Update on Traveling Wave Cavity Progress at Fermilab

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TTC meeting

December 6th, 2023

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- Introduction
- TW SRF cavity development
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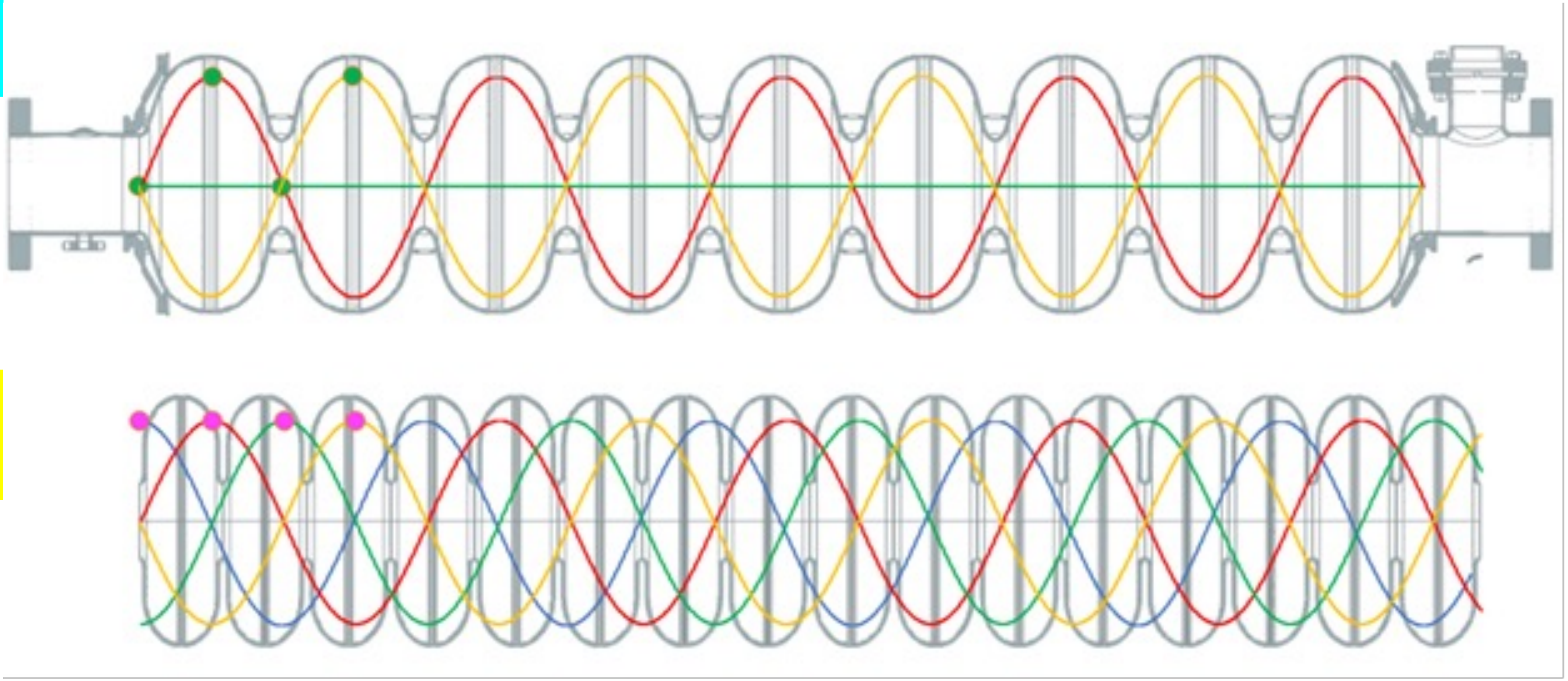
Introduction; Standing Wave and Traveling Wave

Standing Wave
in 9-cell structure

Traveling Wave
in 16-cell structure



Illustrations of time-to-time accelerating field gradient profile in SW mode (Top, 9-cell structure) and TW mode (bottom, 16-cell structure). The points identify the amplitude of the field acting on the particle in sequential time-steps.

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Motivations

- TW enables:
  - >20% increase in acceleration/cavity with higher transit time factor *T (SW ~0.7, TW ~0.9* [1]*).*
  - >20% increase in acceleration/CM with longer cavities (more acceleration field).
- **Overall 50% higher accelerating efficiency than SW structures is feasible.**
- Cost reductions per TW regime rely on mature, industry-standard practices.
- Well-developed TW technology brings a range of exciting high-energy compact linear collider concepts within the realm of possibility.
- An example, the proposed TW-based linear collider HELEN [2] 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.

[1] P. Avrakhov et al., "Traveling Wave Accelerating Structure for A Superconducting Accelerator", Proceedings of the PAC2005, pp. 4296-4298
[2] S. Belomestnykh et al., "Superconducting radio frequency linear collider HELEN," *JINST* **18**, P09039 (2023)

TW SRF cavity development

Conceptual design
Superconducting Traveling-Wave accelerating structure with feedback waveguide to circulating RF power from the structure output to the structure input.

