Development of the SC squeezed elliptical cavity with β=0.81 for the Fermilab ProjectX linac.

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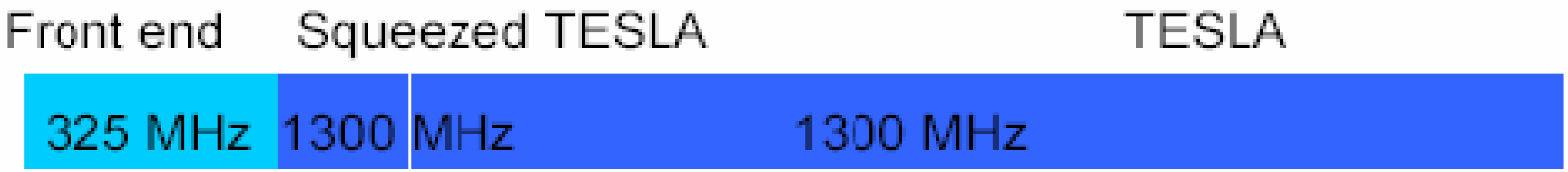
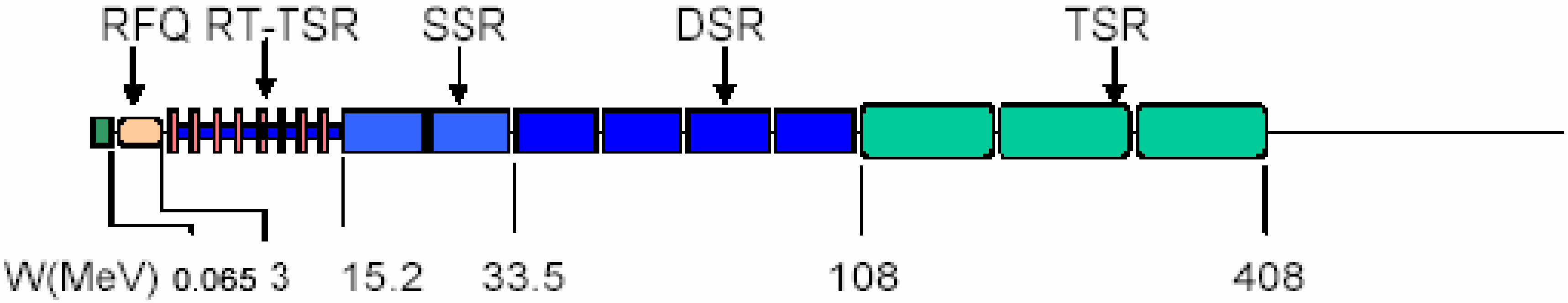
01.12.2009

Major Linac Sections

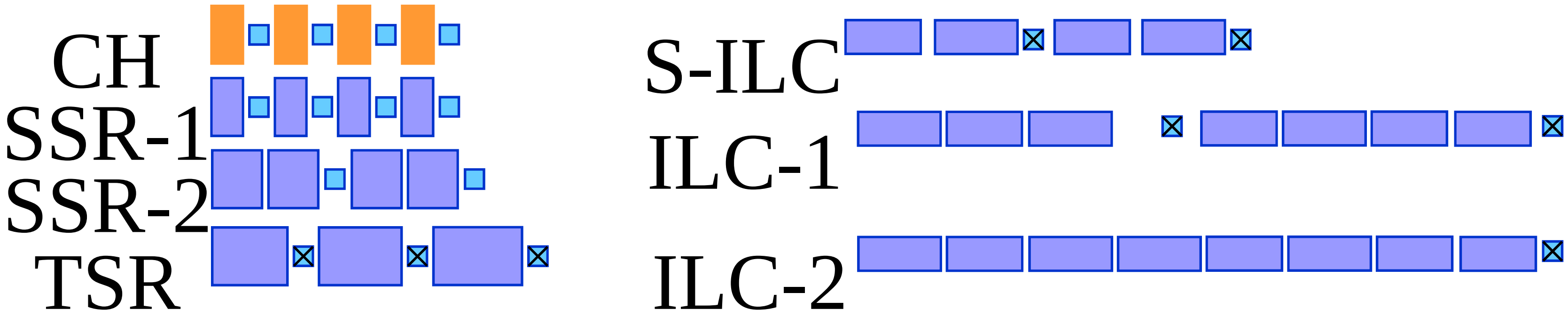


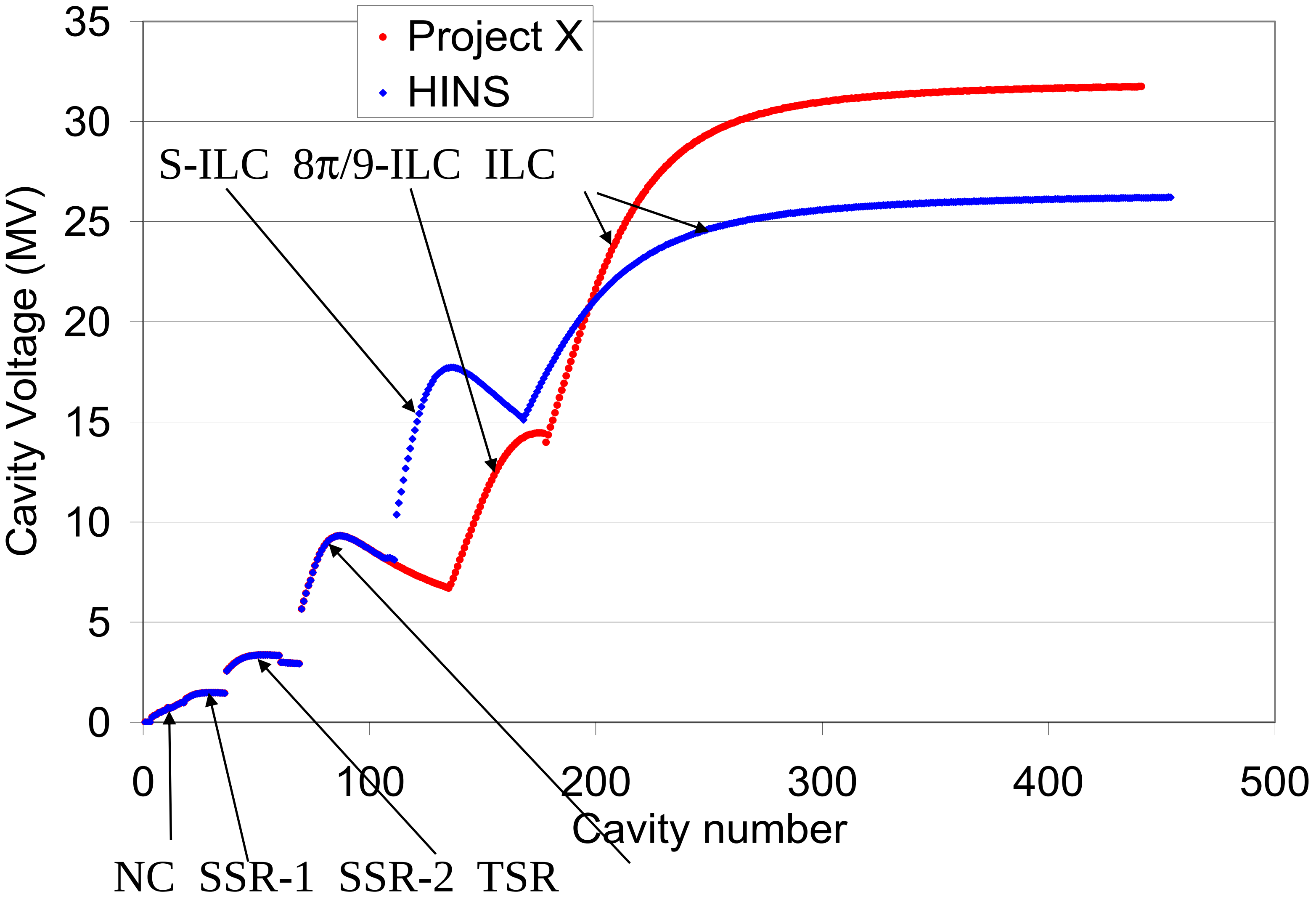
Front End



Cavity parameters and focusing lattice (Proton driver, 40 mA peak current, by P.Ostroumov)

