OPTIMIZATION OF A TRAVELING WAVE SUPERCONDUCTING RF CAVITY FOR UPGRADING THE INTERNATIONAL LINEAR COLLIDER TO 3 TeV

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OUTLINE

- Introduction
- Advantages of Travelling Wave (TW)
- Challenges for TW structure
- Optimization of TW structure
- Making TW structures multipactor-free.
- Fabrication design proposals.
- Losses in the feedback waveguide
- High level parameter lists for 2 TeV and 3 TeV ILC upgrades
- Possible Further increase of the real-estate gradient to 80 MV/m!

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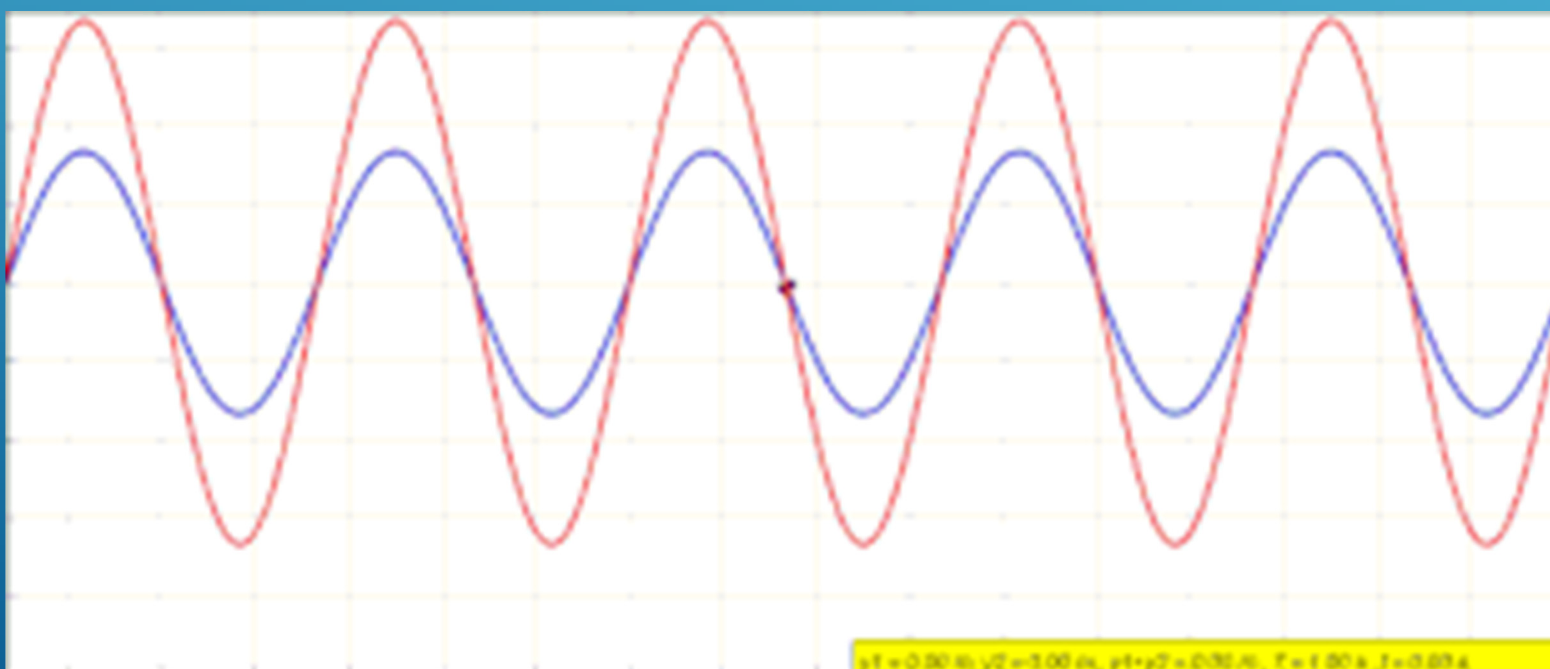
- *Explore the option of Niobium Traveling Wave (TW) structures*

