Progress and Challenges in Traveling-wave (TW) SRF cavity*

F. Furuta†, V. Yakovlev, T. Khabiboulline, K. McGee, S. Kazakov, Fermi National Accelerator Laboratory, Batavia, USA
R. Kostin, P. Avrakhov, Euclid Techlabs, Bolingbrook, IL, USA

Abstract

Traveling-wave technology can push the accelerator field gradient of niobium SRF cavity to 70MV/m or higher beyond the fundamental limit of 50~60MV/m in Standing-Wave regime. The early stages of TW SRF cavity developments had been funded by several SBIR grants to Euclid Techlabs and completed in collaboration with Fermilab through a 1-cell prototype and a *proof-of-principle* 3-cell TW cavity development and testing. The TW resonance excitation in a SRF cavity at 2K liquid helium was demonstrated as the 1st time using the TW 3-cell at Fermilab. To advance TW technologies necessary more for future accelerator-scale TW cavity, Fermilab proposed a half-meter scale TW RF design. Here we report the recent progress in the 3-cell and the challenges towards a half-meter scale TW cavity.

INTRODUCTION

Presently all SRF cavities operate in a standing wave (SW) resonance field in which particles experience an accelerating force alternating from zero to peak. Niobium SRF cavities have a theoretical peak magnetic field which limits the accelerating field to 50 - 60 MV/m using standard available designs. A travelling wave (TW) regime evades this limit by generating a resonance field propagates along the cavity length. Particles in such traveling resonance field can experience a *constant* acceleration force, thus an energy gain per unit length can be higher than that of SW regime. This phenomenon is defied by the cavity's transit time factor T ($T=E_{acc}/E_{ave.}$, E_{acc}; accelerating gradient, E_{ave}; average field gradient over the cell gap) A TW structure proposed in the early study showed a T of 0.9 [1], which is >20% higher than T of most common 1.3GHz SW 9-cell design (T ~0.7). This approach explores the path to 70 MV/m and higher for the same peak surface magnetic field condition of standard Niobium materials and processing technology. A higher cavity quality factor with higher R/Q of TW design can also be expected [2], which will lower the heat load and cryogenic power. Increased cavity energy gain per unit length and higher cavity quality factor can dramatically reduce the scale and running cost of SRF accelerators. An example, the proposed TW-based linear collider HELEN can achieve a 250 GeV center-of-mass energy in only 7.5 km, in stark contrast to the 30-km scale of the SW ILC structure [3].

*Fermilab is managed by Fermi Research Alliance, LLC (FRA), acting under Contract No. DE-AC02-07CH11359 with the U.S. Department of Energy, Office of Science, Office of High Energy Physics.
† ffuruta@fnal.gov

3-CELL TRAVELING WAVE CAVITY

Early Achievements

The early stages of TW SRF cavity developments have been funded by several SBIR grants to Euclid Techlabs (DOE SBIR Grant # DE-SC0006300) and completed in collaboration with Fermilab through a 1-cell prototype and a 3-cell *proof-of-principle* TW cavity fabrication and testing. It demonstrated the feasibility of the fabrication and processing of multi-cell TW structure [4] and achieved the TW resonance excitation in the 3-cell TW cavity at room temperature [5, 6].

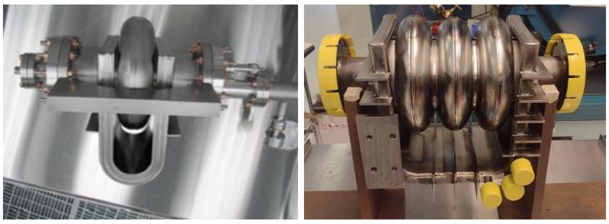

Figure 1: 1-cell prototype (left) [4] and 3-cell *proof-of-principle* TW cavity (right).

TW Resonance Control in the 3-cell Cavity

To excite TW resonance in the 3-cell cavity, the following technical concepts were investigated and demonstrated during the early R&Ds; 1) the stiffened cavity design, 2) RF control using two input power couplers, and 3) a special tuner device [5, 6].

The loaded quality factor Q_{load} at 2 K in VTS will be around 10^8, making the cavity bandwidth very narrow and sensitive to microphonics. The stiffening ribs were welded on the waveguide (WG) to reinforce the resonator (Fig. 1 right). Based on the simulations, the stiffened cavity design and fine tuning of RF input signals would be enough to withstand microphonics detuning.