Section	CH	SSR-1	SSR-2	TSR	S-ILC	ILC-1	ILC-2
β_G	-	0.2	0.4	0.6	0.83	1	
# of res.	16	18	33	42	56	63	224
# of cryost.	-	2	3	7	7	9	28
E_{peak} (MV/m)	-	30	28	30	52	52	
Focusing	SR	SR	SRR	FRDR	FR^{2}DR$^{2\,*}$	FR^{4}DR^3	FR^{8}DR^8
$L_{Focsuing}$, m	0.515-0.75	0.75	1.6	3.81	6.1	12.2	24.4

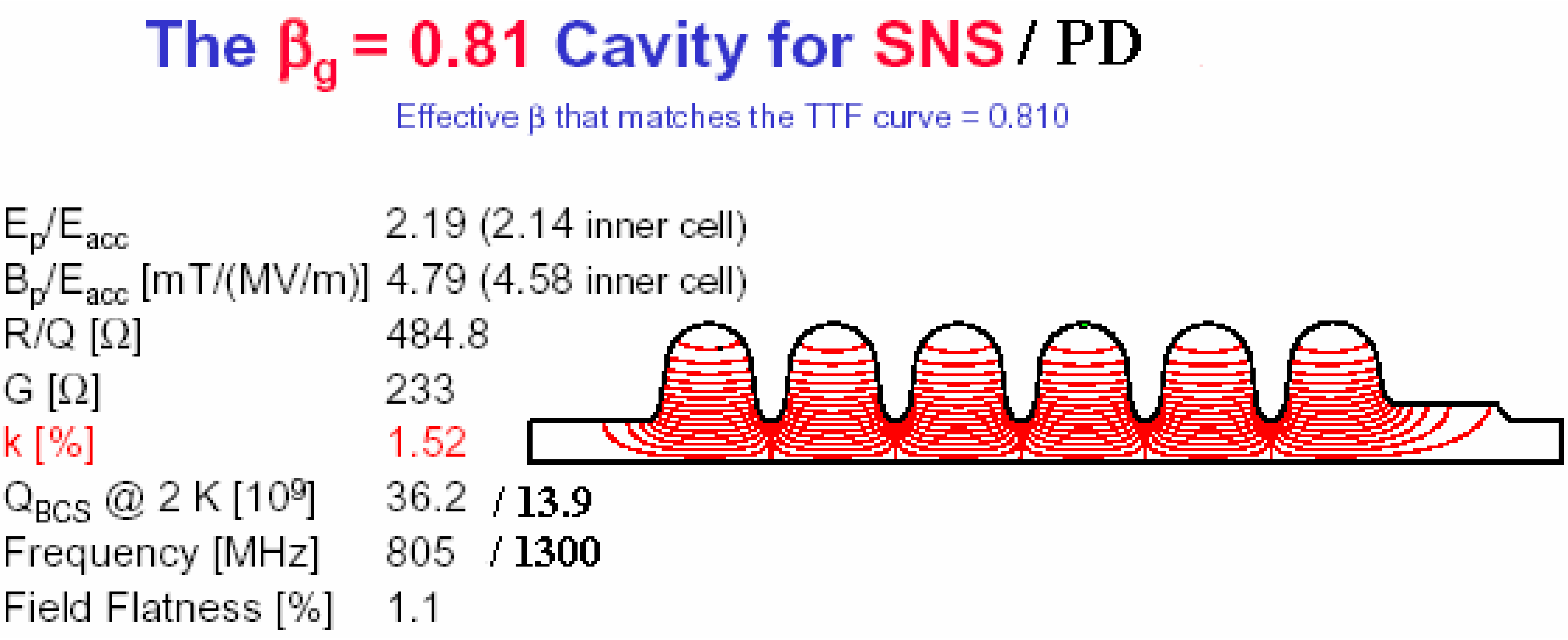



Project X
HINS
S-ILC
8π/9-ILC
ILC
NC
SSR-1
SSR-2
TSR
Cavity Voltage (MV)
Cavity number
0
5
10
15
20
25
30
35
0
100
200
300
400
500

Different approaches:

1. Scaling of SNS 6-cell cavity to 1300 MHz, 2004

Need a special cryostat.



The β_g = 0.81 Cavity for SNS / PD

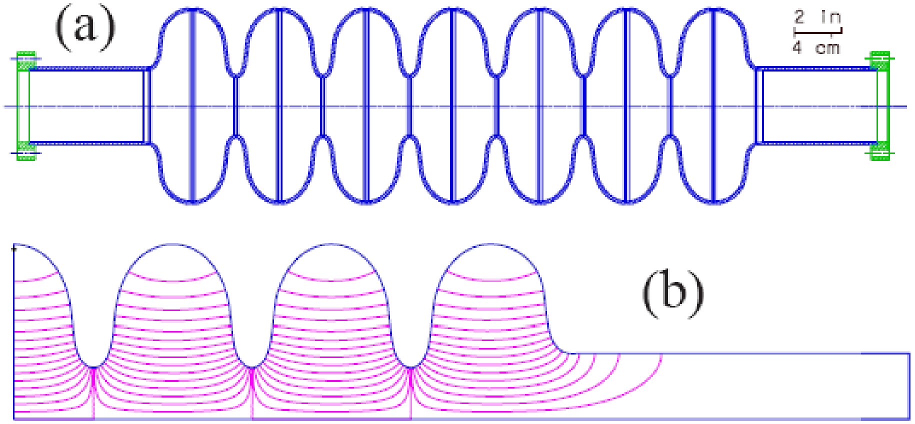
Effective β that matches the TTF curve = 0.810

E_p/E_{acc}	2.19 (2.14 inner cell)
B_p/E_{acc} [mT/(MV/m)]	4.79 (4.58 inner cell)
R/Q [Ω]	484.8
G [Ω]	233
k [%]	1.52
Q_{BCS} @ 2 K [10^9]	36.2 / 13.9
Frequency [MHz]	805 / 1300
Field Flatness [%]	1.1