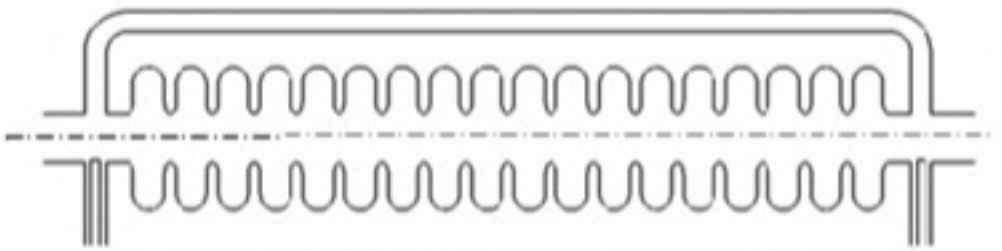
Feasibility study
a single-cell cavity w/ feedback waveguide to demonstrate high gradient operation and conduct RF field measurements.

A proof-of-principle
- 3-cell TW cavity and a special tuner fabricated
- Demonstrated TW excitation at room temp.

In progress
- The 1st cold test to demonstrate TW resonance excitation in 2K liquid is ongoing at IB1 VTS.

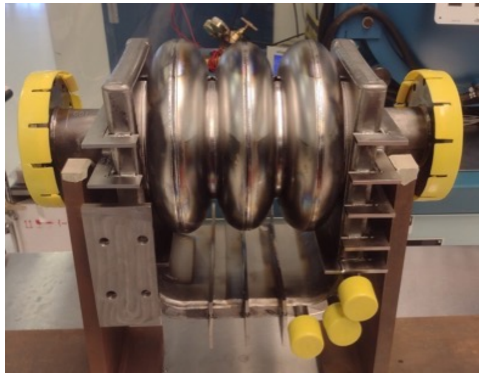
New Project

In progress
- FY23 US-Japan "Developing high-gradient traveling wave SRF accelerating cavity" in collaboration between KEK-Jlab-FNAL is awarded for 1-year which focuses on EBW optimization for the iris joint within the narrow gap.


Conceptual design by Pavel Avrakhov

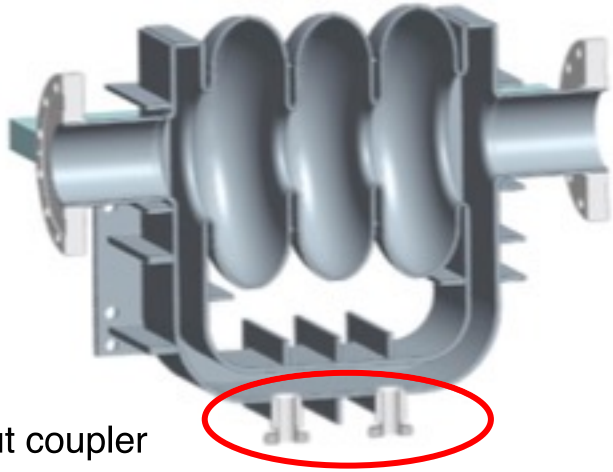

1-cell w/ WG

A proof-of-principle 3-cell TW cavity

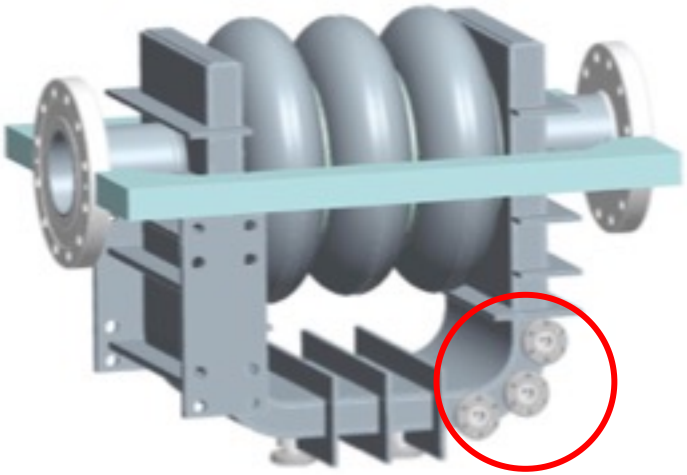


The early stages of the 3-cell developments had been funded by SBIR grant to Euclid Techlabs (DOE SBIR Grant # DE-SC0006300).

