Traveling Wave Demonstration in SRF Cavity With a Feedback Waveguide

The 2024 International Workshop on Future Linear Colliders (LCWS2024)
Session - Accelerator: Superconducting RF
Presenter : Roman Kostin, Euclid Techlabs

July 10, 2024 - The University of Tokyo, Japan

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Euclid Techlabs/Euclid Beamlabs

Euclid is an accelerator R&D company with broad area of expertise:

- Advanced materials manufacturing – conductive ceramics, ferroelectric materials, diamonds
- Accelerator components design and manufacturing – NC RF, SRF and dielectric structures
- Beam manipulations – beamline designs, time resolved TEM

A sampling of organizations that Euclid works with

U.S. DEPARTMENT OF ENERGY
CERN
NIST National Institute of Standards and Technology
JEOL
ILC
ANL
IHEP
Brookhaven National Laboratory
Argonne NATIONAL LABORATORY
Fermilab
ILLINOIS TECH CAPP
Jefferson Lab
BERKELEY LAB BELLA
SLAC FACET-II

And much more

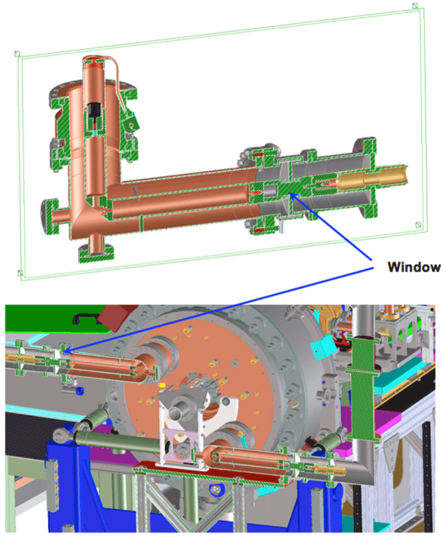
Euclid Techlabs, LLC
367 Remington Blvd, Bolingbrook, IL 60440
5.0 ★★★★★ 1 review
View larger map

accelerator R&D lab in IL

10000 Virginia Manor Rd #330
10000 Virginia Manor Rd #330, Beltsville, MD 20705
View larger map

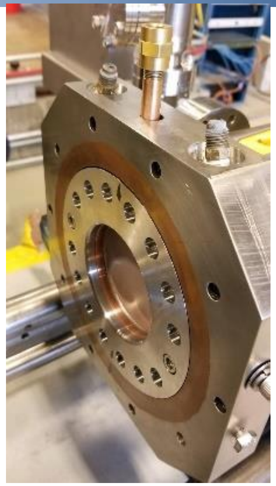
material science lab in MD

Low RF Loss DC Conductive Ceramic Windows

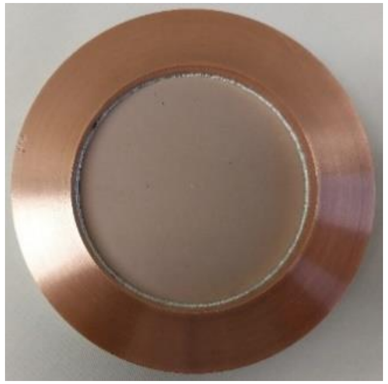


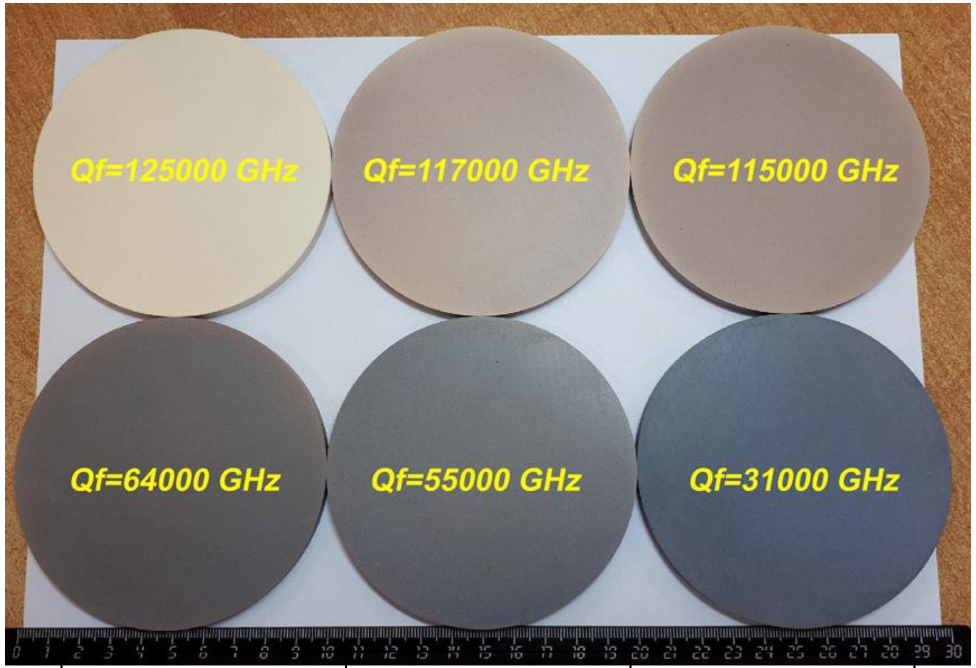
Major reasons for window failure include charging from the "triple junction“, multipacting and electron halo.

A new low-loss microwave ceramic material with increased DC electrical conductivity and low loss tangent for use in high power coupler windows.



- Increased conductivity from 10^{-12} to 10^{-8} S/m
- Relative dielectric constants ε_r=15
- Loss tan ~ 1×10^{-5} @ 650 MHz

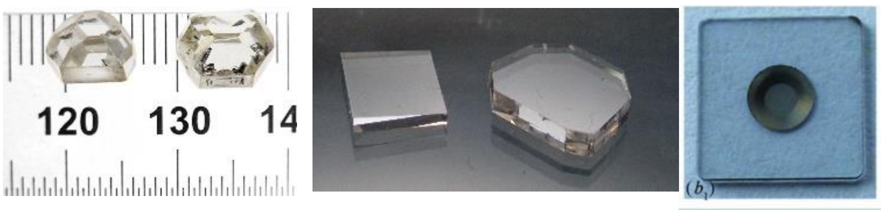


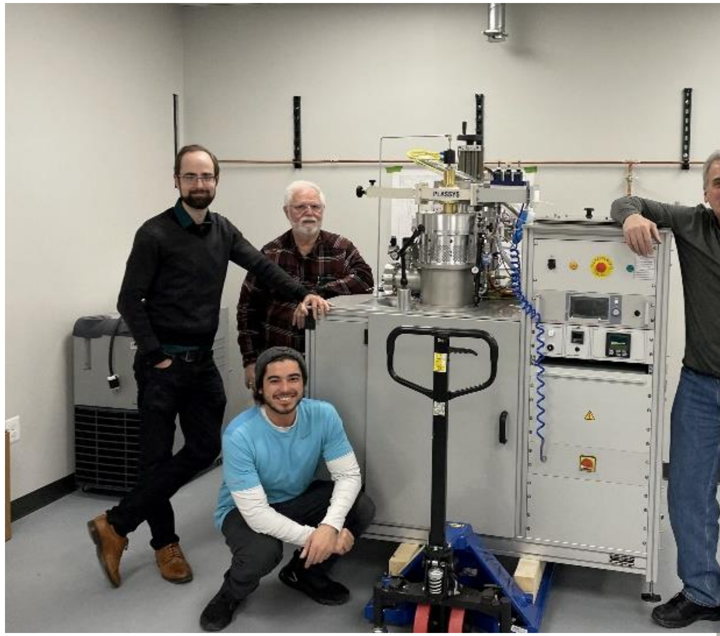


5.2x10^-6	5.5x10^-6	5.6x10^-6
1.0x10^-5	1.9x10^-5	2.1x10^-5

https://euclidtechlabs.com/

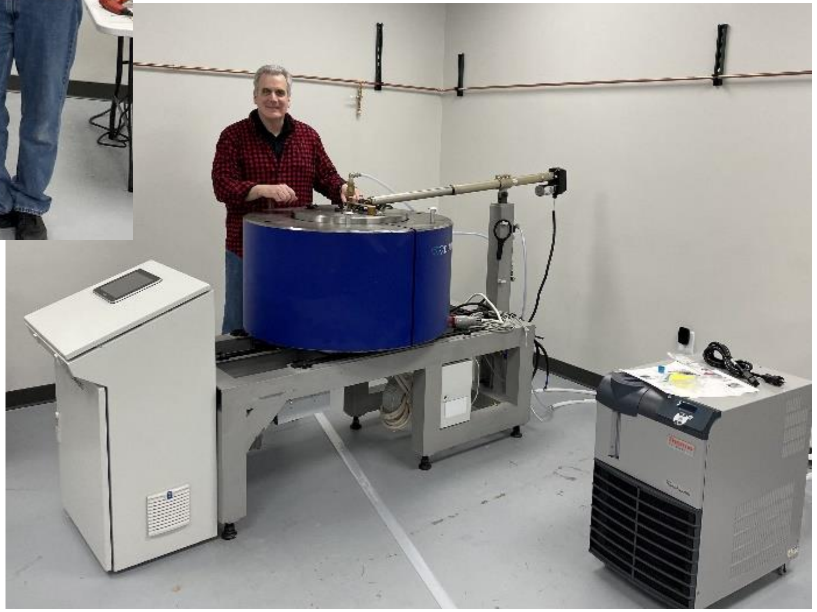
X-ray Optics for Light Sources. Domestically Produced Synthetic Diamonds for SLAC and ANL.





Presently, there are no suppliers in the US to provide scalability and manufacturability of high-quality HPHT diamonds for the rapidly developing field of X-ray optics for the next generation X-ray sources.