Geometrical Parameters

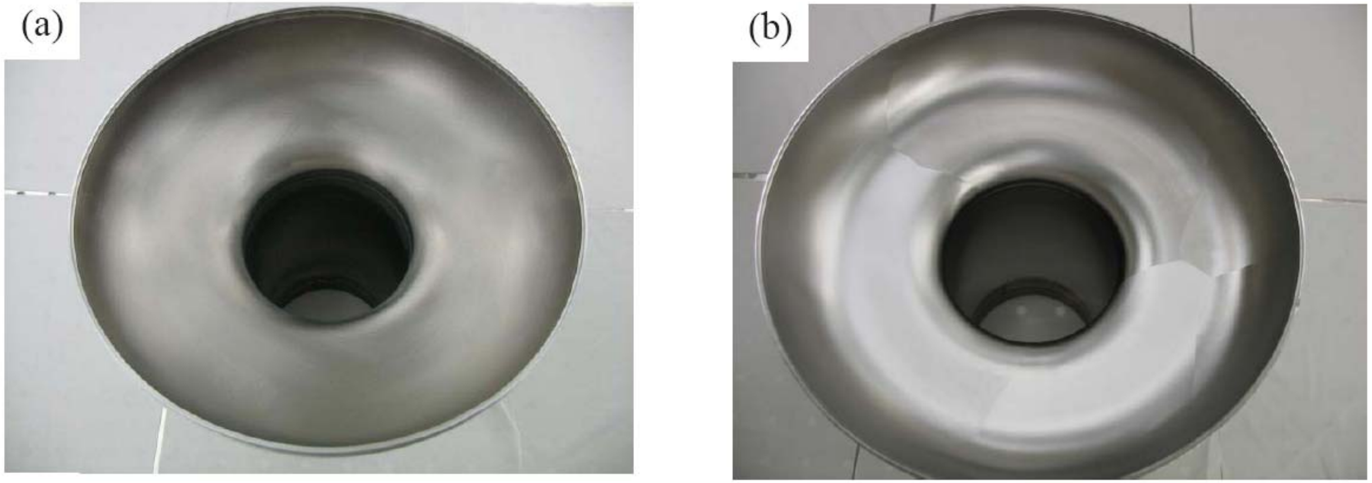
	Inner cell	End Cell Left	End Group (coupler	
			Left	Right
L [mm]	46.75	46.75	46.75	
R_{iris} [mm]	30.22	30.22	30.22	43.35
D [mm]	101.65	101.65	102.86	
d [mm]	9.29	8.05	9.29	8.05
r	1.8	1.6	1.8	1.6
R	1.0	1.0	1.0	
α [deg]	7.0	10.072	7.0	10.0

2. 7-cell β=0.81 MSU cavity



(a) Drawing of 7-cell $\beta = 0.81$ Proton Driver cavity (blue = Nb; green = Nb-Ti). (b) Electric field lines for the right half of the cavity.

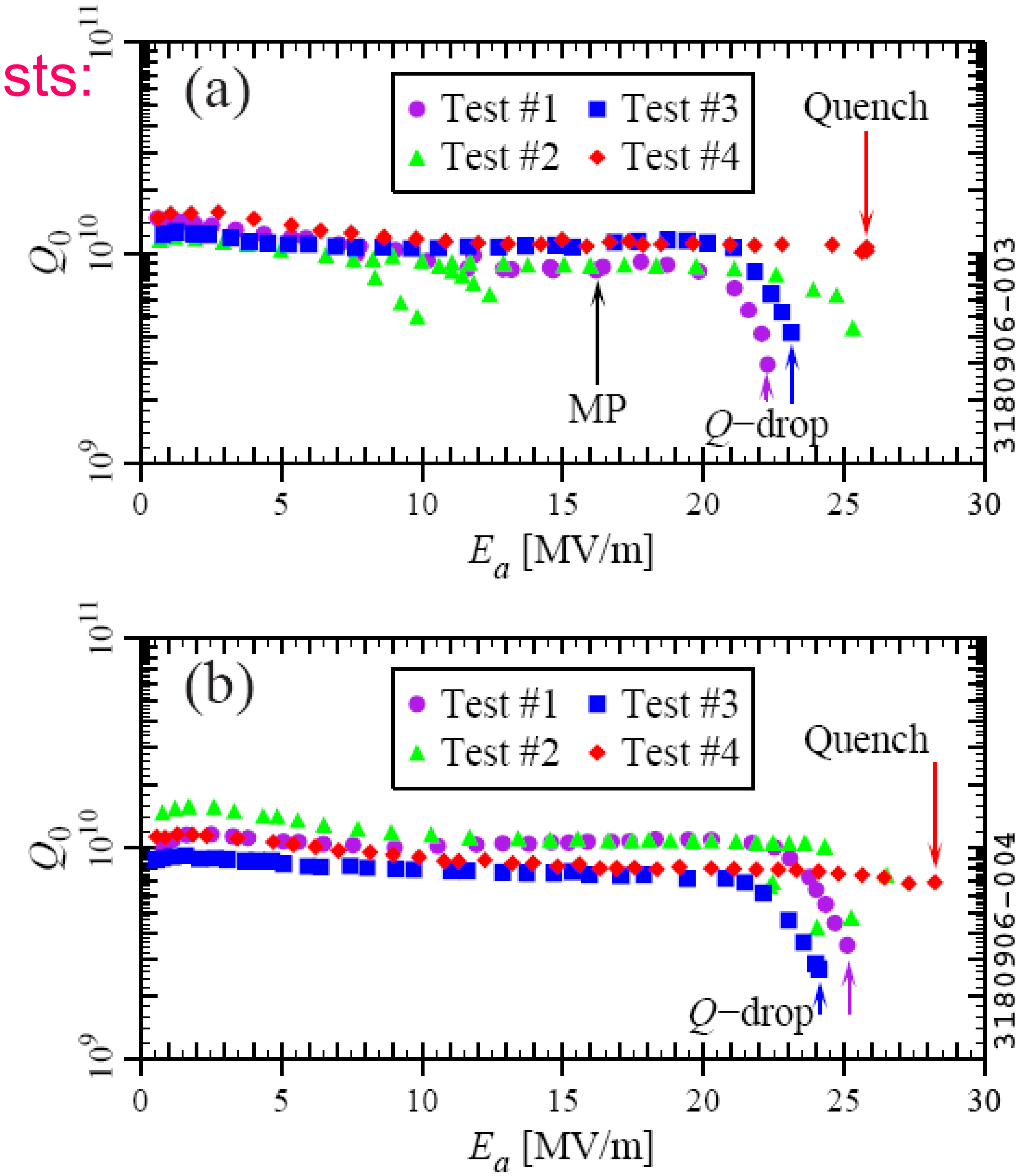
Cavity	TTF 9-cell	SNS 6-cell	Proton Driver 7-cell	Proton Driver 1-cell
geometrical β	1	0.81	0.81	0.81
wall inclination	13.3°	7°	7°	7°
E_p/E_a	2.0	2.19	2.19	2.18
cB_p/E_a	1.28	1.44	1.41	1.58
cell-to-cell coupling	1.8%	1.5%	1.6%	-
R/Q per cell	115 Ω	80.8 Ω	79.1 Ω	62.3 Ω
Geometry factor	270 Ω	233 Ω	227 Ω	229 Ω



(a) Fine grain and (b) large grain half-cells after the iris weld.

