Development of a half-meter scale Traveling-Wave (TW) SRF cavity

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Abstract. Traveling-wave (TW) technology can push the accelerator field gradient of niobium SRF cavity to 70 MV/m or higher beyond the fundamental limit of 50~60 MV/m in Standing-Wave regime. The 1st demonstration of TW resonance excitation in a proof-of-principle 3-cell SRF cavity in 2 K liquid helium was successfully carried out at Fermilab in collaboration with Euclid Techlabs [1]. In parallel with that, the RF design process of 0.5~1 meter scale TW cavity was begun at Fermilab for advancing TW technologies necessary more for future accelerator-scale one. Considering the physical dimensions of existing SRF facilities (for fabrication, processing, and cryogenic testing) and the lessons learned from the 3-cell, Fermilab has proposed a preliminary RF design of a half-meter scale TW SRF cavity [2]. It consists of a 7-cell structure and a power feedback waveguide (WG) loop with new RF configurations to control TW resonance. Here we report a preliminary RF design, development plans, and activities toward a TW 7-cel SRF cavity.

1 Introduction

Niobium SRF cavities have a theoretical peak magnetic field which limits the accelerating field to 50 - 60 MV/m using standard available designs. Presently all SRF cavities operate in a standing wave (SW) resonance field in which particles experience an accelerating force alternating from zero to peak. In contrast that, a travelling wave (TW) regime generates 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 a SW regime. This phenomenon is defined by the cavity's transit time factor T ($T=E_{acc}/E_{ave}$., E_{acc} - accelerating gradient including variation in time, E_{ave} - accelerating gradient without time dependence). A TW structure proposed in the early study showed a T of 0.9 [3], 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 a higher R/Q of TW design can also be expected [4], 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 future 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 (International Linear Collider) structure [5].

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2 TW resonance excitation in the 3-cell structure

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 [6, 7]. A 3-cell proof-of-principle TW cavity was fabricated, processed, and tested at a cryogenic temperature [8]. The 1st TW resonance excitation in a 2 K liquid helium using a low RF power was successfully achieved at Fermilab. An example of TW resonance excited at 1301.06MHz at 2 K was shown in Fig. 1 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). The suppressed backward wave signal is >30dB less than the forward one, a purity of tuned TW wave in the 3-cell estimated from the monitoring signals was more than 99%. Details of the 3-cell development and testing are presented in this workshop [1].

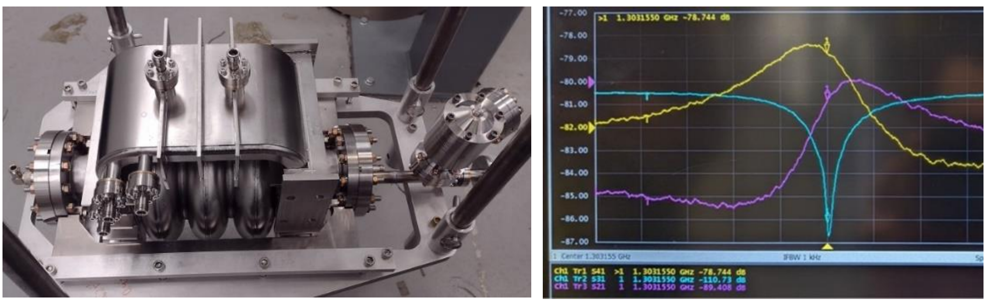

Fig. 1. the 3-cell assemble for a cryogenic testing in VTS (Vertical cavity Test Stand) at Fermilab (left) and an example of TW resonance excitation signals in 2K helium (right).

3 A half-meter scale TW SRF cavity

While the preparation of the 3-cell cryogenic testing in TW regime had been proceeded, Fermilab begun the RF design process of 0.5~1 meter scale TW cavity for advancing TW technologies necessary more for future accelerator scale one. Considering the physical dimensions of existing SRF facilities (for fabrication, processing, and cryogenic testing) and the lessons learned from the 3-cell, a preliminary RF design of a half-meter scale TW SRF cavity which consists of a 7-cell structure and a power feedback waveguide (WG) loop with new RF configurations to control TW resonance was proposed (Fig. 2) [2]. The inner cell shape is identical to that of the 3-cell TW cavity.

