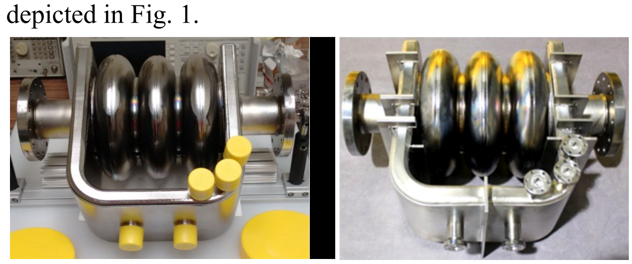

Figure 1: 3-Cell traveling wave cavity with (right) and without (left) stiffening ribs on the waveguide.

The full sized traveling wave cavity was designed to use two TTF-3 couplers with loaded Q=10^6 and does not need such reinforcement [3]. Bead-pull measurements were made for both cavities and are depicted in Figure 2. Also shown on this figure is the field distribution along the cavity calculated by CST for a cavity model at room temperature before any chemistry (consisting of 200 μm surface etching by BCP). The integral Nb RRR300 expansion coefficient from 2K to 293K is $\alpha = 1.00143$. As one can see from Fig. 2, cavity #2 has a field distribution similar to the calculation.

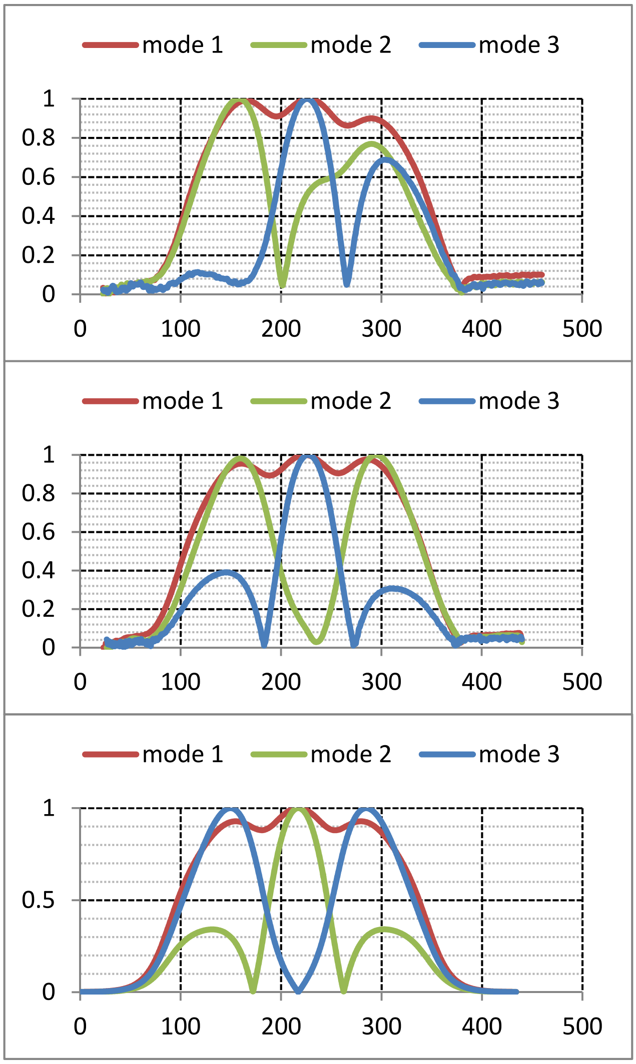

Figure 2: (Top to bottom) Bead-pull measurements of 3-Cell traveling wave cavities #1, #2 and simulated field distributions from CST for 3 cavity modes.

Table 1: Cavity Frequencies and Q-factors

Cavity 1		Cavity 2		CST	
f, MHz	**Q_0**	**f, MHz**	**Q_0**	**f, MHz**	**Q_0**
1044.499	2634	1047.469	2595	1037.34	2768
1173.648	2994	1173.136	2932	1164.92	3108
1277.913	5983	1279.697	6060	1274.09	6115
1303.468	6367	1304.226	6410	1300.91	6319
1305.772	6123	1308.039	6320	1301.05	6692
1372.614	3681	1378.148	3600	1364.10	3911

Cavity spectra and Q-factors were also measured and compared to simulations (Table 1). Along with the cell modes the cavities also have waveguide modes. Cell modes correspond to raw 3, 4 and 5. Surface conductivity for simulations was chosen equal to $\sigma = 7 \cdot 10^6 [S/m]$. The dielectric permittivity equals $\varepsilon = 1.0008 [F/m]$ and corresponds to room air. The measured Q-factors differ from the simulation by up to 9%, and the resonant frequency difference is within 10 MHz.

TRAVELING WAVE ADJUSTMENT

One of the cavities was sent for finishing machining, i.e. welding of the waveguide stiffening ribs (Fig. 1, right); the other was used for bench tuning studies at room temperature. The experiment layout is shown in Fig. 3 and corresponds to the schematic in Fig. 4.

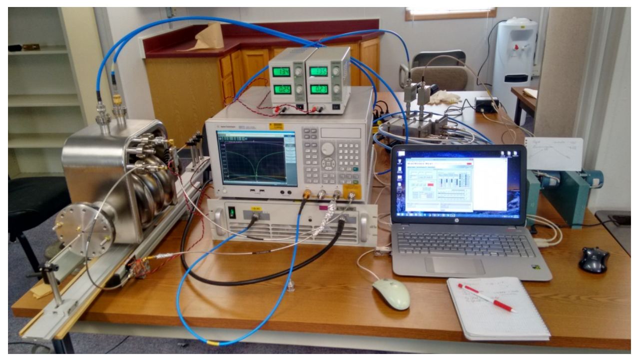

Figure 3: 3-Cell traveling wave niobium cavity room temperature test layout.