Commissioning the CVD reactor in Beltsville, MD

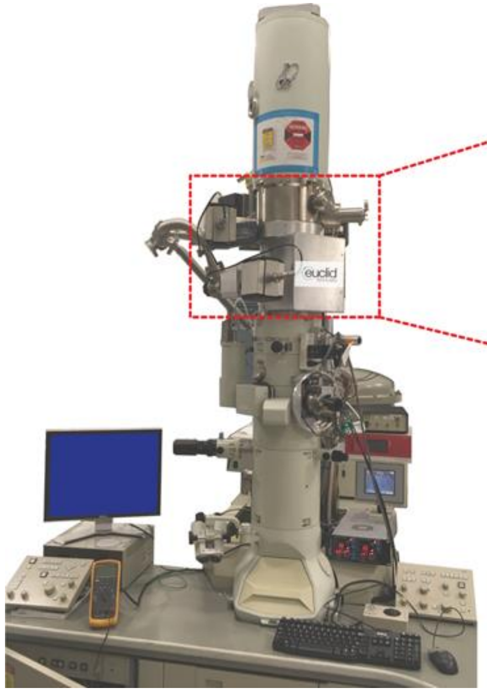


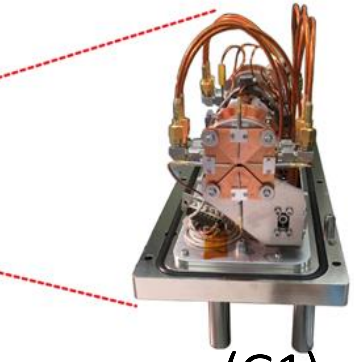
HPHT diamond growth reactor at Beltsville, MD lab

With Euclid's 2021 DOE SBIR Ph2 projects, we have commissioned the first HPHT and CVD diamond growth reactor. Euclid had previously developed techniques for growing near dislocation free diffraction-grade diamonds that were characterized and highly praised by APS/ANL and SLAC

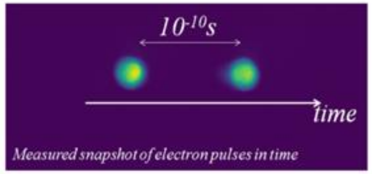
In collaboration with ANL and SLAC

Ultrafast Pulser for Transmission Electron Microscopy (in collaboration with BNL, NIST)





(G1)



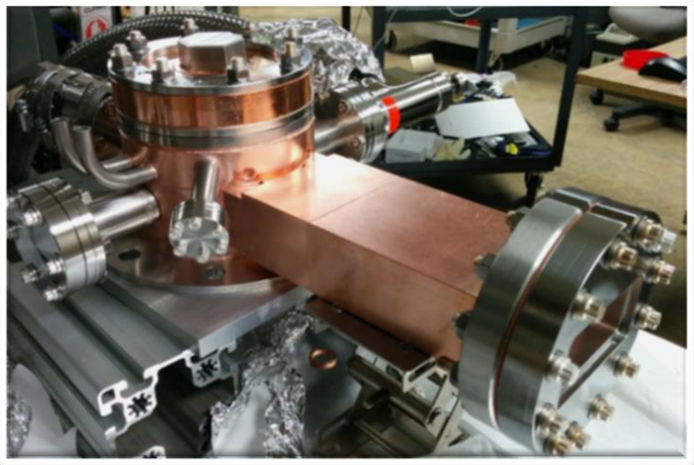
Measured snapshot of electron pulses in time

As a successful result of the DoE SBIR "Stroboscopic TEM Pulser" project, Euclid was awarded a Phase III contract ($680k) for Transmission Electron Microscope (TEM) modification at NIST in 2016-2018. The NIH $1.4M and Chan-Zuckerberg $180k awards started in 2021. Currently Euclid is installing the UltraFast Pulser at California Institute of Technology (Caltech) as part of the NIH project, and another at ER-C, Europe's largest electron microscopy center, in Jülich, Germany.

In February 2023, we confirmed full compatibility on a state-of-the-art aberration corrected instrument at JEOL Ltd (Japan)

Commercial products: Electron Sources for Accelerators

S-band 1000 pps Photogun



S-band 100MV/m Photogun

S-band Thermionic RF gun

L-band 100nC Photogun

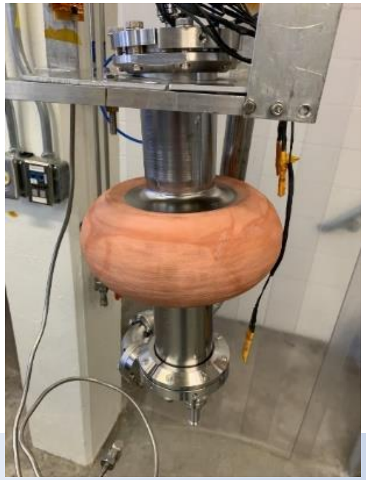
1.3GHz SRF Photogun

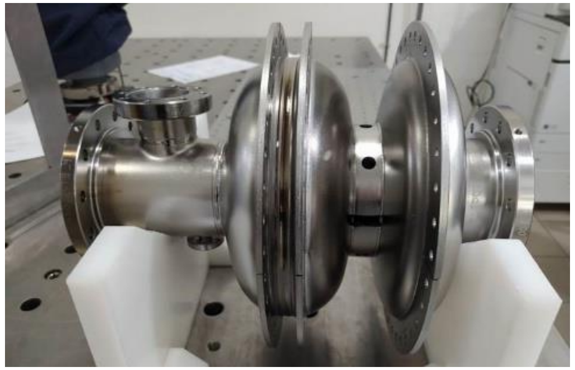
Superconducting RF Cavities and SRF Technologies for Industrial Accelerators

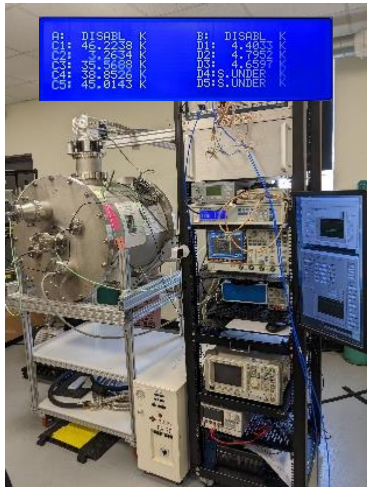
Development of MeV-range ultrafast electron diffraction/microscopy (UED and UEM) is a priority for the DOE. Euclid is developing the SRF photocathode gun that is a promising candidate to produce highly stable electrons for UEM/UED applications

Design optimization of TW structures was done. It is shown that a TW structure can have an accelerating gradient that is about 1.5 times higher than contemporary standing wave structures with the same critical magnetic field.

Euclid is developing SRF technology for conduction cooled industrial accelerator

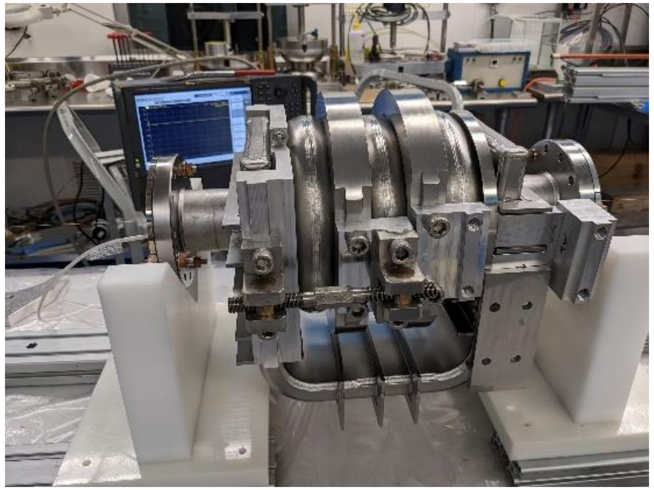




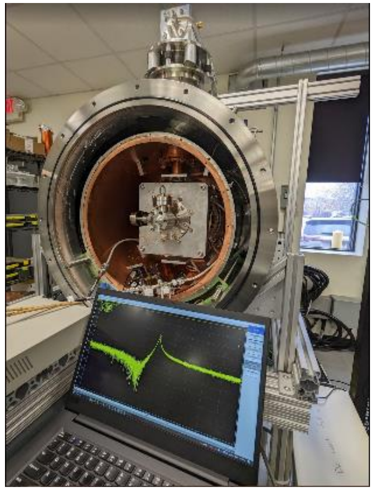


```
A:   DISABL  K        B:   DISABL  K
C1:  46.2238 K        D1:   4.4033 K
C2:   3.2634 K        D2:   4.7952 K
C3:  35.5688 K        D3:   4.6597 K
C4:  38.8526 K        D4:S.UNDER   K
C5:  45.0143 K        D5:S.UNDER   K
```

1.3 GHz SRF Photogun



3-Cell Traveling Wave Cavity



Euclid's Conduction Cooled Cryomodule

(in collaboration with FNAL, BNL and Jlab)

