Alternative accelerating structures for CLIC main linac based on dielectrics

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Outline

- **Background & Introduction**
- **Dielectric-Lined Accelerating (DLA) Structures**
- **Dielectric Disk Accelerating (DDA) Structures**
    - **TM01 operation mode**
    - **TM02 operation mode**
    - **Wakefield Studies for a TM02 DDA structure**
- **Summary & Outlook**

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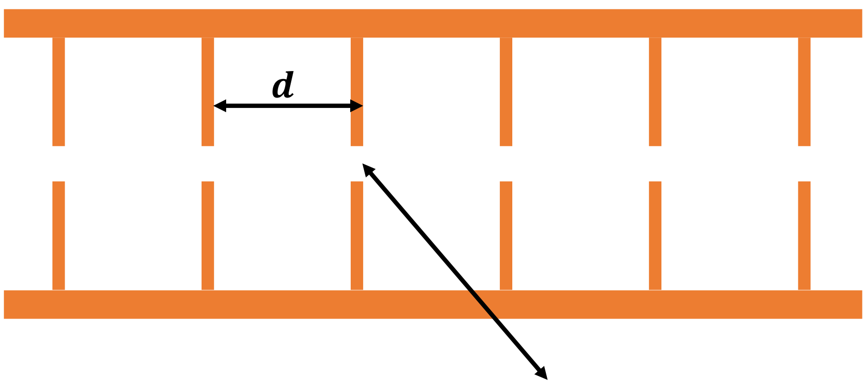
Introduction

- **Slow wave accelerators: Irises-loaded accelerating structures**



Irises-loaded structure

X-band CLIC accelerating structure

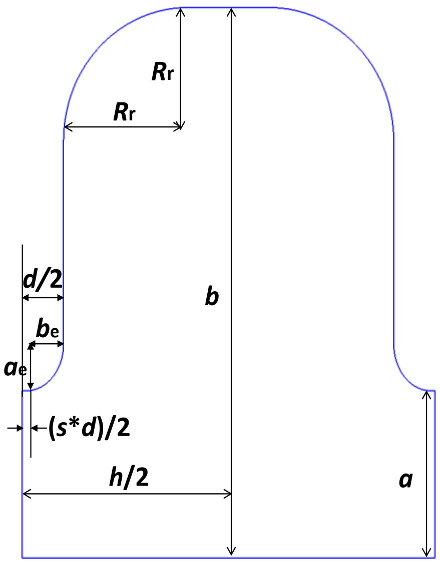
Irises form periodic structure in waveguide:

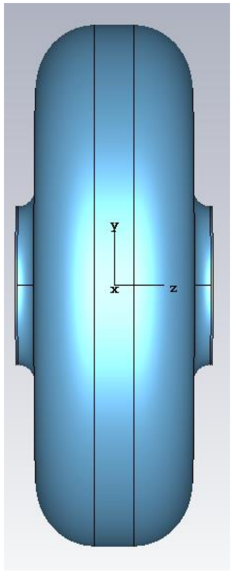
- Irises reflect part of the wave;
- Irises slow down the phase velocity so that it equals the particle velocity;
- The group velocity is usually around 1% of *c*.

- In CLIC studies, gradient up to 100 MV/m (pulse length of 200 ns) has been demonstrated at X-band frequency with rf pulses of 100s ns.

CLIC-G Accelerating Structure

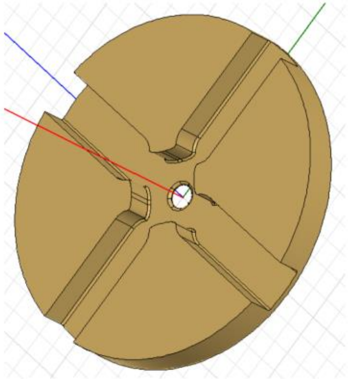
Without HOM Damping

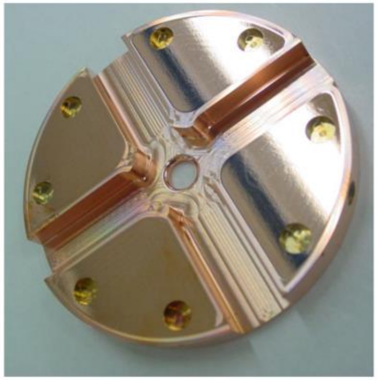


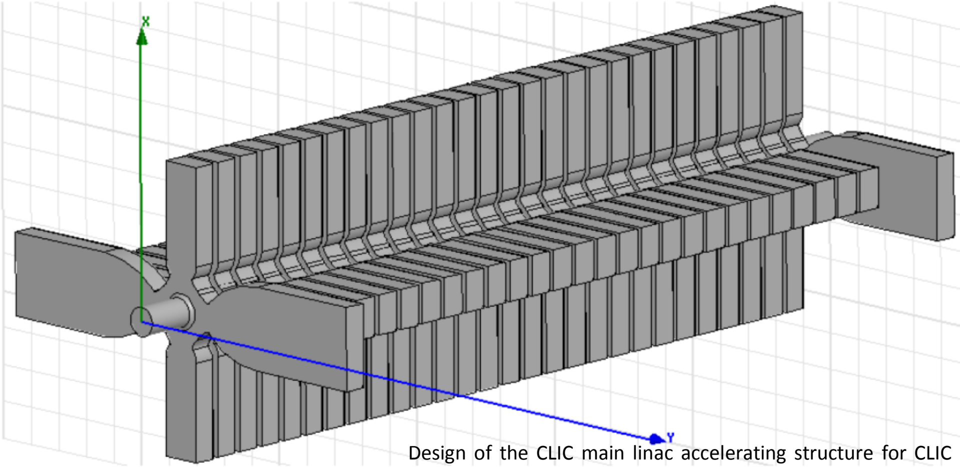


Undamped Geometry	CST	HFSS
Phase advance	120°	120°
Frequency [GHz]	11.9949	11.9943
Unloaded Q_0	7295.2	7245
r'/Q_0 [Ω/m]	15892	15924
v_g/c	0.018	0.018

With HOM Damping







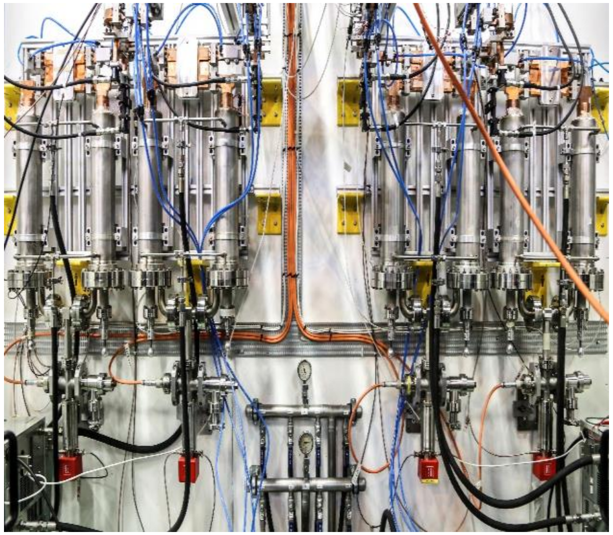
Design of the CLIC main linac accelerating structure for CLIC Conceptual Design Report, Proceedings of Linear Accelerator Conference LINAC2010, A. Grudiev, W. Wuensch

Test Stands at CERN

- Xbox 1: 50 MW klystron, 50 Hz, connection with CLEAR (e^- linac)
- Xbox 2: 50 MW klystron, 50 Hz
- Xbox 3: 4x6 MW klystrons, 400 Hz, 4 structure test slots
- Sbox: 43 MW klystron, 25 Hz, S-band (2.9985 GHz)

50 MW klystron with pulse duration of 1.2 µs

Pulse Compressors



CLIC test platform

Courtesy of slides from Jan Paszkiewicz, CERN

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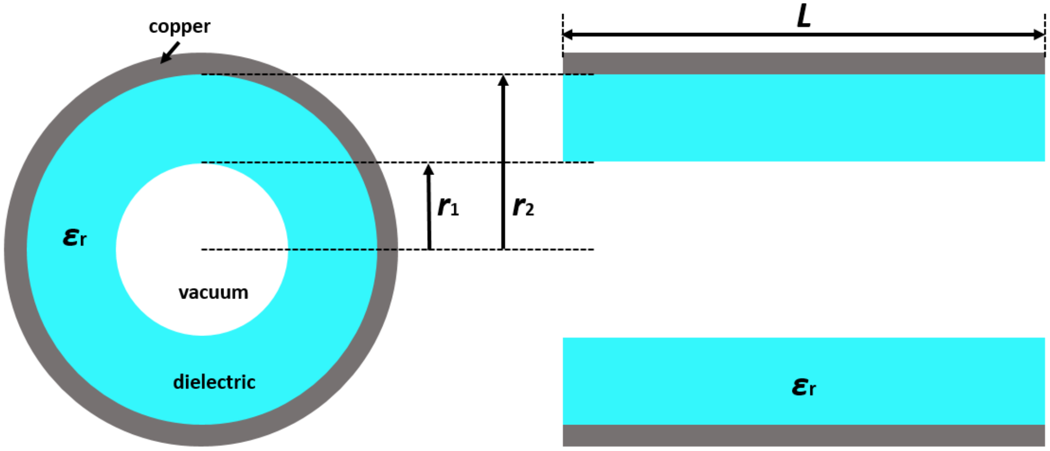