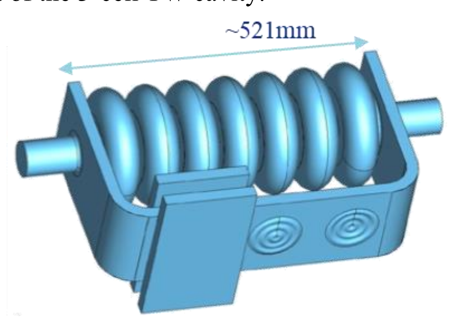

Fig. 2. Preliminary RF design of a TW 7-cell cavity.

3.1 Double directional coupler on WG loop

The 3-cell TW cavity employed two RF input couplers and three RF monitoring couplers system to excite and control TW resonance in the structure [7]. In the preliminary 7-cell RF design, a double directional coupler system is proposed. Two RF input couplers of the 3-cell are replaced with a single high-power input directional coupler which simplifies the RF operation by eliminating the need to adjust phase and amplitude of two separate RF sources. This will also reduce construction cost and complexity by reducing the number of high-power input couplers. Three RF monitoring couplers of the 3-cell are also replaced with another single monitoring directional coupler which will significantly simplify the signal processing scheme and eliminates additional antenna calibrations. The designs of RF couplers are shown in Fig. 3.

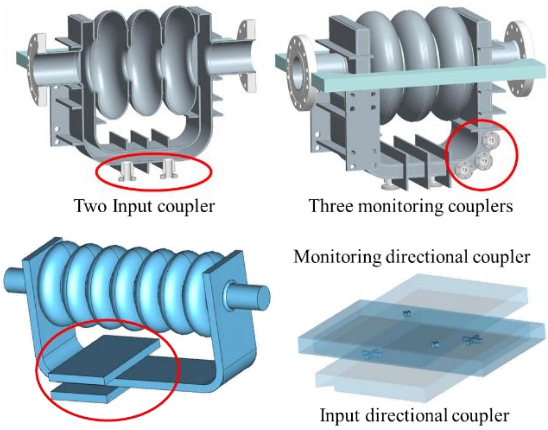

Fig. 3. RF power input and monitoring coupler designs for the 3-cell (top) and 7-cell (bottom).

3.2 Two WG tuner (matcher) system on WG loop

For the 3-cell TW cavity, a special tuner device (matcher) to eliminate mode splitting and deliver a pure traveling wave during a high-power RF operation was designed and fabricated [9]. This proof-of-principle matcher for the 3-cell has a position adjustability in one direction and can deform a WG wall by pushing. To fit a matcher system into an accelerator-scale, two matcher system on WG loop is proposed to a 7-cell. Two matchers will be attached on optimized two locations and deform WG wall by pulling and pushing. Two wave-formed circle walls are shown on the WG loop in Fig. 4 to simulate two matcher system. A compact matcher will be designed, fabricated, and tested to show propagation of a pure travelling wave mode in a 7-cell prototype.

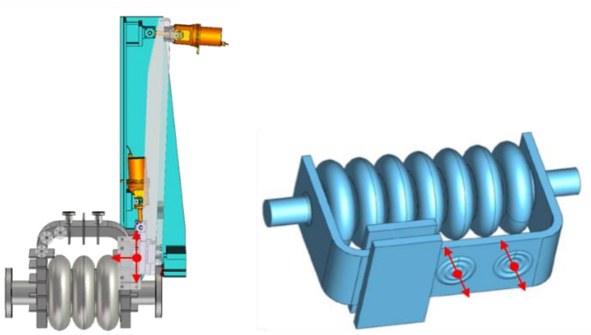

Fig. 4. The model of the 3cell with matcher (left) and the macther locations for a 7-cell (right)

4 Technical developments toward a TW 7-cell

Objectives of a prototype TW 7-cell are to conduct proof-of-principle demonstration for new coupler and WG tuner designs, necessary for scaling up to a full-size (1 m) cavity and to demonstrate 70 MV/m with scalable ancillary systems at cryogenic temperatures. Two goals are set as the 1st milestones toward a TW 7-cell cavity: 1) demonstrate novel techniques to establish and control TW resonance in a mock-up WG loop, 2) demonstrate a high gradient in a TW shape bare 7-cell cavity (no WG loop) in SW regime.