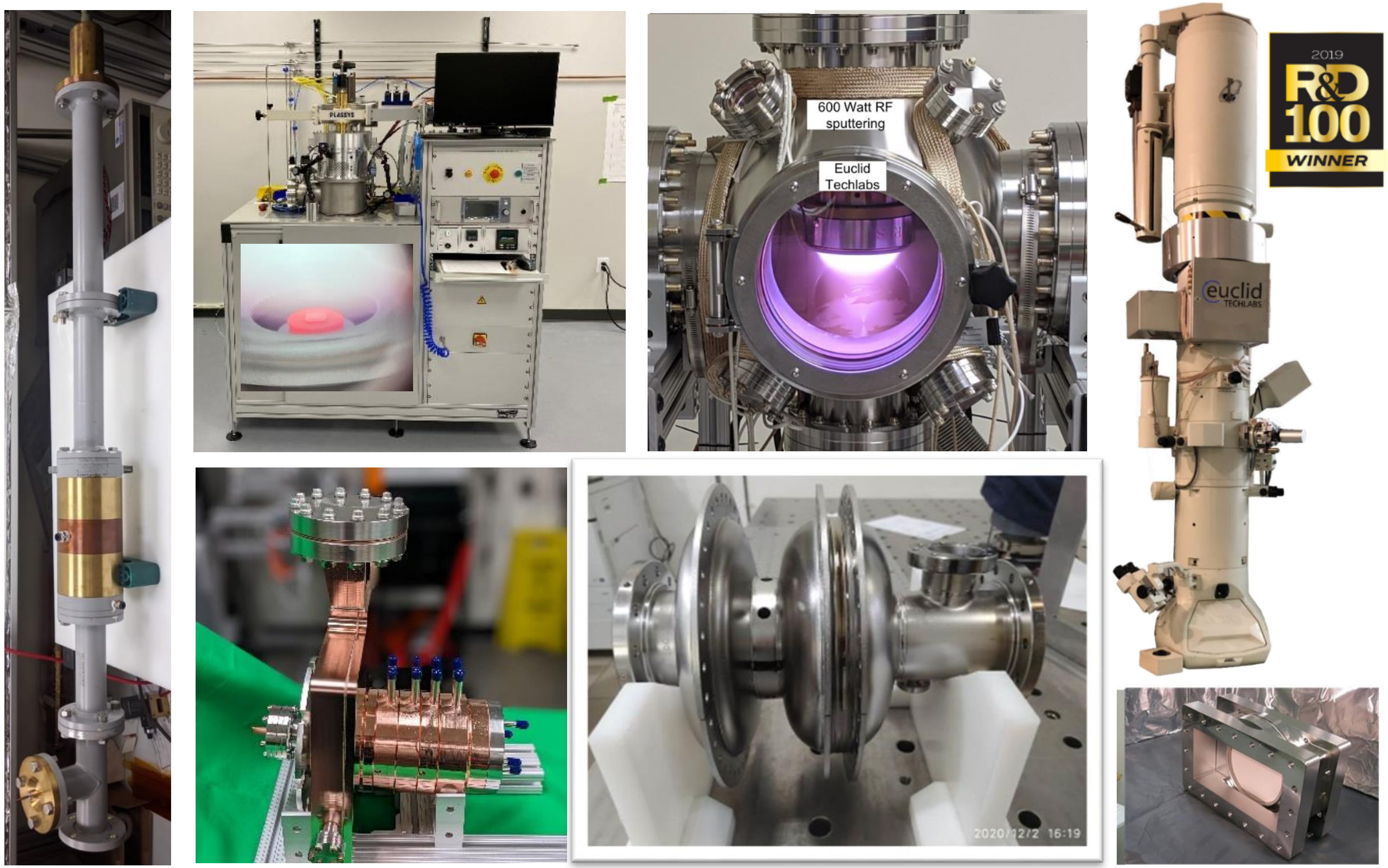
Products & Capabilities Snapshot

Products

- UltraFast Pulser (UFP^{TM}) for TEM
- Dislocation free (HPHT&CVD) diamond for Xray optics
- Compact X-Ray Source
- NCRF and SRF electron sources
- Low loss ceramics (linear and non-linear)
- LINAC
- RF window
- In flange BPM

Capabilities

- Femtosecond Laser Ablation System
- Thin Film Deposition Lab
- EM/RF Testing Lab
- Radiation Shielding/Testing Lab
- Cryogenic 4K measurements
- Custom designs and consulting

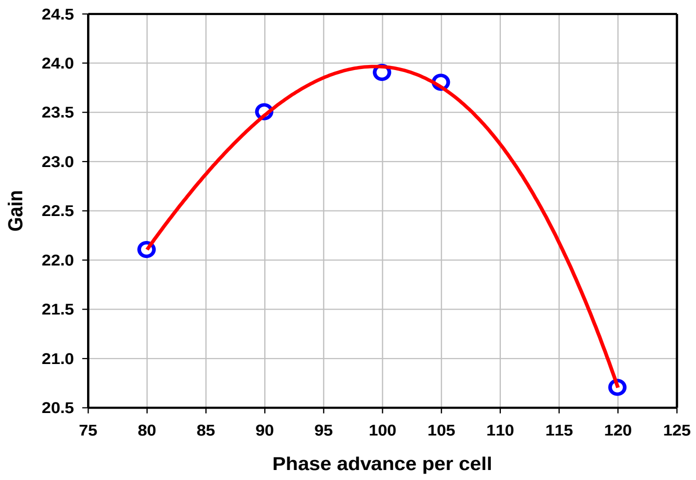


Motivations

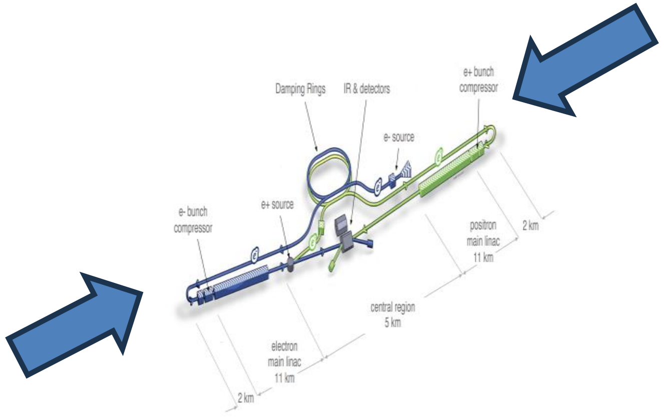
- TW enables:
  - >20% increase in Eacc b.o. higher transit time factor *T at lower phase advances (SW ~0.64, TW ~0.87* [1]*).*

$$T = \frac{\sin\theta/2}{\theta/2}$$

  - >20% increase in Eacc b.o. longer cavities (more real estate gradient)
- **Overall 50% higher accelerating efficiency than SW structures is feasible: Eacc>70MV/m**
- TW SRF makes linear collider a bit closer to reality.
- Initially was intended for ILC, now considered for HELEN
- The proposed TW-based linear collider HELEN [2] can achieve a 250 GeV center-of-mass energy in only 7.5 km, in contrast to the 30-km scale of the SW ILC structure.



Eacc gain at 70mm aperture

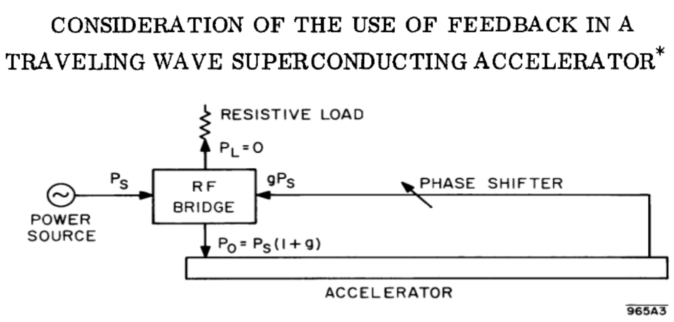


[1] P. Avrakhov et al., "Traveling Wave Accelerating Structure for A Superconducting Accelerator", Proceedings of the PAC2005, pp. 4296-4298

[2] S. Belomestnykh et al., “Superconducting radio frequency linear collider HELEN,” *JINST* **18**, P09039 (2023)

TW SRF cavity development milestones

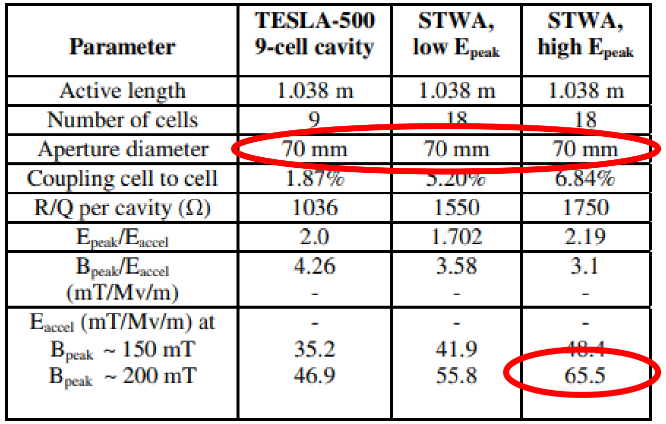
TW SRF proposed by **R.B. Neal at SLAC** 1968!



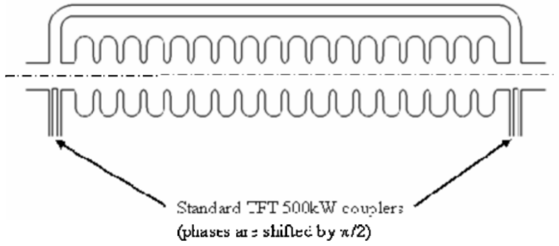
SLAC-TN-68-1
January 1968
R. B. Neal

CONSIDERATION OF THE USE OF FEEDBACK IN A TRAVELING WAVE SUPERCONDUCTING ACCELERATOR*

First materialization of the concept **2005**



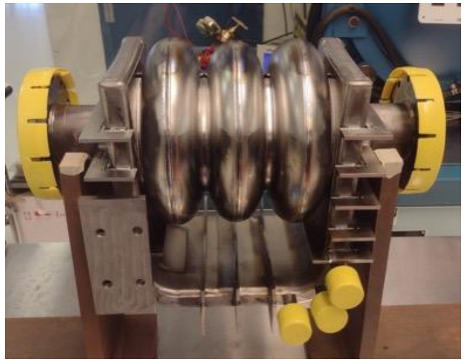
Parameter	TESLA-500 9-cell cavity	STWA, low E_{peak}	STWA, high E_{peak}
Active length	1.038 m	1.038 m	1.038 m
Number of cells	9	18	18
Aperture diameter	70 mm	70 mm	70 mm
Coupling cell to cell	1.87%	5.20%	6.84%
R/Q per cavity (Ω)	1036	1550	1750
E_{peak}/E_{accel}	2.0	1.702	2.19
B_{peak}/E_{accel} (mT/Mv/m)	4.26 -	3.58 -	3.1 -
E_{accel} (mT/Mv/m) at B_{peak} ~ 150 mT B_{peak} ~ 200 mT	- 35.2 46.9	- 41.9 55.8	- 48.4 65.5



[1] P. Avrakhov, A. Kanareykin, N.Solyak: "Traveling Wave Accelerating Structure for A Superconducting Accelerator", Proceedings of the PAC2005, pp. 4296-4298

[2] Roman Kostin et al 2015 Supercond. Sci. Technol. 28 095007

Euclid Techlabs funded by
DOE SBIR DE-FG02-06ER84462
1-cell SW cavity developed by **Euclid**
Processed and tested at **Fermilab 2010**

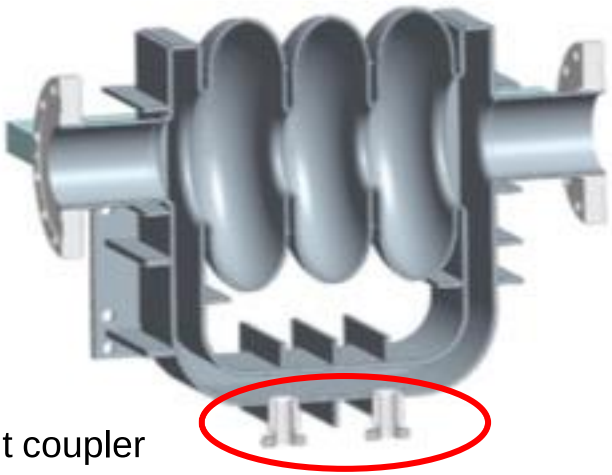


Euclid Techlabs funded by DOE SBIR DE-SC0006300
3-cell TW cavity developed by **Euclid** - 2013
Processed and tested at **Fermilab** – 2022
First TW SRF demonstrated 2023!