Advantages of DLA:

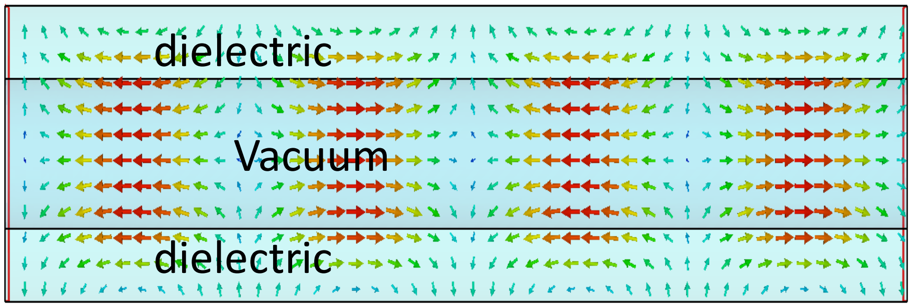
- Simple geometry for easy fabrication;
- No field enhancements on irises;
- Potential high gradient;
- Easy to damp HOMs;

Disadvantages of DLA:

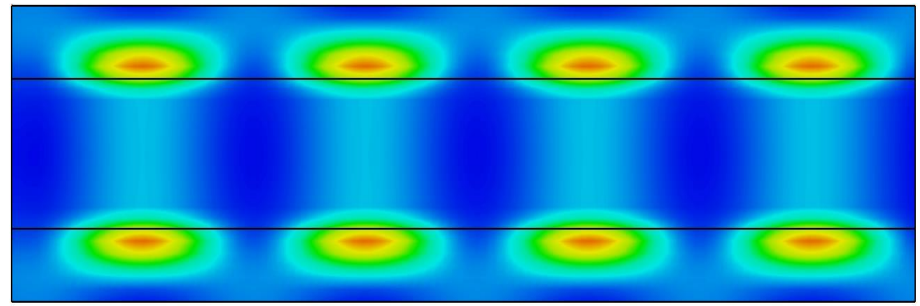
- Low power efficiency due to high group velocity >10% of *c*

DLA Structures

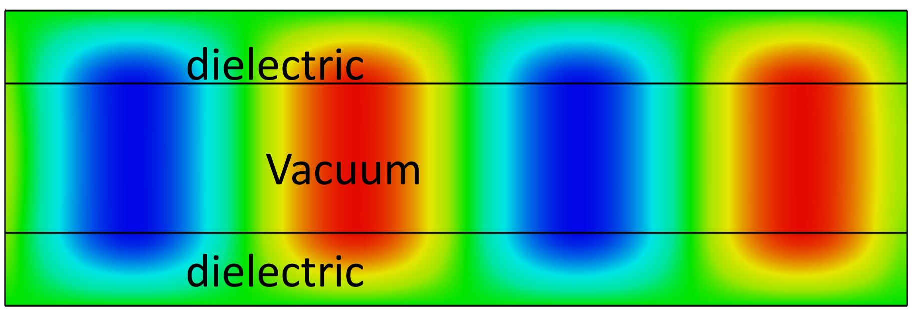
E-field of the TM01 mode ($v_{\mathrm{p}} = c$)



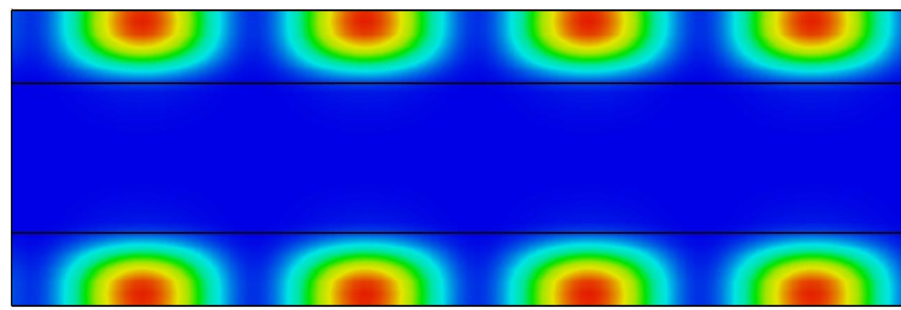
Electric energy density



Ez of the TM01 mode ($v_{\mathrm{p}} = c$)

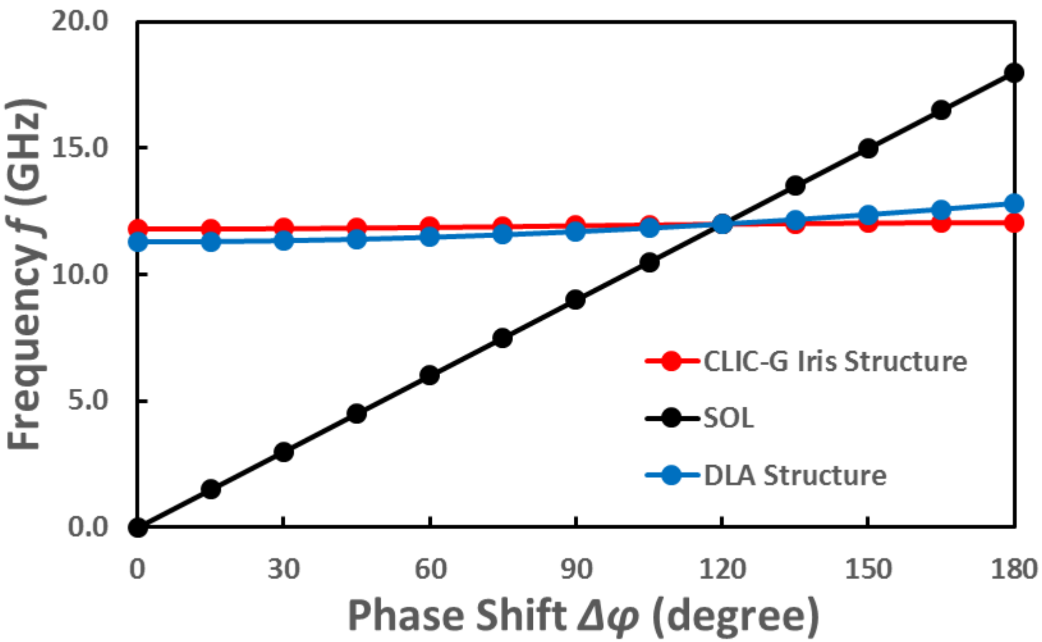


Magnetic energy density



1) **The axial accelerating field is the maximum electric field in the structure;**
2) **The phase velocity of TM01 mode can be slowed down to c;**
3) **Most of energy is stored in dielectric area, resulting in low power efficiency.**

Dispersion Curves



TM01 mode

1) The red line for CLIC-G iris gradually saturates, and group velocity gradually decreases to 0 with the increase of phase advance;

2) The blue line for DLA structure gradually increases, but group velocity can't be 0 with the increase of phase advance.

RF parameters on DLA structures

	CLIC-G iris structure	Quartz (SiO_2)	Diamond	Alumina (Al2O3)	MgCaTi	BaTi
Dielectric constant ε_r		3.75	5.7	9.64	20	35
Dielectric loss tangent δ		0.00005	0.0001	0.000006	0.0001	0.0001
Structure length [mm]	8.33	8.33	8.33	8.33	8.33	8.33
Phase advance	120°	120°	120°	120°	120°	120°
Inner radius r_1 [mm]	3.15	3.15	3.15	3.15	3.15	3.15
Outer radius r_2 [mm]		7.22	6.20	5.364	4.624	4.245
Frequency [GHz]	11.9943	11.9990	11.9958	11.9966	11.9942	11.9919
Unloaded Q_0	7245	6127	3998	4231	2214	1691
r'/Q_0 [Ω/m]	15924	10719	11166	10427	8463	6878
r' [MΩ/m]	115	66	45	44	19	12
v_g/c	0.018	0.273	0.183	0.111	0.057	0.034
Es/Ea	2.4819	1.0757	1.0755	1.0756	1.0760	1.0760
Es/Ea [dielectric]		1.0289	1.0024	1.0010	1.0152	1.0141
Power required to generate 100 MV/m [MW]	45.0	1013	652	424	266	197