The WG of the 3-cell cavity has two RF input couplers and three RF monitoring couplers (Fig. 2). During the study at room temperature, a "forward" and a "backward" traveling waves inside the cavity and WG loop were mathematically extracted from the monitoring coupler signals. The "backward" traveling wave was suppressed by RF power redistribution and phase control between the two input signals. With these controls and signal processing, the desired "forward" traveling wave was successfully established in the 3-cell cavity at room temperature. Figure 3 shows RF feed and measurement scheme at room temperature for the 3-Cell TW cavity by Euclid [5].

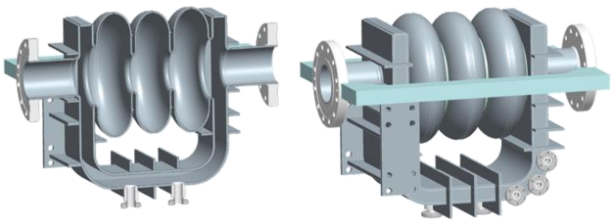

Figure 2: 3D models of the 3-cell, two RF input couplers (left) and three RF monitoring couplers (right) on WG.

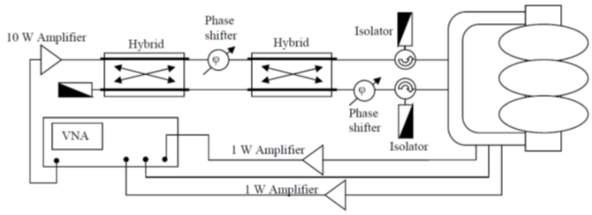

Figure 3: RF feed and measurement scheme at room temperature for the 3-Cell cavity [5].

Lorentz force compensation was also considered to maintain the TW resonance at 2 K VTS conditions. A special tuner device (matcher) for the 3-cell cavity was designed and fabricated to attach on the WG. A matcher will deform the WG wall and decouple partial modes to compensate the Lorentz force [6]. The preliminary test on the matcher test assembly at room and liquid nitrogen temperatures indicated the feasibility of achieving TW resonance in 2 K. Figure 4 shows 3D model of the 3-cell protype and the matcher.

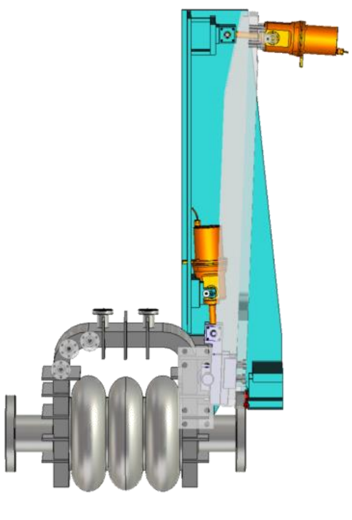

Figure 4: 3D model of the cavity with the matcher on WG.

TW RESONANCE EXCITATION AT CRYOGENIC TEMPERATURE

Cavity Preparation for Cryogenic Testing

Prior to the first cryogenic testing, the 3-cell had a surface processing consist of 120µm Buffered Chemical Polishing (1:1:2, 48% HF: 69.5% HNO_3: 85% H_3PO_4) at Argonne National Lab (ANL) [7], High Pressure DI water Rinsing (HPR) and a heat treatment in high-vacuum furnace (800 degC, 3hrs) at Fermilab, and final 10µm BCP at ANL followed by HPR at Fermilab [8]. then, the cavity was proceeded to cell tuning. Cell tuning hardware for the 3-cell cavity is designed and fabricated by Euclid Techlabs (Fig. 5). The 3-cell cavity was tuned in SW mode to the simulated field distributions from CST MWS [9] for 3 cell TW mode. The TW operation frequency should be close to the second eigenmode shown with a grey line in Fig. 5.

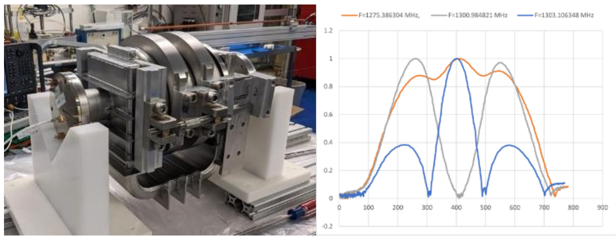

Figure 5: the 3-cell with tuning hardware (left). The field profiles post tuning in SW mode.

After cell tuning, the cavity had HPR and assembly for the cryogenic testing in Vertical Cavity Test Stand (VTS) at Fermilab (Fig. 6). Two feedthroughs with straight antenna tip were installed on WG as RF input coupler. Three feedthroughs with loop antenna are also installed on WG as RF monitoring purpose. Each loop antenna is oriented to couple with a forward wave, backward wave, and a calibration signal in WG, respectively. Special tuner was not attached on WG for the 1st test since no need to tune WG during a low RF power test was expected.