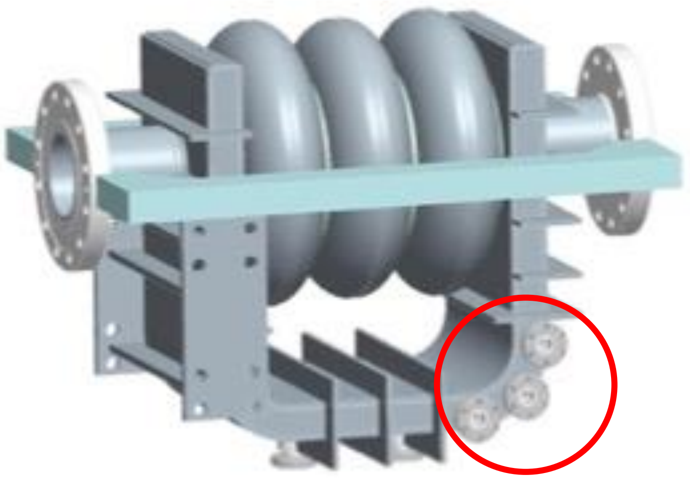
- Very limited funding – extremely slow progress!
- Special thanks to
  - V.Yakovlev,
  - H.Padamsee
  - S.Belomestnyh

  for pushing interest to this technology!
- See the next talk by Fumio Furuta on 0.5m long structure

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

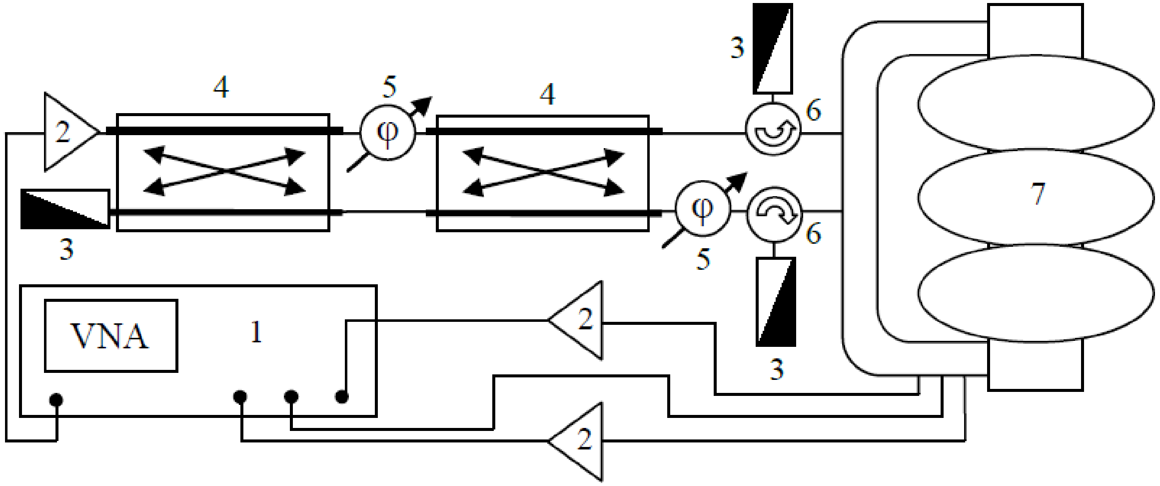


Two Input coupler



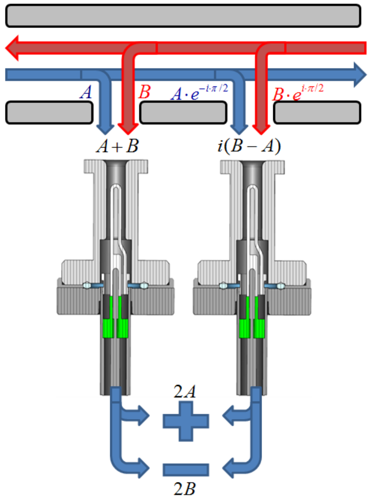
Three monitoring couplers

- Forward wave signal
- Calibration signal
- Backward wave signal



RF feed and measurement scheme for the 3-Cell TW[3]

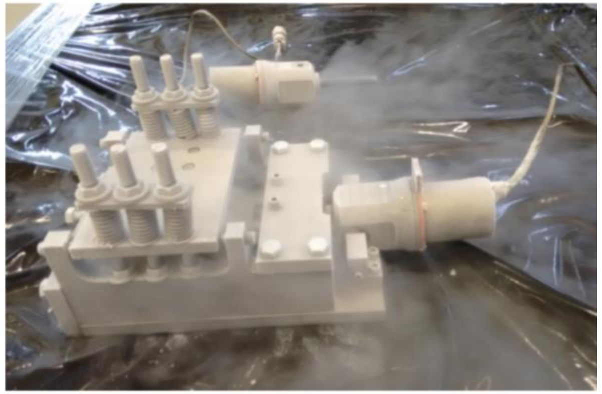
1 –Vector Network Analyzer (VNA);
2 – power amplifier;
3 – matched load;
4 – 3dB hybrid;
5 – phase shifter;
6 – circulator;
7 – resonator



[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

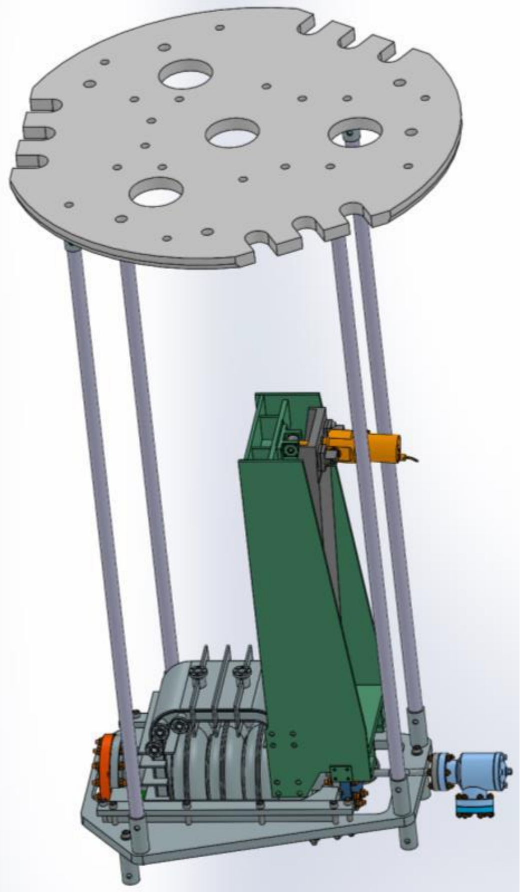
- 2D tuner/matcher – deform WG and move along the WG to compensate phase and amplitude of reflection
- designed and fabricated to compensate Lorentz force and maintain the TW resonance at 2 K VTS conditions.
- The preliminary LN2 test of the matcher confirmed the design feasibility
- Matcher was designed to fit the VTS pit.



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

Model of the 3-cell with one Matcher.