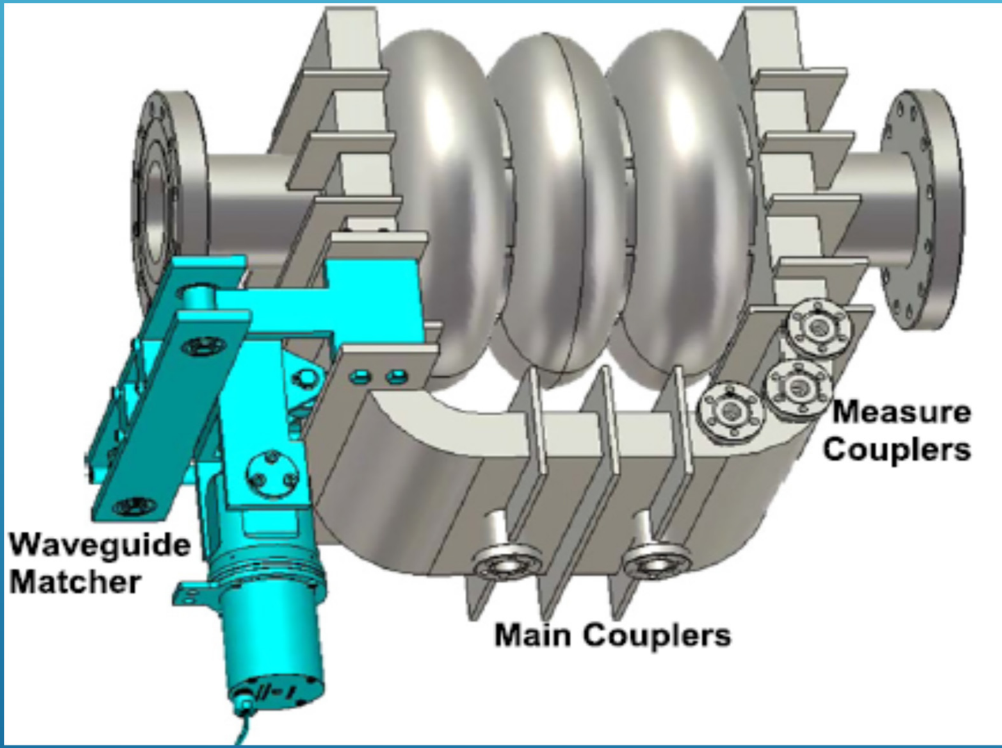
ANIMATIONS OF TW AND SW

- Red = standing wave – With High Peak Fields
- Green (= Acceleration) => and
- Blue (= Return) <= Waves are Travelling Waves with Lower peak fields
- Need to Guide blue wave via a separate return wave-guide attached to both ends
- to avoid SW peak fields



POSSIBLE REALIZATION

Prototype built by Euclid labs and Fermilab



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  - *Hpk* = 200 mT, *Epk* = 120 MV/m
  - Smaller aperture is allowed because bunch charge for 3 TeV ILC upgrade will about 3 X less to get acceptable IP background…
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    esulting in much lower wakefields in accelerating structure

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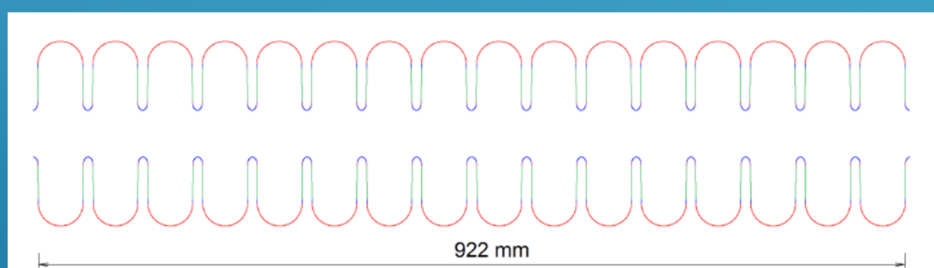
- Higher group velocity makes field profile tuning easier than for SW

