High gradient SRF Travelling-Wave Acceleration Structures for future Linear Colliders.

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FRIB

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Bio

Vyacheslav P. Yakovlev received PhD in accelerator physics from Budker Institute for Nuclear Physics (Budker INP), Novosibirsk, Russia, in 1988, where he worked as a Research scientist and since 1988 as a Senior Scientist. From 1994 to 1996 he was an Associate Professor at Novosibirsk State Technical University. Since 1996 he worked at Yale Beam Physics Lab, Physics Department, Yale University, and Omega-P Inc as a Senior Scientist. Since 2007 he works at Fermilab as a Senior Scientist. From 2011 to 2021 he was the Head of SRF Development Department at Application Science and Technology Division of Fermilab. Since 2021 to present he is the Head of Quantum Microwave System Department, Superconducting Quantum Materials and Systems Division. He is also a Special Projects Supervisor in SRF Systems Department, Applied Physics and Superconducting Technology Division at Fermilab. From 2018 to present he is an Adjunct Professor of Accelerator Science, Facility for Rare Isotope Beams, Michigan State University, Lansing.

Abstract

A niobium-based superconducting standing-wave RF structure has an acceleration gradient limited to about 50 MV/m by the critical RF magnetic field. To overcome this barrier, we investigate a variant of niobium-based traveling-wave (TW) structures. It is shown that the TW structure can have an acceleration gradient above 70 MV/m, which is about 40% higher than that of state-of-the-art standing-wave structures with the same critical magnetic field. The implementation of this work opens the way to upgrade the energy of the International Linear Collider well beyond 1 TeV. The challenges and progress in the development of the TW SRF are presented, as well as the first experimental results for a prototype TW SRF cavity with a feedback waveguide. A traveling wave is demonstrated for the first time in an SRF cavity at 2K.

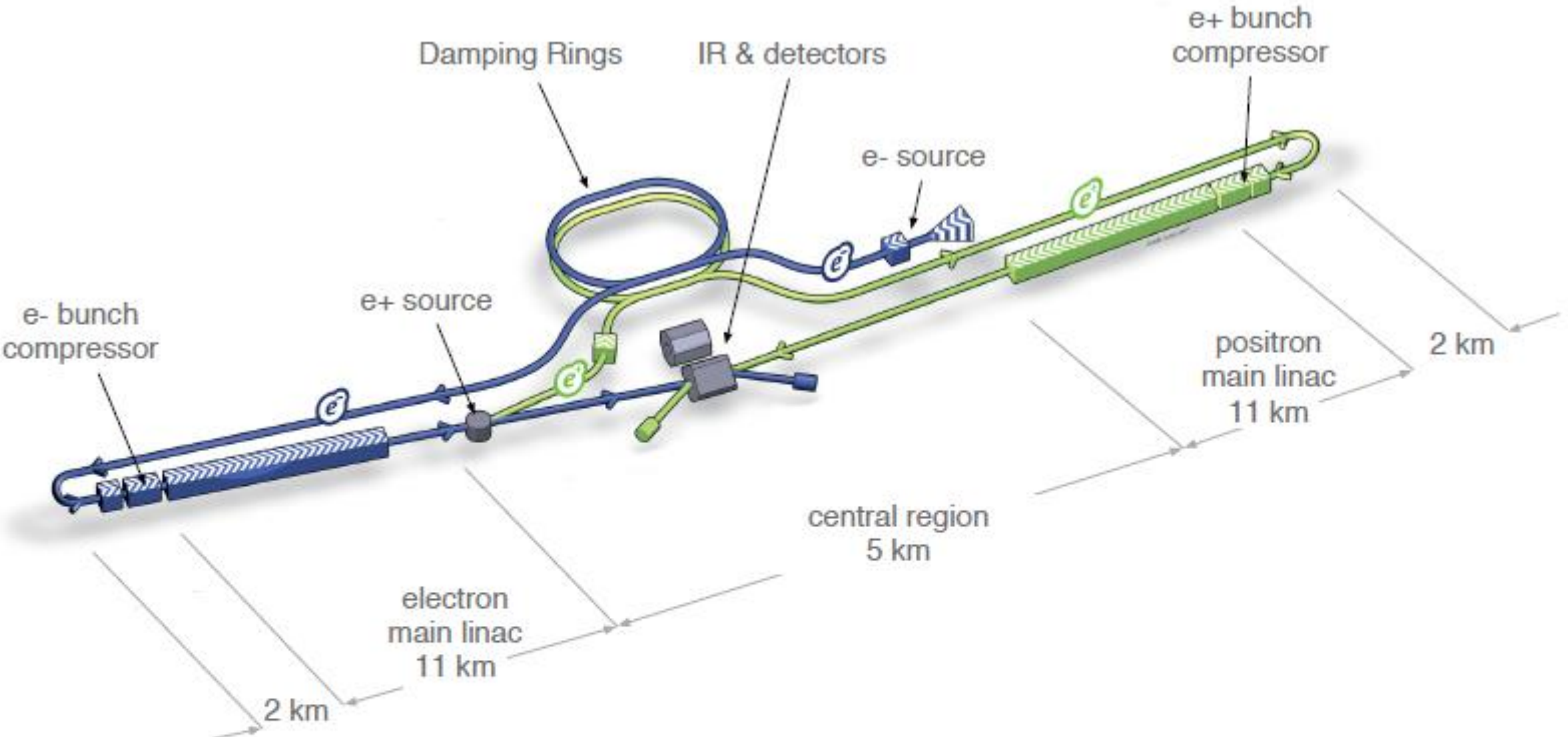
Outline

- Introduction
- Advantages of TW
- Challenges for TW structure
- One-cell cavity with feedback waveguide
- 3-cell TW cavity status
- R&D plans
- Summary

"A Higgs factory is the next step toward fully revealing the secrets of the Higgs boson within the quantum realm. We advocate substantial US participation in the design and construction of accelerators and detectors for an offshore facility, and we advocate investment of effort to support development of the Future Circular Collider-electron (e^-) positron (e^+) (FCC-ee) and the International Linear Collider (ILC), along with a parallel and increasingly intensive program of R&D pursuing revolutionary accelerator and detector technologies."

- Report of the 2023 Particle Physics Project Prioritization Panel (P5)

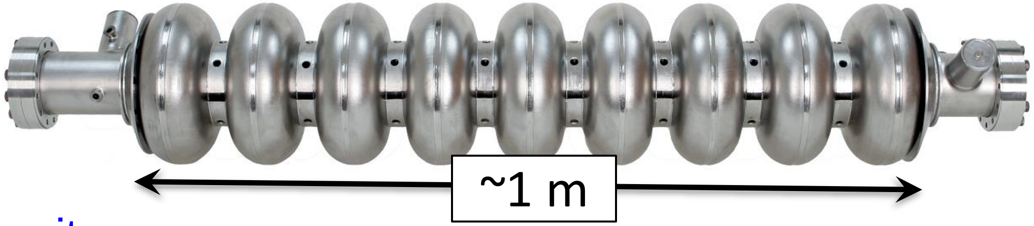
ILC SRF e+e- collider



- **The ILC is a proposed next-generation e+e- collider. It starts with the center-of-mass energy of 250 GeV as the “Higgs factory”.**
- **The precision study of the Higgs boson is the next major goal in collider physics; the**
- **Such high precision measurements will provide guidance to the next energy scale for future facilities. and exotic Higgs decays, for example into a light dark sector.**

Linear collider:

- ☐ Center of mass energy: up to 500 GeV
- ☐ Duty cycle: 1-2%.
- For 500 GeV cm the linac (250 GV/linac) length is **2x11 km** at the acceleration gradient of <u>**30**</u> MV/m for TESLA-type 1.3 GHz cavity.



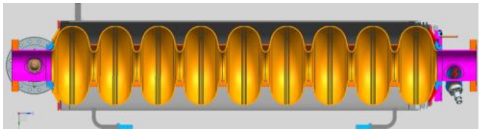
- TESLA-type cavity:
- Frequency: 1.3 GHz;
- Length: ~1 m;
- π –mode, Standing Wave
- Acceleration gradient is limited by quench and field emission.

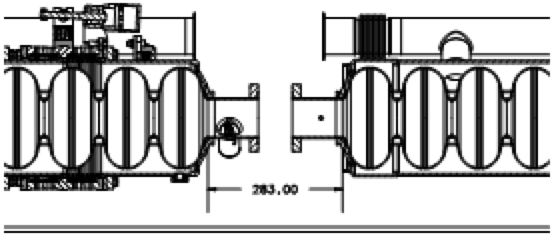
Increase of the cavity acceleration gradient →decrease of number of cavities and therefore the cost

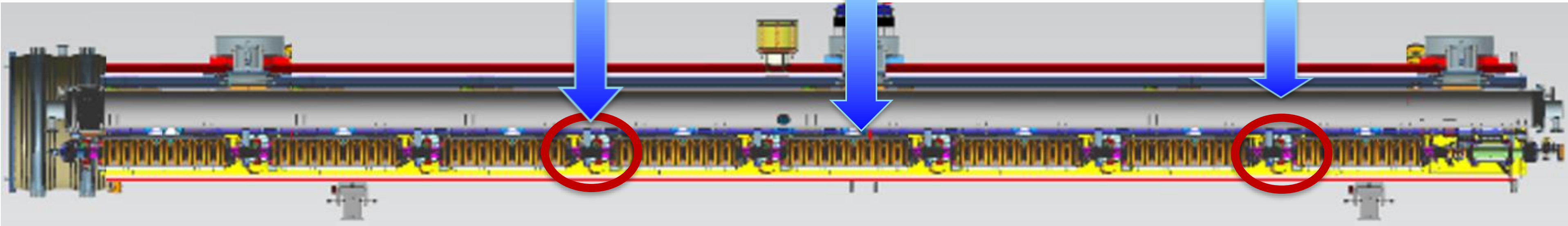
“Real estate” gradient is 250 GV/11 km = **23** MV/m.

- Gaps between the cavities
  - beam pipes,
  - tuners,
  - bellows,
  - couplers

SRF cavity, 1 m







- Focusing elements (CM contains 8 cavities and 1 quad
- Gaps between the cryo-modules for gate valves, etc..

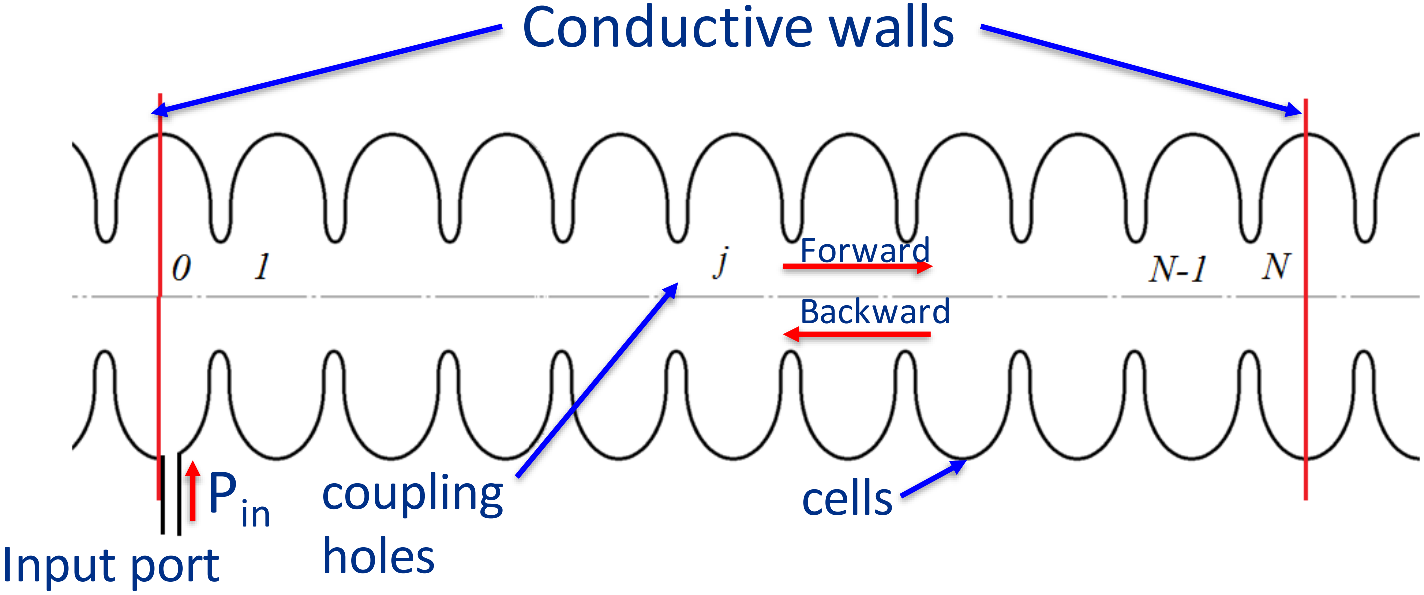
  It is unavoidable.