Assembly test



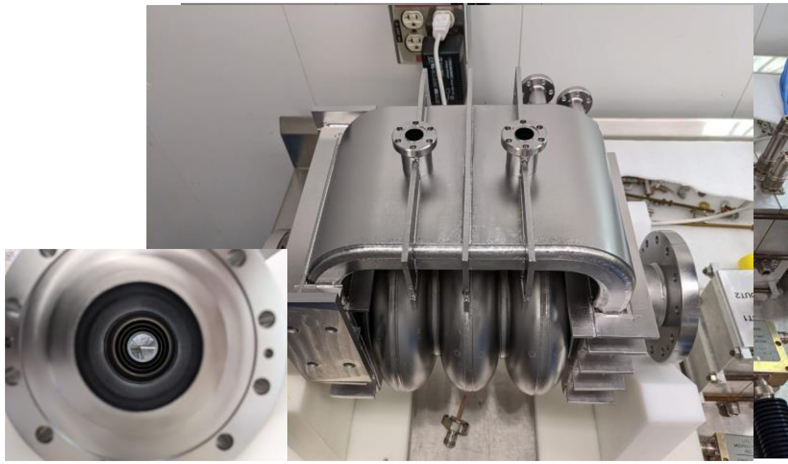
Model of the cavity w VTS HW

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

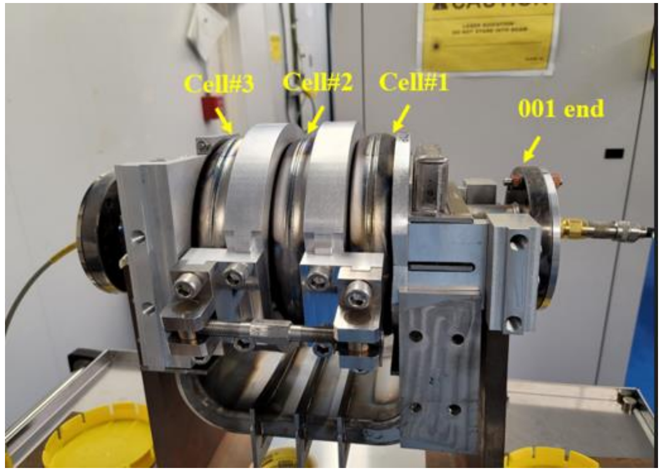
TW 3-cell VTS preparations

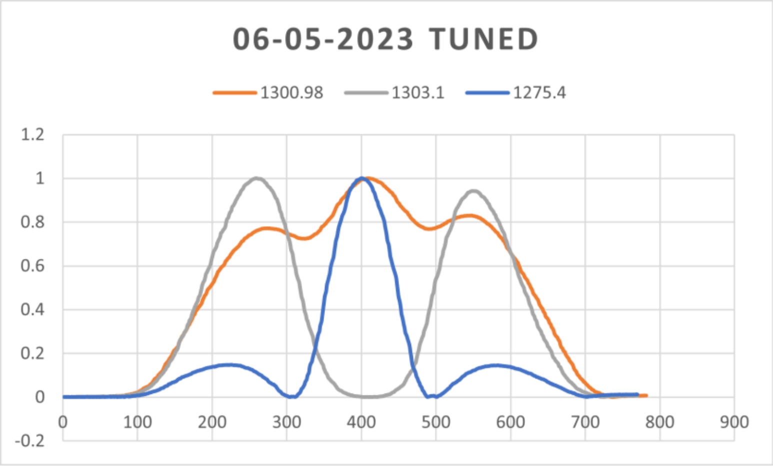
BCP at ANL

HPR at IB4, FNAL

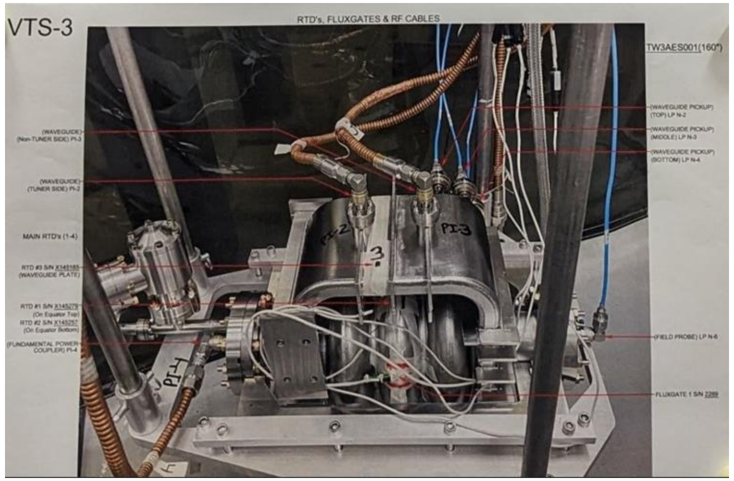


Cavity after 120um rotational BCP
800C bake, external BCP to remove oxides





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



VTS instrumentations

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

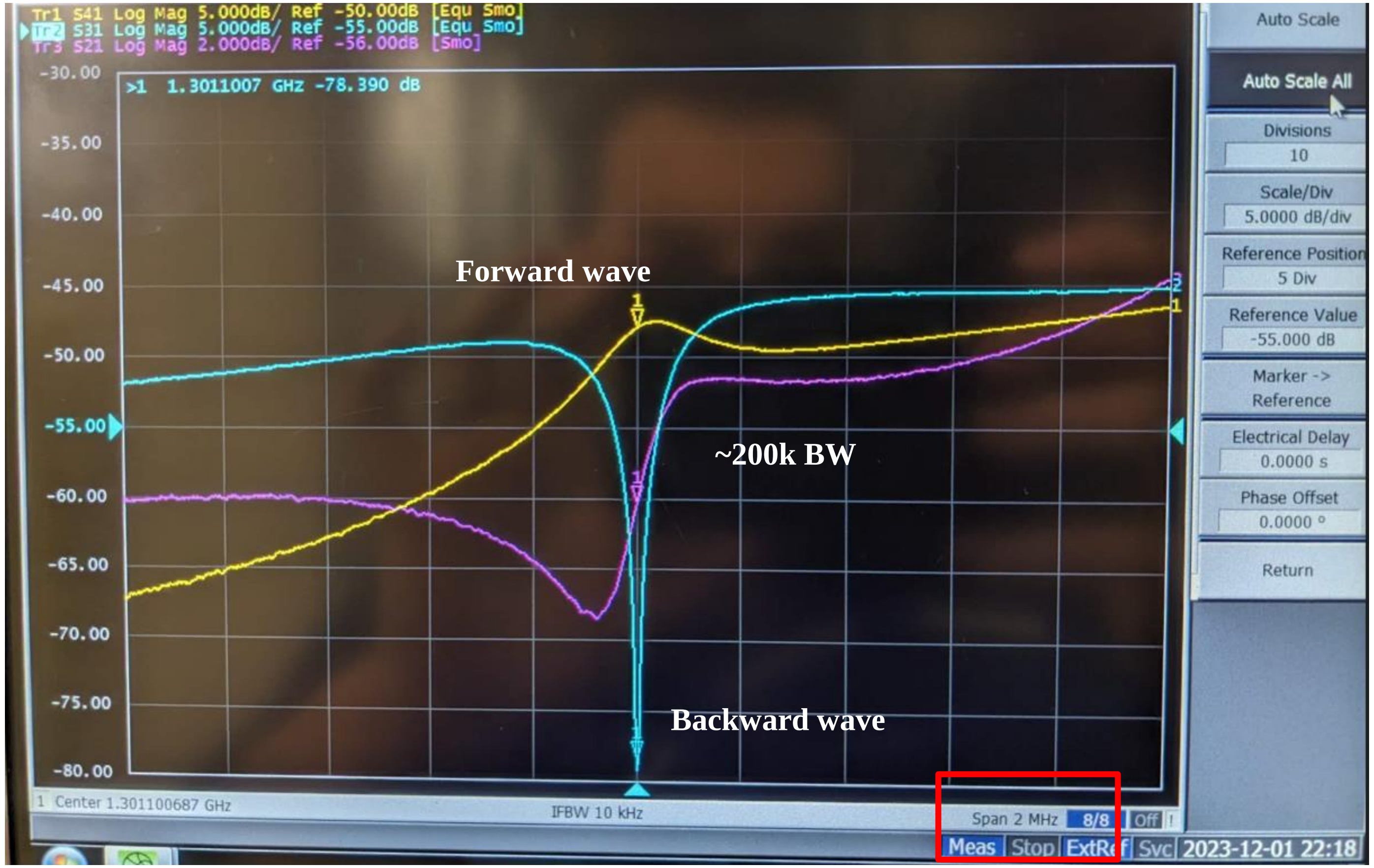
```
IF Bandwidth 1 kHz
Tr1 S21 Log Mag 10.00dB/ Ref 0.000dB [Equ D&M Smo]
Tr2 S41 Log Mag 5.000dB/ Ref -70.00dB [Equ Smo]
Tr3 S31 Log Mag 5.000dB/ Ref -70.00dB [Equ Smo]
>1  1.3005250 GHz -35.734 dB
1 Center 1.300525 GHz          IFBW 1 kHz          Span 2 MHz  32/32  Off
Ch1 Tr1 S21  >1  1.3005250 GHz -35.734 dB
Ch1 Tr2 S41   1  1.3005250 GHz -89.377 dB
Ch1 Tr3 S31   1  1.3005250 GHz -53.643 dB
```

The 3-cell on RF test bench

An example of TW at 1300.53MHz (700k away from resonance 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



Tr1 S41 Log Mag 5.000dB/ Ref -50.00dB [Equ Smo]
Tr2 S31 Log Mag 5.000dB/ Ref -55.00dB [Equ Smo]
Tr3 S21 Log Mag 2.000dB/ Ref -56.00dB [Smo]

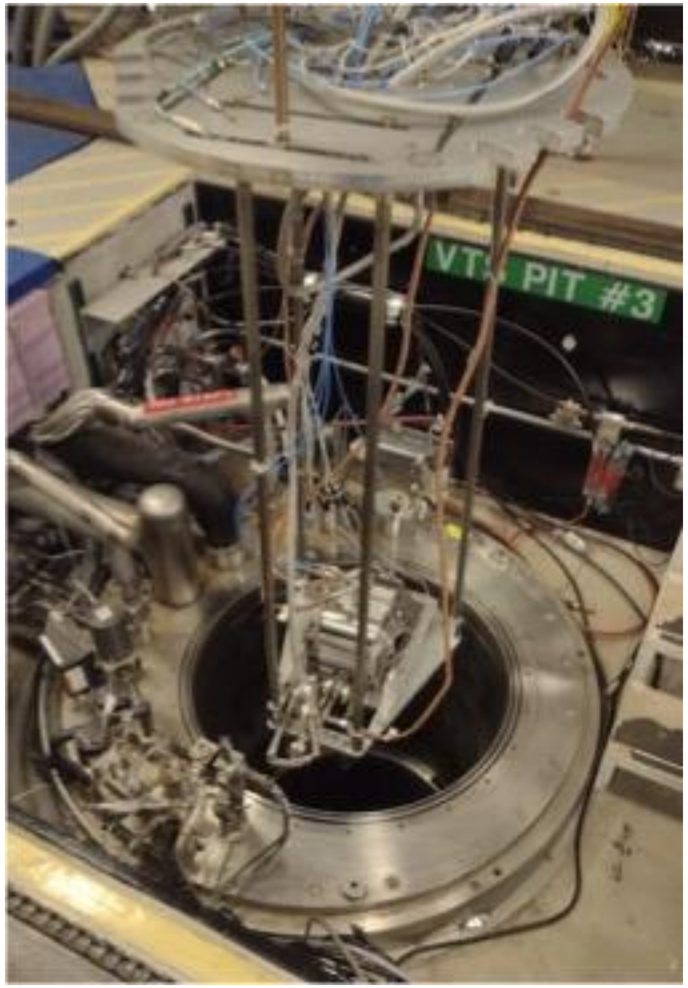
>1 1.3011007 GHz -78.390 dB

Divisions: 10
Scale/Div: 5.0000 dB/div
Reference Position: 5 Div
Reference Value: -55.000 dB
Electrical Delay: 0.0000 s
Phase Offset: 0.0000 °