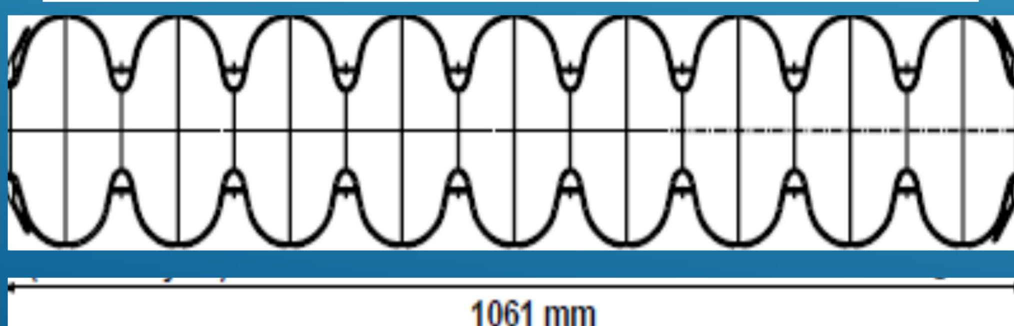
CHALLENGES FOR TW - 1

- 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.

TW

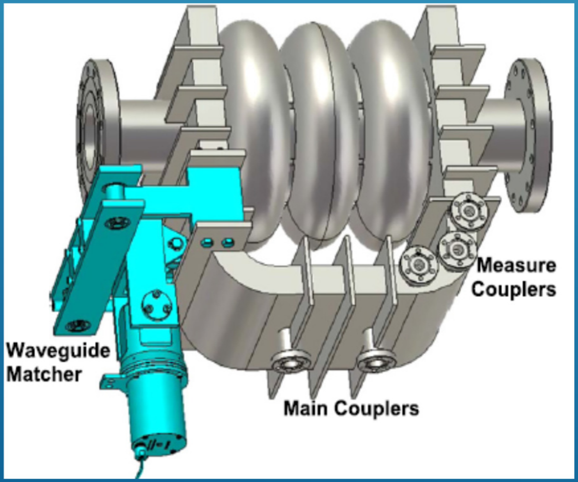


SW
TESLA



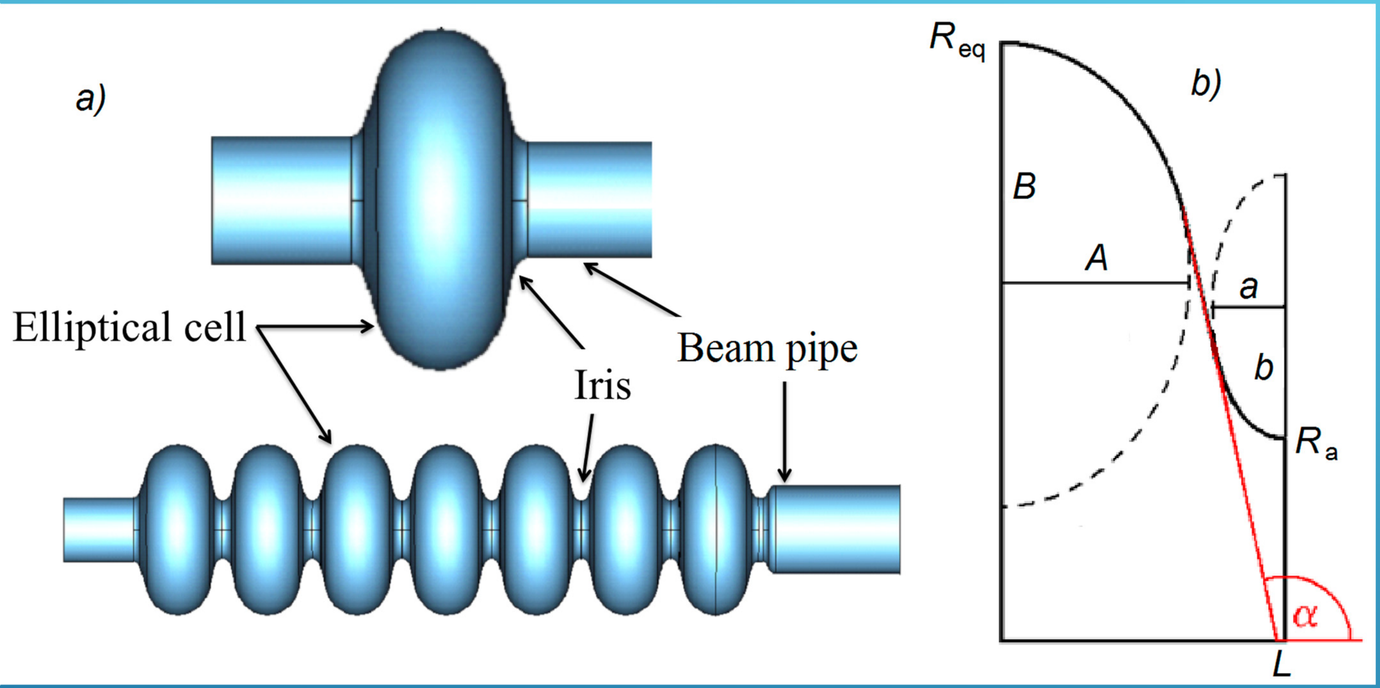
Challenges for TW - 2

- 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
- Multipacting has been studied
- HOM propagation and HOM damping study started – results encouraging



3-cell unit prepared at Fermilab by Euclid Corp – not yet tested

DEFINITIONS: GEOMETRY OF AN ELLIPTICAL CAVITY



Best cavity preparations today allow Epk = 100 - 120 MV/m and Bpk = 2000 - 2100 mT
=> Optimize TW shapes for Epk/Bpk = 100/200 and Epk/Bpk = 120/ 200

Reduce aperture from 70 mm to 50 mm
3 TeV upgrade will have lower bunch charge

PARAMETERS FOR ILC 2 TEV AND 3 TEV
(DETAIL PARAMETERS AVAILABLE IN POSTER)