Longer cavities → smaller number of gaps → higher real estate gradient and therefore lower the cost.

However, the length of the π –mode SW structure is limited by field flatness.

Standing–Wave acceleration structures

Standing Wave structures:


Conductive walls

Forward

Backward

P_{in}

coupling holes

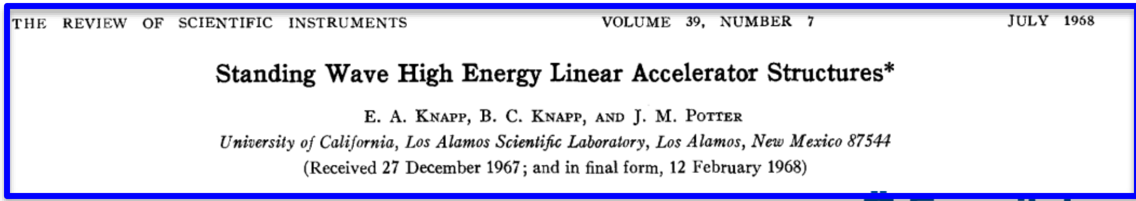
cells

Input port

Putting reflective conductive walls in the middle of the end cells, we do not violate boundary conditions for EM field for TM_{010}-like modes.

Forward and backward travelling waves form standing wave.

- N may be small, even $N=2$;
- Frequency may be small, up to hundreds of MHz→ proton acceleration
- Suitable for SRF
- $P_{in} << P_{forward} \approx P_{backward}$


THE REVIEW OF SCIENTIFIC INSTRUMENTS VOLUME 39, NUMBER 7 JULY 1968

Standing Wave High Energy Linear Accelerator Structures*

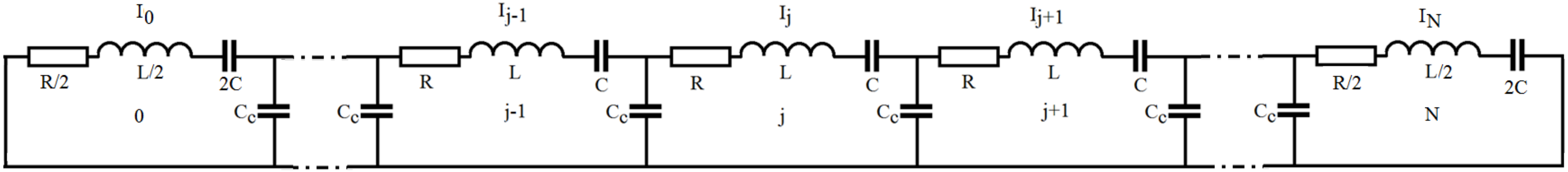
E. A. Knapp, B. C. Knapp, and J. M. Potter

University of California, Los Alamos Scientific Laboratory, Los Alamos, New Mexico 87544

(Received 27 December 1967; and in final form, 12 February 1968)

Standing–Wave acceleration structures

Equivalent circuit of the SW structure containing half-cells on the ends:



$$X_0\left[1-\frac{\omega_0^2}{\omega^2}+i\frac{\omega_0^2}{Q_0\omega^2}\right]+K\frac{\omega_0^2}{\omega^2}X_1=0$$

$$X_j\left[1-\frac{\omega_0^2}{\omega^2}+i\frac{\omega_0^2}{Q_0\omega^2}\right]+\tfrac{1}{2}K\frac{\omega_0^2}{\omega^2}\left[X_{j-1}+X_{j+1}\right]=0 \quad (1)$$

$$X_N\left[1-\frac{\omega_0^2}{\omega^2}+i\frac{\omega_0^2}{Q_0\omega^2}\right]+K\frac{\omega_0^2}{\omega^2}X_{N-1}=0$$

In matrix form:

$$M\hat{X}-\frac{\omega_0^2}{\omega^2}\hat{X}=0$$

here $M_{jj}=1;\ j=0,1,\dots N;$

$$M_{jj-1}=\frac{K}{2W(j)};\ j=1,2,\dots N;$$

$$M_{jj+1}=\frac{K}{2W(j)};j=0,1,\dots N-1.$$

and $W(j)=1, j=1,2,\dots N-1$

$$W(j)=\frac{1}{2}, j=0,N$$

Here ω_0 corresponds to the center of dispersion curve.

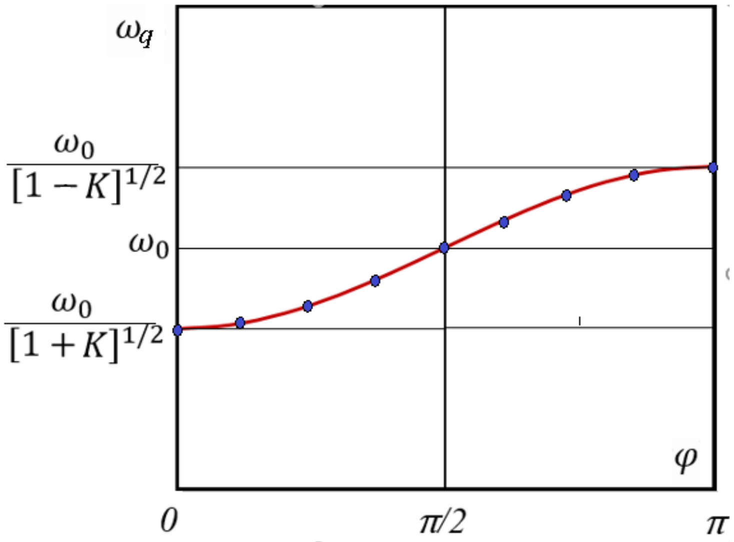
Standing –Wave acceleration structures (Lecture 9)

Eigenvectors and eigenvalues:

3-cell cavity (N=2)

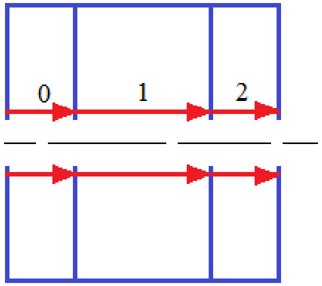
$$\hat{X}_j^q = cos\frac{\pi q j}{N};\ \omega_q^2 = \frac{\omega_0^2}{1+Kcos\frac{\pi q}{N}}, q = 0,1,\dots N$$

Phase advance per cell: $\varphi = \frac{\pi q}{N}, q = 0,1,..N$



0-mode (q=0):

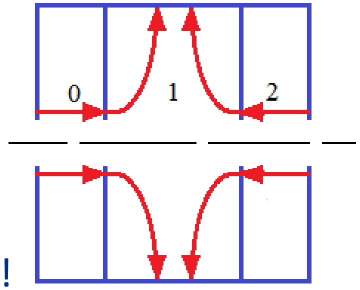
$\varphi = 0 \quad \omega = \frac{\omega_0}{(1-K)^{1/2}}$



π/2-mode (q=1):

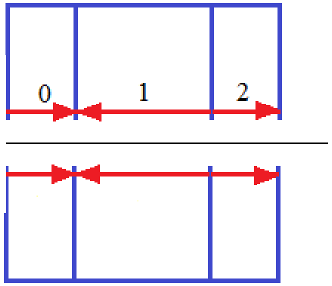
$\varphi = \pi/2 \quad \omega = \omega_0$

Even cell is empty!



π-mode (q=2):

$\varphi = \pi \quad \omega = \frac{\omega_0}{(1+K)^{1/2}}$



Orthogonality:

$$\hat{X}^q \cdot \hat{X}^r \equiv \sum_{j=0}^{N} W(j)\,\hat{X}_j^q \hat{X}_j^r = \frac{N\delta_{qr}}{2W(q)},\quad \delta_{qq} = 1, and\ \delta_{qr} = 0, if\ q \neq r$$

Standing –Wave acceleration structures

- Perturbation of the cell resonance frequencies causes perturbation of the mode resonance frequencies $\delta\omega_q$;
- the field distribution $\delta\hat{X}_q$.

$$\omega_{0j}^{2\prime} = \omega_0^2 + \delta\omega_{0j}^2 \quad \rightarrow \quad \hat{X}^{q\prime} = \hat{X}^q + \delta\hat{X}^q, \quad \hat{X}^q \cdot \delta\hat{X}^q$$

Variation of the equation (1) in matrix form $M\hat{X} - \frac{\omega_0^2}{\omega^2}\hat{X} = 0$, see Slide 31

gives $M\delta\hat{X}^q = \frac{\omega_0^2}{\omega_q^2}\left[\delta\hat{X}^q + \Omega\hat{X}^q - \frac{\delta\omega_q^2}{\omega_q^2}\hat{X}^q\right]$,

(here $\Omega = \begin{bmatrix} \frac{\delta\omega_{01}^2}{\omega_0^2} & \cdots & 0 \\ \vdots & \ddots & \vdots \\ 0 & \cdots & \frac{\delta\omega_{0N}^2}{\omega_0^2} \end{bmatrix}$)

$$\boxed{\begin{aligned} \frac{\delta\omega_q^2}{\omega_q^2} &= [2W(q)/N] \cdot \hat{X}^q\Omega\hat{X}^q; \\ \delta\hat{X}^q &= \sum_{q'\neq q} \frac{2W(q')\hat{X}^q\Omega\hat{X}^q}{N\left(\frac{\omega_q^2}{\omega_{q'}^2} - 1\right)}\hat{X}^{q'} \end{aligned}}$$

$$\boxed{\left|\delta\hat{X}^q\right| \sim \frac{\left|\delta\omega_{0j}\right|_{av}}{\left|\omega_q - \omega_{q\pm1}\right|}}$$

Standing –Wave acceleration structures

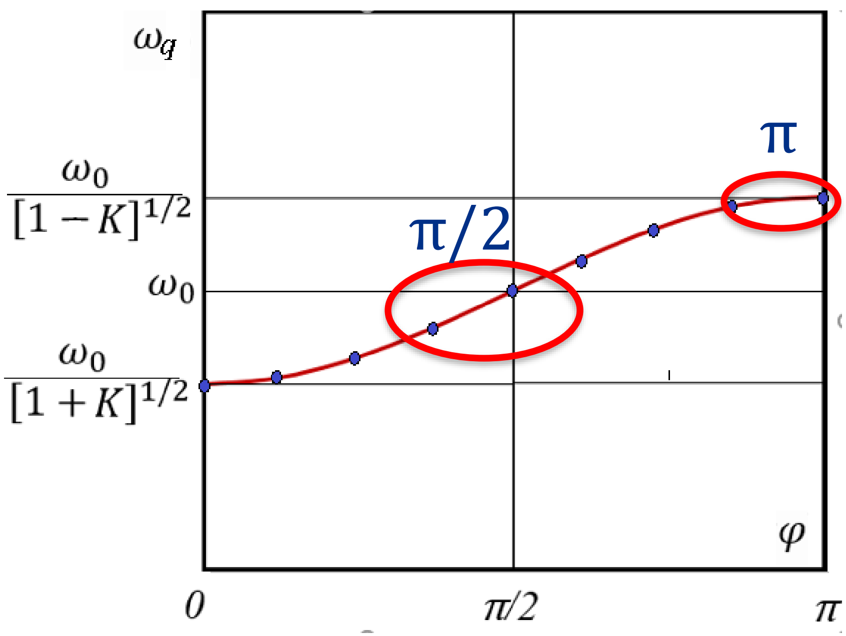
π/2-mode ($q=N/2$): N-even, N is the number of cells in the cavity

$$|\delta\hat{X}^{N/2}| \sim \frac{|\delta\omega_{0j}|_{av}}{|\omega_{N/2}-\omega_{N/2-1}|} \sim N\frac{|\delta\omega_{0j}|_{av}/\omega_0}{K}$$

π-mode ($q=N$):

$$|\delta\hat{X}^{N}| \sim \frac{|\delta\omega_{0j}|_{av}}{|\omega_{N}-\omega_{N-1}|} \sim N^2\frac{|\delta\omega_{0j}|_{av}/\omega_0}{K}$$

SW π-mode is much less stable than π/2-mode !