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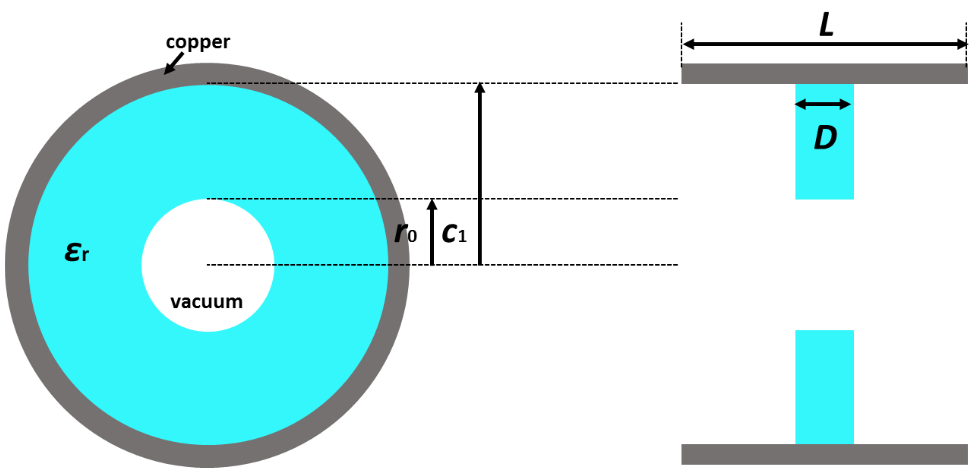
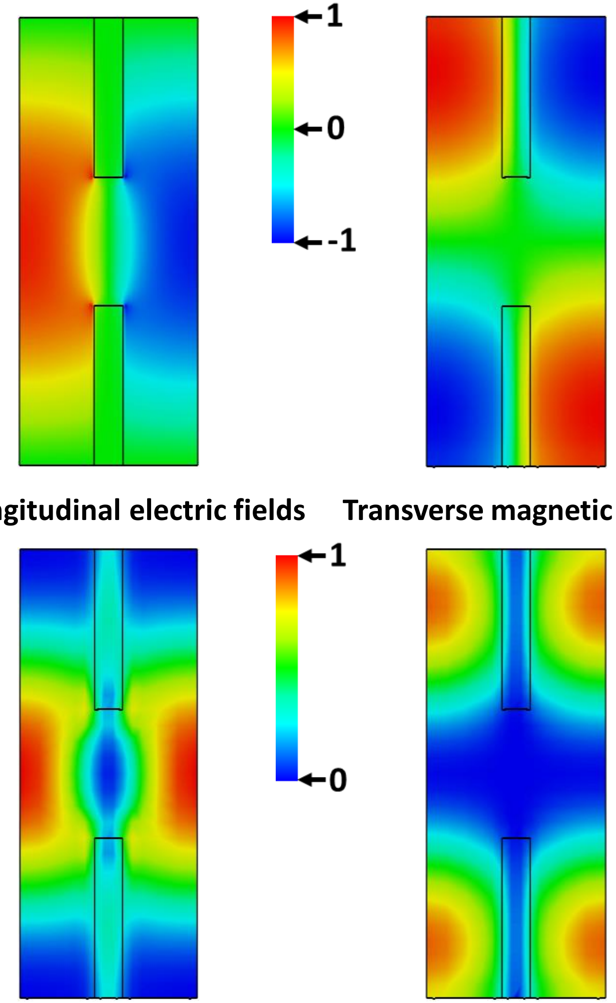
DDA Structures-TM_{01} mode



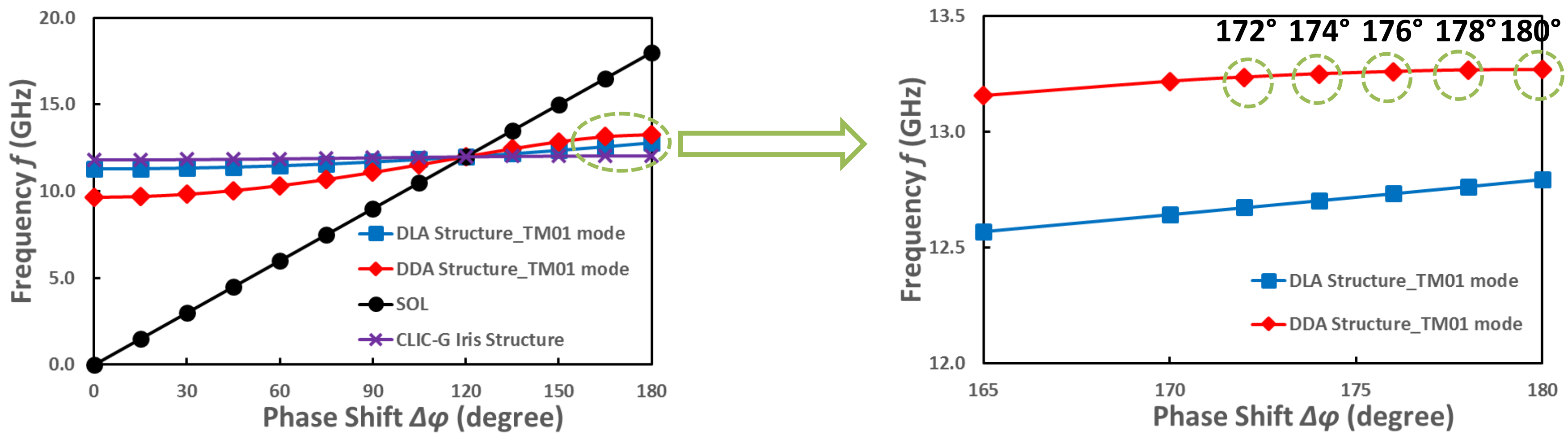


Longitudinal electric fields | Transverse magnetic fields

Electric energy density | Magnetic energy density

- We can adjust r_0, c_1, D and ε_r to get the desired frequency of 12 GHz.
- Such a structure has a periodicity L which can be used to slow down the group velocity of accelerating mode.

Dispersion Curves



Geometry parameters	DDA_TM01 mode
Dielectric constant ε_r	9.64
Dielectric loss tangent δ	6e-6
Structure length L [mm]	8.333
r_1 [mm]	3.15
r_2 [mm]	10.59
D [mm]	2

- The group velocity for a DDA TM01-mode structure gradually decreases to 0;
- The phase shift of 172°-180° can be chosen to generate a low group velocity for accelerating modes.

Comparisons

	CLIC-G	DLA	DDA_TM01_0.96π-mode	DDA_TM01_0.99π-mode	DDA_TM01_π-mode
Dielectric constant εr		9.64	9.64	9.64	9.64
Dielectric loss tangent		6e-6	6e-6	6e-6	6e-6
Period length [mm]	8.33	8.33	11.94	12.36	12.50
Phase advance	120°	120°	172°	178°	180°
Frequency [GHz]	11.9943	11.9924	11.9973	11.9973	11.9953
Unloaded *Q0*	7245	4232	14815	14870	14872
r'/*Q0* [Ω/m]	15924	10423	9544	10027	10092
r' [MΩ/m]	115	44	141	149	150
vg/*c*	0.018	0.111	0.073	0.018	0
Es/Ea	2.4819	1.0762	4.3071	3.4399	2.8773
Es/Ea [dielectric]		1.0029	0.91723	0.64648	0.65432
Power required to generate 100 MV/m [MW]	45	424	304	71	