COMPARE TO CLIC 3 TEV

		ILC1 From TDR	ILC2 From 1 TeV	ILC3 TeV From 1 TeV	CLIC 3 TeV
Energy	TeV	1	2.0	3.0	3.0
Luminosity	$X10^{34}$	4.9	7.9	6.1	5.9
AC Power	MW	300	245 -315	453	590
Cap Cost	BILCU	13.3	+4.9 – 5.2 (18.2-18.5)	+ 11.5 (24.8 Total)	24.2 total BCHF
Gradient	MV/m	45	70	70	72/100
Q of new linac	10^{10}	2	2	2	5700

AC power much less than CLIC

Total cost comparable to CLIC

See: WEPFAV006 *ILC Energy Upgrade Paths to 3 Tev*
H. Padamsee

FIRST OPTIMIZATIONS WITH E_{PK}/B_{PK} = 100/200 AND 120/200. APERTURE 2Ra = 50 mm

Table 3: Parameters of optimized cells with limiting surface fields: (1) E^*_{pk} = 100 MV/m and B^*_{pk} = 200 mT, and (2) E^*_{pk} = 120 MV/m and B^*_{pk} = 200 mT; $L - A = 5$ mm, aperture radius $R_a = 25$ mm. E^*_{acc} is the accelerating rate when the limiting surface fields are achieved.