4.1 A Low-Cost Mock-Up of WG loop

This plans to fabricate a low-cost mock-up of WG loop using alternatives to niobium materials such as copper or aluminum 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 demonstrated. Mock-up WG loop will consist of a double directional coupler, two dummy matchers to deform WG wall, and straight and bending sections. Fig. 5 shows preliminary RF design of the loop. The whole length of mock-up WG loop will be finalized to imitate an RF loop length of a TW 7-cell. RF design and drafting of WG loop and each component are in progress. This effort 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.

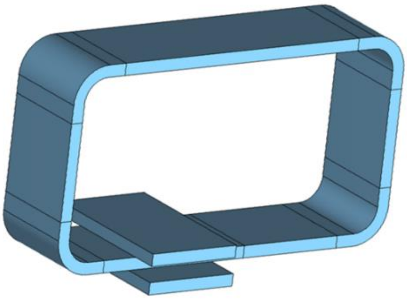

Fig. 5. Preliminary RF design of mock-up WG loop.

4.2 Fabrication of TW shape bare 7-cell cavity

It is important to demonstrate a feasibility of high gradient in a TW shape multi-cell structure separately from a WG loop. Our approaches are to fabricate a bare niobium 7-cell cavity using the TW specific elliptical design with simple beam tubes (Fig. 6), chemically process the cavity, then validate its performance in standing wave mode at cryogenic temperature using a high-power RF source. Standard and well-established cavity manufacturing methods, such as deep drawing of half cells and electron beam welding (EBW), will be applied.

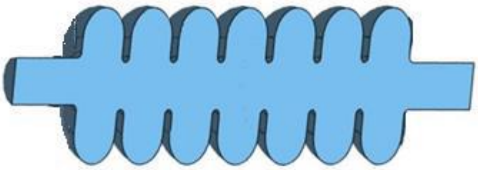

Fig. 6. Preliminary cross section image of TW shape bare 7-cell cavity

4.2.1 Fabrication of TW shape inner half-cell

The efforts begun with a fabrication of TW shape half cells and an optimization of iris joint welding under narrow gap of TW shape (Fig. 7). This was funded by the U.S.-Japan Science and Technology Cooperation Program in High Energy Physics (LAB 23-2858) as a 1-year project and carried out in collaboration between Fermilab, Jefferson lab, and KEK.

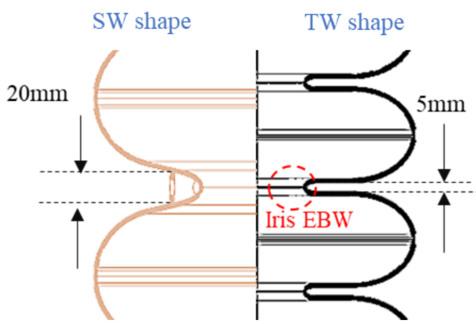

Fig. 7. A comparison of iris joint gap of a 1.3GHz SW shape and TW shape multi-cell cavity.

Fermilab designed a set of deep drawing die for the inner half-cell including a mechanical analysis with ANSYS (Fig. 8). Jefferson lab and KEK advised on ANSYS simulation code and results based on their expertise and experiences. KEK fabricated the set of die per the optimized design provided by Fermilab and performed the test presses with Cu and Nb sheets (Fig.9). Profile measurements on those pressed half cups are also performed at KEK using a coordinate measuring machine (CMM). Fermilab personnel visited KEK and participated the activities.

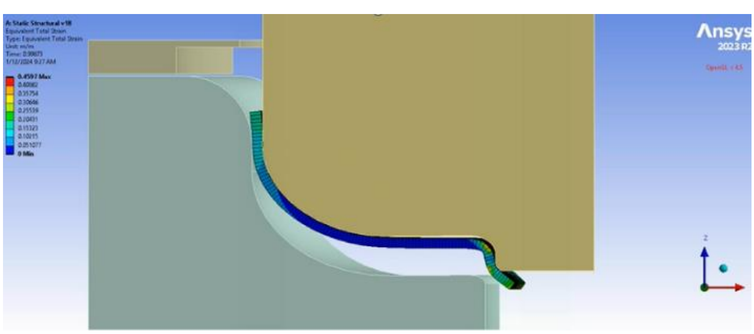

Fig. 8. An example of ANSYS simulation outcomes.