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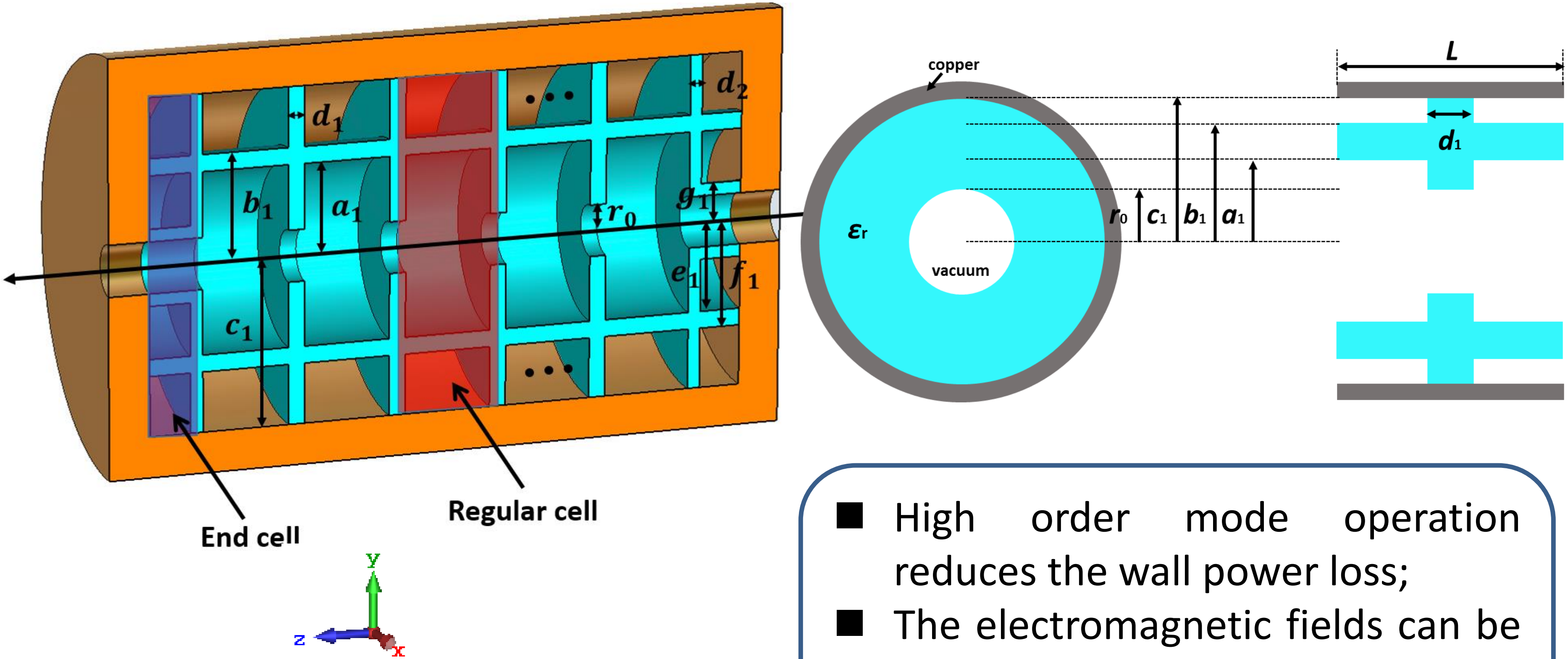
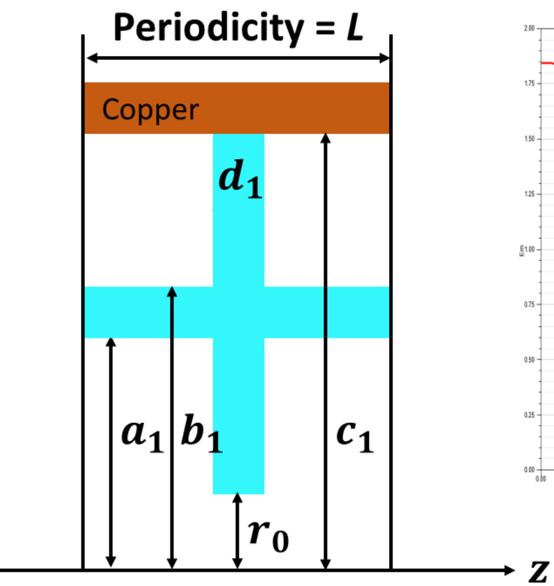
DDA Structures-TM02 π-mode

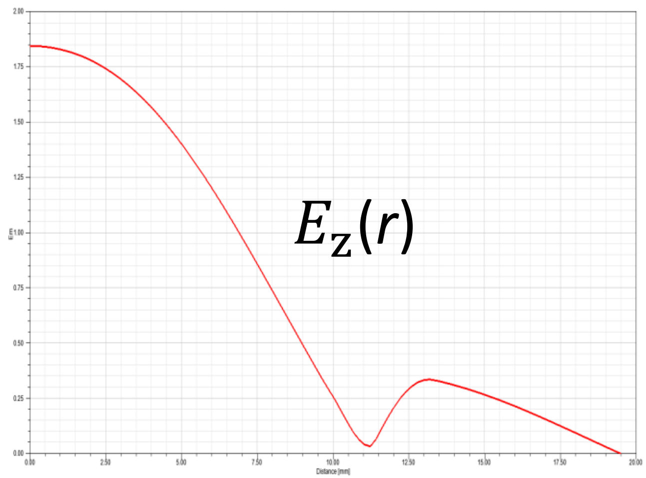


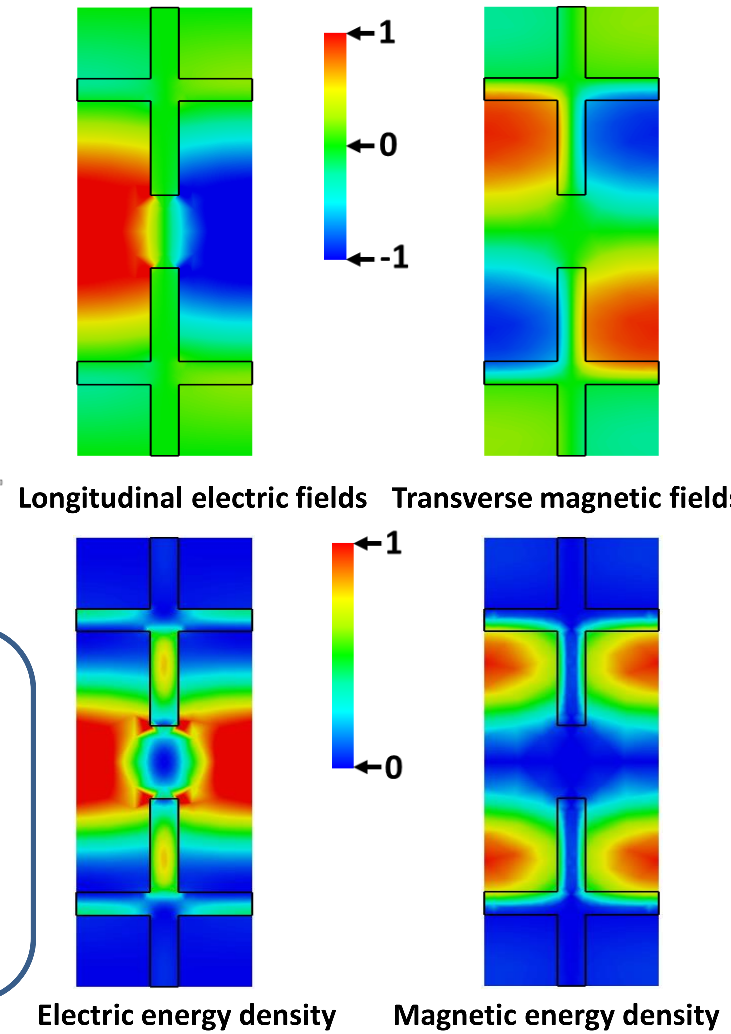
- High order mode operation reduces the wall power loss;
- The electromagnetic fields can be controlled by dielectric parts;
- High power efficiency.

D. Satoh, et al. Phys. Rev. Accel. Beams 19, 011302 (2016)

Regular cell

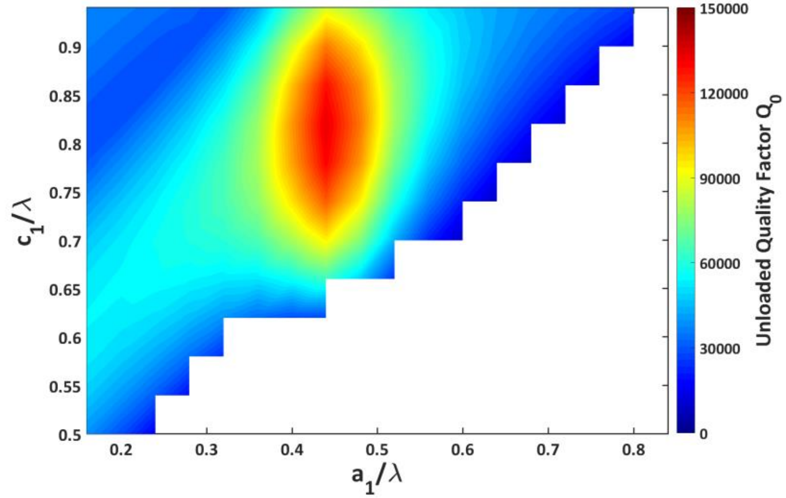


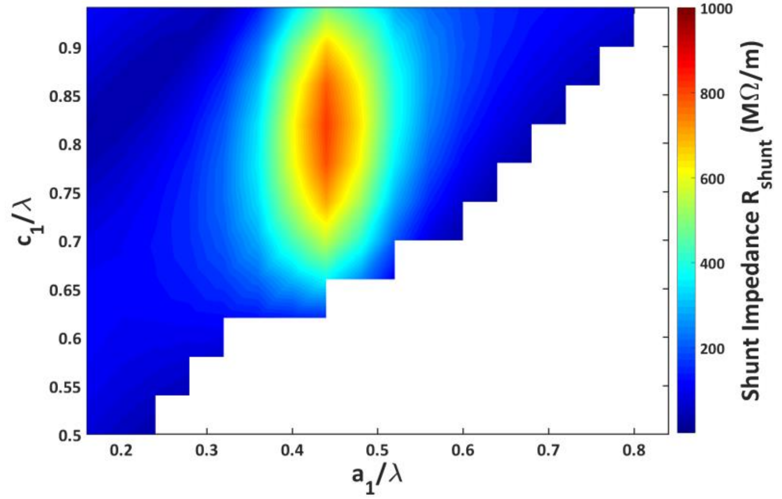




- Most of the RF energy is stored in the vacuum region;
- The total RF loss including both the wall loss on the conducting cylinder and dielectric loss in the DDA structure can be drastically reduced, thereby resulting in both an extremely high quality factor and a very high shunt impedance at room temperature.