For long π-mode cavities problems with

- Tuning
- Field flatness after cooling down

$$\omega_q^2=\frac{\omega_0^2}{1+K\cos\frac{\pi q}{N}}, q=0,1,\dots N$$

Gradient limitations are determined by surface fields:

- RT cavities:
  - -breakdown (determined mainly by E_{peak})
  - -metal fatigue caused by pulsed heating (determined by B_{peak})
- SRF cavities:
  - -quench (determined by B_{peak})

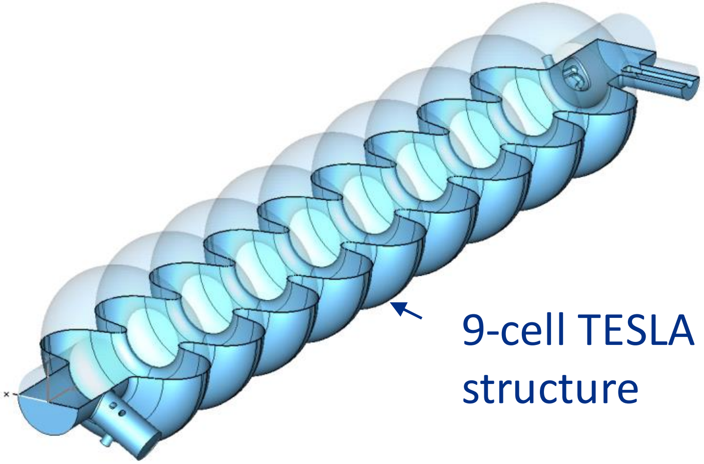
Field enhancement factors:

- Surface electric field enhancement: $K_e = E_{peak}/E$, E_{peak} is maximal surface electric field. K_e *is* dimensionless parameter.

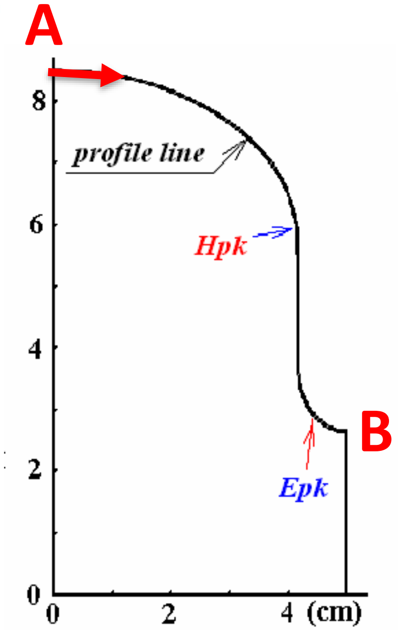
- Surface magnetic field enhancement: $K_m = B_{peak}/E$, B_{peak} is maximal surface magnetic field. K_m is in mT/(MV/m)

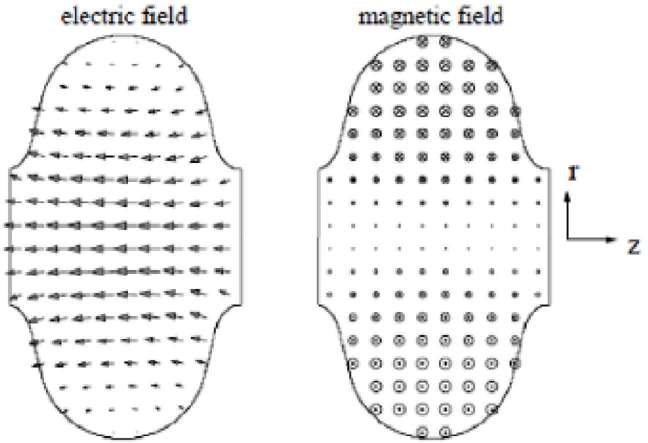
RF cavity parameters:

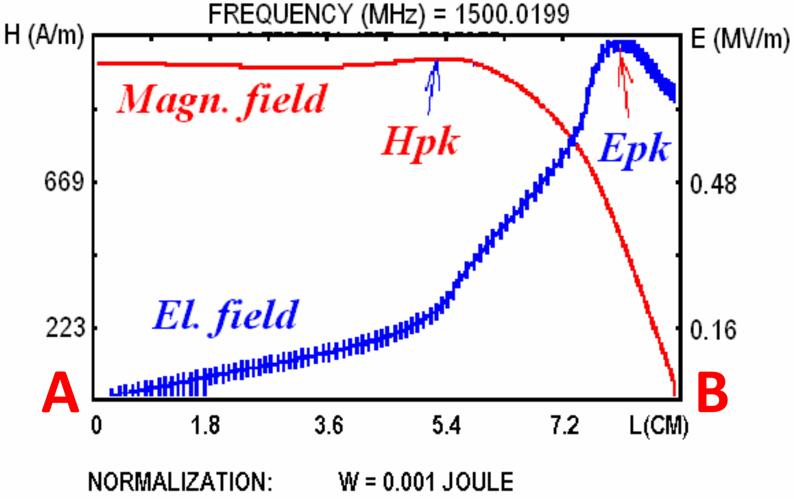
Field enhancement factors – example:



9-cell TESLA structure







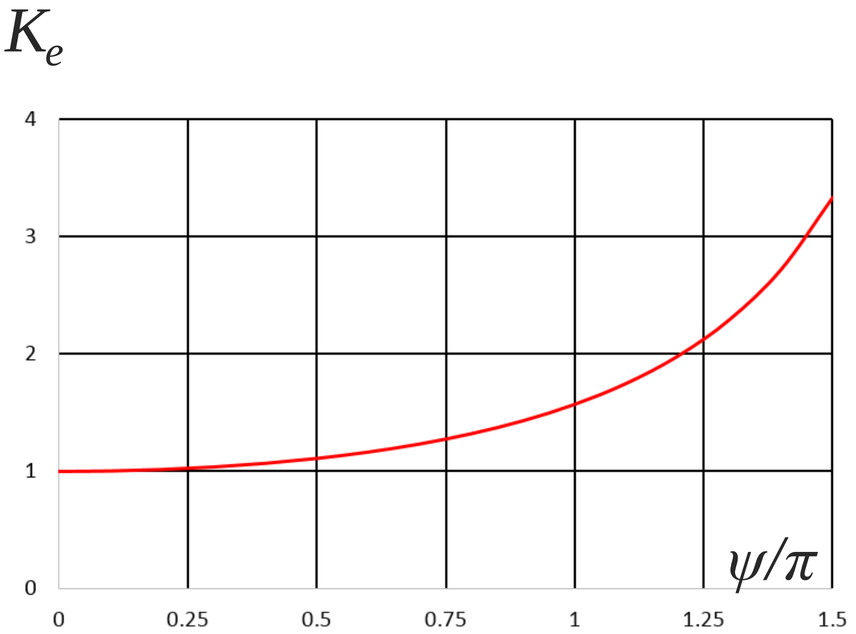
$$K_e = E_{peak}/E = 2; \quad K_m = B_{peak}/E = 4.16\, mT/MV/m$$

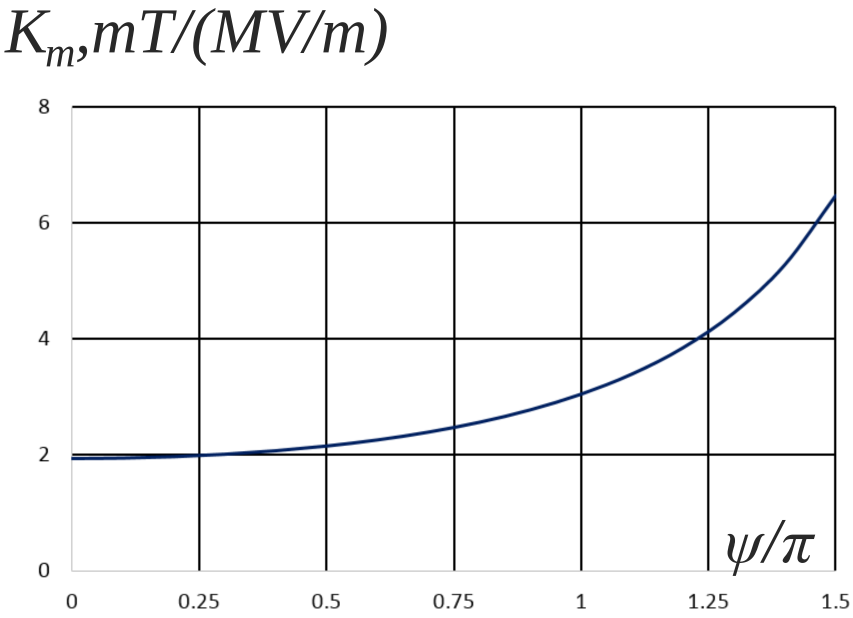
Geometry of an inner half-cell of a multi-cell cavity and field distribution along the profile line.

RF cavity parameters:

For a pillbox cavity:

- Surface electric field enhancement: $K_e = E_{peak}/E = 1/T(\psi)$ $(E_{peak}=E_0,\ E= E_0 T(\psi)$, *see Lecture 7, slide 48*$)$
- Surface magnetic field enhancement: $K_m = B_{peak}/E =$ $= 1.94/T(\psi)\ [mT/(MV/m)]$ $(B_{peak} = E_0 \cdot J_1(2.405r/b)_{max}/c = 0.582E_0/c)$





Higher gradient in the cavities:

- **Nb cavity processing improvement;**

  The Standing Wave (SW) TESLA Niobium-based structure is limited to a gradient of about 50 MV/m by the critical RF magnetic field (200 – 210 mT).

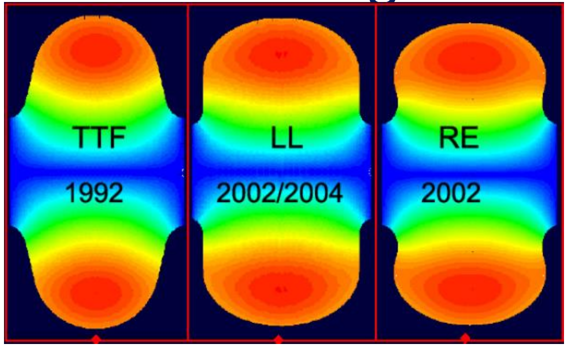
- **Advanced shape of SW cavity cell**

  Advanced shape cavities will be limited by the critical RF magnetic field to about 60 MV/m

  –Re-entrant, Low-Loss, Ichiro, Low Surface Field

  –For advanced shape, we lower *Hpk/Eacc* (by10-20%)

  •but we raise *Epk/Eacc* (15-20%)



- **New materials**

  Extensive R&D is still required

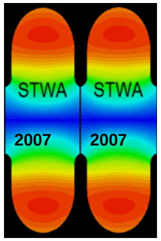
  How to break through the gradient barrier <u>with Niobium</u>?