Fig. 9. Nb TW shape half cups as pressed.

Fig. 10 shows an example of CMM results of the Nb half cups as pressed (not trimmed). A square with a green dashed line indicates the pressed cup profiles are within ±0.1 mm from the design. A square with a red dashed line indicates the profiles exceed more than 0.1 mm, the max was +0.3 mm, from the design. Outcomes and raw data of CMM are shared and discussed between the three labs. Fermilab and Jefferson lab are making feedback into the model of die and simulations, major focuses are paid on an iris shape and a spring back effect (Fig. 11). The Nb half-cups fabricated by the test presses are usable to exercise and optimize EBW under narrow gap, KEK is preparing a welding test of iris joint.

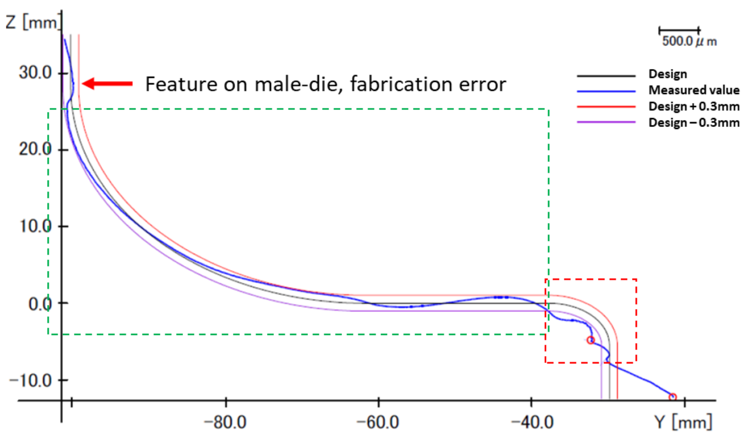

Fig. 10. An example of CMM results on TW half cups by KEK.

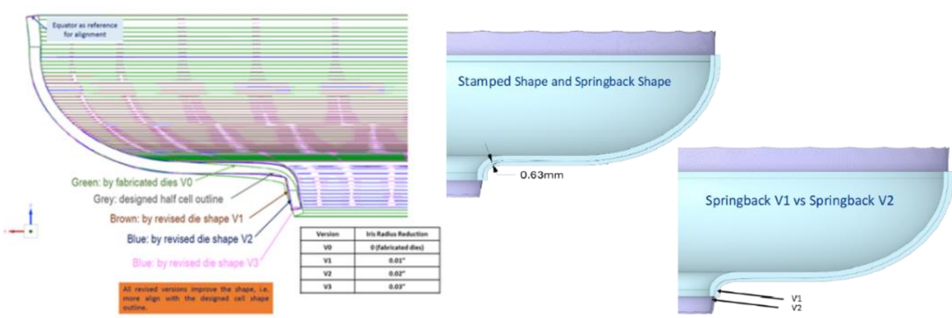

Fig. 11. Revised die designs and simulation results by Fermilab (left) and LS-DYNA simulation results by Jefferson lab (right).

5 Summary

Development of a half-meter scale (7-cell) TW SRF cavity was launched to advance TW technologies necessary for future accelerator-scale TW cavity. A preliminary RF design is proposed by Fermilab based on the lessons learned from the 3-cell TW developments and accomplishments. New RF features to excite and control TW resonance in the structure are also proposed in that design. The 1st milestones towards a TW 7-cell cavity are set. TW shape half-cell fabrication was carried out in collaboration between Fermilab, Jefferson lab, and KEK as a 1-year project under the US-Japan program. Fabrication of a low-cost mock-up waveguide loop to demonstrate new RF features, such as double directional coupler and two WG tuner (matcher) system, is in progress under the Fermilab LDRD program.

Acknowledgments

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