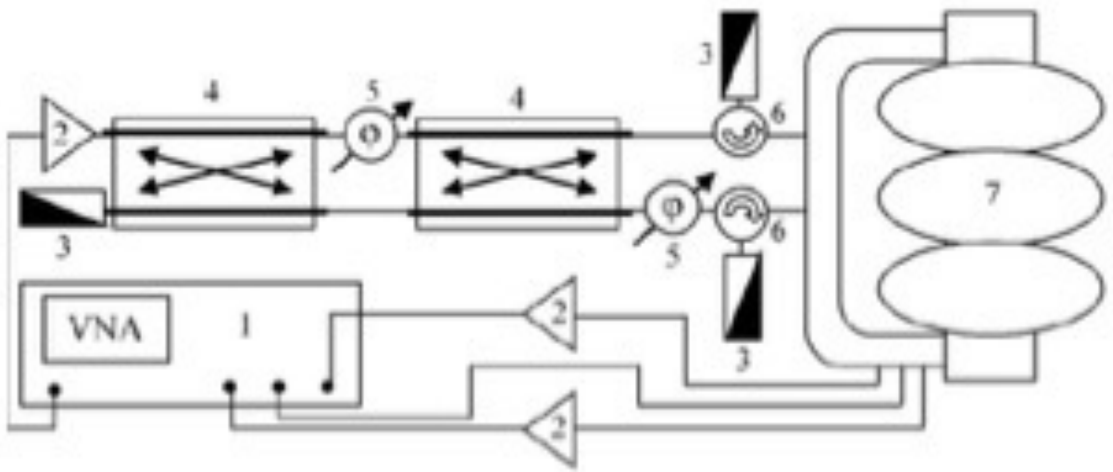
RF feed and measurement scheme for the 3-Cell TW cavity



Two Input coupler



Three monitoring couplers
- Forward wave signal
- Calibration signal
- Backward wave signal

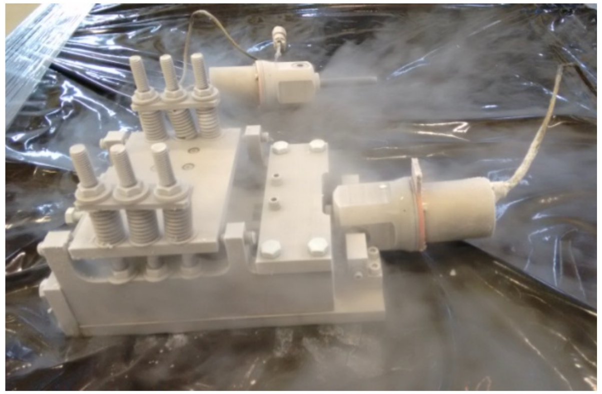


RF feed and measurement scheme for the 3-Cell TW[3]
1 –Vector Network Analyzer (VNA);
2 – power amplifier;
3 – matched load;
4 – 3dB hybrid;
5 – phase shifter;
6 – circulator;
7 – resonator

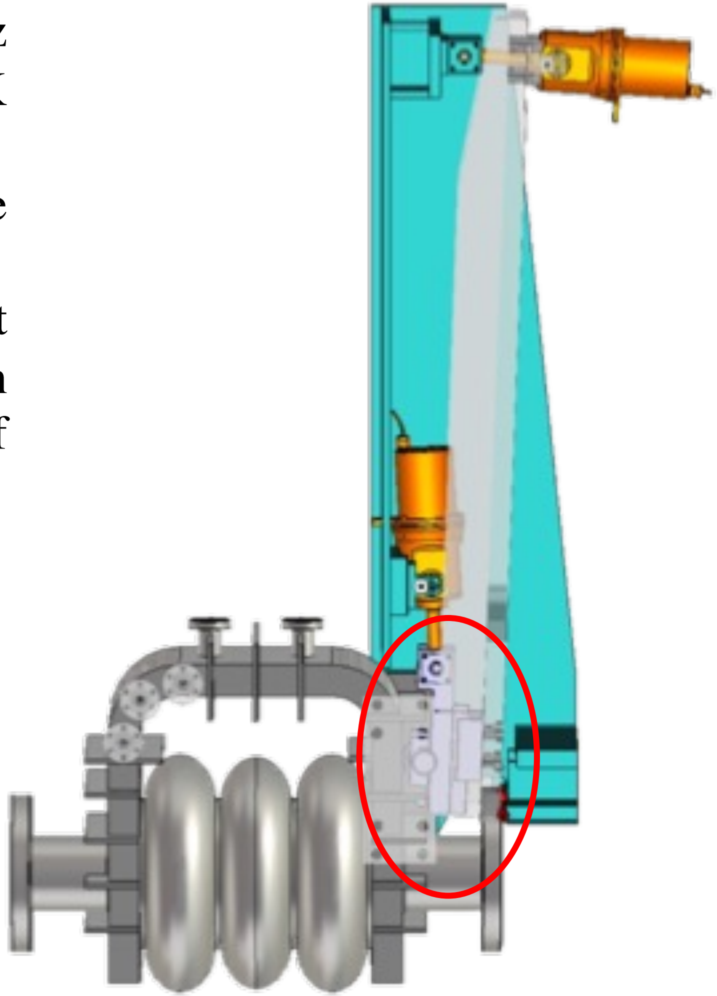
[3] R. Kostin et al. "Progress towards 3-cell super-conducting traveling wave cavity cryogenic test," *Journal of Physics: Conf. Series* 941 (2017) 012100

Special tuner (Matcher) for the 3-cell TW cavity

- designed and fabricated to compensate Lorentz force and maintain the TW resonance at 2 K VTS conditions.
- will deform the waveguide wall and decouple partial modes to compensate the Lorentz force.
- The preliminary test on the matcher test assembly at room and liquid nitrogen temperatures indicated the feasibility of achieving TW resonance in 2 K.