New types of cavities should be explored

The cavity gradient → Improve K_m, K_e → **smaller phase advance per cavity**

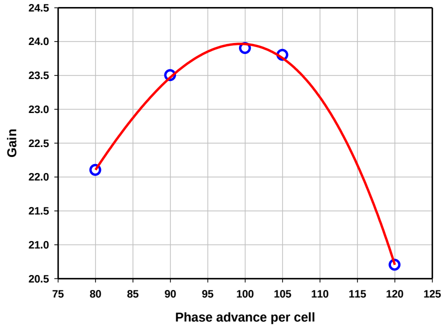
The real estate gradient → longer cavity → **smaller phase advance per cavity**

The cavity with phase advance per cell ~ π/2 should be used to resolve <u>both</u> issues.



But for a SW cavity having phase advance per cavity < π most of the cells have reduced field → average gradient is small.

The only choice: explore the option of Niobium Traveling Wave (TW) structures



Advantages of TW Structures

- ☐ Travelling wave improves transit time factor and therefore allows lower BOTH B_{pk}/E_{acc} and E_{pk}/E_{acc}
  - RF power returns not through the accelerating structure (to form a standing wave with harmful peaks), but through a separate feedback Nb waveguide

- ☐ Travelling wave cavities operate at maximal group velocity in contrast to SW operating at zero group velocity, and therefore allow
  - Longer cavities → smaller gaps between cavities → higher average gradient;
  - Smaller aperture → additional increase in gradient because smaller B_{pk}/E_{acc} and E_{pk}/E_{acc}
  - Field profile tuning easier,

- ☐ Travelling wave $\sim\pi/2$ structures offer higher G*R/Q → lowers Cryo power.

- ☐ Using in the TW cavity the “Low-Loss” cell shape + reduced aperture it is possible to lower B_{pk}/E_{acc} by 48% over the TESLA structure!

- ☐ **Opening the door to E_{acc} > 70 MV/m !!**

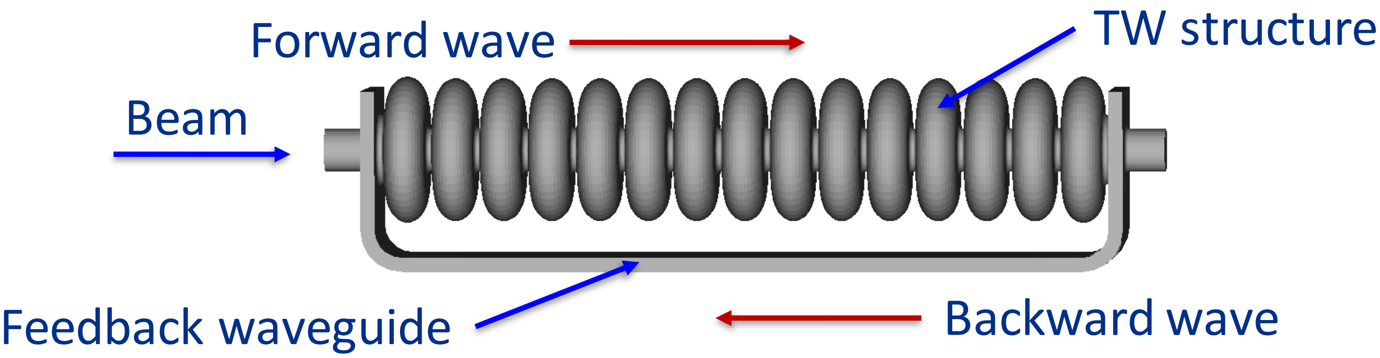
Advantages of TW Structures (cont)

- Smaller aperture (see above) is allowed because bunch charge for 3 TeV ILC upgrade will about 3 X less to get acceptable IP background…

- Putting SRF on the Road to ILC – 3 TeV with Niobium

- No need to struggle with exotic new superconductors or overlayers

- Small decay in the cavities → feedback waveguide:



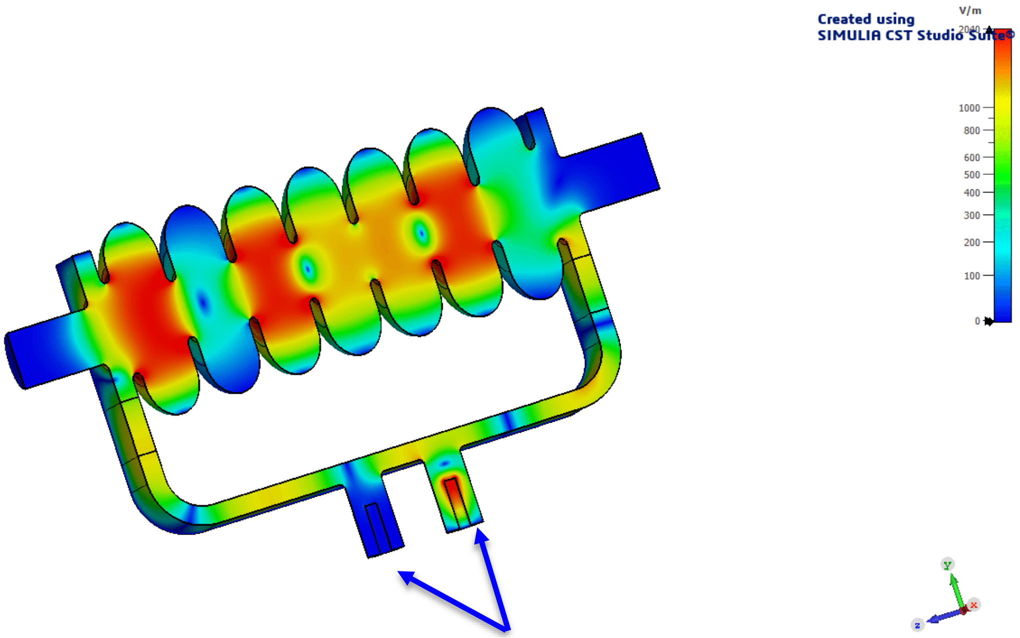
Forward wave

TW structure

Beam

Feedback waveguide

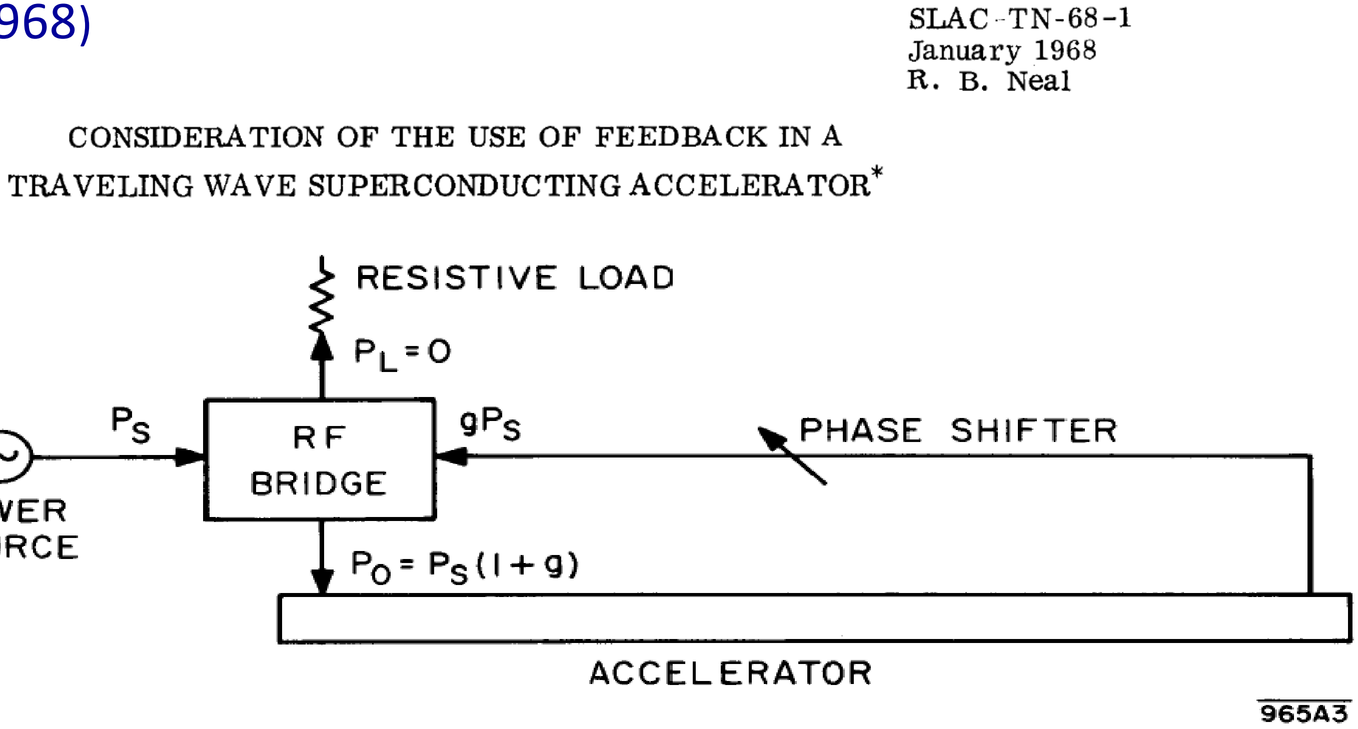
Backward wave



Couplers distanced by λ/2. Phase is shifted by 90°

Acceleration structure with feedback waveguide has a long story:

- First acceleration structures were TW structures with feedback ! (1947).
- High-gradient RT TW structure with feedback has been built in 1995 (J. Haimson)
- First suggested SC acceleration structure were TW structures with feedback (R.B. Neal, 1968)



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

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

1. R.B.R. Shersby-Harvi and L.B. Mullett, Proc. Phys. SOC. London E, 270 (1949).
2. J. Haimson, and B. Mecklenburg, AIP Conference Proceedings 337, p. 311, 1995.
3. R.B. Neal, SLAC-PUB-0438, 1968.

Challenges for TW Structures

☐ Requires twice the number of
advance (about 105 degrees)

☐ Cavity fabrication and surface processing procedures and fixtures must deal with (roughly) double the number of cells per structure.