1 Center 1.301100687 GHz
IFBW 10 kHz
Span 2 MHz
2023-12-01 22:18

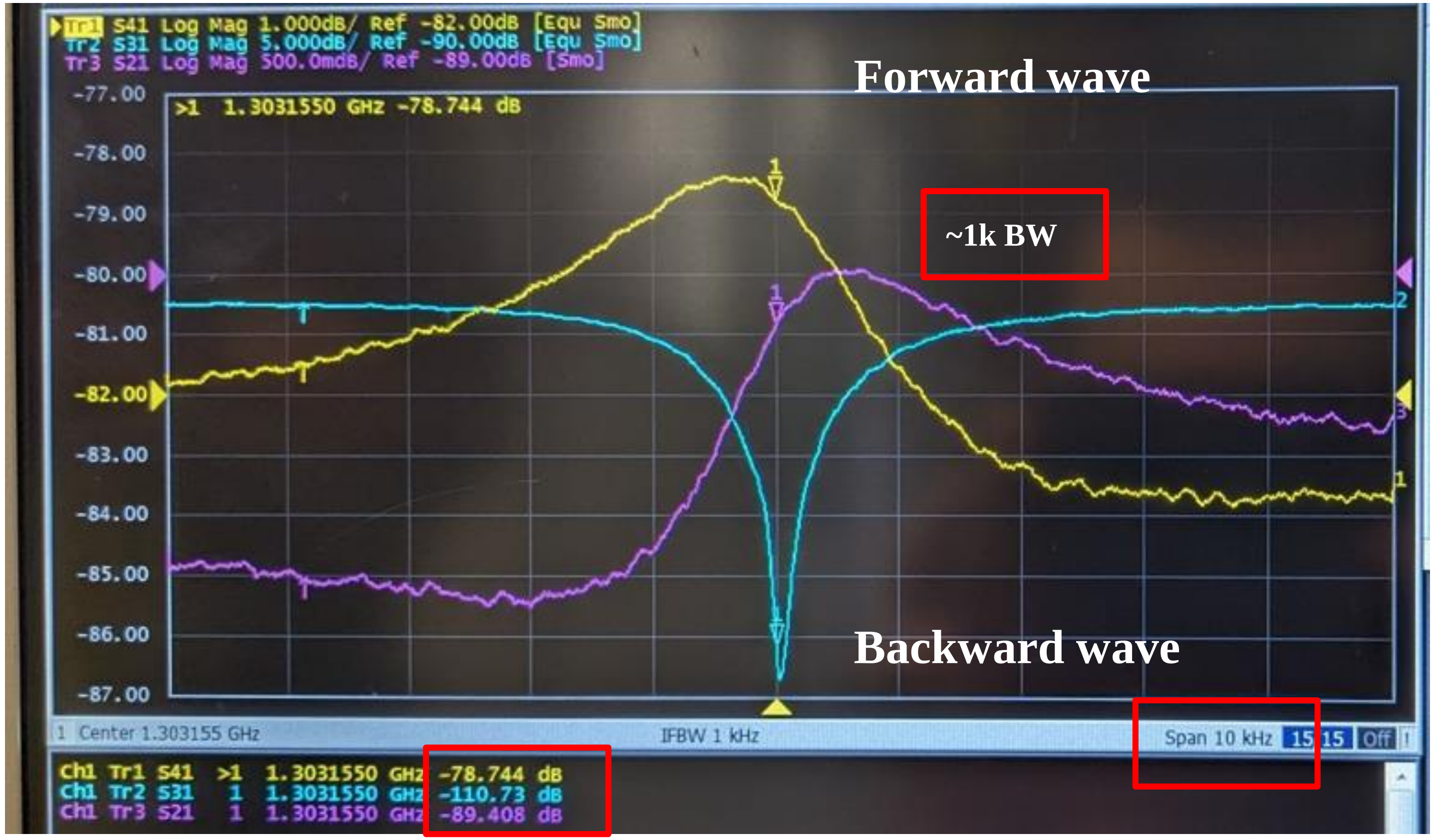
An example of TW at 1301.100 MHz excited at room temperature

- 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

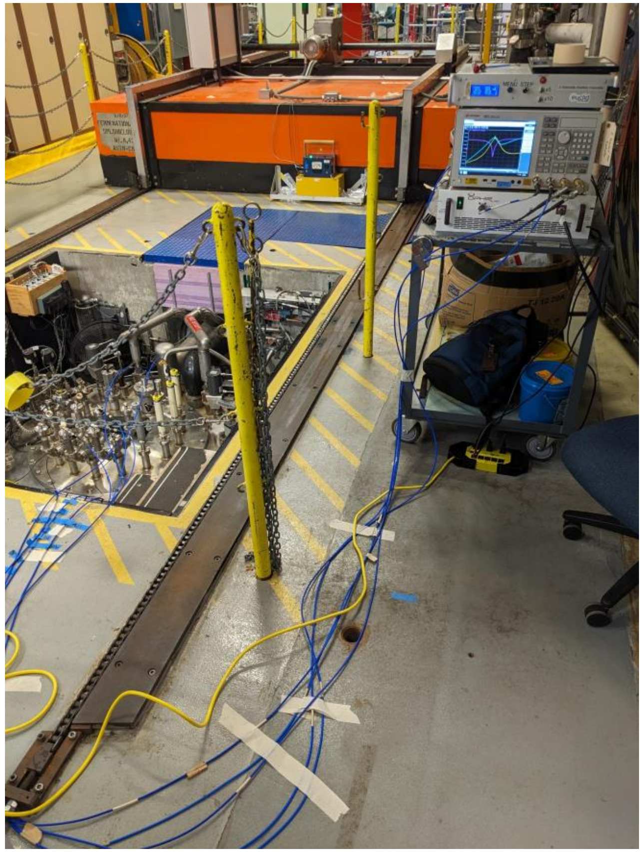
TW demonstration; Cavity under vacuum, in 2K liquid helium, VTS



Forward wave

~1k BW

Backward wave

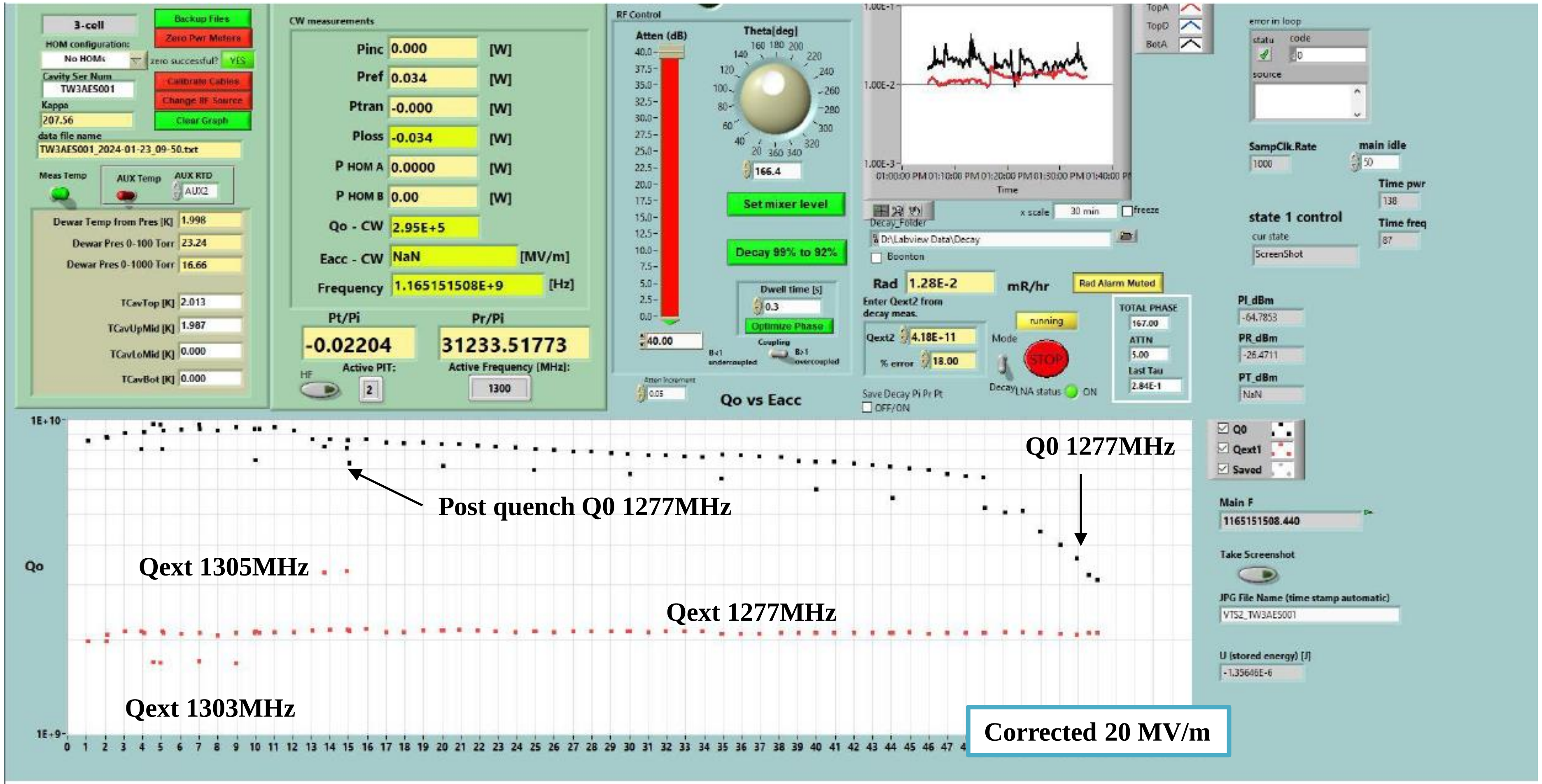


An example of TW at 1303.155 MHz being tuned at 2K

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

- QL~1E6 – easier to tune, matcher was not installed
- **TW demonstrated at 2K for the first time!**

VTS test 1/23/24: SW regime, high Q



HOM configuration: No HOMs

zero successful? YES

Cavity Ser Num: TW3AES001

Kappa: 207.56

data file name: TW3AES001_2024-01-23_09-50.txt

AUX RTD: AUX2

Dewar Temp from Pres [K]: 1.998

Dewar Pres 0-100 Torr: 23.24

Dewar Pres 0-1000 Torr: 16.66

TCavTop [K]: 2.013

TCavUpMid [K]: 1.987

TCavLoMid [K]: 0.000

TCavBot [K]: 0.000

Pinc: 0.000 [W]

Pref: 0.034 [W]

Ptran: -0.000 [W]

Ploss: -0.034 [W]

P HOM A: 0.0000 [W]

P HOM B: 0.00 [W]

Qo - CW: 2.95E+5

Eacc - CW: NaN [MV/m]

Frequency: 1.165151508E+9 [Hz]

Pt/Pi: -0.02204

Pr/Pi: 31233.51773

Active PIT: 2

Active Frequency (MHz): 1300

Atten: 40.00

Theta: 166.4

Dwell time [s]: 0.3

Atten Increment: 0.05

x scale: 30 min ☐ freeze

Decay_Folder: D:\Labview Data\Decay

☐ Boonton

Rad: 1.28E-2 mR/hr

Enter Qext2 from decay meas.