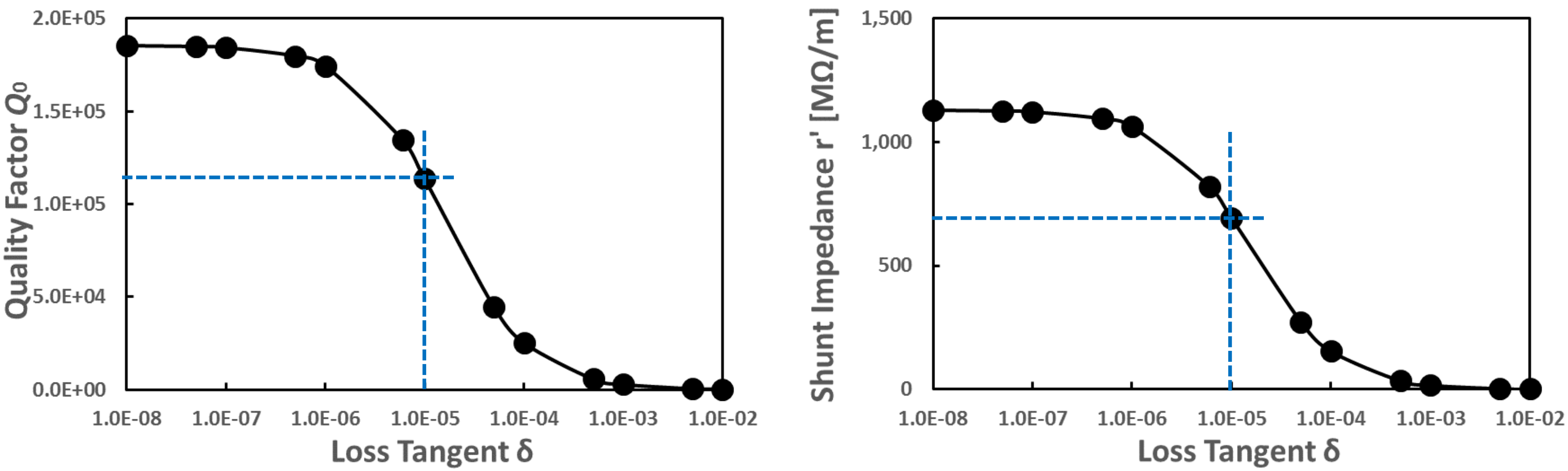
Optimization for a regular cell





Optimum parameters	
Dielectric constant ε_r	9.64
Dielectric loss tangent δ	6E-6
Inner radius r_0 [mm]	3.15
Outer radius c_1 [mm]	20.5
a1 [mm]	11.10
b_1 [mm]	13.16
d_1 [mm]	2.0
Structure period length L [mm]	12.50
Phase advance	180°
Acceleration mode	TM02 π-mode
Frequency [GHz]	11.9969
Unloaded Q_0	134542
r'/Q_0 [Ω/m]	6089
r' [MΩ/m]	819

Regular cell with different loss tangent



- ❑ Dielectric loss tangent δ affects quality factor Q_0 and shunt impedance *r'*;
- ❑ The highest quality factor and shunt impedance: Q_0 = 185000, *r'* = 1100 MΩ/m
- ❑ When loss tangent δ = 1E-5, Q_0 = 113733, *r'* = 693 MΩ/m. This can be achievable from other labs.

RF Properties

$N_{2\pi/3}^{CLIC-G} = 26 \iff N_{\pi}^{DDA} = 18$

$N = 1 \quad L = 12.5\ \text{mm}$

$E_{acc}^{Load} = 100\ \text{MV/m}$

$V_{acc} = NLE_{acc}^{Load} = 1.25\ \text{MV}$

$$P_{dis} = \frac{V_{acc}^2}{r'NL} = 0.1526\ \text{MW}$$

$$P_b = V_{acc} I_b = 1.4875\ \text{MW}$$

$$P_0 = P_{dis} + P_b = 1.640\ \text{MW}$$

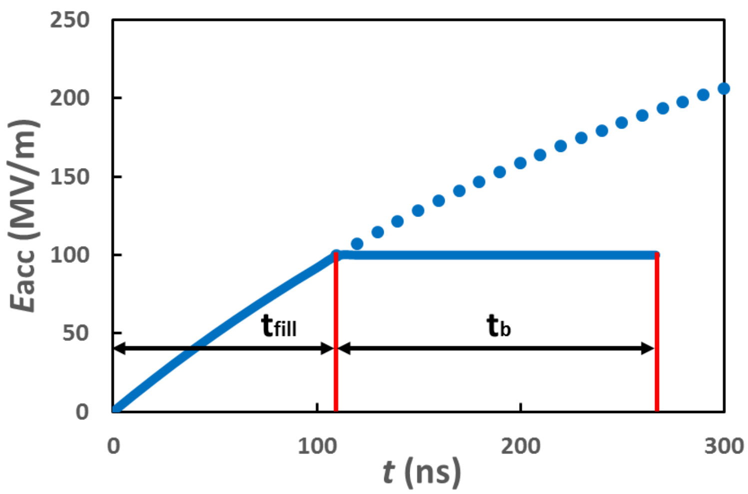
$$\beta = \frac{P_0}{P_{dis}} = 10.746$$

$$\tau = \frac{2Q_0}{\omega(1+\beta)} = 303.83\ \text{ns}$$

$$E_{acc}^{Unload} = \sqrt{\frac{P_0 r'}{NL}} = 327.8\ \text{MV/m}$$

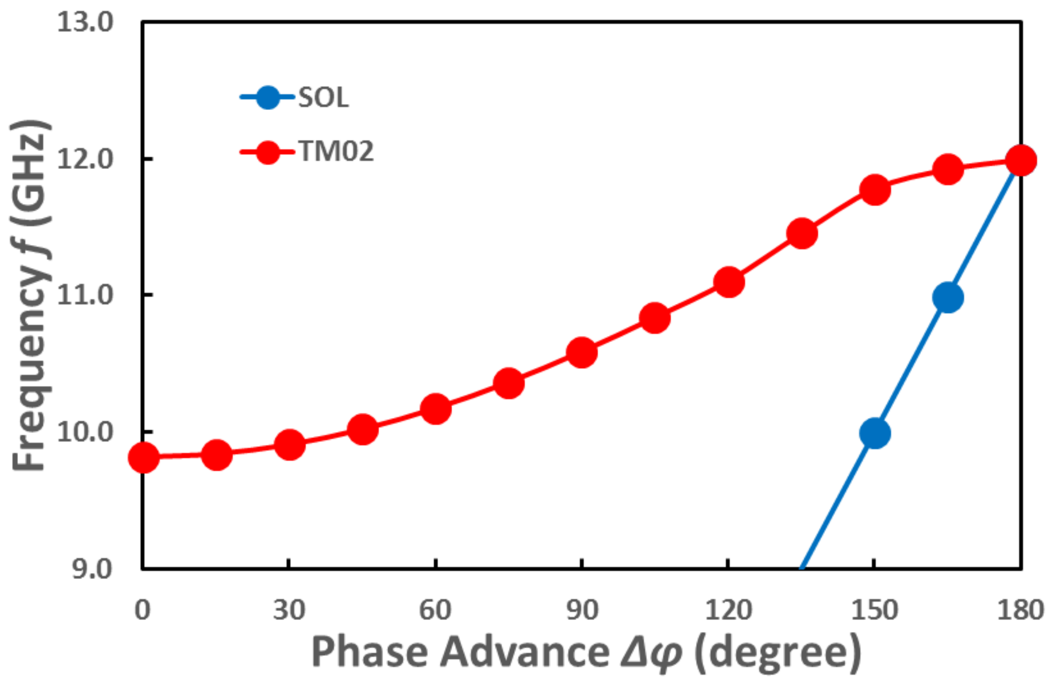
$$\boldsymbol{E_{acc} = E_{acc}^{Unload}\left(1 - e^{-\frac{t}{\tau}}\right)}$$

RF properties	CLIC-G (28 cells)	DDA (1 cell)	DDA (1 cell)
Dielectric loss tangent δ		6E-6	1E-5
Acceleration mode	2π/3	TM02 π-mode	TM02 π-mode
Shunt impedance r' [MΩ/m]	92	819	693
Peak input power [MW]	61.3	1.64	1.67
Loaded gradient E_{acc}^{Load} [MV/m]	100	100	100
Filling time t_{fill} [ns]	67	110 .6	117.4
t_b [ns]	155.6	155.6	155.6
RF to beam efficiency	28.5%	53.0%	50.8%