☐ A feedback waveguide for redirecting high power from the end of the structure

Challenges for TW Structures

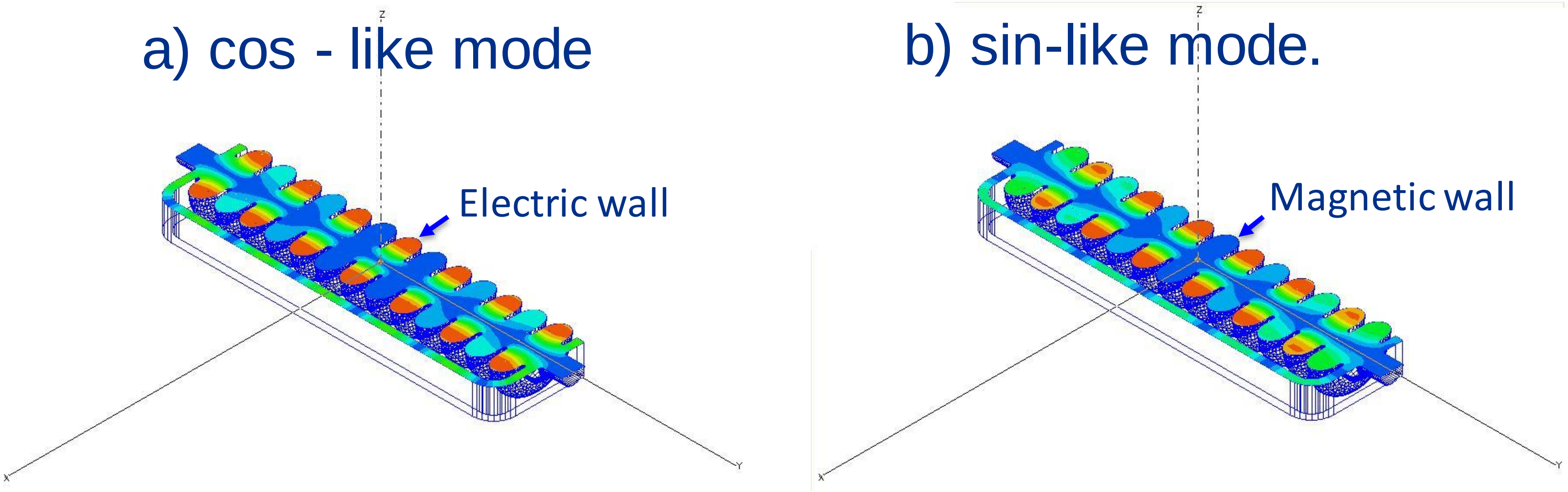
- Requires twice the number of cells per meter to provide the proper phase advance (about 105 degrees)

- Cavity fabrication and surface processing procedures and fixtures must deal with (roughly) double the number of cells per structure.

- A feedback waveguide for redirecting high power from the end of the structure back to the front end of accelerating structure.
    - The feedback requires careful tuning to compensate reflections along the TW ring to obtain a pure traveling wave (a special “matcher “ in addition to a main tuner to reach partial standing wave degeneracy)

Electro-dynamics of a TW structure with a feedback waveguide

Two orthogonal degenerated standing waves shifted in phase by 90° compose TW:



a) cos - like mode

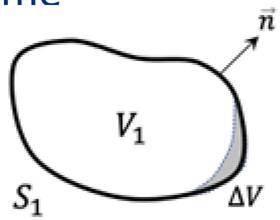
b) sin-like mode.

An example of the orthogonal eigenmodes in the 13-cell cavity with the adjusted feedback waveguide. Resonance frequencies are equal.

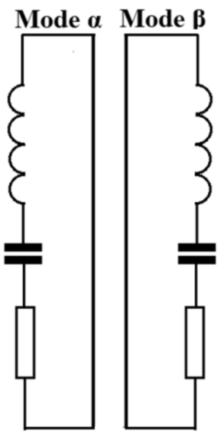
However, in a real cavity the partial modes degeneration may not exist because of mode interaction effect caused by

- Input couplers
- Fabrication errors
- Probes

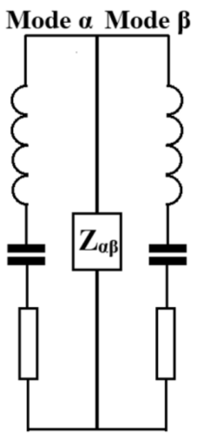
In this case the frequencies are split. The split is determined by a coupling parameter depending on the field distribution of the modes α and β, and the cavity volume perturbation ΔV: $\omega_{\pm}^2 \approx \frac{1}{2}\left[\left(\omega_\alpha'^2 + \omega_\beta'^2\right) \pm \sqrt{\left(\omega_\alpha'^2 - \omega_\beta'^2\right)^2 + \left|z_{\alpha\beta}\right|^2 \omega_\alpha'^2 \omega_\beta'^2}\right]$



where the coupling is $z_{\alpha\beta} \approx -i\,\frac{\int_{\Delta V}\left(\mu_0 \vec{H}_\alpha^* \cdot \vec{H}_\beta - \varepsilon_0 \vec{E}_\alpha^* \cdot \vec{E}_\beta\right) dV}{\mu_0 \int_{V_1} \left|\vec{H}_\alpha\right|^2 dV}$

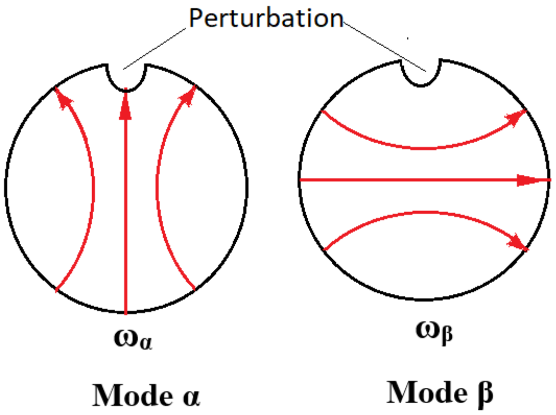


Uncoupled



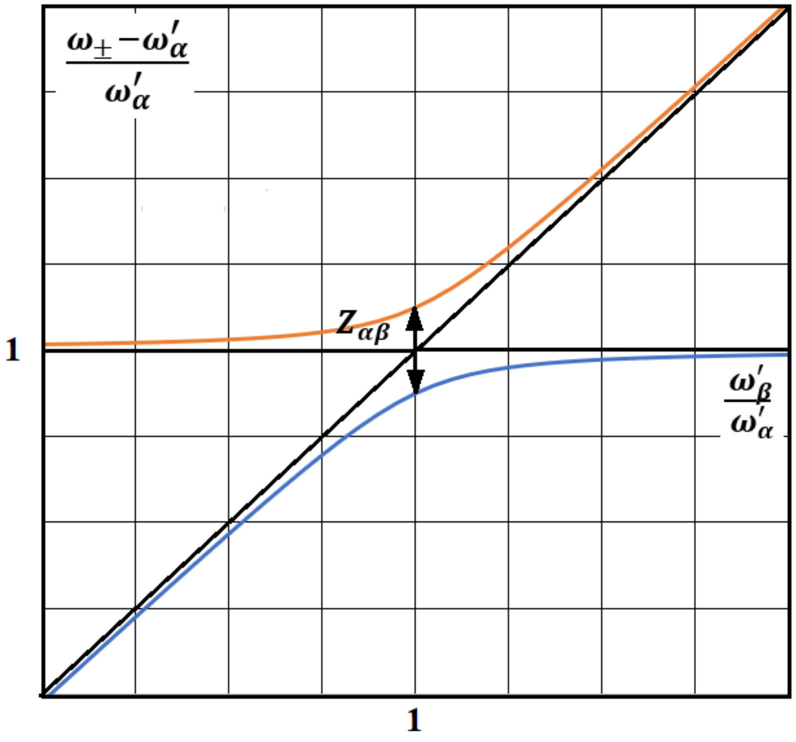
Coupled

TE111 in a pillbox cavity:



In absence of perturbation $\omega_\alpha = \omega_\beta$

In presence of perturbation $\omega_\alpha \neq \omega_\beta$

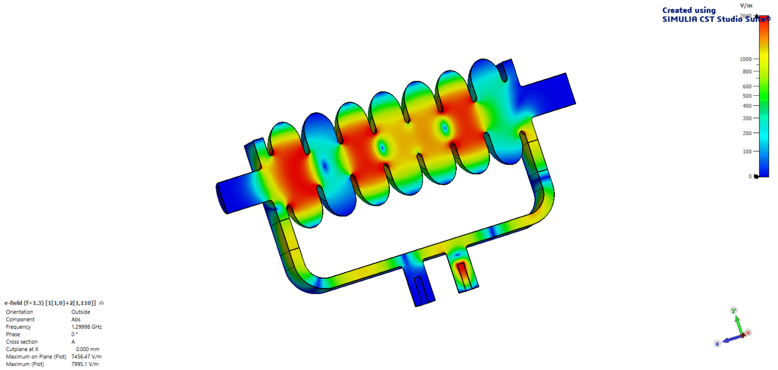


Resonance frequencies ω_+ (red curve) and ω_- (blue curve) of the coupled degenerate modes versus ω'_β at fixed ω'_α (ω'_α and ω'_β frequencies of the degenerated modes in presence of perturbation, but without coupling).

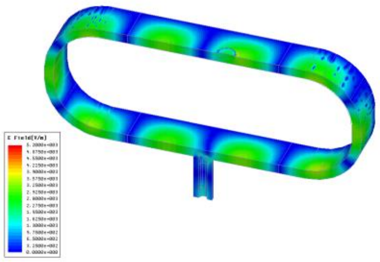
Ergo: to restore degeneration in presence of perturbations caused by the couplers and fabrication errors one should introduce in general case two additional compensators, “matchers”.

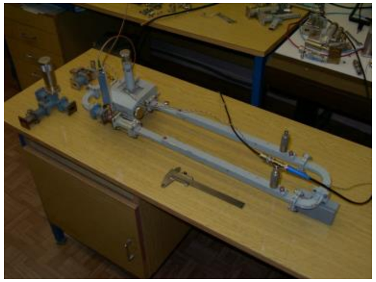
TW excitation:

1. Two input couplers distanced by λ/2. Phase is shifted by 90° . The phases may be adjusted. One “matcher” is necessary.

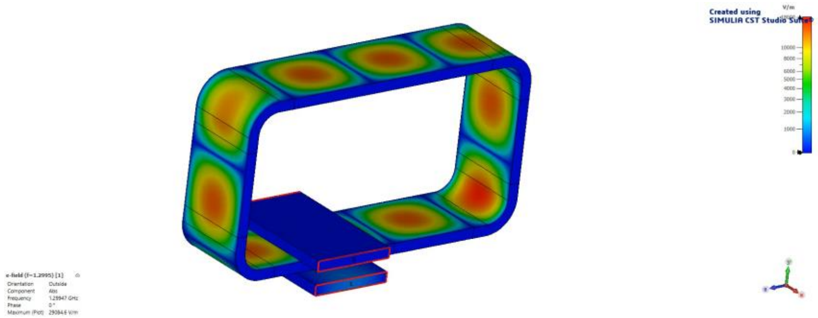


2. One coupler. The modes are split by one bandwidth, the coupler is placed between the SW modes nodes. Two “matchers” are necessary.