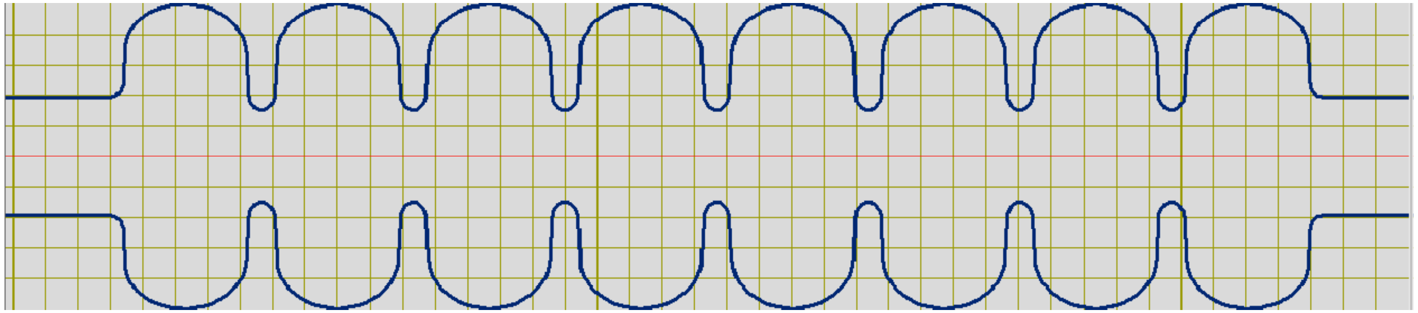
Completed fine grain (top) and large grain (bottom) 7-cell cavities

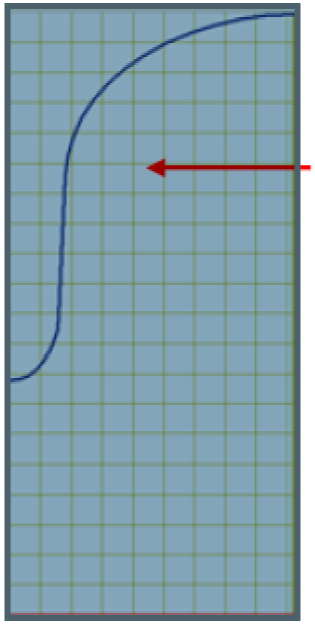
Single cell tests:



RF test results at 2 K for (a) the first and (b) the second large grain cavities.

3. 8-cell β=0.81 FNAL cavity, 2005

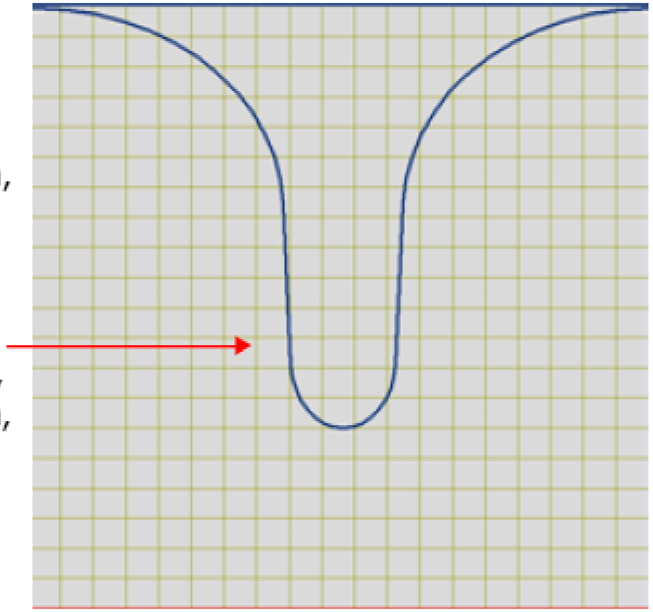




Beam pipe: D=78 mm.

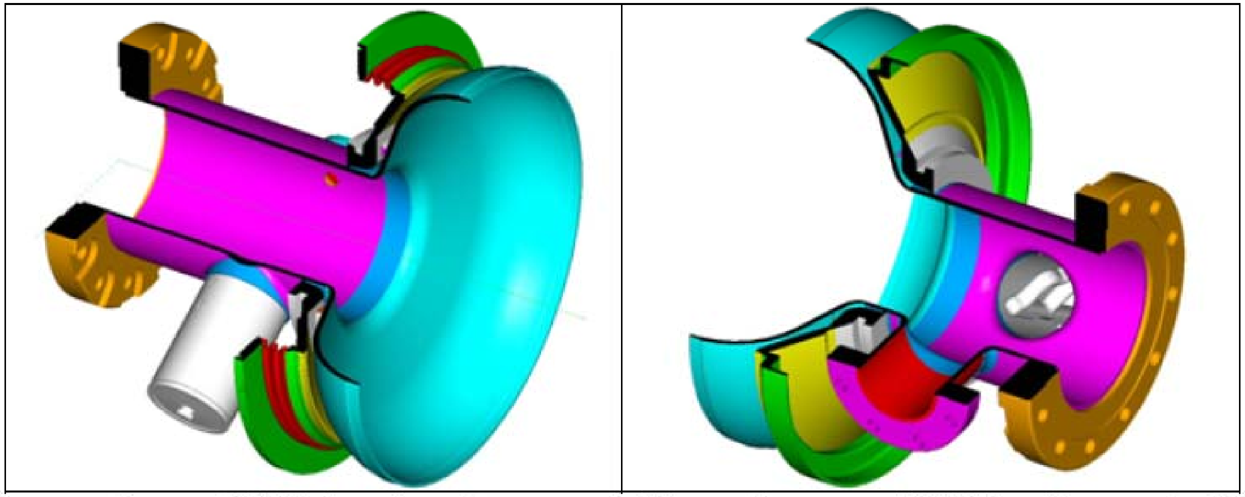
End half-cell: L=46.5mm, Ri=39.0mm, Re=99.715mm, Riz=8.0mm, Rir=11.2mm, Rez=37.513mm, Rer=27.675, Alpha=2.5deg.

Mid half-cell: L=46.752mm, Ri=30.0mm, Re=99.715mm, Riz=8.0mm, Rir=11.2mm, Rez=37.633mm, Rer=33.87mm, Alpha=2.5deg.

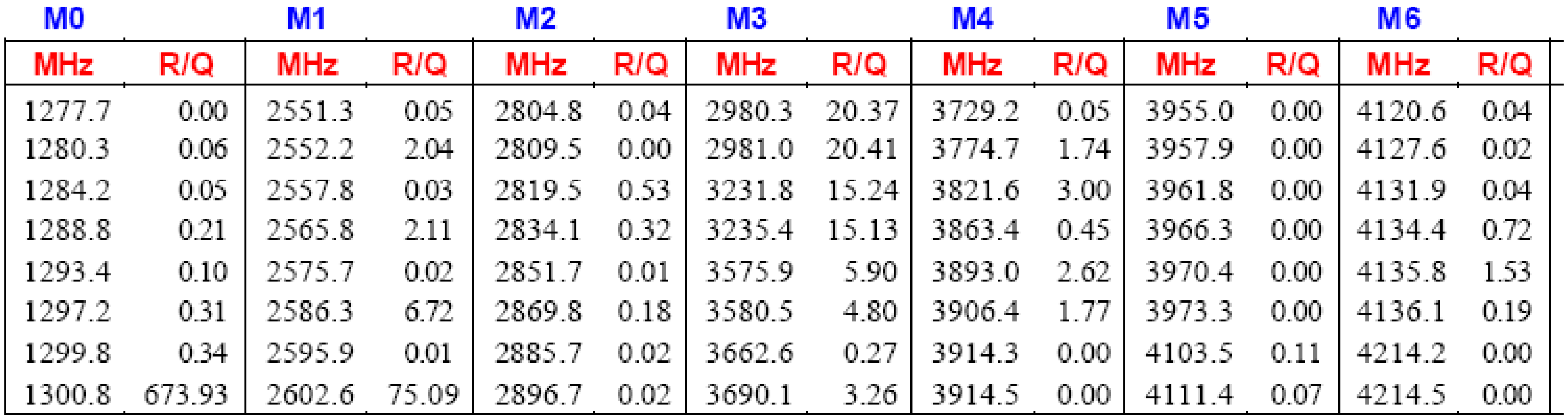


TD-Notes 2005-043 - http://tdserver1.fnal.gov/tdlibry/TD-Notes/2005%20Tech%20Notes/TD-05-043.pdf