Dispersion curve

Reference: Nagle, Knapp and Knapp, 1964 and 1968



$$f = \frac{f_r}{\sqrt{1 + k\cos\Delta\varphi}}$$

$$f_r = \frac{\sqrt{2} f_\pi f_0}{\sqrt{f_\pi^2 + f_0^2}} = 10.7442\ \text{GHz}$$

$$k = \frac{f_\pi^2 - f_0^2}{f_\pi^2 + f_0^2} = 0.198$$

Bandwidth $BW = f_r k = 2.17\ \text{GHz}$

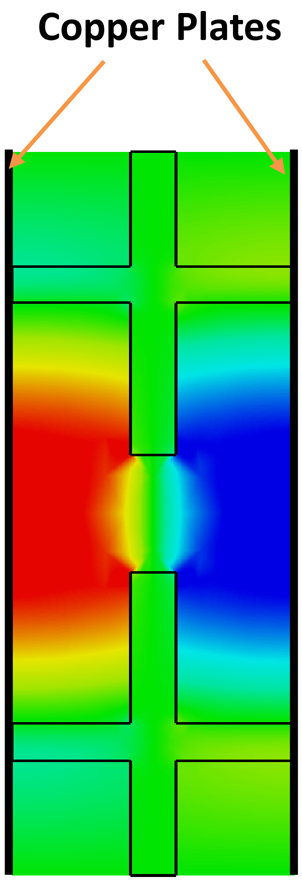
To avoid mode overlapping: $N < \sqrt{\frac{Q_\pi \pi^2 k}{4}} = 256$; $N < \frac{Q_{\pi/2}\pi k}{2} = 39221$

The frequency separation for modes: $\Delta f_{N-1,N}^{\pi} = f_r \frac{k\pi^2}{4N^2} = 21\ \text{MHz}$; $\Delta f_{N-1,N}^{\pi/2} = f_r \frac{k\pi}{4N} = 6.7\ \text{MHz}$

Maximum number of cells can be 255

;

Regular cell with copper plates

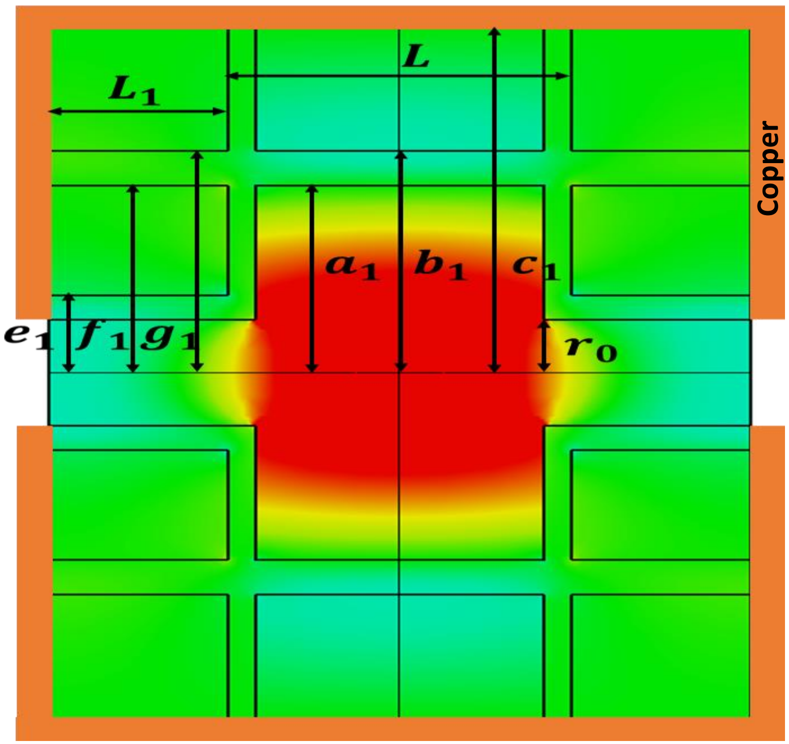


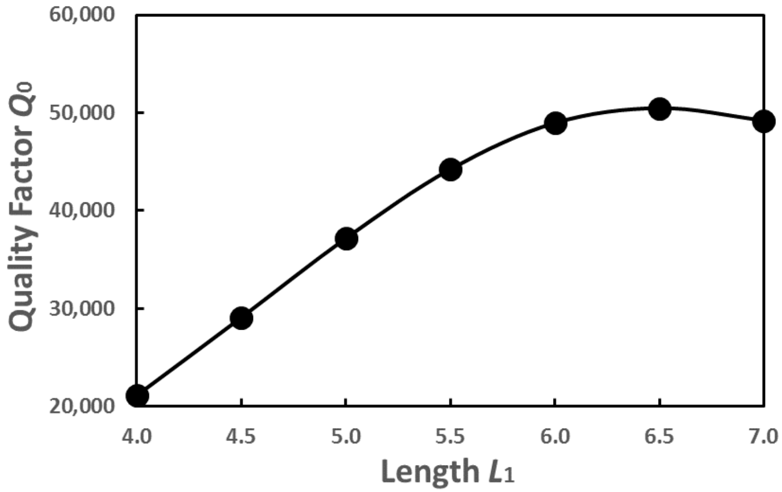
- Copper plates: 2.8% RF loss comes from dielectric loss, 97.2% RF loss comes from copper wall loss;
- Periodic boundary: 27.4% RF loss comes from dielectric loss, 72.6% RF loss comes from copper wall loss;

Acceleration mode	TM02 π-mode
Frequency [GHz]	11.9964
Unloaded Q_0	13931
r'/Q_0 [Ω/m]	6089
r' [MΩ/m]	85

End cell is added to reduce the wall loss

End cell

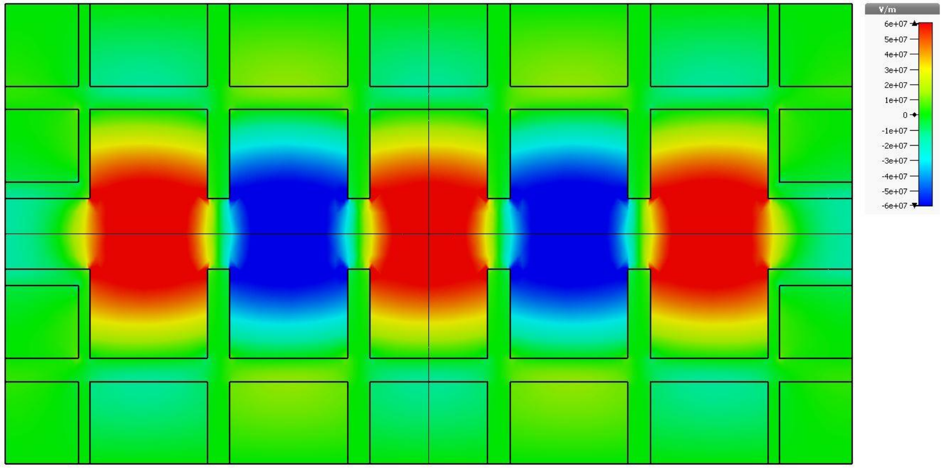




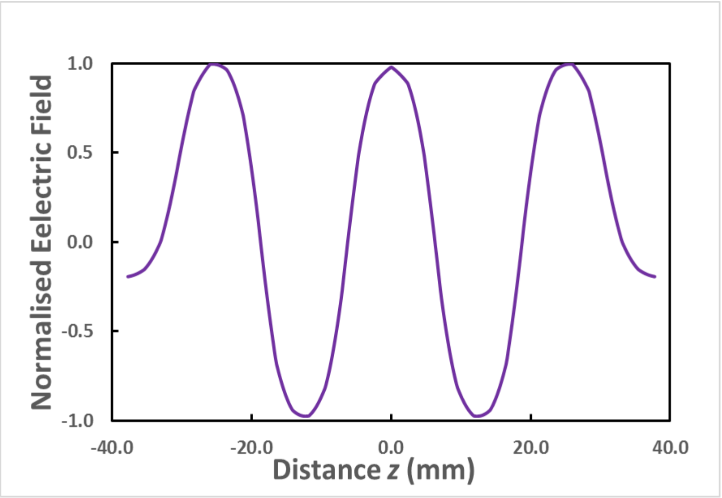
e_1 [mm]	4.6
L_1 [mm]	6.5
f_1 [mm]	11.1
g_1 [mm]	13.16
Frequency [GHz]	11.9942
Unloaded Q_0	50464
r' [MΩ/m]	181

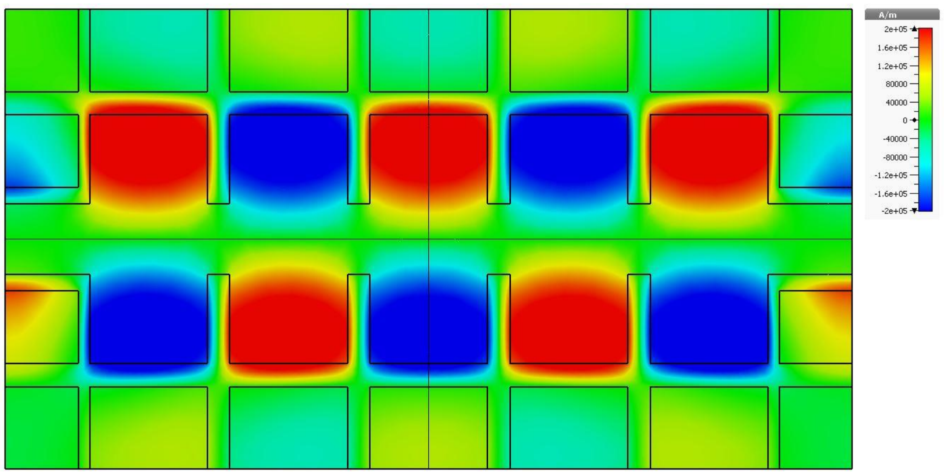
- Frequency is sensitive to e_1 and L_1;
- The ratio of copper wall loss to total power loss is reduced from 97.2% to 89.3%

Multi-cell DDA structure



Longitudinal electric fields





Transverse magnetic fields

- Quality factor Q_0 = 97146, shunt impedance r’ = 508 MΩ/m for a 5-cell cavity with same dielectric material;
- Q_0 and r’ can be increased to 110840 and 695 MΩ/m for a 9-cell cavity;
- Quality factor and shunt impedance increase with the number of cells.