Qext2: 4.18E+11

% error: 18.00

LNA status: ON

Save Decay Pi Pr Pt ☐ OFF/ON

TOTAL PHASE: 167.00

ATTN: 5.00

Last Tau: 2.84E-1

error in loop: statu ✓ code 0 source

SampClk.Rate: 1000

main idle: 50

Time pwr: 138

Time freq: 87

state 1 control — cur state: ScreenShot

PI_dBm: -64.7853

PR_dBm: -26.4711

PT_dBm: NaN

☑ Q0
☑ Qext1
☑ Saved

Main F: 1165151508.440

JPG File Name (time stamp automatic): VTS2_TW3AES001

U (stored energy) [J]: -1.35646E-6

Q0 1277MHz

Post quench Q0 1277MHz

Qext 1305MHz

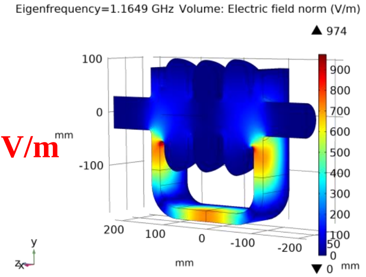
Qext 1277MHz

Qext 1303MHz

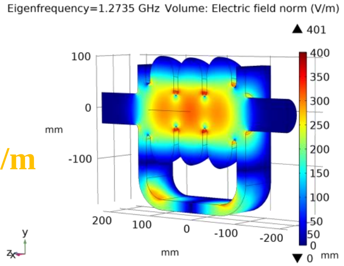
Corrected 20 MV/m

Comments: Lower sparce black dots – post quench curve; red lower dots 4-9MV/m – Qext1 for second mode; red upper dots 13-15MV/m – Qext2 for third mode.

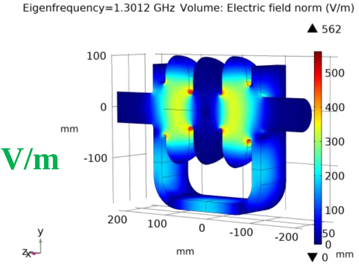
Eacc=19 MV/m



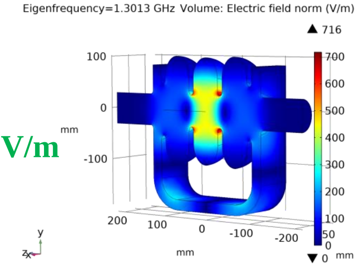
Eacc=20 MV/m



Eacc= 25 MV/m

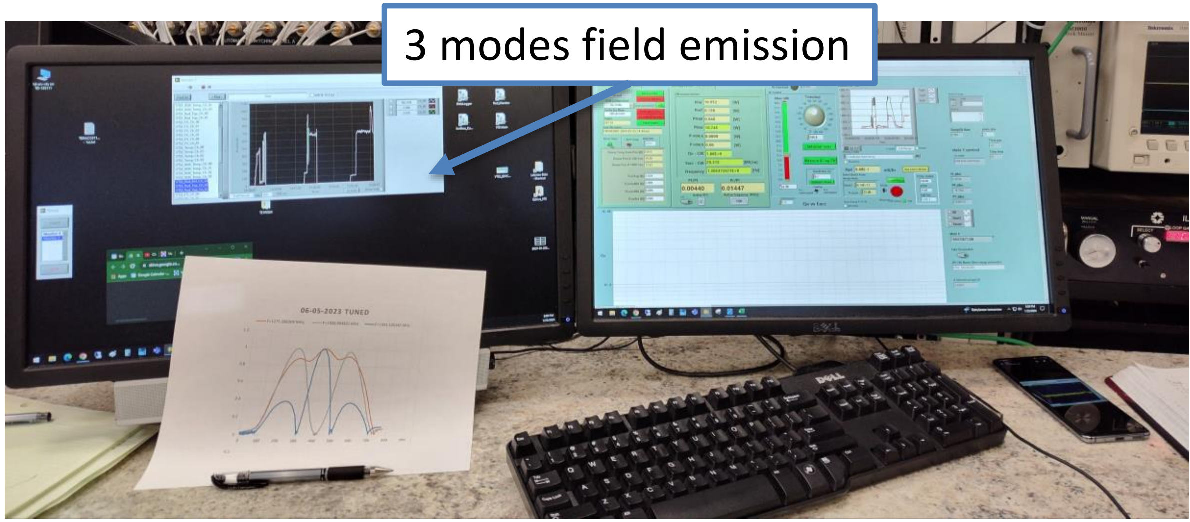


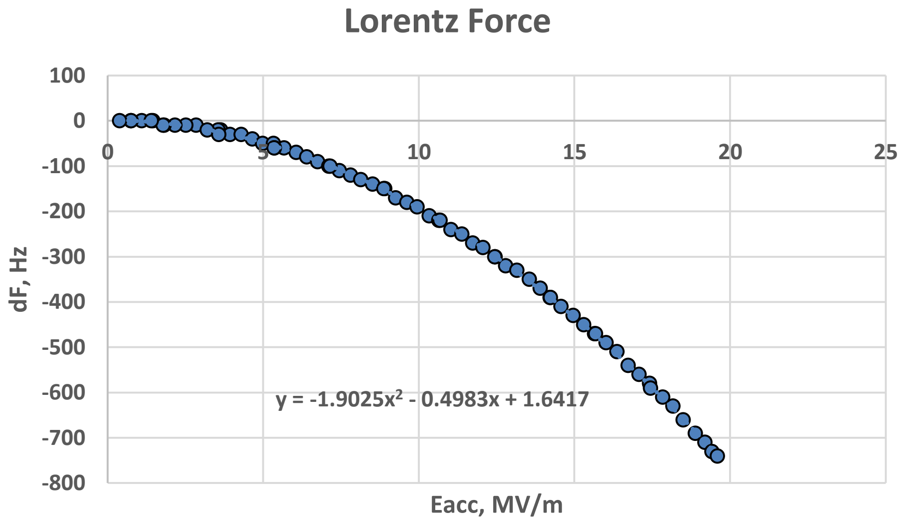
Eacc= 28 MV/m



VTS test 1/23/24: SW regime, high Q continued

- Field emission was observed for all modes
- WG limits the Eacc, but in TW regime WG field is 3 times less.
- LFD is K_L=-1.9 Hz/(MV/m)^2 – lower than estimated in TW regime.
- Cavity was designed/reinforced to withstand 0.1mbar of VTS helium pressure fluctuations and LFD
- It was found that VTS pressure fluctuation is actually 0.1ubar level (TW operation was stable) – good chance for TW at high Q high Eacc!


3 modes field emission



Next steps

- Final goal for this cavity is TW at as high as possible gradient: Eacc=30MV/m with QL~1E8 and 300W SSA at VTS
- What is needed:
  - VTS reconfiguration for TW excitation and detection
  - Enhanced processing – EP
- We start with QL~1E7 - coming this month, matcher will be installed with VTS reconfigured for TW excitation
- Next step QL~1E8 - harder to tune but higher gradient achievable, thus limiting factor can be processing
- EP processing and high Q high gradient test.

Summary

- SRF TW cavity development through the 3-cell has been progressing at Fermilab
- Cavity was processed: 120um rotational BCP
  800C bake, external BCP to remove oxides
- Tuning has been done: custom HW was designed, successfully used
- TW excitation at room temperature demonstrated
- TW excitation at cryogenic temperature and QL~1E6
- SW regime high gradient tested: Eacc=20-25MV/m reached.
- What’s next: TW @ high Q, high Eacc with VTS reconfiguration

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

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- Gennady Romanov

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- Thomas Reid
- Ben Guilfoyle

VTS support

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- Abraham Diaz
- David Burk
- Paul Dubiel
- Man Kwan (Trista) Ng

Cryo support

- Dan Marks

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- Pavel Avrakhov

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- John Rathke (AES)

and more….

Fermilab

3-cell SCTW cavity TW mode RF parameters

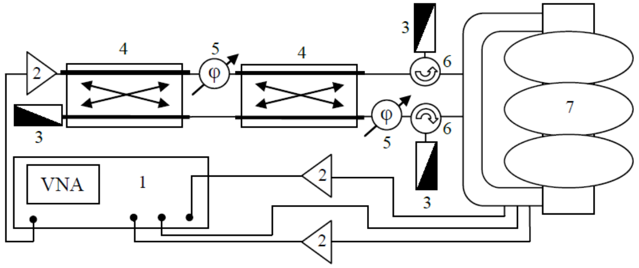
- TW excitation is possible by two FPC couplers excitation with power and phase redistribution
- RF parameters are in the Table below
- VTS measurement requires æ parameter to get Eacc from reactive power (wW or Q2Pt)
- æ is taken from R/Q but it is nothing else as a proportion coefficient between Eacc and wW
- R/Q make sense for TW mode but not so much for SW in the 3-cell structure as shunt impedance (or voltage gain) can be zero, see the next slide

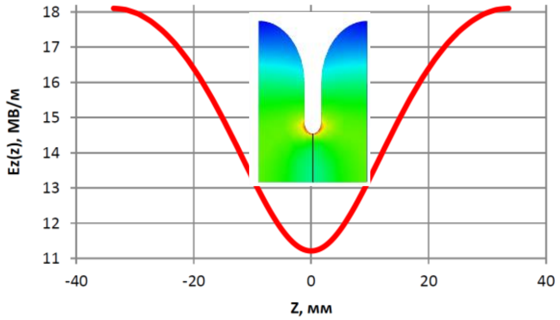
$$R_{ш} = \frac{\left[\int \left| E_z(z) \right| \cdot dz\right]^2}{P_П} = \frac{V^2}{P_П}$$

$$r/Q = \frac{R_{ш.эф}}{Q_0 \cdot l} = \frac{V_{эф}{}^2}{l \cdot \omega \cdot W_З}$$