Matcher for the 3-cell tested in liq. N2 temp [4]

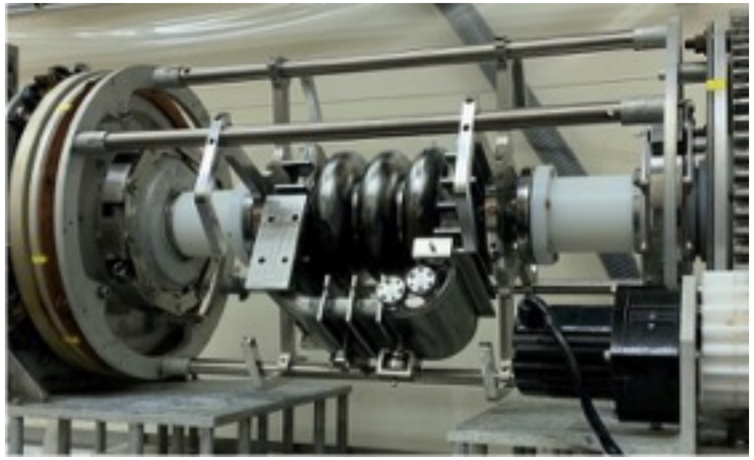


Model of the 3-cell with one Matcher.

Assembly test

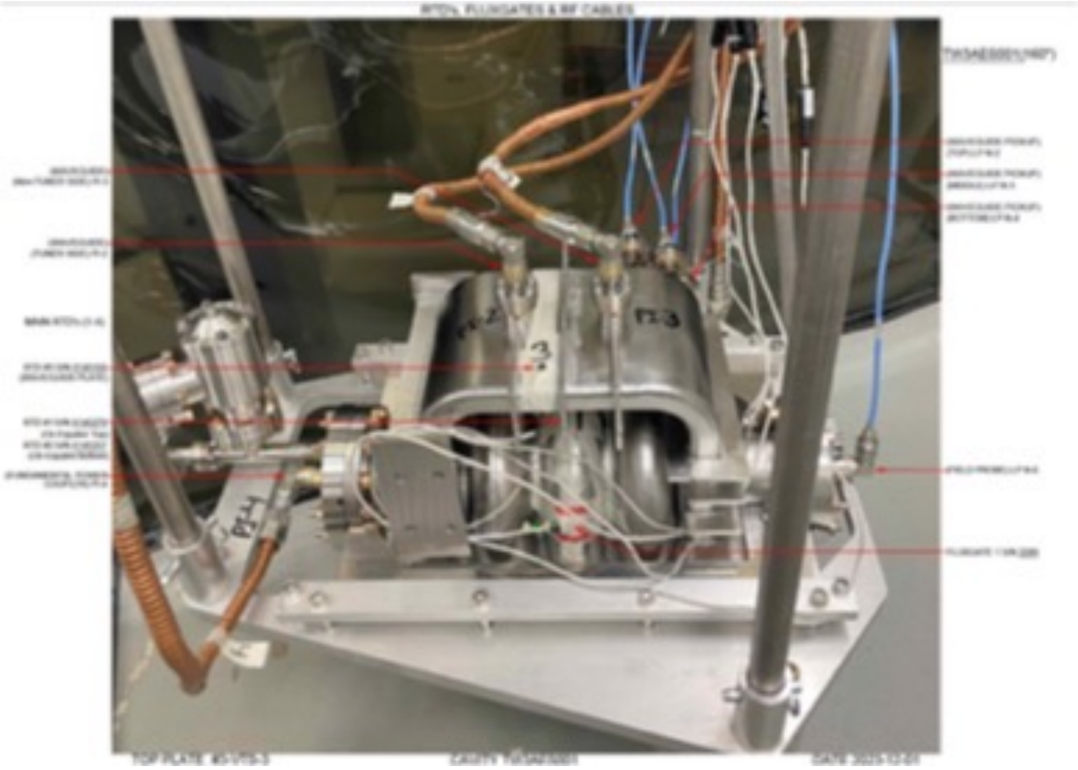
[4] R. Kostin et al., "A tuner for a superconducting traveling wave cavity prototype," *Journal of Instrumentation* 10.10 (2015): P10038