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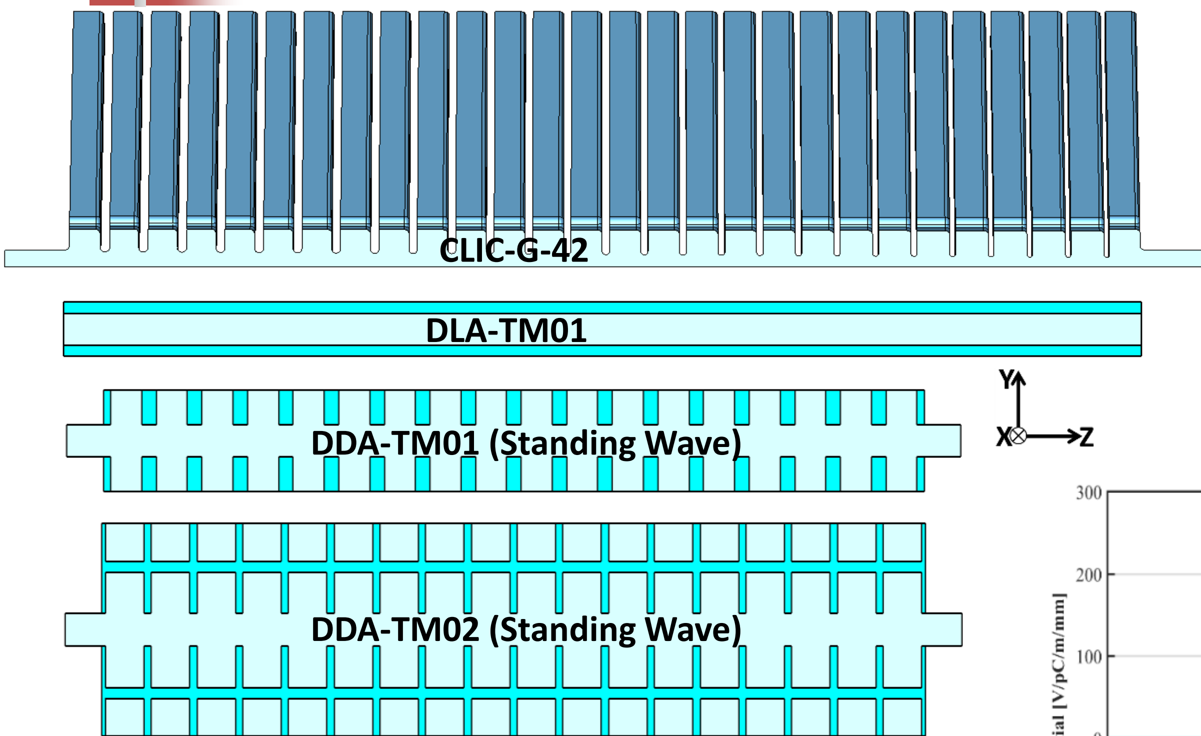
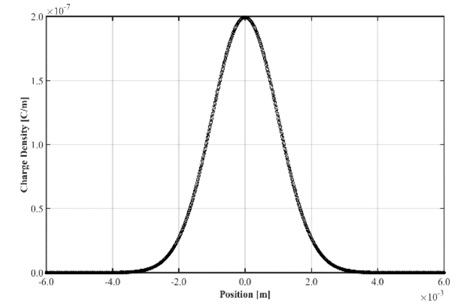
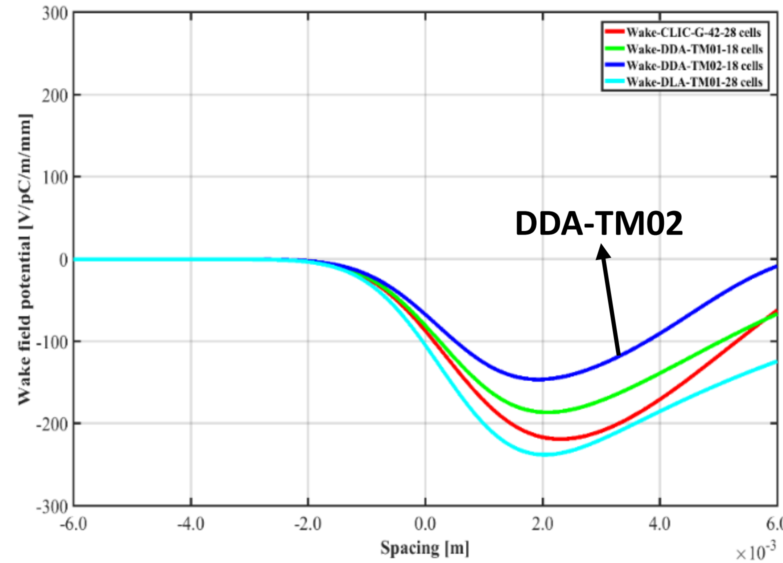
Short-range Wakefields



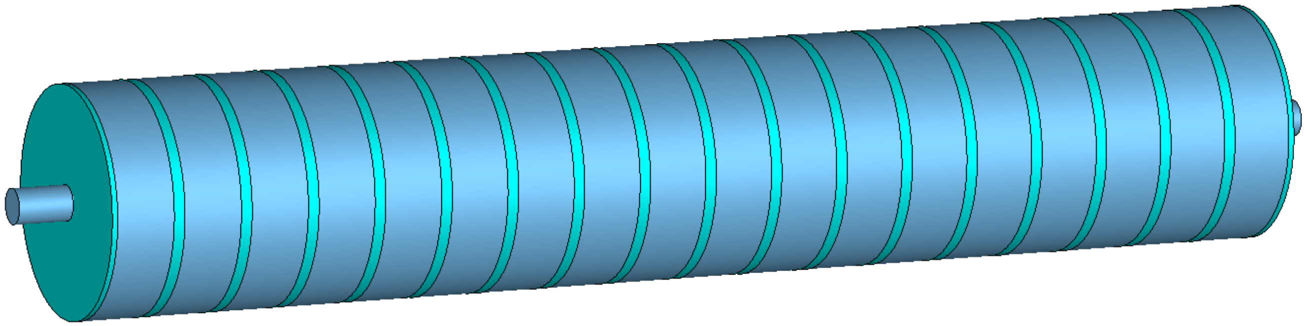
Charge Density

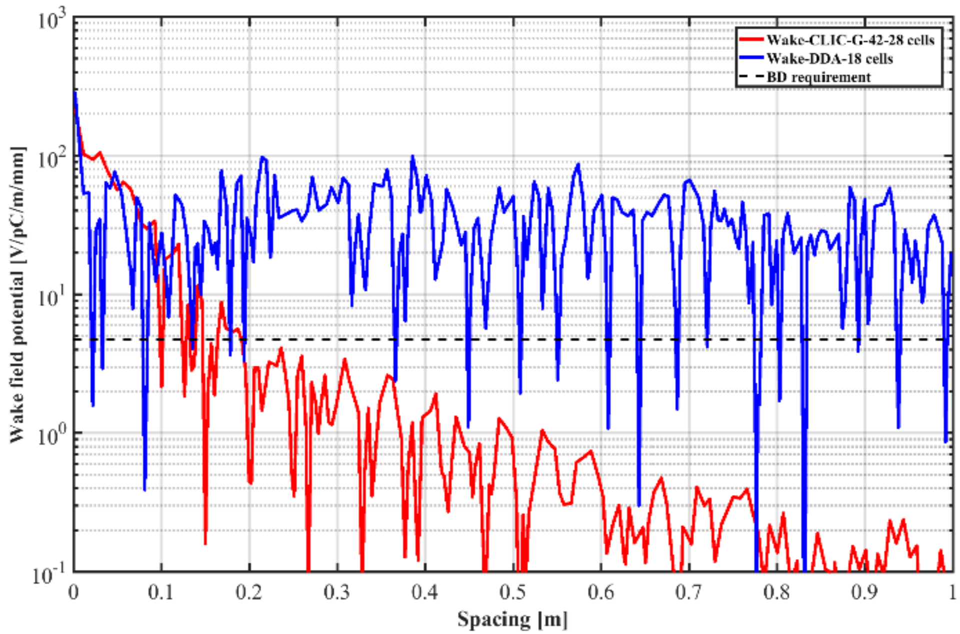




- CLIC-G: 28*8.332 ↔ DDA TM02-π: 18*12.5, so the number of regular cell is 18, no end cells are included;
- Convergence studies: dx = dy = dz = 0.05 mm;
- Bunch charge Q = 1.0 nC, bunch sigma = 1.0 mm, offset = 0.5 mm.