Geometrical Beta of Sections	0.81	1
RF frequency (MHz)	1300	1300
Cavity Type	FNAL	TTF
Number of Cells Per Cavity	8	9
Cell-to-Cell Coupling Constant	0.018	0.0187
Unloaded Qo	>5E9	>1E10
External Q	700000	1500000
External Q Variation	+/- 20%	+/- 20%
R/Qo (function of beam velocity)	674	1036
Cavity Active Length (geometrical)	0.74718	1.03774
Cavity Total Length incl. Couplers	0.96718	1.25774
Cavity Slot Length incl. avg. Bellows	1.03218	1.32274
Iris Diameter	60	70
Beam pipe Diameteter	78	78
ID at Equator	199.43	206
Epeak (max)	58.6484	52
Bpeak/Eacc	4.33	4.26
Bpeak	102.813	110.76
Epeak/Eacc	2.47	2
Eacc (max, on crest for Beta-design)	23.74	26

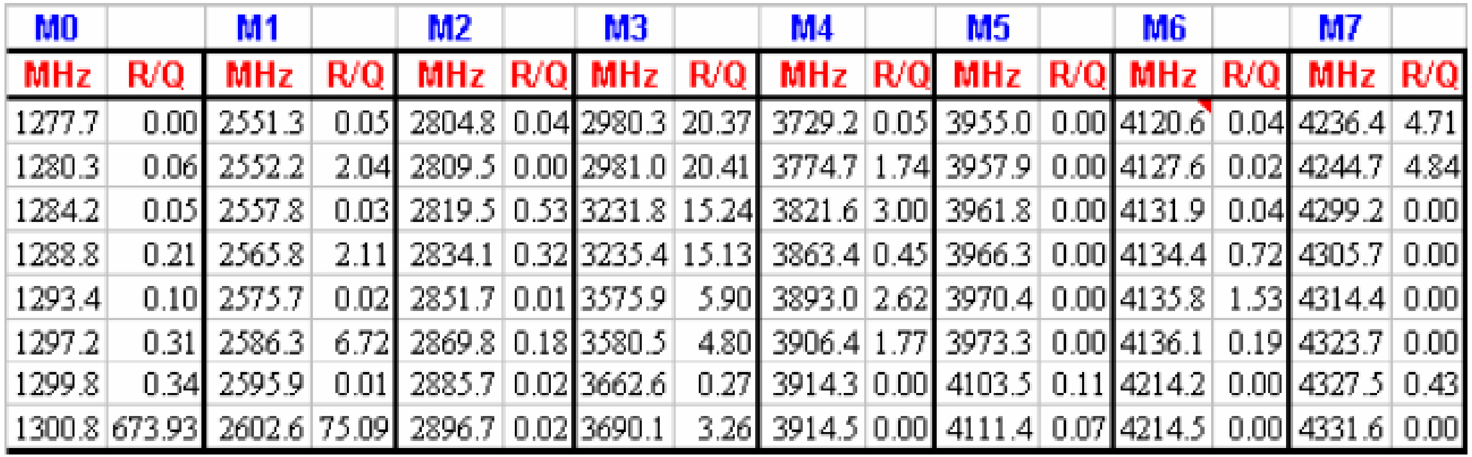


Squeezed TESLA cavity end-group assemblies are the same as TESLA cavity except end-cell geometry



M0		M1		M2		M3		M4		M5		M6	
MHz	R/Q	MHz	R/Q	MHz	R/Q	MHz	R/Q	MHz	R/Q	MHz	R/Q	MHz	R/Q
1277.7	0.00	2551.3	0.05	2804.8	0.04	2980.3	20.37	3729.2	0.05	3955.0	0.00	4120.6	0.04
1280.3	0.06	2552.2	2.04	2809.5	0.00	2981.0	20.41	3774.7	1.74	3957.9	0.00	4127.6	0.02
1284.2	0.05	2557.8	0.03	2819.5	0.53	3231.8	15.24	3821.6	3.00	3961.8	0.00	4131.9	0.04
1288.8	0.21	2565.8	2.11	2834.1	0.32	3235.4	15.13	3863.4	0.45	3966.3	0.00	4134.4	0.72
1293.4	0.10	2575.7	0.02	2851.7	0.01	3575.9	5.90	3893.0	2.62	3970.4	0.00	4135.8	1.53
1297.2	0.31	2586.3	6.72	2869.8	0.18	3580.5	4.80	3906.4	1.77	3973.3	0.00	4136.1	0.19
1299.8	0.34	2595.9	0.01	2885.7	0.02	3662.6	0.27	3914.3	0.00	4103.5	0.11	4214.2	0.00
1300.8	673.93	2602.6	75.09	2896.7	0.02	3690.1	3.26	3914.5	0.00	4111.4	0.07	4214.5	0.00

R/Q (Ohm) for the first few monopole passbands.



M0		M1		M2		M3		M4		M5		M6		M7	
MHz	R/Q	MHz	R/Q	MHz	R/Q	MHz	R/Q	MHz	R/Q	MHz	R/Q	MHz	R/Q	MHz	R/Q
1277.7	0.00	2551.3	0.05	2804.8	0.04	2980.3	20.37	3729.2	0.05	3955.0	0.00	4120.6	0.04	4236.4	4.71
1280.3	0.06	2552.2	2.04	2809.5	0.00	2981.0	20.41	3774.7	1.74	3957.9	0.00	4127.6	0.02	4244.7	4.84
1284.2	0.05	2557.8	0.03	2819.5	0.53	3231.8	15.24	3821.6	3.00	3961.8	0.00	4131.9	0.04	4299.2	0.00
1288.8	0.21	2565.8	2.11	2834.1	0.32	3235.4	15.13	3863.4	0.45	3966.3	0.00	4134.4	0.72	4305.7	0.00
1293.4	0.10	2575.7	0.02	2851.7	0.01	3575.9	5.90	3893.0	2.62	3970.4	0.00	4135.8	1.53	4314.4	0.00
1297.2	0.31	2586.3	6.72	2869.8	0.18	3580.5	4.80	3906.4	1.77	3973.3	0.00	4136.1	0.19	4323.7	0.00
1299.8	0.34	2595.9	0.01	2885.7	0.02	3662.6	0.27	3914.3	0.00	4103.5	0.11	4214.2	0.00	4327.5	0.43
1300.8	673.93	2602.6	75.09	2896.7	0.02	3690.1	3.26	3914.5	0.00	4111.4	0.07	4214.5	0.00	4331.6	0.00

(R/Q) [Ohm/m^2] for different passbands

Idea: Utilization of ILC Type-4 cryomodule

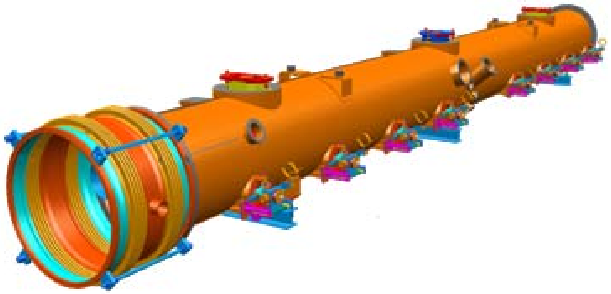
✓Development of a new type of CM is time-consuming and expensive;

✓The idea is to replace 9-cell TESLA cavities in type-4 ILC CM by squeezed $\beta = 0.81$ cavities;

✓ The cavity has 11 cells and the same length as for 9-cell, $\beta = 1$ cavity;

✓The required power is about the same, and the same couplers may be used as for $\beta = 1$ cavity;

✓ Exactly the same auxiliary components (vacuum vessel, tuner, tooling, etc) may be used.