TW 3-cell VTS preparations

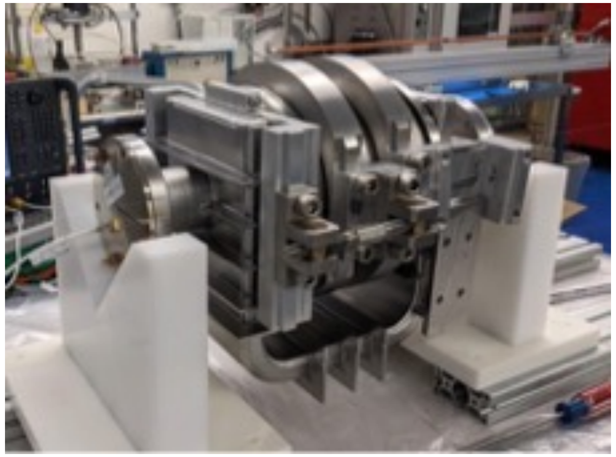


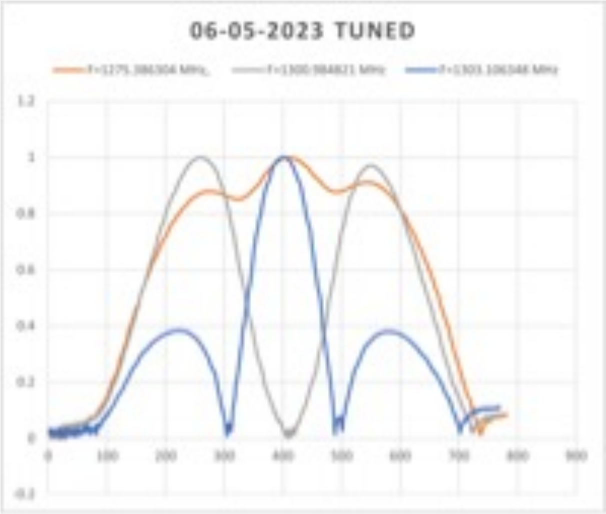
BCP at ANL

HPR at IB4, FNAL



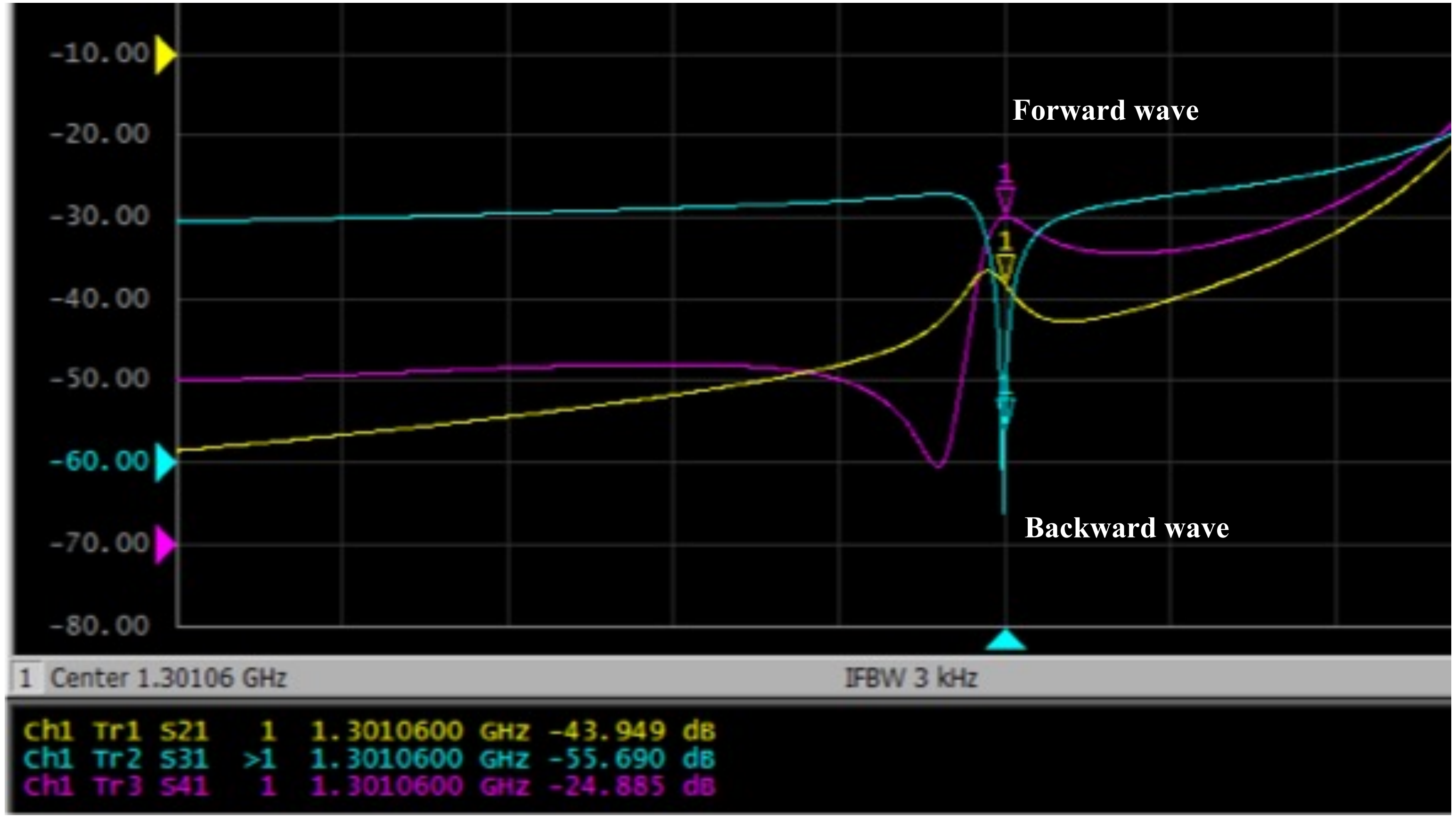
VTS instrumentations

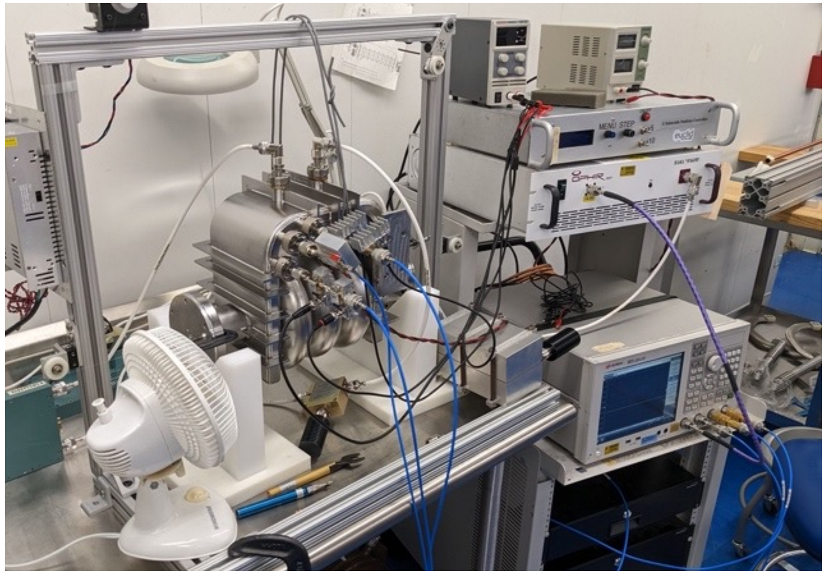




Tuning hardware on the 3-cell and the field profiles (SW mode) post tuning.