Optimization	100/200	TESLA 120/200	120/200	120/200	120/200	120/200
Phase advance θ, deg	105	90	95	100	105	110
A, mm	28.631	23.826	25.428	27.029	28.631	30.232
B, mm	97.44	36.4	38.1	39.9	40.91	42.1
a, mm	6.084	4.512	4.840	5.171	5.494	5.817
b, mm	11.098	7.52	8.136	8.772	9.379	9.986
E_{pk}/E_{acc}	1.655	2.0 1.727	1.730	1.734	1.739	1.745
B_{pk}/E_{acc}, mT/(MV/m)	3.309	4.2 2.878	2.883	2.890	2.898	2.909
R_{sh}/Q, Ohm/m	1789	1037 2127	2096	2063	2029	1992
α, degrees	94.73	90.91	90.33	89.61	88.77	87.71
R_{eq}, mm	106.156	98.950	98.991	99.068	99.016	99.011
v_{gr}/c	0.01365	0.01831	0.01776	0.01710	0.01635	0.01551
E^*_{acc}, MV/m	60.4	69.5	69.4	69.2	69.0	68.8
$E^*_{acc} \cdot 2L$, MV	4.06	4.00	4.22	4.43	4.64	4.85

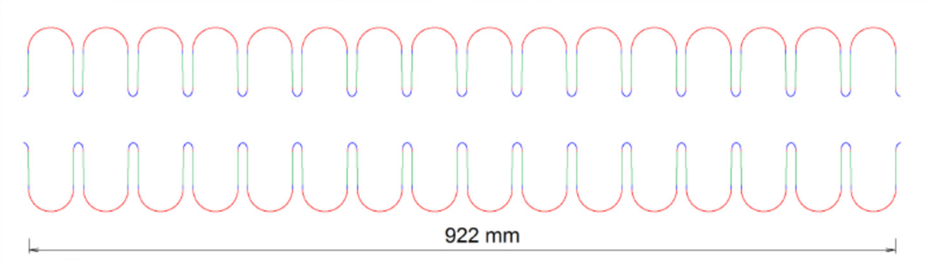
OPTIMIZATION 120/200. APERTURE 2Ra = 40 MM (MORE AMBITIOUS!)

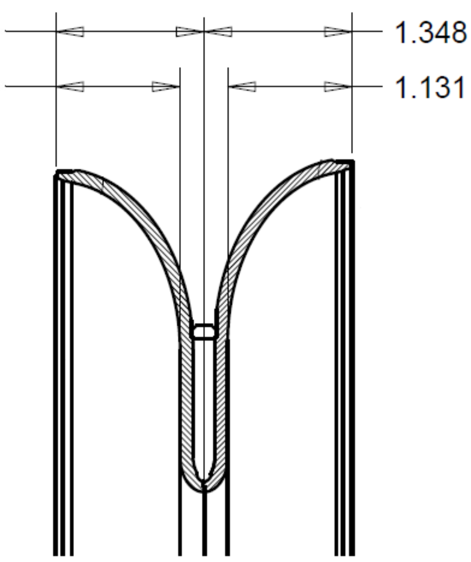
Table 4: Parameters of optimized cells with limiting surface fields $E^*_{pk} = 120$ MV/m and $B^*_{pk} = 200$ mT; $L - A = 5$ mm, aperture radius $R_a = 20$ mm. E^*_{acc} is the accelerating rate when the limiting surface fields are achieved.

Optimization	120/200
Phase advance θ, deg	90
A, mm	23.826
B, mm	35
a, mm	3.874
b, mm	6.777
E_{pk}/E_{acc}	1.639
B_{pk}/E_{acc}, mT/(MV/m)	2.732
R_{sh}/Q, Ohm/m	2367
α, degrees	91.74
R_{eq}, mm	97.990
v_{gr}/c	0.009315
E^*_{acc}, MV/m	73.2
$E^*_{acc} \cdot 2L$, MV	4.22