Major changes:

- Magnet configuration change from FR^2DR^2 to ILC-like R^4FDR^4FD with doublet instead of quad;
- Long cavities (up to 11-cell) instead of short (8-cell).

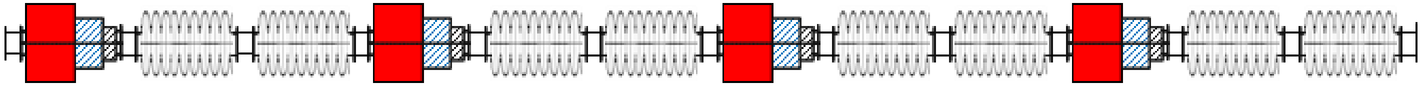
Proposed changes in Project X compared to baseline Proton Driver Optics

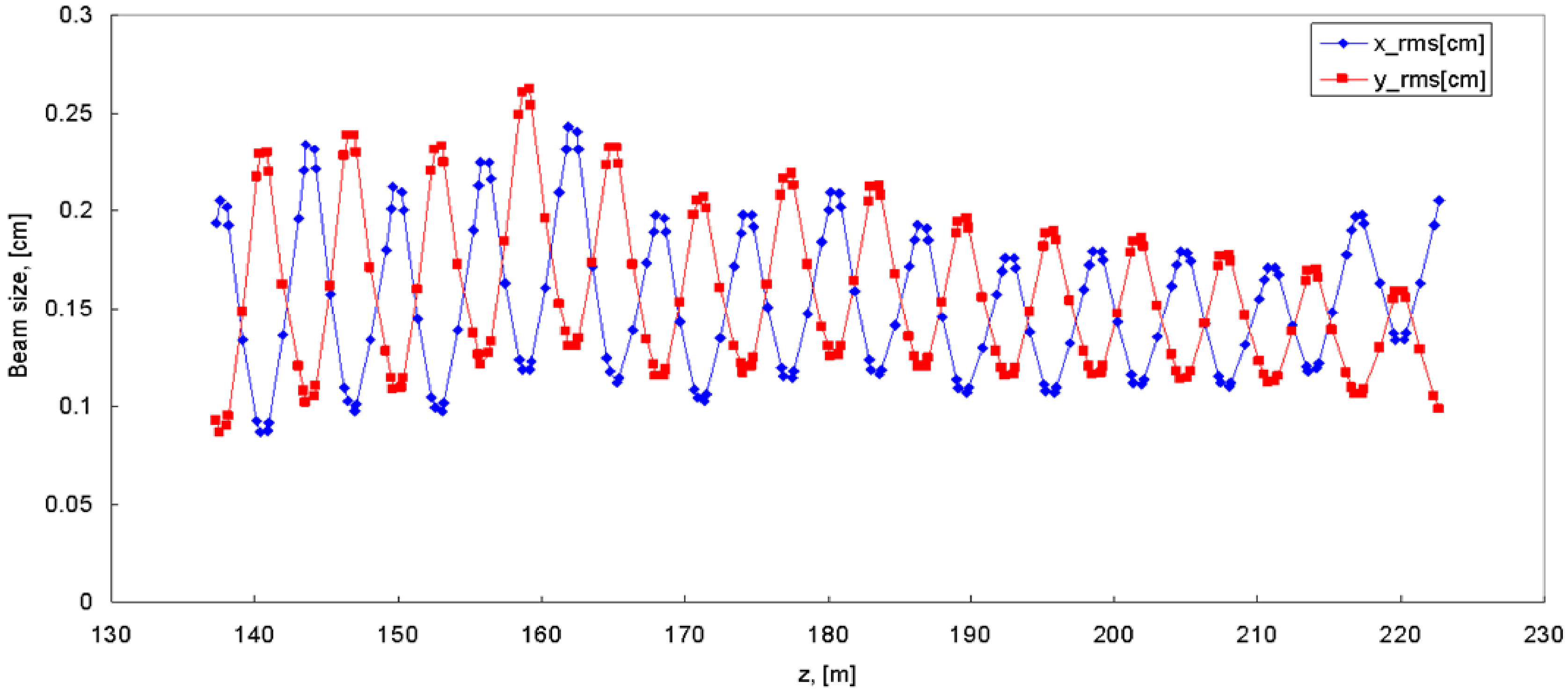
- Gradient 26 MeV/m ➔ 25 MeV/m. Surface field: E_{pk}=50 MV/m
- In ILC1 and ILC-2 sections: TTF-3 type cryomodule with two quads inside is replaced by TTF-4 cryomodule with 1 quad in the middle
    - ILC compatible solution
- To save the same focusing properties in ILC-1 section an additional quadrupole in separate cryostat is added (needs to be designed)
    - ILC desires the same solution
- S-ILC section is based on the same TTF-4 cryomodule (!). Quad is replaced with doublet (focusing-defocusing quads). Additional doublet in the separate cryostat, similar to ILC-1.

S-ILC section:

a) Basic variant: 7 CMs, 56 8-cell Cavities, gradient=23.7 MeV/m. Surface electric field in the cavity is 52 MV/m.

1CM (need to be designed) = FR^{2}DR^2 + FR^{2}DR^2



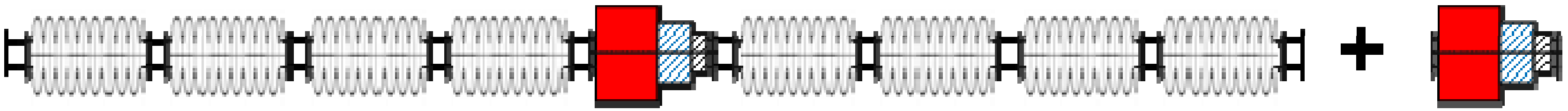


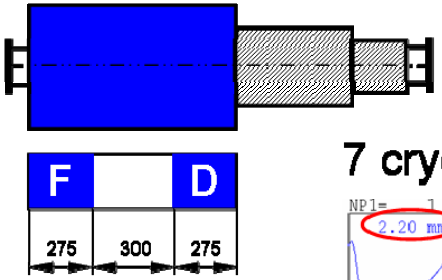
Design work: New cryostat, cavity and cavity auxiliaries (helium vessel, tuner, tooling etc.)

b. The variant based on the Type-4 ILC CM. Very relaxed version:

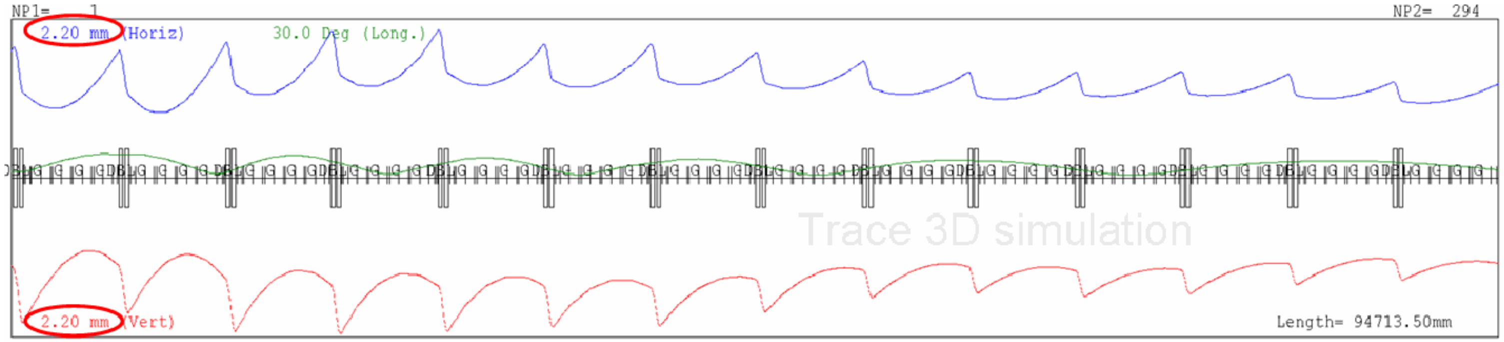
7 CMs, 56 11-cell cavities, gradient=19 MeV/m (E_{pk}= 46MV/m)

$FR^2DR^2 + FR^2DR^2 \xrightarrow{\text{Optic Change:}} R^4FD + R^4FD$





7 cryomodules with acceleration:

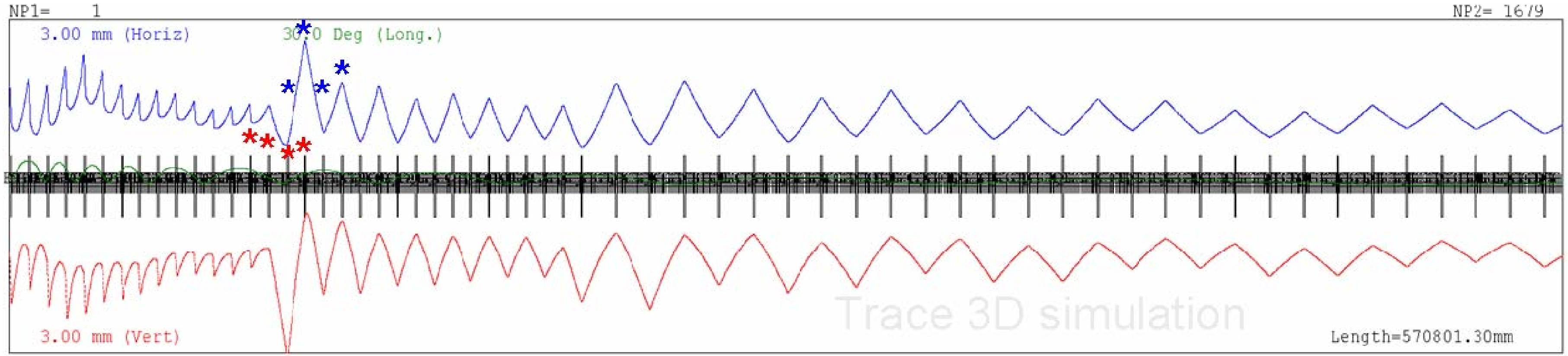


Lower gradient was chosen in order to make transition to β=1 in the end of CM. 6 CM with 11-cell cavities may be used with the surface electric field of 53.6 MV/m.

Matching between S-ILC and ILC

Different approaches for transverse matching were applied:
4 quad matching in Trace 3D and Mad 8.51;
matching with quads in combination with doublets;
varying doublet quads separately;
drift length between sections was varied

Finally, good convergence was achieved by performing manual two-step matching procedure (using Trace3D code):



Focusing parameters

Section	S-ILC	ILC-1	ILC-2
Focusing	FDR^4	FR^4DR^4	$R^4FR^8DR^4$
Length of the focusing period, [m]	6.7	13.5	25.3
Number of cells	11	9	9
Effective length, [cm]	27.5	65	65
Gradient, [T/m]	11.5	2.6	2.3
Maximum gradient, [T/m]	11.5	3.4	3.0

Acceleration parameters

Section	S-ILC	ILC-1	ILC-2
β	0.81	1.0	1.0
Number of cryomodules	7	8	29
Number of resonators	56	64	232
Number of cells	11	9	9
Accelerating gradient, [MV/m]	20.6	25	25

11-CELL CAVITY OPTIMIZATION:

Longer structures allow more effective use of a cryomodule length providing higher acceleration gain.

The β=0.81 structure with the same length as β=1 ILC structure:

- The number of cavities is 11 (L=102.8 mm versus 103.8 mm for ILC cavity);
- The coupling *k* is to be higher than for β=1 :
  For ILC cavity *N*=9 *k*=1.87%, for 11-cell β=0.81 cavity *k*=2.47%. An aperture for a longer structure is bigger.

$$\frac{\Delta f}{f} \sim \frac{k}{N^{\frac{3}{2}}}$$

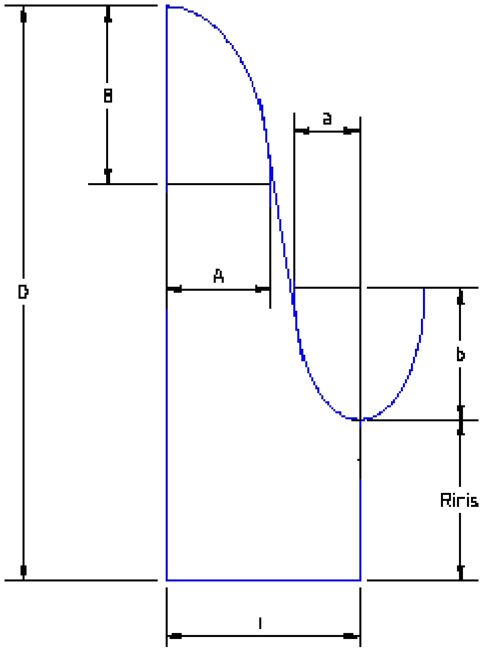
- The surface fields are to be the same as for ILC cavity, thus, the acceleration gradient for a longer structure is smaller.
- Longer cavities can be used in more narrow energy range.
- The risk of occurrence of trapped modes is greater in longer structure.

The 11-cell cavities have the same length as 9-cell ILC cavity and can use the same auxiliary components (dressing, couplers, HOM dampers, etc.)

The structure cell optimization:

Maximal surface magnetic field is fixed to be the same as for ILC cavity.

- Maximal surface electric field does not exceed one for ILC cavity.
- The coupling is proportional to $N^{3/2}$ to keep the same field flatness.
- The geometrical dimensions are determined to maximize the acceleration gradient.