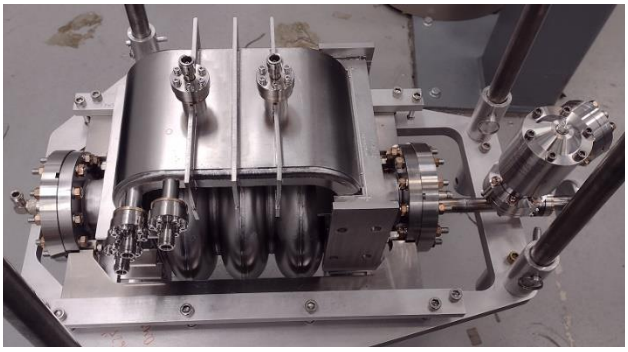

Figure 6: the 3-cell assemble for VTS.

The 1st TW Resonance Excitation in the 3-cell SRF cavity at Cryogenic Temperature

Same RF feed and measurement configurations shown in Fig. 3 were used for the 1st cryogenic testing of the 3-cell. After tuning two RF input signals, TW resonance was successfully excited in the 3-cell cavity in 2K helium. This is the very 1st demonstration of TW excitation in a SRF cavity at a cryogenic temperature. An example of TW resonance excited at 1301.06 MHz at 2K was shown in Fig. 7 with two processed signals; yellow line shows a maximum forward wave signal, blue line shows a suppressed backward wave, and an unprocessed signal from the calibration signal (purple). A suppressed backward wave signal is >30dB less than A forward one, a purity of tuned TW wave in the 3-cell estimated from the monitoring signals was more than 99%.

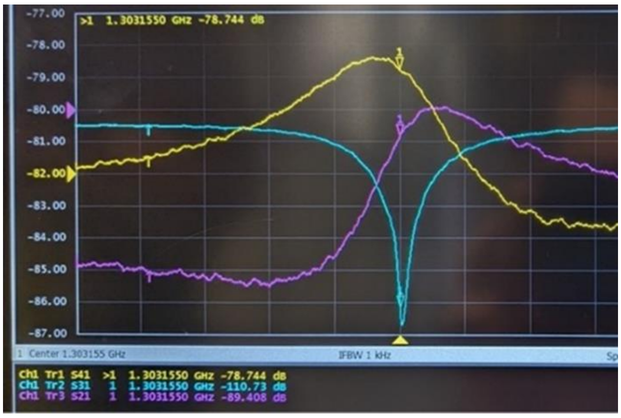

Figure 7: An example of TW resonance excitation signals in 2K helium.

DEVELOPMENT OF A HALF-METER SCALE TW CAVITY

To advance TW technologies necessary for future accelerator-scale TW cavity more, RF design process began at Fermilab with the development of plans for a 0.5~1 meter prototype TW cavity. A preliminary RF design of a half-meter scale (7-cell) TW cavity with new RF and TW control schemes was proposed by applying "lessons-learned" from the 3-cell and considering the physical dimensions of existing SRF facilities [10]. The inner cell shape is identical to that of the 3-cell.

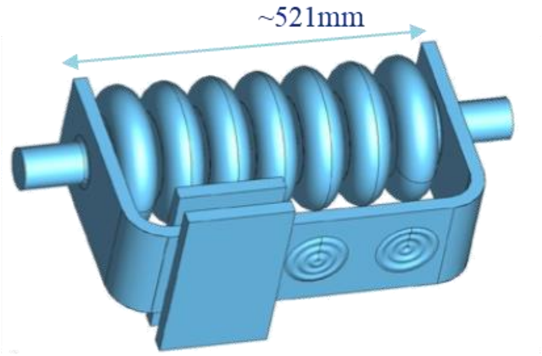

Figure 8: Preliminary RF design of prototype TW 7-cell cavity [10].

Double Directional Coupler structure on WG

The 3-cell's two-coupler system is replaced with a single, high-power directional coupler to simplify the RF operation by eliminating the need to adjust phase and amplitude of two separate RF sources. This will reduce a fabrication cost and complexity by reducing the number of high-power input couplers. The 3-cell's three monitoring couplers are also replaced with a single directional coupler, which is significantly simplifies the signal processing scheme and eliminates additional antenna calibrations. Two directional couple structures attached on WG loop can be seen in Fig. 8.