MANUFACTURING ISSUES

SHORT CELL LENGTH FOR TW POSES A PROBLEM: *HOW TO JOIN SHORTER CELLS?*





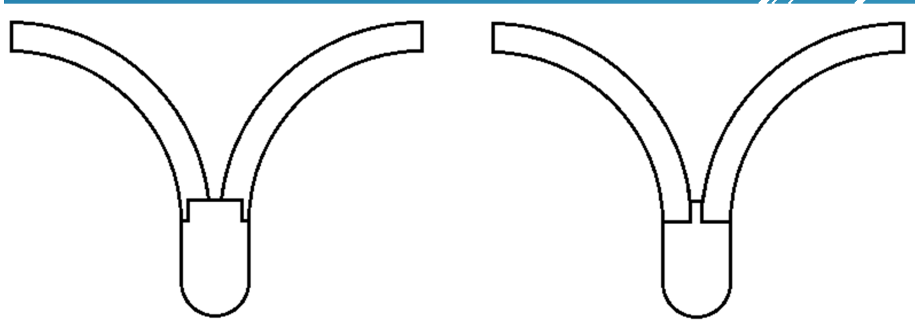
A solution done by AES (see Fig.):

Instead of two half-cells welded together,

the half-cells are welded to the iris disc.

An example of a cavity with L - A = 5.5 mm.

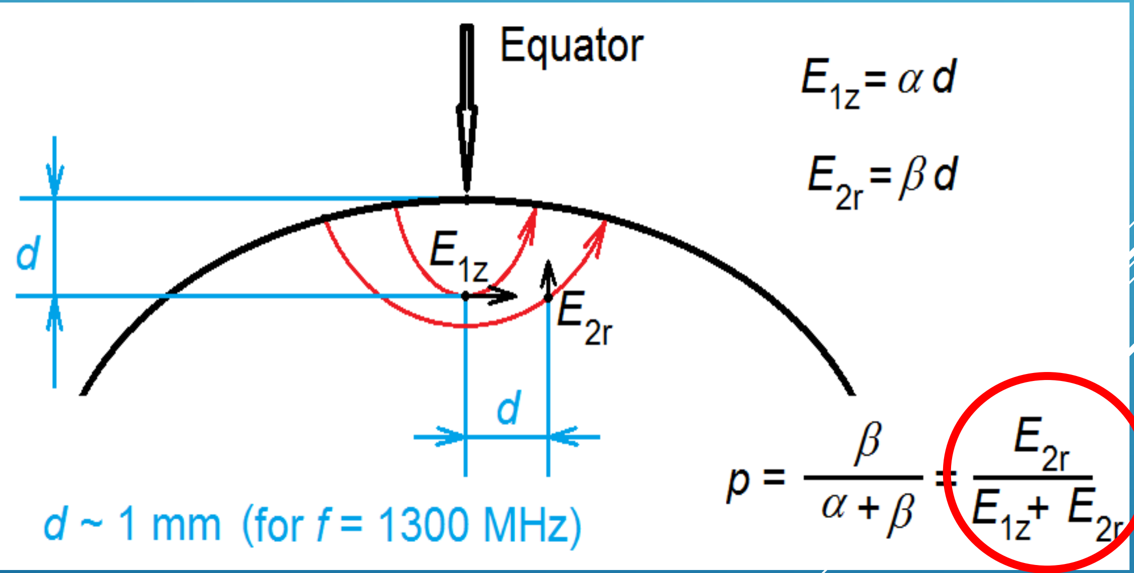
- This design makes it possible to get rid of the stiffening rings because the iris disc is stiff.
- The radius of curvature at the iris tip becomes comparable to the thickness of the niobium sheet,
- => Difficult to make by deep drawing.
- With a solid diamond machined disc, this problem is removed.
- Smooth => Good for field emission



New possible design of the cells' connection.