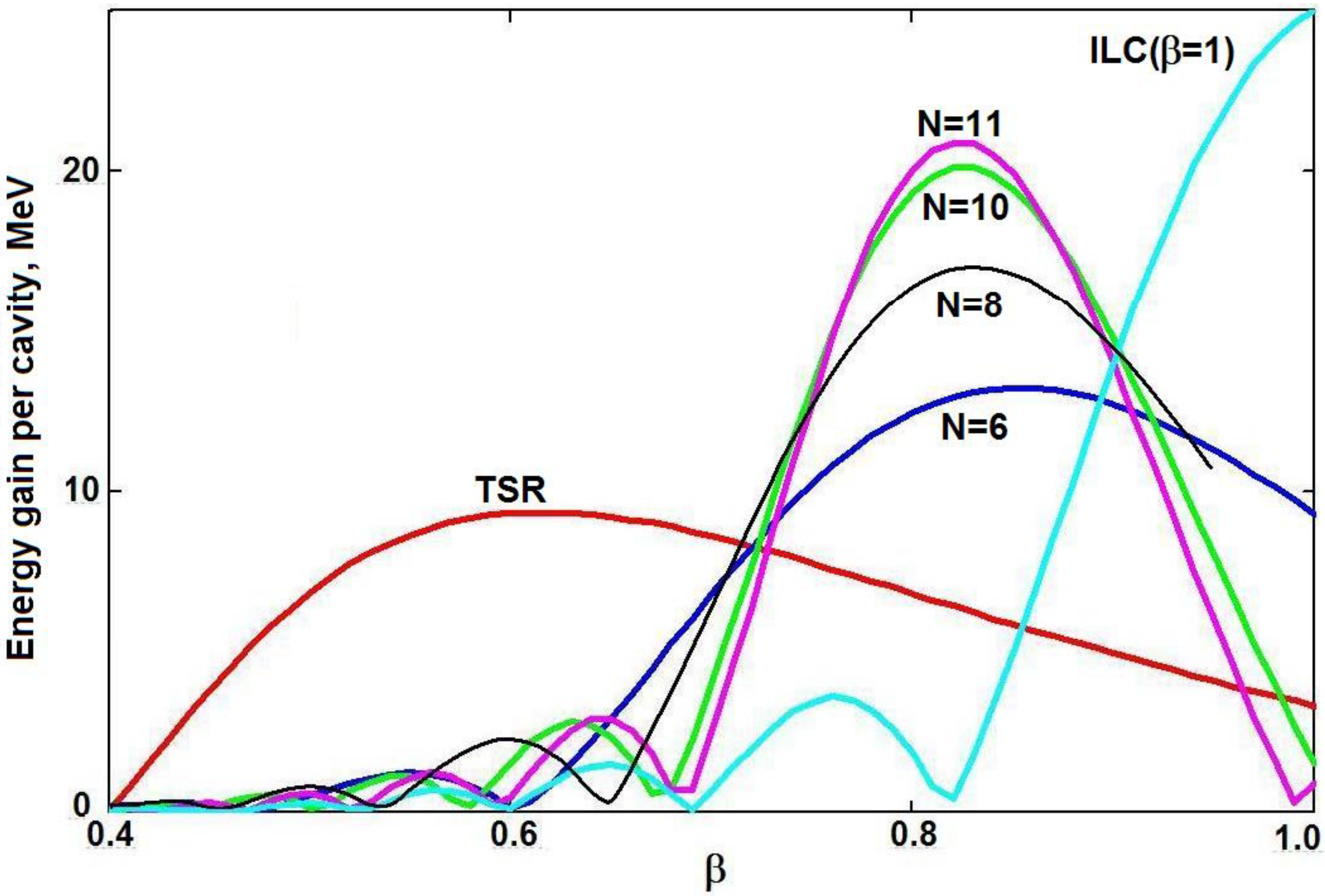
Cell shape parametrization

Parameters of the optimal cell for different cavity length.

	Inner cell						
Number of cells	**k,%**	**A, mm**	**B, mm**	**a, mm**	**b, mm**	**D, mm**	**Riris, mm**
6	1.1	34.333	36.05	11.3	22.6	100.539	27.5
10	2.2	33.133	34.8	12.5	21.88	102.646	34
11	2.7	33.133	34.8	12.5	20.63	103.327	36

Maximal gradient is achieved when the surface electric field is equal to one in the ILC cavity.

Energy gain per cavity



Energy gain per cavity vs. β.

β = 0.81 cavity:
11-cell (pink);
10-cell (green);
8-cell (black);
6-cell (blue)

ILC β = 1 cavity (pale blue);
Triple-spoke cavity (brown).

11-cell cavity may provide the energy gain ~40% higher than 6-cell cavity and >20% higher than 8-cell cavity.

To accelerate protons from ~430 MeV to ~1250 MeV one needs 56 11-cell cavities, i.e. 7 cryomodules.

Monopole modes, 11-cell beta=0.81 cavity

1 branch

mode number	Fi, deg	frequency, MHz	R/Q, Ohm
1	16.36	1265.738	1.63E-04
2	32.73	1267.8	3.10E-03
3	49.09	1271.053	1.76E-03
4	65.45	1275.234	1.03E-02
5	81.82	1280.006	6.46E-03
6	98.18	1284.98	1.82E-02
7	114.55	1289.758	1.08E-02
8	130.91	1293.95	2.78E-02
9	147.27	1297.215	3.82E-03
10	163.64	1299.287	1.99E-01
11	180	1300.005	7.51E+02

The modes 13-15 of the 3d branch have the highest (R/Q). The resonance frequencies are about 2848 MHz, that is far of the nearest beam current harmonic of 325 MHz, 2925 MHz. However, chopping 33% at 53 MHz will produce a first side spectrum line at 2872 MHz, that is still far of the resonance taking into account spread of frequencies of ~6 MHz (DESY measurements). Chopping 6% at 89 kHz produces much smaller spectrum line. Anyway, more detailed analysis is necessary.

2&3 branches

mode number	frequency, MHz	R/Q, Ohm
1	2696.84	5.92E-01
2	2698.78	3.84E-01
3	2701.87	7.35E-01
4	2705.90	6.94E-02
5	2710.64	1.50E-01
6	2715.68	8.22E-03
7	2720.78	3.60E-01
8	2725.59	1.01E-02
9	2729.78	4.41E-01
10	2732.94	3.18E-02
11	2737.53	2.48E+00
Mixmode 12	2737.57	5.04E-01
13	2847.79	6.13E+00
14	2847.89	2.39E+01
15	2848.08	1.00E+01
16	2848.34	2.93E-01
17	2848.69	2.39E+00
18	2849.1	8.56E-02
19	2849.54	1.26E+00
20	2849.93	2.43E-02
21	2850.44	3.71E+00
22	2850.46	8.77E-02

Dipole modes, 11-cell beta=0.81 cavity

mode number	frequency, MHz	transverse impedance/Q, Ohm/cm^2
1	1754.7	0.000355294
2	1755.99	0.0773029
3	1757.75	0.000861171
4	1759.61	0.473891
5	1761.34	0.000492231
6	1762.83	5.88134
7	1764.05	13.6904
8	1764.98	4.3609
9	1765.63	0.00924244
10	1766.02	0.144142
11	1822.49	1.14278
12	1822.49	0.677775
13	1874.05	1.66406e-005
14	1886.47	0.0103965
15	1906.51	0.0023291
16	1933.42	0.00443845
17	1966.18	0.00247328
18	2003.39	0.0144589
19	2043.08	0.000550195
20	2082.42	0.00158643
21	2117.35	0.00224054
22	2142.34	6.40971e-005

The modes 6-8 of the 1d branch have the highest (R/Q). The resonance frequencies are about 1763-1765 MHz, that is far of the nearest beam current harmonic of 325 MHz, 1625 MHz. However, chopping 33% at 53 MHz will produce a third side spectrum line at 1784 MHz, that is still far of the resonance.