TW demonstration; Cavity with air, room temp. at RF test bench



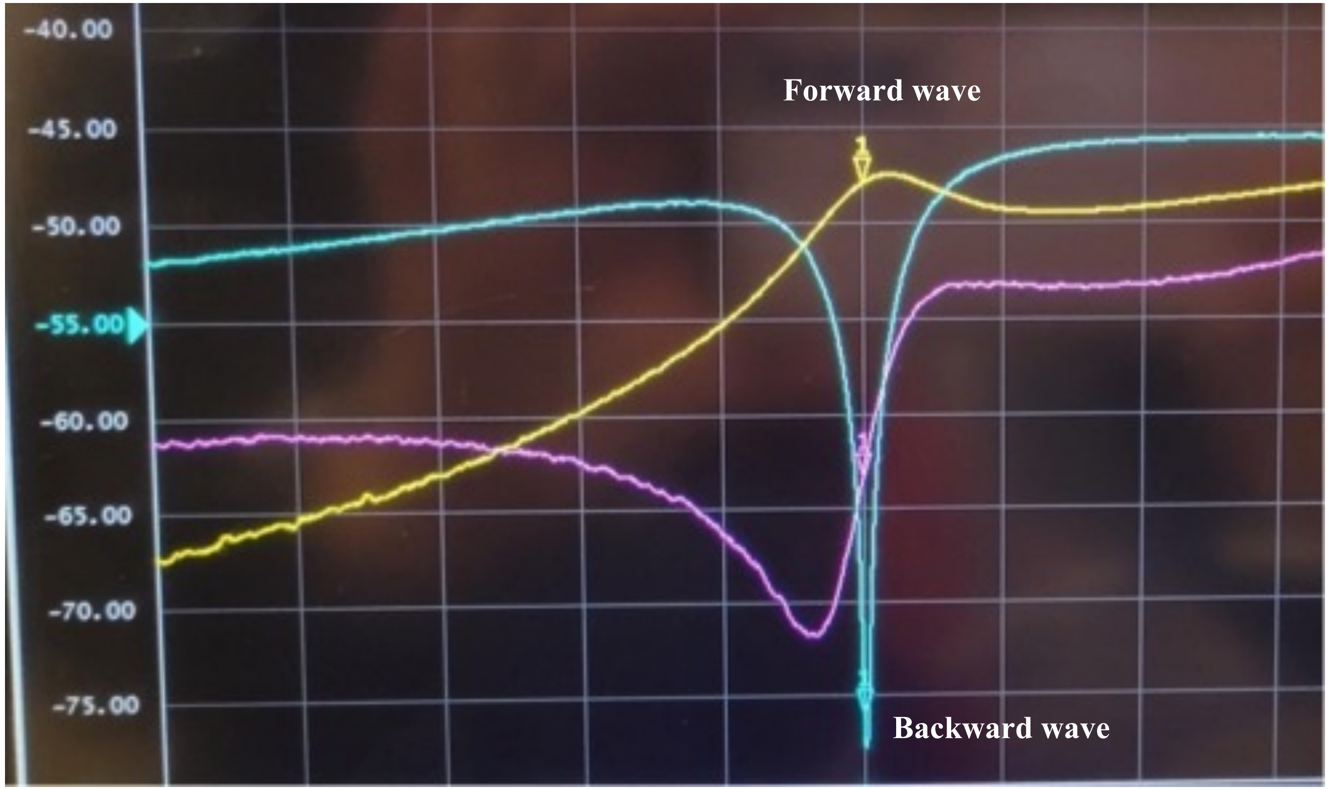


The 3-cell on RF test bench

An example of TW at 1301.06 MHz excited at room temperature after cell tuning

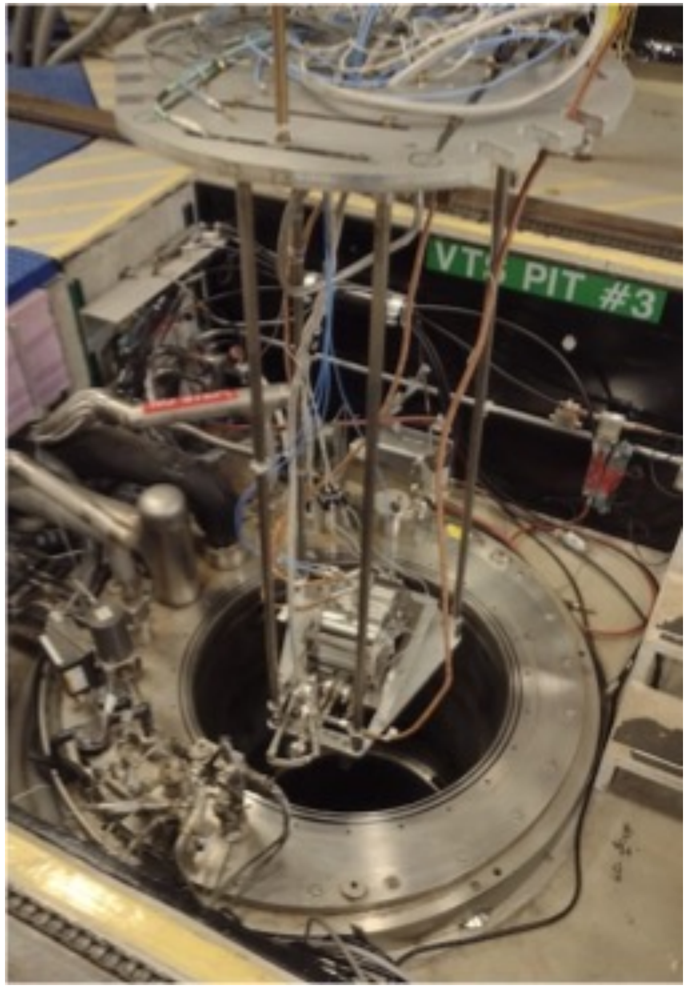
- Magenta; a forward wave signal
- Blue; a suppressed backward wave signal (~30dB less than forward)