GENERAL 2-PT MULTIPACTOR CONSIDERATIONS

- According to [19], existence of multipactor is defined by the geometrical parameter *p*:
- Experimental data presented in this book [19] shows that at p = 0.3 and higher there is a strong multipactor.
- The TESLA shape cavity has p = 0.286 and has a weak multipactor activity,
- With some degree of caution, one can say that
- p = 0.28 is a safety limit for avoiding multipactor.



[19] V. Shemelin, S. Belomestnykh. Multipactor in accelerating cavities. Springer, Switzerland, 2020. ISBN 978-3-030-49437-7

MULTIPACTOR CONSIDERATION (2)

Table 6: Parameters of some TW cells from Table 3 before and after transformation removing multipactor conditions. Right column - parameters of the TESLA cavity, for comparison.

Optimization	120/200	120/200	120/200	TESLA SW
Phase				(100/210)
advance θ, deg	90	95	100	180
	before/after	before/after	before/after	
A, mm	23.826	25.428	27.029	42
B, mm	36.4/24	38.1/28	39.9/30	42
a, mm	4.512	4.840	5.171	12
b, mm	7.52	8.136	8.772	19
E_{pk}/E_{acc}	1.727/1.728	1.730/1.730	1.734/1.734	1.99
$\delta[E_{pk}/E_{acc}]$, %	0.081	0.010	0.013	
B_{pk}/E_{acc}, mT/(MV/m)	2.878/2.897	2.883/2.904	2.890/2.913	4.16
$\delta[B_{pk}/E_{acc}]$, %	0.651	0.734	0.809	
R_{sh}/Q, Ohm/m	2127/2.151	2096/2115	2063/2081	993
R_{eq}, mm	98.950/96.458	98.991/97.002	98.569/97.144	103.35
Aperture radius R_a, mm	25	25	25	35
p	0.302/0.270	0.301/0.278	0.303/0.279	0.286

To solve MP problem

a small change of the cell shape

without compromising the optimized parameters by < 1 % for E_{pk}/E_{acc} and B_{pk}/E_{acc}

decreases the value of *p* to a safe value.

LOSSES IN THE FEEDBACK WAVEGUIDE

How much can losses in the feedback waveguide decrease the efficiency of the TW operation?

Power of losses can be expressed as $P_{loss} = V^2/R_{sh}$, V is the voltage on the whole cavity, R_{sh} is the shunt impedance of the whole cavity. So, the power circulating in the ring is

$$P = \frac{V^2}{R_{sh}} \cdot \frac{Q}{L\omega_0} \cdot v_{gr} = \frac{V^2}{R/Q} \cdot \frac{v_{gr}}{L^2\omega_0}.$$

Using for a 1 m long structure V = 70 MV, R/Q = 2000 Ohm, $w_0/2p$ = 1.3 GHz, and v_{gr} = 0.01c we have the power circulating in the ring P = 900 MW. Power of losses in the whole structure is P_{loss} = 240 W (CW).

For a standard waveguide *a* x *b* = 165.1 x 85.55 mm with a H10 wave and surface resistance 27 nOhm, losses in the waveguide are 1.3 % of the losses in the structure.

MORE EXCITEMENT!

CAN TW STRUCTURES DELIVER > 80 MV/M?

HIGH GROUP VELOCITY OF TW ALLOWS LONGER CAVITY!

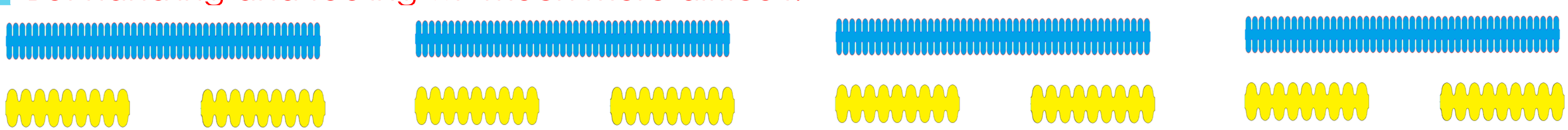
We know that a TESLA SW π-structure can be tuned, if it has $k_{SW} = 1.8 \cdot 10^{-2}$. To have the same error in the field, we have to have a number of cells in a TW structure equal to