3. Directional Coupler (DC) is used. Two “matchers” are necessary. The 2^d DC is used to measure the backward wave.



Path for TW cavity for ILC

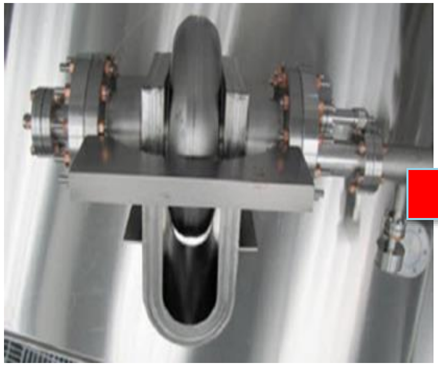
❑ General studies:

- New approach of multi-parametric optimization developed, which takes into account both maximally possible fields, *E* and *H*.
- Optimization shows that TW structure can have the accelerating gradient above 70 MV/m with the same critical magnetic and electric fields that in the SW structure.
- No multipactor in the cavity and in a feedback waveguide
- No cavity length limitation by a coupling between cells
- Tuning and “matching” (achieving of travelling wave) procedures are developed
- High-power coupler concept is developed
- TW RF diagnostics is developed

Path for TW cavity for ILC

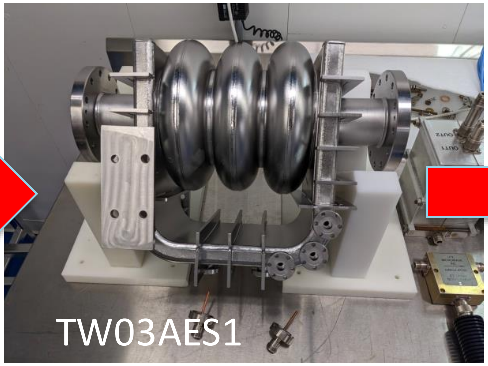
❑ Strategy of technology development for TW: step-by-step approach

HG tests of a single cell cavity with feedback WG*:



- Designed, manufactured (**AES**), processed;
- Reached 26 MV/m with inferior (easier) treatment of BCP

HG tests of a 3- cell TW cavity with feedback WG*:



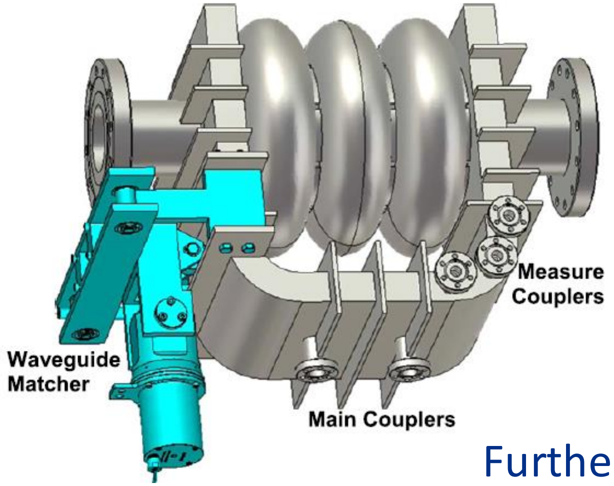
- Designed, manufactured (**AES**), processed (BCP);
- TW is achieved at 2K!
- HG tests are scheduled for November 2024

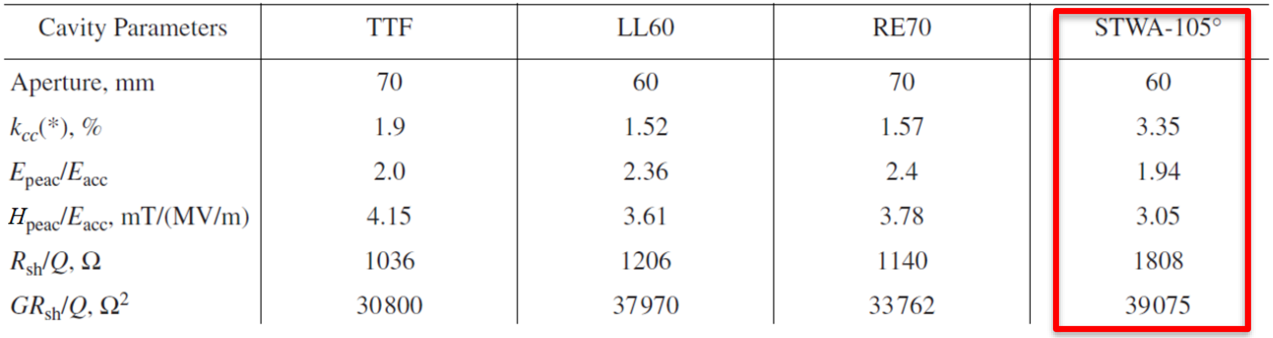
HG tests of a 0.5 m- long TW cavity with feedback WG, HP couplers, tuners and diagnostics (in collaboration with Cornell):

- The cavity cell RF optimization is **OK**
- Cavity-WG transition RF design is **OK**
- TTF-III HP coupler are supposed to be used.
- He vessel design – not started yet
- Tuners design – not started yet

*Euclid Techlabs DOE SBIR DE-FG02-06ER84462 and DE-SC0006300.

Status of the 1.3 GHz, 3-cell TW cavity 2K tests:





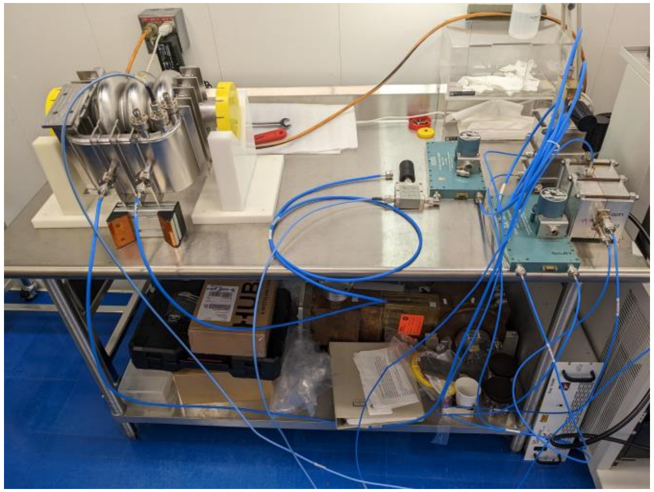
Cavity Parameters	TTF	LL60	RE70	STWA-105°
Aperture, mm	70	60	70	60
$k_{cc}(*)$, %	1.9	1.52	1.57	3.35
E_{peac}/E_{acc}	2.0	2.36	2.4	1.94
H_{peac}/E_{acc}, mT/(MV/m)	4.15	3.61	3.78	3.05
R_{sh}/Q, Ω	1036	1206	1140	1808
GR_{sh}/Q, Ω^2	30800	37970	33762	39075

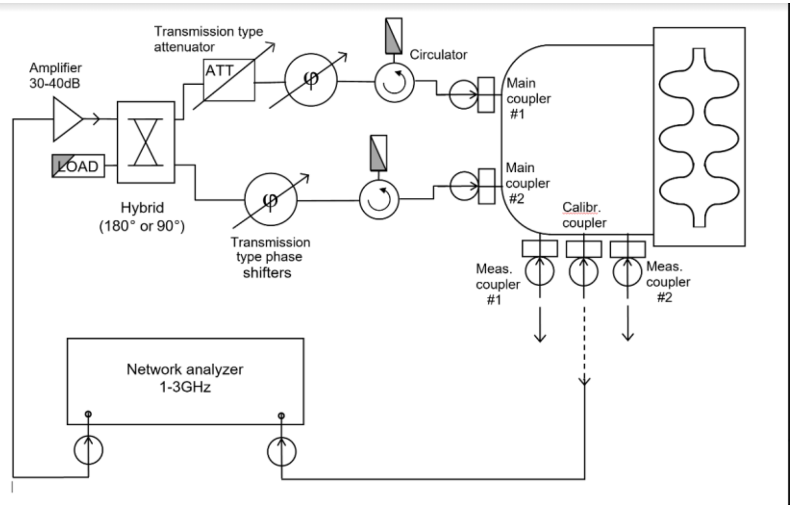
Further optimization has been performed - H. Padamsee, et all, SRF21

- The cavity – OK
- The “matcher” -OK
- Diagnostics – OK
- The input couplers - OK
- Processing fixtures – OK
- The cavity processing* - OK

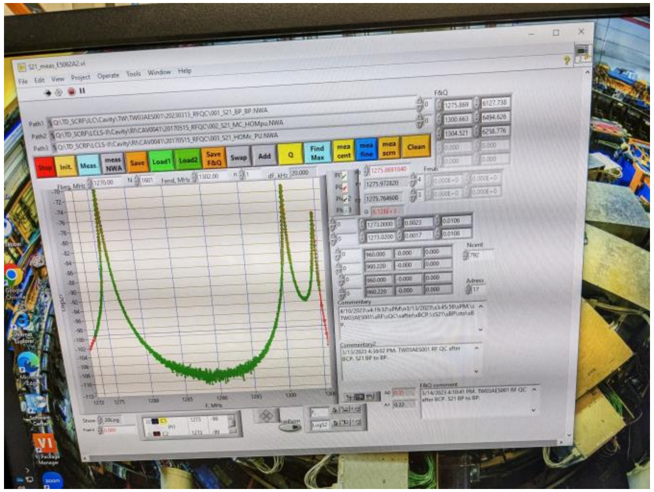
*120um rotational BCP, 800c bake, external BCP to remove oxides

3-cell TW cavity tests. RF measurements



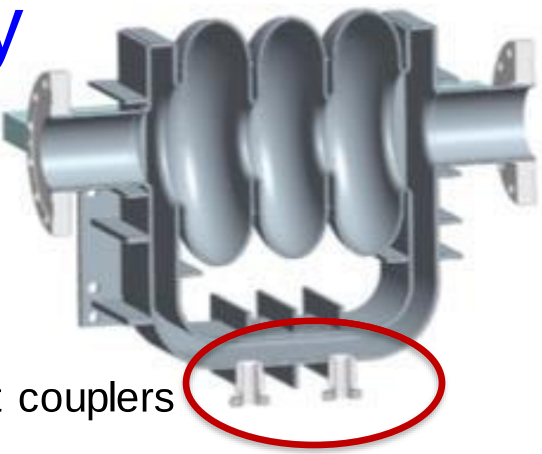


Setup 1

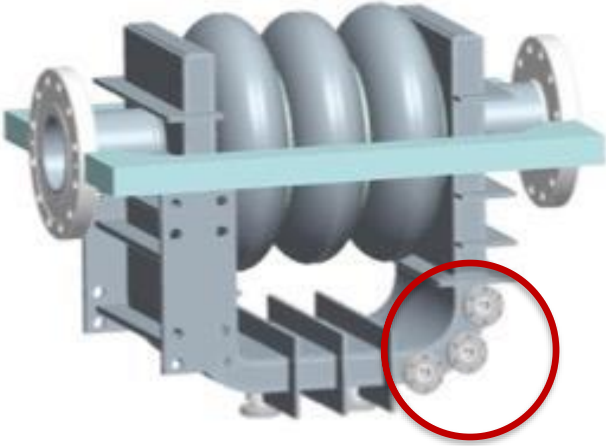


3 modes

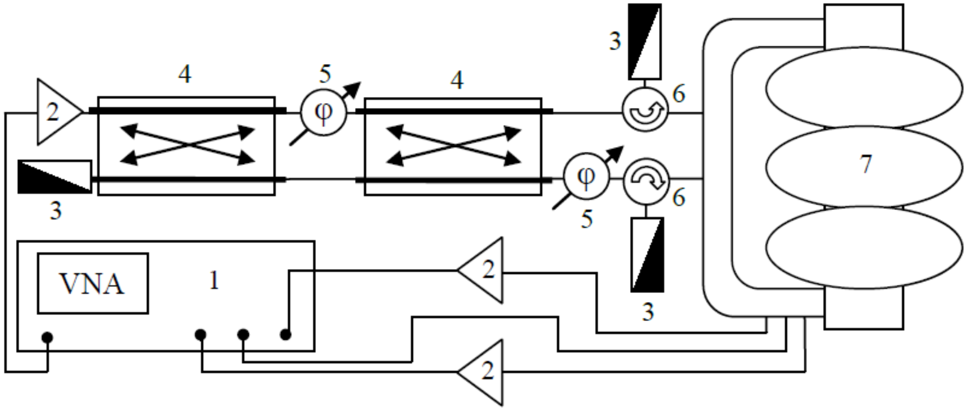
RF feed and measurement scheme for the 3-Cell TW cavity



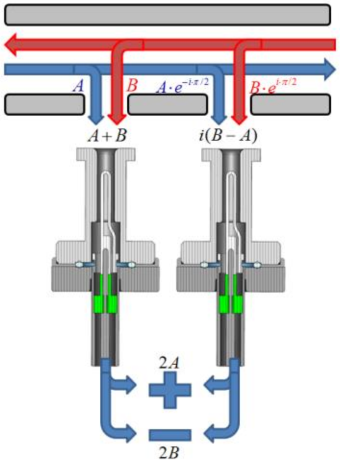
Two Input couplers



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

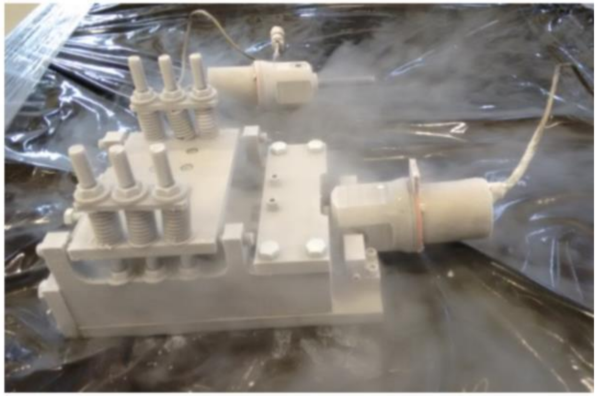


RF feed and measurement scheme for the 3-Cell TW[3]
1 – Vector Network Analyzer (VNA);
2 – power amplifier;
3 – matched load;
4 – 3dB hybrid;
5 – phase shifter;
6 – circulator;
7 – resonator