- Yellow; a signal from the calibration pick up.

TW demonstration; Cavity under vacuum, at room temp. in VTS



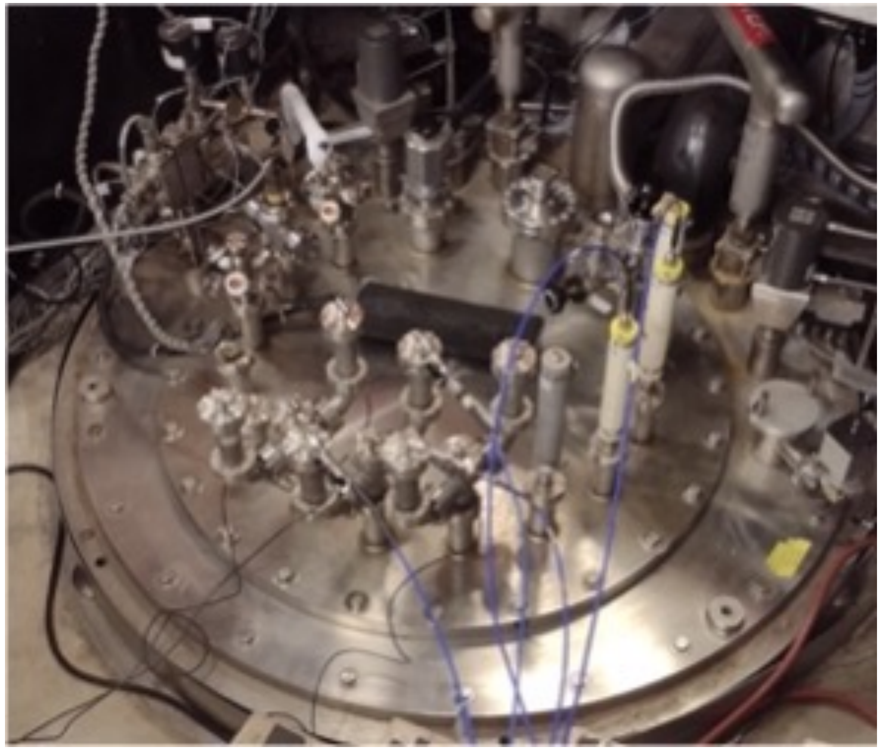
An example of TW at 1301.100 MHz excited at room temperature

- Yellow; a forward wave signal
- Blue; a suppressed backward wave signal (~30dB less than forward)
- Purple; a signal from the calibration pick up.