Two Waveguide Tuner (matcher) System

In general case simulations, single matcher was not sufficient to eliminate mode splitting and deliver a pure travelling-wave mode. Two matchers system with an improved shape will be designed, fabricated, and tested to show propagation of a pure travelling-wave mode in 7-cell TW cavity. Two wave-formed circle wall are applied on WG to simulate two matcher system (Fig. 8).

The 1st milestones toward a TW 7-cell

Oen of 1st milestones is to demonstrate a feasibility of high gradient in a TW shape multi-cell structure separately from WG with new RF schemes. We plan to fabricate a TW shape "bare" 7-cell cavity (no WG loop) and focus on a high gradient demonstration with that in SW regime. Preliminary fabrication test of TW shape half cells and welding test under narrow gap of TW shape iris were carried out in collaboration between FNAL, Jlab, and KEK [11] supported by the U.S.-Japan Science and Technology Cooperation Program in High Energy Physics (LAB 23-2858).

Another is to conduct a *proof-of-principle* demonstration for new coupler and WG tuner design. We plan to fabricate a low-cost mock-up WG loop using alternatives to niobium materials such as copper or aluminium which can effectively model the most important RF properties of these novel techniques and motivate later investment in a full-scale niobium version once the operative principles have been effectively demonstrated. This is supported by Laboratory Directed R&D (LDRD) program at Fermilab. LDRD is a national program sponsored by the DOE that allows National Laboratories to internally fund R&D projects per DOE Order O413.2C.

SUMMARY

The 1st demonstration of TW excitation in a SRF cavity at a cryogenic temperature was successfully accomplished with the 3-cell TW cavity in collaboration between Fermilab and Euclid Techlabs. Next milestone of the TW 3-cell is a high gradient test in TW regime, which is under preparation now at Fermilab. The matcher developed for the 3-cell will also be installed and tested.

A half-meter scale (7-cell) TW cavity with new RF and TW control schemes is proposed to advance TW technologies necessary for future accelerator-scale TW cavity. The 1st milestones towards a TW 7-cell cavity are set, some preliminary portion was completed under US-Japan program. New TW resonance excitation and control schemes being developed under Fermilab LDRD program.

REFERENCES

[1] P. Avrakhov *et al.*, "Traveling Wave Accelerating Structure for A Superconducting Accelerator", in *Proc. PAC05*, Knoxville, TN, USA, May, 2005, pp. 4296-4298. doi:10.1109/PAC.2005.1591799

[2] V. Shemelin *et al.*, "Optimization of a traveling wave superconducting radiofrequency cavity for upgrading the Interna-

tional Linear Collider", *Phys. Rev. Accel. Beams*, vol. 25, p. 021001, 2022.
doi:10.1103/PhysRevAccelBeams.25.021001

[3] S. Belomestnykh *et al*., "Superconducting radio frequency linear collider HELEN," JINST 18, P09039 (2023)
doi:10.1088/1748-0221/18/09/P09039

[4] R. Kostin *et al.,* "A high gradient test of a single-cell superconducting radio frequency cavity with a feedback waveguide", *Supercond. Sci. Technol*., vol. 28, p. 095007, 2015.
doi:10.1088/0953-2048/28/9/095007

[5] R. Kostin *et al.,* "Progress towards 3-cell super-conducting traveling wave cavity cryogenic test", *J. Phys. Conf. Ser.*, vol. 941, p. 012100, 2017.
doi:10.1088/1742-6596/941/1/012100

[6] R. Kostin *et al.,* "A tuner for a superconducting traveling wave cavity prototype", *J. Instrum.* vol. 10, p. 10038, 2015.
doi:10.1088/1748-0221/10/10/P10038

[7] T. Reid, *et al.,* "New SRF Structures Processed at the ANL Cavity Processing Facility", in *Proc. SRF'19*, Dresden, Germany, Jun.-Jul. 2019, pp. 434-437.
doi:10.18429/JACoW-SRF2019-TUP018

[8] F. Furuta *et al.,* "Development of 3-cell traveling wave SRF cavity", in *Proc. SRF'23*, Michigan, USA, June 2023.
doi:10.18429/JACoW-SRF2023-TUPTB043

[9] CST – Computer Simulation Technology,
https://www.cst.com/

[10] S. Kazakov, "Internal RF design report on a half-meter scale 1.3GHz TW cavity", unpublished

[11] F. Furuta *et al.,* "Development of a half-meter scale Traveling-Wave (TW) SRF cavity", will be published in *Proc. LCWS2024*, Tokyo, Japan, July 2024