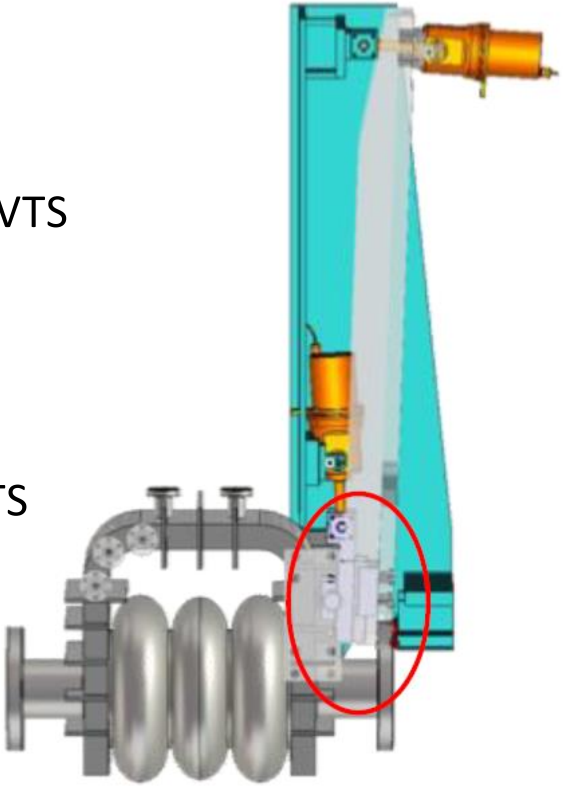


Special tuner (Matcher) for the 3-cell TW cavity

- 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



Model of the 3-cell with one Matcher.

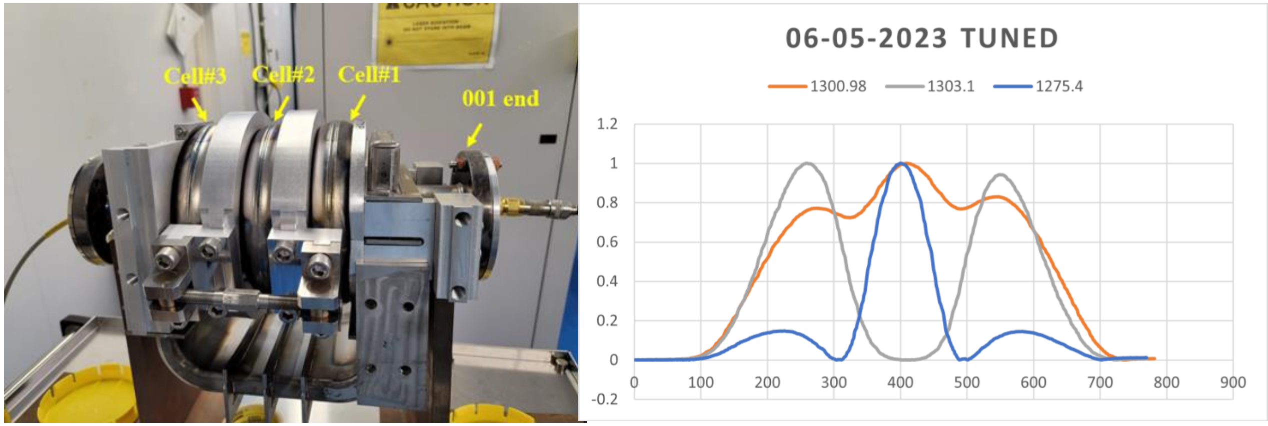
Assembly test

TW 3-cell VTS preparations

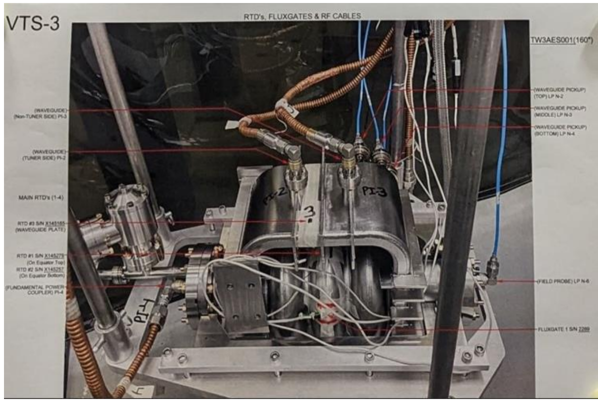
BCP at ANL

HPR at IB4, FNAL

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

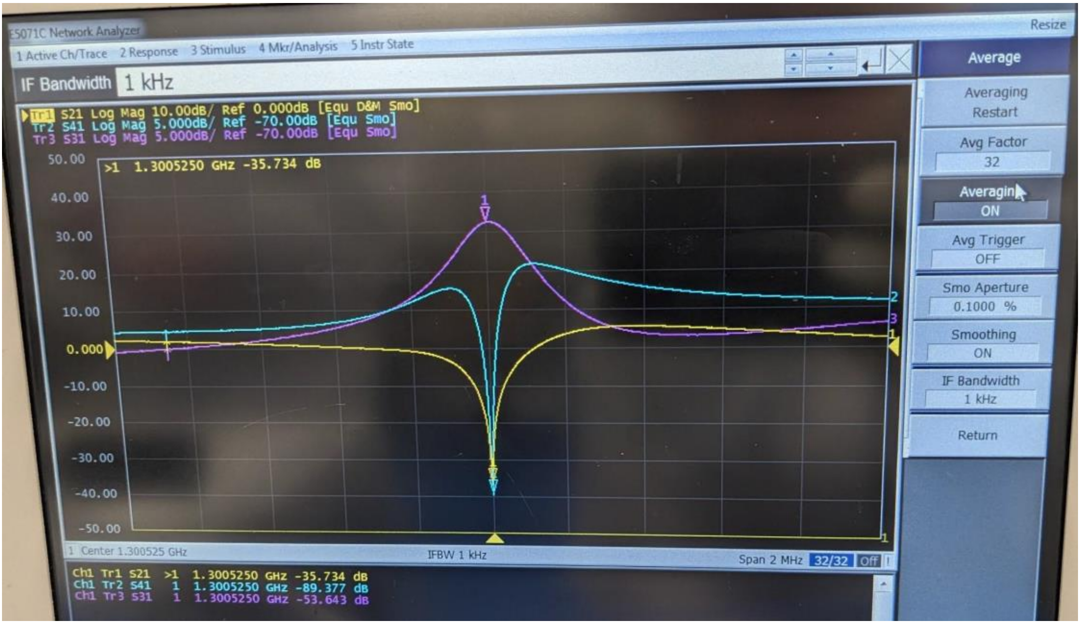


Custom tuning hardware on the 3-cell and the field profiles (SW mode) post tuning.



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
```

Avg Factor 32
Averaging ON
Avg Trigger OFF
Smo Aperture 0.1000 %
Smoothing ON
IF Bandwidth 1 kHz

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.

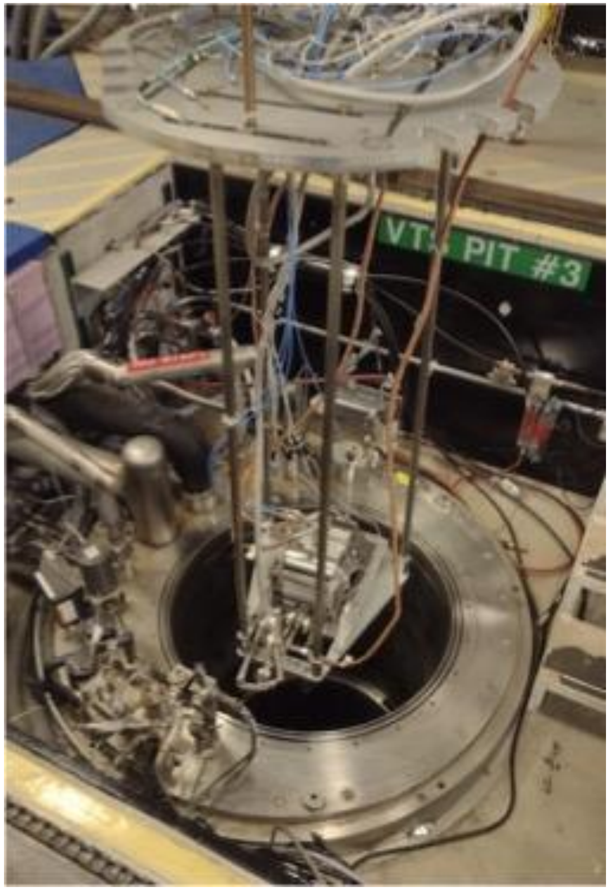
TW demonstration; Cavity under vacuum, at room temp. in VTS

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



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