The 3-cell installation into VTS pit

TW demonstration; Cavity under vacuum, in 2K liquid helium, VTS



Top plate in VTS pit with TW test arrange.

An example of TW at 1303.155 MHz being tuned at 2K

- Yellow; a forward wave signal
- Blue; a suppressed backward wave signal (>30dB less than forward)
- Purple; a signal from the calibration pick up.

Summary

- SRF TW cavity development through the 3-cell has been progressing at Fermilab in collaboration with Euclid Techlabs.
- Preliminary TW resonance excitation in the 3-cell structure in 2K liquid helium was demonstrated.
- More hardware improvements and TW study with the 3-cell will be continued at Fermilab.
- Next stage of development toward a half-meter scale TW cavity fabrication has been discussing.
- A preliminary 7-cell TW cavity RF design and configurations being proposed in Fermilab (not presented during this TTC).

Acknowledgment

Thank to all colleagues supported the 3-cell TW works!!

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euclid TECHLABS

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- Paul Dubiel
- Man Kwan (Trista) Ng

Cryo support
- Dan Marks

and more,,,

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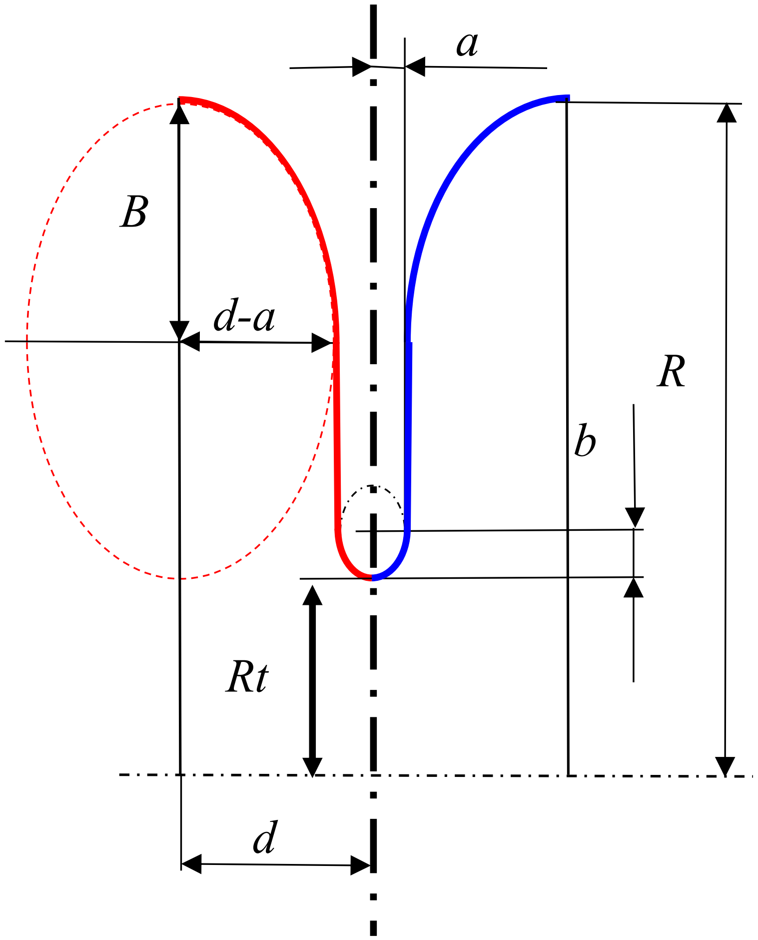
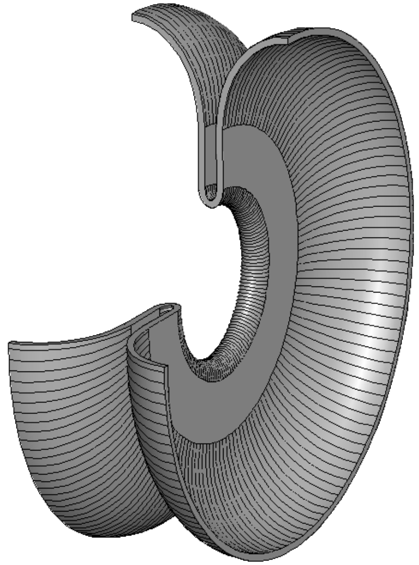
Appendix; 3-cell TW cavity inner cell shape



Parameter	105º
Aperture (mm)	60
d (mm)	33.63
a (mm)	5.3
b (mm)	7.69
R (mm)	100.21
B (mm)	38.5
KE	1.939
KH (mT/MV/m)	3.054
$KE_{STWA} / KE_{Reentrant}$	0.8079
$KH_{STWA} / KH_{Reentrant}$	0.8079
$Acc.\ rate_{STWA} / Acc.\ rate_{Reentrant}$	1.2378



The cell shape has been optimized to reach the maximum accelerating gradient while keeping the magnitude of surface magnetic and electric fields less than the experimentally verified limits.

105º phase advance

24 % gradient gain