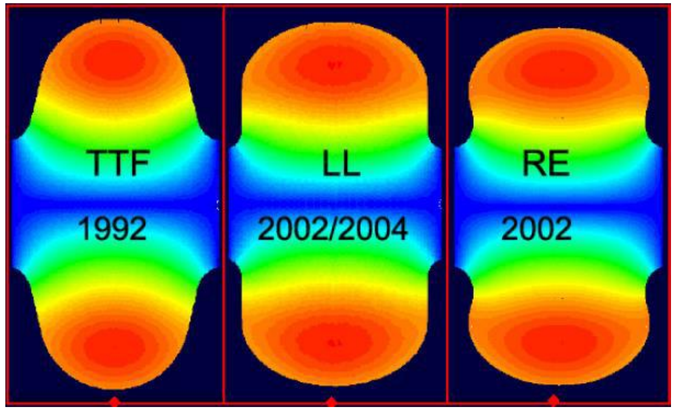
$$æ^2 = \frac{r}{Q}/L = \frac{E_{acc}{}^2}{\omega \cdot W} = \frac{E_{acc}{}^2}{Q_2 \cdot P_t}$$

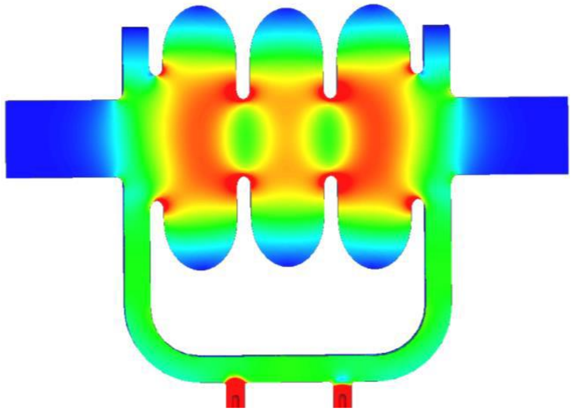
$$E_{acc} = æ \cdot \sqrt{Q_2 \cdot P_t}$$



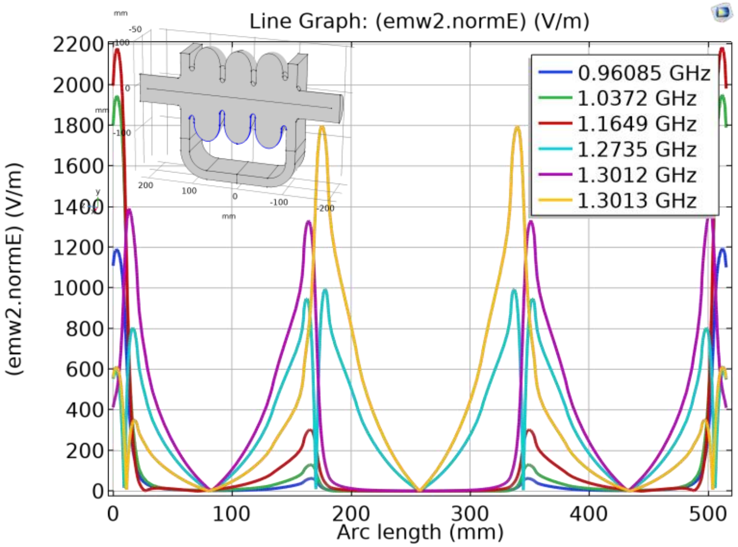


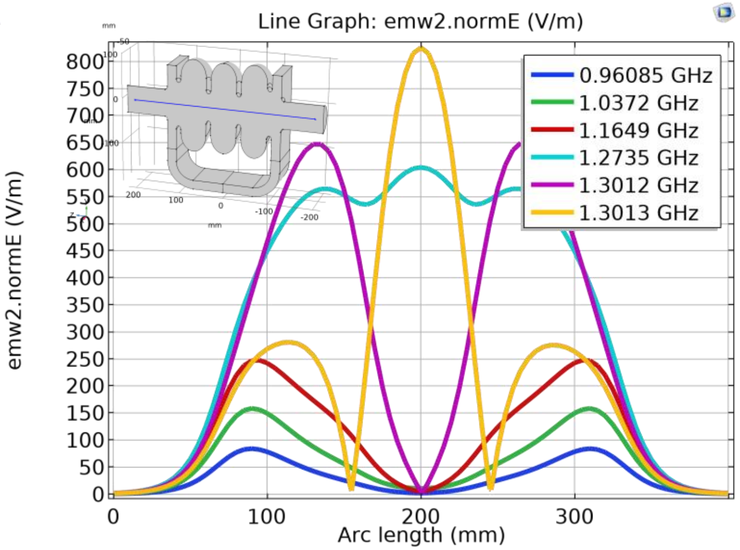
Parameter	Value
Phase advance, deg	105
Cell length, mm	67.26
Aperture R, mm	60
rsh/Q, Ω/m	1808
G, Ω	194
βgr, %	2.9
K_E	1.94
K_H	3.05
æ, Ω/m2	94.65

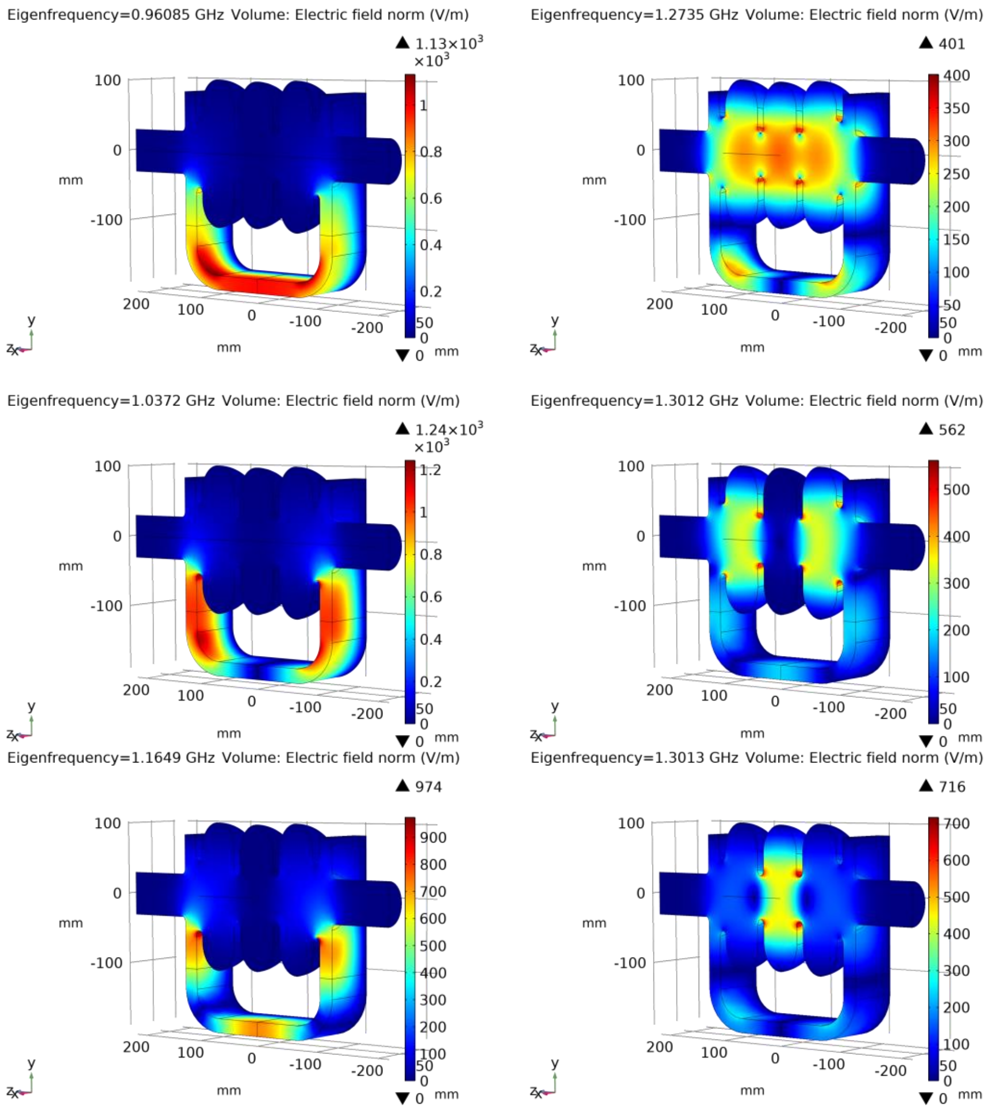




3-cell SCTW cavity Standing Wave modes parameters







$$\ae^2 = \frac{{E_{acc}}^2}{Q_2 \cdot P_t} \Rightarrow \zeta^2 = \frac{{E_{pk}}^2}{\omega \cdot W} = \frac{{E_{pk}}^2}{Q_2 \cdot P_t}$$

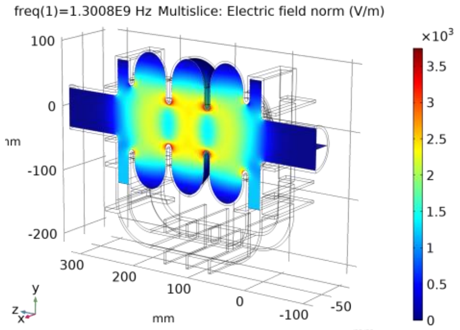
$$E_{pk} = \zeta \cdot \sqrt{Q_2 \cdot P_t}$$

$K_E = \mathrm{Epk/Eacc} \sim 1.94$

æ=94.65

ζ=æ ∗ Ke = 186 (from known Ke and æ)

Also: $\zeta = \sqrt{\frac{{E_{pk}}^2}{\omega \cdot W}} = 181$ for acc part only!



Frequency (GHz)	Epk (V/m)	Wst*2 (J)	$\zeta = \sqrt{\frac{{E_{pk}}^2}{\omega \cdot W}}$, Ω/m2
0.960848	1806.45	5.95E-09	301
1.03717	1946.295	5.63E-09	321
1.164893	2180.612	5.44E-09	346
1.273506	998.8066	6.09E-09	143
1.3012	1393.405	5.84E-09	202
1.301318	1801.715	5.60E-09	266
1.30082 (TW)*	3700	5.13E-08	181*/186