```
Tr1 S41 Log Mag 1.000dB/ Ref -82.00dB [Equ Smo]
Tr2 S31 Log Mag 5.000dB/ Ref -90.00dB [Equ Smo]
Tr3 S21 Log Mag 500.0mdB/ Ref -89.00dB [Smo]
>1  1.3031550 GHz -78.744 dB
1 Center 1.303155 GHz          IFBW 1 kHz          Span 10 kHz 15/15 Off
Ch1 Tr1 S41  >1  1.3031550 GHz -78.744 dB
Ch1 Tr2 S31   1  1.3031550 GHz -110.73 dB
Ch1 Tr3 S21   1  1.3031550 GHz -89.408 dB
```

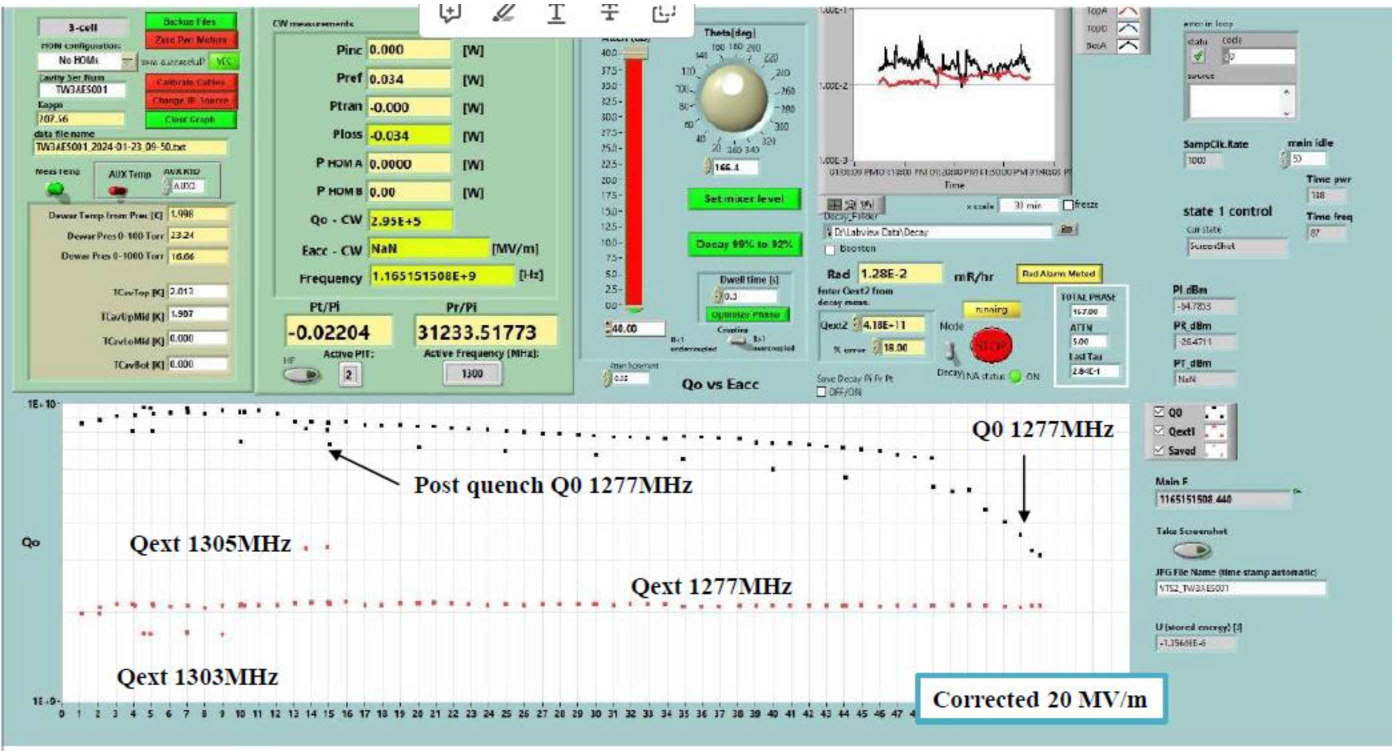
An example of TW at 1303.155 MHz being tuned at 2K

- 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



3-cell
HOM configuration: No HOMs
Cavity Ser Num: TW3AES001
Kappa: 207.56
data file name: TW3AES001_2024-01-23_09-50.txt
AUX RTD: A.000
Dewar Temp from Pres [K]: 1.998
Dewar Pres 0-100 Torr: 23.24
Dewar Pres 0-1000 Torr: 16.66
TCavTop [K]: 2.012
TCavUpMid [K]: 1.907
TCavLoMid [K]: 0.000
TCavBot [K]: 0.000

CW measurements
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

Theta[deg]: 166.4
Atten (dB): 40.00
Atten Increment: 0.25
Dwell time [s]: 0.3
x scale: 30 min
Decay_Folder: D:\Labview Data\Decay
Rad 1.28E-2 mR/hr
Enter Qext2 from decay meas.
Qext2 4.18E+11
% error 18.00
TOTAL PHASE 157.00
ATTN 5.00
Last Tau 2.84E-1
SampClk.Rate 1000
main idle 50
Time pwr 138
Time freq 87
state 1 control
cur state: ScreenShot
PI_dBm -94.7853
PR_dBm -26.4711
PT_dBm NaN
Main F 1165151508.440
JPG File Name (time stamp automatic): VTS2_TW3AES001
U (stored energy) [J]: -1.35668E-6

Qo vs Eacc

Q0 1277MHz

Post quench Q0 1277MHz

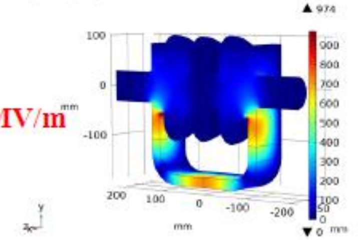
Qext 1305MHz

Qext 1277MHz

Qext 1303MHz

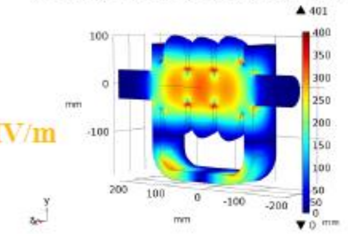
Corrected 20 MV/m

Eigenfrequency=1.1649 GHz Volume: Electric field norm (V/m)



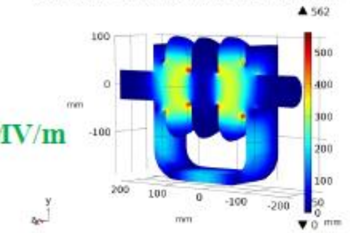
Eacc=19 MV/m

Eigenfrequency=1.2735 GHz Volume: Electric field norm (V/m)



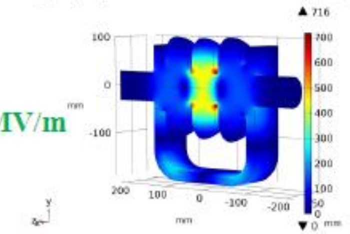
Eacc=20 MV/m

Eigenfrequency=1.3012 GHz Volume: Electric field norm (V/m)



Eacc= 25 MV/m

Eigenfrequency=1.3013 GHz Volume: Electric field norm (V/m)



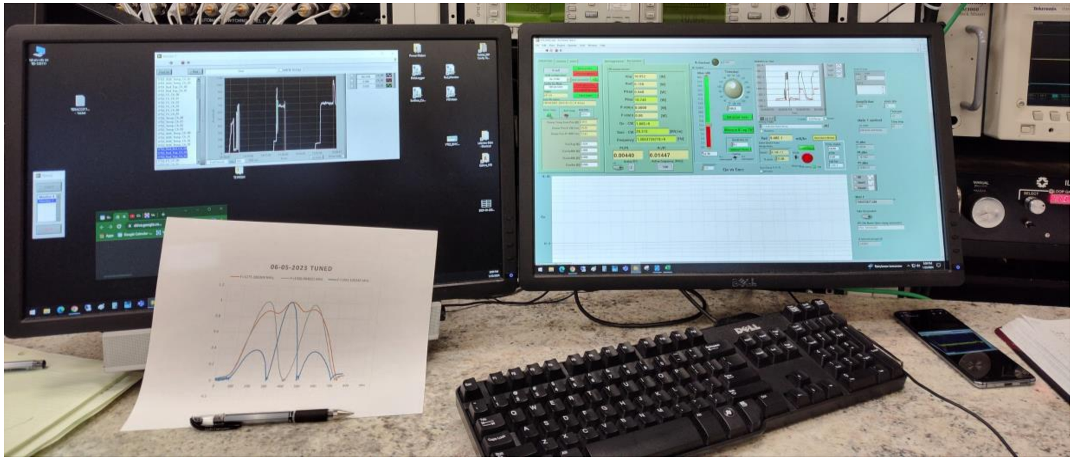
Eacc= 28 MV/m

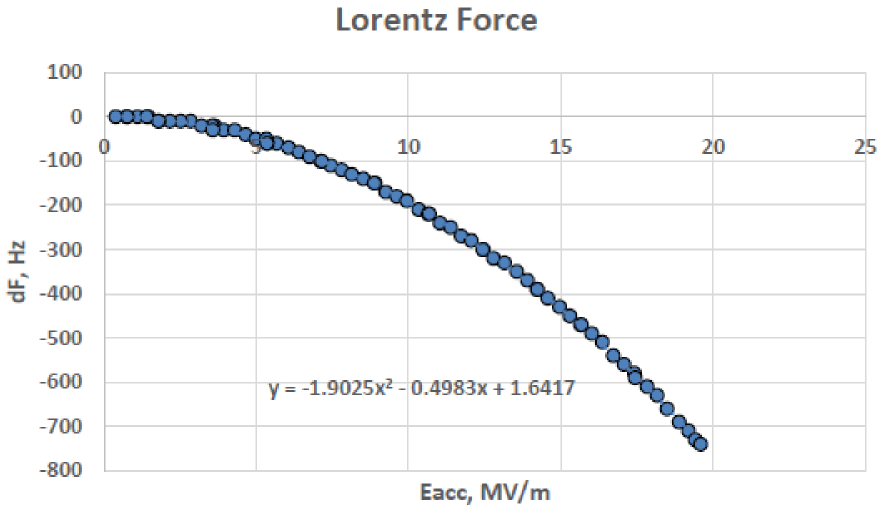
Comments: Lower sparce black dots – post quench curve; red lower dots 4-9MV/m – Qext1 for second mode; red upper dots 13-15MV/m – Qext2 for third mode.

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 KL=-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!





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 BCP800C 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

Further R&D plans

- Design of the 0.5 m long TW SRF structure and its components including
  - The cavity;
  - Tuners (the main tuner and the “matcher”);
  - He vessel
  - Diagnostics probes
- Manufacturing, processing and HG tests of the bare TW cavity (3 years).
- Manufacture and tests of the dressed cavity with the main tuner and TTF-III couplers.

Acknowledgment

Thanks to all colleagues support the TW SRF cavity efforts!

- Fumio Furuta
- Kellen McGee
- Vyacheslav Yakovlev
- Sergey Belomestnykh
- Genfa Wu
- Allan Rowe
- Hasan Padamsee (Cornell)
- Valery Shemelin (Cornell)
- Roman Kostin (Euclid)
- Pavel Avrakhov (Euclid)
- Alexei Kanareykin (Euclid)

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- Timergali Khqabiboulline
- Gennady Romanov

Cavity Support

- Damon Bice
- Chad Thompson
- Thomas Reid
- Ben Guilfoyle

VTS Support

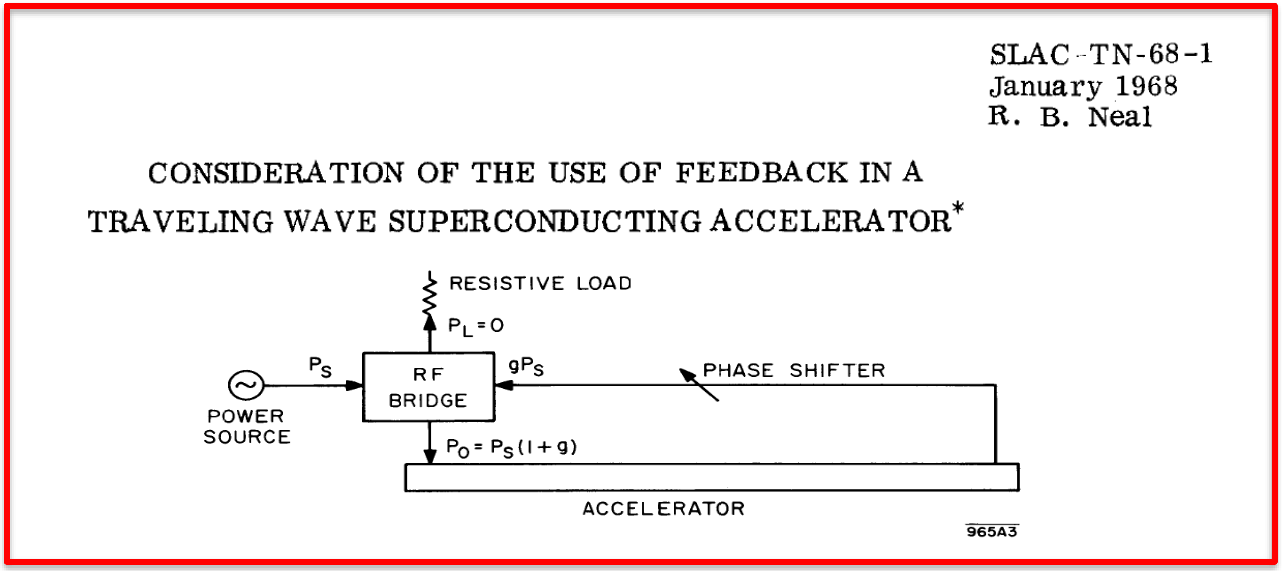
- Alexander Netepenko
- Abraham Diaz
- David Burk
- Paul Dubiel
- Mak Kwan (Trista) Ng

Engineering Support

- John Rathke (AES)
- Cryo Support
- Dan Marks

and more

- ❑ TW SRF cavity has a long story



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

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

- ❑ And may have a bright future!