$$N_{TW} = 2(k_{TW}/k_{SW}) \cdot N_{SW}^2.$$

The length of this structure will be $L_s = N_{TW} \cdot L_c$, where L_c is length of a cell, $L_c = \lambda\theta/(2\pi)$. Uniting all the above expressions, one can write

$$Ls = \frac{2N_{SW}^2}{\pi k_{SW}} \cdot \frac{\beta\lambda}{\sin\theta}.$$

If the structure length will be 2.4 m, we can remove the non-accelerating intervals between cavities ≈ 40 cm and have a useful acceleration 2.4 m/2 m ≈ 1.2 times higher, e.g. 84 MeV/m instead of 70 MeV/m! But handling and tooling will much more difficult.



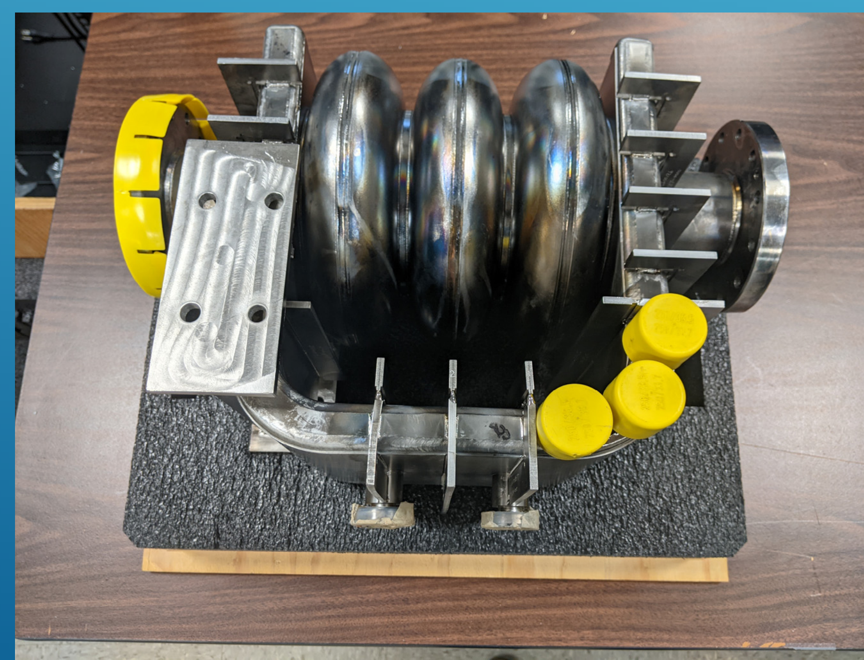
MAIN RESULTS

1. Small values of the wall thickness leads to a design with an iris disk. No stiffening rings. Can be made with a diamond turning – high smoothness, better accuracy of shape.
2. Small aperture increases accelerating rate and can be used for low charge bunches.
3. New approach of optimization takes into account both maximally possible fields, *E* and *H*.
4. Multipactor can be excluded.
5. No cavity length limitation by a coupling between cells.
6. **TW structure can have the accelerating gradient above 70 MV/m with the same critical magnetic and electric fields that in the SW structure.**
7. **TW structure has R/Q 2 times higher than TESLA structure. This is equivalent to a factor of 2 higher Q for reducing dynamic heat loss.**

Many significant challenges remain along the development path to the TW niobium structure. Realization of this work opens possibilities to ILC energy upgrades beyond 1 TeV to 3 TeV.

A START FOR TRAVELLING WAVE STRUCTURES

- 1-cell prepared by Euclid Corp with Fermilab
- Reached 26 MV/m with inferior (easier) treatment of BCP.
- Should do better with EP/baking
- 3-cell is now ready for tests at FNAL



Thank you for your attention!