Progress towards 3-cell superconducting traveling wave cavity cryogenic test

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Abstract. This paper describes a superconducting L-band travelling wave cavity for electron linacs as an alternative to the 9-cell superconducting standing wave Tesla type cavity. A superconducting travelling wave cavity may provide 20-40\% higher accelerating gradient by comparison with conventional cavities. This feature arises from an opportunity to use a smaller phase advance per cell which increases the transit time factor and affords the opportunity to use longer cavities because of its significantly smaller sensitivity to manufacturing errors. Two prototype superconducting travelling wave cavities were designed and manufactured for a high gradient travelling wave demonstration at cryogenic temperature. This paper presents the main milestones achieved towards this test.

1. Introduction
A superconducting traveling wave (SC TW) cavity design was proposed \cite{1} as a higher performance substitute for the conventional Tesla-style standing wave (SW) cavity \cite{2}. The reason is that SC TW cavity can eventually provide a 46\% higher accelerating gradient, which is critical for multi-kilometer high energy accelerators like the ILC \cite{3}. The SC TW cavity utilizes a power feedback waveguide to recirculate the RF power at the end of the acceleration section, i.e. the cavity uses a principle similar to that of the traveling wave ring resonator (TWR). The acceleration section of the cavity was optimized \cite{4} such that it could provide a 24\% higher accelerating gradient with the same field on the surface as a conventional SW cavity. The smaller phase advance per cell (105 degrees) provides a higher transit time factor. Also, the TW cavity is significantly less sensitive to manufacturing errors\cite{4}, i.e. it could be made much longer then SW cavity, which is length-restricted to 1 meter because of field flatness degradation. The SC TW cavity is restricted only by cryomodule length and technological issues: manufacturing and cleaning of long cavities. Thus, for the structures studied here, the real estate gradient may be increased by 22\% by eliminating beam pipes that contain no RF field in a cryomodule as long as only one cavity may be employed \cite{4}.

Development of this new type of cavity was started from a single cell prototype as usual. The cavity was built, cleaned and tested at the Fermilab Vertical Test Stand (VTS). This cavity was designed to check manufacturing and cleaning challenges because of its more complicated design using a superconducting feedback waveguide. The single cell prototype was tested in the SW regime. An accelerating gradient of 26 MV/m was obtained, comparable to a Tesla single cell cavity with the same surface treatment (BCP only) \cite{4}. Thus, the presence of the feedback waveguide did not limit cavity performance and the next step could be taken towards development of a full sized SC TW cavity.
The next step is demonstration of a traveling wave in superconducting cavity. Full sized SC TW cavity testing is practically impossible because it requires a specially designed cryomodule, high power couplers and other hardware compatible with the cavity. A small prototype was proposed – a 3-cell SC TW cavity which could be tested in Fermilab VTS with the existing 500 W power supply. The three-cell prototype makes the test possible, because it is small and fits the VTS and can be excited by simple feedthroughs with small power supply. However, this makes the cavity sensitive to external loads because of its narrow bandwidth (~20 Hz). The cavity was optimized to withstand external pressure variations – stiffening ribs and rings were added to the mechanical design. Nevertheless, the cavity was still sensitive to the effects of the Lorentz force and a special tuner [5] was designed and built to compensate it. This paper presents some of the final stages towards cryogenic test of the three-cell prototype: preliminary RF measurements and final manufacturing phase.

2. Room temperature experimental results

2.1. RF Quality Control (RFQC)

Two niobium cavities were manufactured. Routine cavity measurements which are usually referred to RF quality control (RFQC) were done, such as quality factor Q, resonant frequency f, and field distribution on the axis E_z(z). Following that, one of the cavities was used for tuning studies at room temperature. The other cavity will be tested in liquid helium at Fermilab. This cavity requires additional waveguide reinforcements because of the small bandwidth during the test. The full sized traveling wave cavity was designed to use two TTF-III couplers with loaded Q=10^6 and does not need such reinforcement. Bead-pull measurements were made for both three-cell prototypes and are presented in Figure 1. Also shown on this figure is the field distribution along the cavity calculated by CST MWS [6] for a cavity model at room temperature before any chemical treatment (consisting of 200 μm surface etching by BCP) is applied. The integral Nb RRR300 expansion coefficient from 2K to 293K is α =1.00143. As one can see from Figure 2, cavity #2 has a field distribution similar to the MWS results.

Cavity spectra and Q-factors were also measured and compared to simulations (Table 1). Along with the cell modes (mode 3, 4, 5 in Table 1, bolded) the cavities also have waveguide modes (mode 1, 2, 6 in Table 1). Cell modes are the modes with EM fields concentrated in acceleration part of the resonator, WG modes are concentrated in the waveguide. Surface conductivity for simulations was chosen equal to σ = 7·10^6 [S/m]. The dielectric permittivity equals ε = 1.0005 [F/m] and corresponds to room air. The measured Q-factors differ from the simulation by less than 8%, and the resonant frequency difference of cell modes is within 5 and 7 MHz for cavities 1 and 2 respectively. Additional cavity tuning is required to get the frequencies and field distributions closer to the simulated ones. Nevertheless, the cavities were used for room temperature tuning studies and the TW mode was successfully adjusted.

| Mode No. | Cavity 1 | Cavity 2 | HFSS simulation |
|----------|----------|----------|-----------------|
|          | f, MHz   | Δf, MHz  | Q₀              | f, MHz | Δf, MHz  | Q₀ | f, MHz | Q₀ |
| 1        | 1044.499 | 7.40     | 2634            | 1047.47| 10.37    | 2595| 1037.10| 2757|
| 2        | 1173.649 | 8.33     | 2994            | 1173.136| 7.82    | 2932| 1165.32| 3100|
| 3        | 1277.913 | 3.63     | 5983            | 1279.697| 5.42    | 6060| 1274.28| 6098|
| 4        | 1303.469 | 2.31     | 6368            | 1304.226| 3.07    | 6410| 1301.16| 6498|
| 5        | 1305.772 | 4.53     | 6123            | 1308.04| 6.80    | 6320| 1301.24| 6481|
| 6        | 1372.615 | 8.39     | 3682            | 1378.148| 13.93   | 3600| 1364.22| 3900|
Figure 1. (Top to bottom) Bead-pull measurements of 3-Cell traveling wave cavities #1, #2 and simulated field distributions from CST for 3 cell modes.