This method gives an opportunity for amplitude and phase change in input couplers. This is sufficient for traveling wave adjustment at room temperature but not at cryogenic temperatures because of the small bandwidth. An additional tuning element called a matcher is required [8]. Two hybrids and phase shifters are responsible for power and phase redistribution. A 10 W RF amplifier was used for cavity excitation. Phase shifters are the trombone type and have stepper motors for phase variation. These stepper motors were driven by a “Jova” controller connected to a PC through a USB port. This allowed a quick control of cavity excitation which tremendously speeded up the traveling wave adjustment. The 3-Cell superconducting traveling wave cavity has 3 measurement couplers equidistantly located from each other by λ/8. The middle one is required for calibration. Calibration has 2 steps. The first one requires obtaining a minimum signal at the calibration coupler by redistributing power signals in the standing wave regime, i.e. a node is obtained at the location of the coupler. Other measurement couplers should have an equal amplitude signal, as long as they are located equidistantly from the calibration coupler. The second step of calibration is to make signals from these side couplers equal. This was done initially by measurement coupler loop orientation adjustment. It was later found that multiplication by a correction coefficient in the VNA (Vector Network Analyser) is more convenient.

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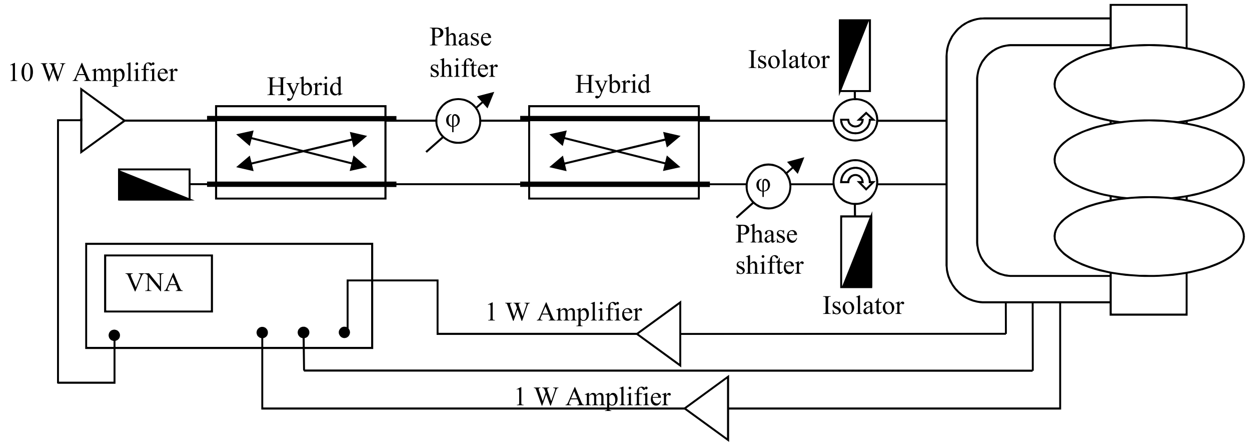

Figure 4: 3-Cell superconducting traveling wave cavity rf feed and measurement scheme

After calibration, measurement coupler signals require further post-processing, i.e. extraction of information about the traveling "clock-wise" wave "b" and "anti-clockwise" wave "a". If the signal from coupler 1 is $[a+b]$, then the signal from coupler 2 is $[a \cdot e^{-i \cdot \lambda/4} + b \cdot e^{+i \cdot \lambda/4}]$. Their sum and difference will give wave "a" and "b" separately. This is possible to realize using a 90 degree hybrid or by standard functions in the VNA as in our case.

The traveling wave was adjusted in the 3-Cell SCTW cavity at different frequencies using amplitude and phase redistribution in the power ports; calibration and signal post-processing is described above. The adjusted TW is shown in Fig. 5.

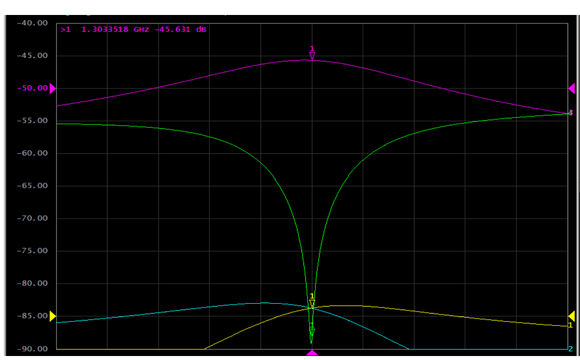

Figure 5: 4 signals at NWA: yellow – signal from measurement loop 1, blue – signal from measurement loop 2, green – mathematically processed signal, corresponding to the backward wave; purple - processed signal, corresponding to the forward wave.

One wave is highly damped while the other has a maximum at the desired frequency. The TW was ruined by compressing the waveguide with a c-clamp but was easily restored by power and phase redistribution in the input power couplers.

CONCLUSION

Two niobium SRF traveling wave cavities with 105 degree phase advance per cell were manufactured, inspected and tested at room temperature. Cavity spectra and Q-factors along with bead-pull measurements were performed. One of the cavities was used for tuning procedure studies of backward wave reduction at room temperature. The cavity feeding scheme was assembled with the option of power and phase redistribution between the input ports. The traveling wave regime was demonstrated in the cavity at various frequencies. The backward wave was highly damped while the forward wave demonstrated a maximum at a desired frequency. The cavity with reinforced waveguide will be tested in liquid helium at the Fermilab test stand in Fall 2016.

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