2.2. Traveling wave adjustment
Cavity #1 was used for bench tuning studies at room temperature. The test layout is shown in Figure 2(b) and corresponds to the schematic in Figure 2(a).

Figure 2. 3-Cell superconducting traveling wave cavity RF feed and measurement scheme (a): 1 – Vector Network Analyzer (VNA); 2 – power amplifier; 3 – matched load; 4 – 3dB hybrid; 5 – phase shifter; 6 – circulator; 7 – resonator; and the photograph of the corresponding test layout (b).
This scheme allows amplitude and phase change in the input couplers. This is sufficient for traveling wave adjustment at room temperature but not at cryogenic temperatures because of the small bandwidth. 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 [7] 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 three measurement couplers located at intervals of λ/8. The middle one is required for calibration, which consists of two steps. The first 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 adjustment of the measurement coupler loop orientation. It was later found that multiplication by a correction coefficient in the VNA (Vector Network Analyser) is more convenient. Figure 3(a) demonstrates signals from the measurement couplers after calibration.

After calibration, the 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 \([a \cdot e^{-i\pi/4} + b \cdot e^{i\pi/4}]\). Their sum and difference will give waves “a” and “b” separately. This is possible to realize using a 90 degree hybrid or by standard functions of the VNA as in our case.

The traveling wave in the cavity #1 was adjusted by amplitude and phase redistribution at a frequency close to the 2-nd cell mode (see Table 1. Mode 4) 1303.35 MHz. The TW regime was observed at frequency range [1303.35+/-0.1] MHz which corresponds to the cavity bandwidth with full degradation at the end of this range. This result was predicted by the mathematical model [8]. Besides that, the 3-cell cavity was designed to operate at a frequency close to the 2\(^{\text{nd}}\) cell mode at 2K (1300.82 MHz) because of a small reflection from the acceleration part of the waveguide. The TW at room temperature was also obtained under similar conditions. Processed signals, which corresponded to forward and backward wave amplitudes, are shown in Figure 3 (b). One wave is highly damped while the other one has a maximum at the desired frequency. The TW was ruined by compressing the waveguide (WG) with a C-clamp but was easily restored by power and phase redistribution in the input power couplers at a different frequency (see Fig. 3 (c)). WG deformations cause reflections and change of electrical length [9]. That is why the operating TW frequency was shifted to 1303.02 MHz.

Figure 3. Calibrated signals from 3 measurement loops in the SW regime (a); adjusted TW in the cavity with deformed (c) and not deformed waveguide (b). Blue and red curves – signals from side measurement loops, green and pink curves (b, c) – mathematically extracted signals of waves circulating in opposite directions. Green curve (a) – middle measurement loop signal.
3. **Final manufacturing**

The cavities require additional stiffening ribs for cryogenic tests because of the narrow bandwidth. The welding process can cause deformations of the cavities thus the tuning procedure should not be done prior to welding. Cavity #1 was chosen for cryo-test and was sent for finishing manufacturing because it required less tuning because the deviations of resonant frequencies were smaller. The cavity with a closed electromagnetic (EM) volume was measured and is shown in Figure 4(a).

![Figure 4](image)

**Figure 4.** The photographs at different time during the welding of stiffening ribs.

Welding stiffening ribs on the waveguide requires a flat surface for good contact. Even if the WG had a flat surface originally it would be deformed during welding. The welding places were flattened by wire EDM (electrical discharge machining) to solve this issue (see Fig. 4 (b)). After that the ribs were welded by EBW (electron beam welding) (see Fig. 4 (c-f)). Fig. 4 (f) shows the finished cavity with all the ribs attached. Flat tuner plates were also welded to three stiffening ribs and required additional CNC machining to equalize their sizes. Two Ti bars were designed and manufactured to fix the length between the beam pipes and are connected by screws to them (see Fig. 5(a)). These bars will be used to fix the cavity to special crate for testing at Fermilab. The whole assembly can be found in Figure 5(b). Holding plates are manufactured and fully compatible with the VTS.

![Figure 5](image)

**Figure 5.** 3D model of 3-cell SC TW resonator (a) and the full assembly for cryogenic test (b).
Once the cavities are fully finished, the RFQC routine will be performed. Frequencies and field distributions will be tuned as usual for any cavity. Additional tuning will take place at the operating TW frequency. The WG deformations should return the operating frequency to the expected value. After all of these procedures, the cavity will undergo the standard routine for SC cavities: chemical etching by BCP, DI water rinsing, drying process, evacuation and 2K test.

4. Conclusions
Two 3-cell Nb cavities with feedback waveguide were manufactured without additional stiffening required for the high power test in liquid helium. The cavities were bench tested. Quality factors, frequencies and field distribution were presented. One of the cavities was used for TW excitation studies at room temperature. As was predicted by the model, TW excitation at room temperature was obtained by power and phase redistribution in input power couplers. After room temperature tests the cavity was sent for welding of additional stiffening ribs, which has been completed. High power tests of the traveling wave prototype superconducting cavity are expected to begin in Spring 2017.

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