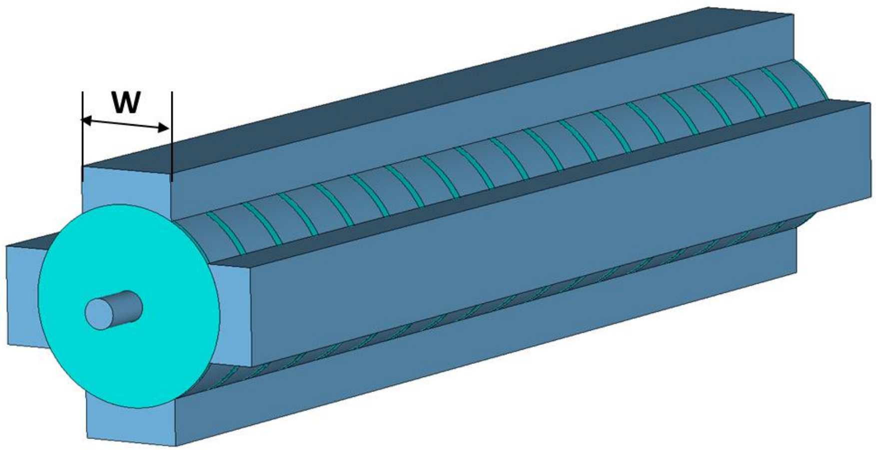
Long-range Wakefields



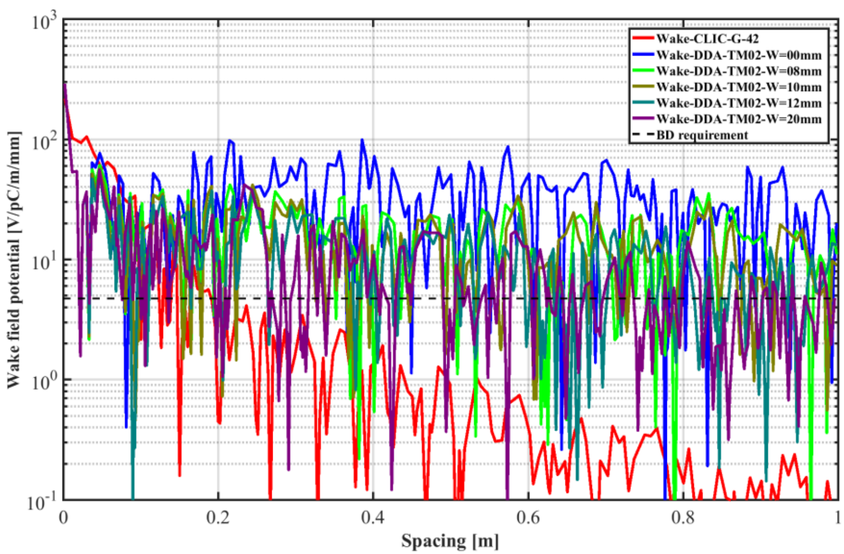


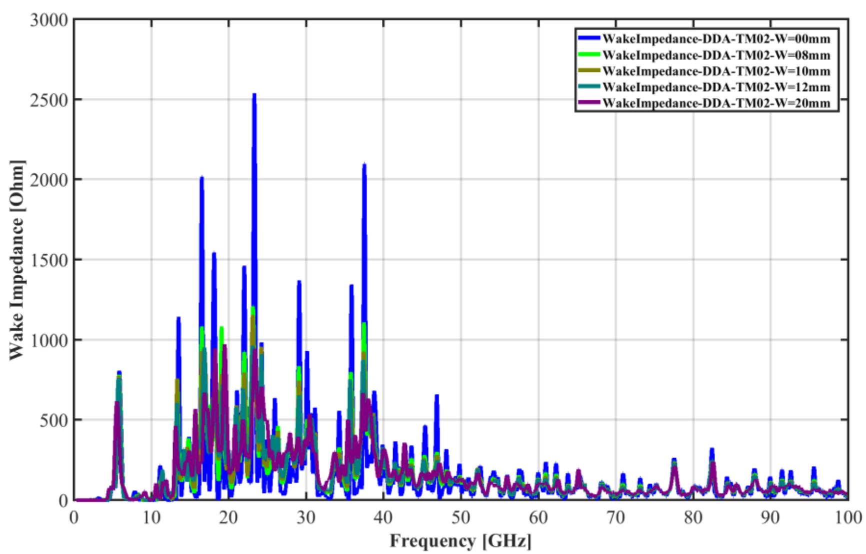
- The same bunch and structure parameters are used for Gdfidl simulations: dx = dy = dz = 0.05 mm, bunch charge *Q* = 1.0 nC, bunch sigma = 1.0 mm, offset = 0.5 mm;
- The envelope of transverse wakefields oscillate with the wakelength due to high order modes trapped inside the DDA;
- Damping schemes

Adding Damping Waveguide

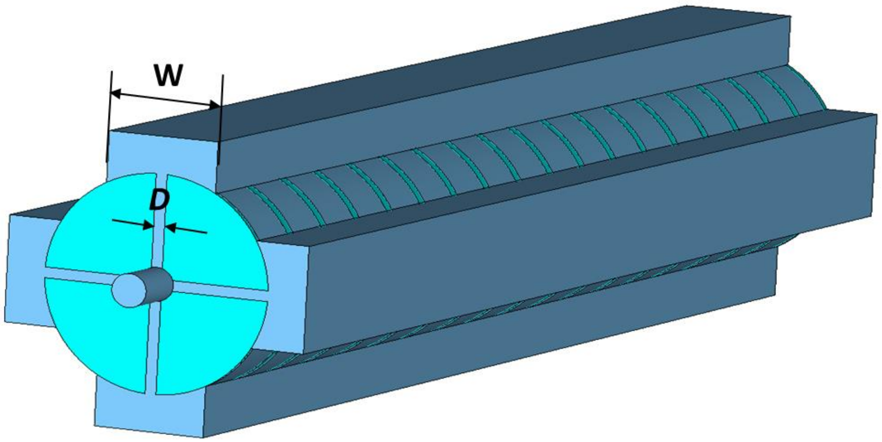


W [mm]	quality factor Q_0	shunt impedance r' [MΩ/m]	7 bunches			Envelope [7 bunches]		
			F_c	F_{rms}	F_{worst}	F_c	F_{rms}	F_{worst}
0	134542	819	149	752	5051	4086	2836	19483
8	113810	680	6	37	174	213	149	999
10	103330	612	8	67	408	269	211	1420
12	84336	489	6	26	149	123	101	661
20	< 40000	< 200	15	54	352	40	37	185
BD requirement				< 2	< 5		< 2	< 5

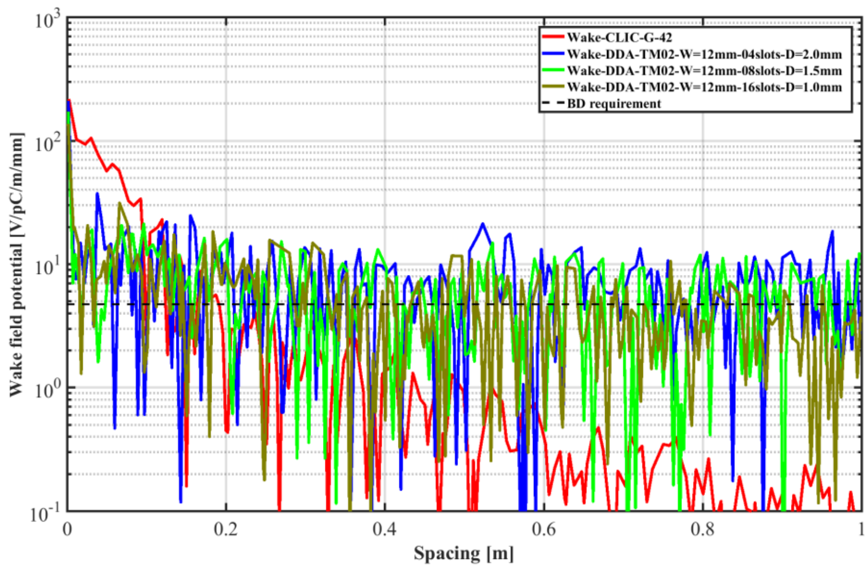




Adding Dielectric Slots (W=12 mm)

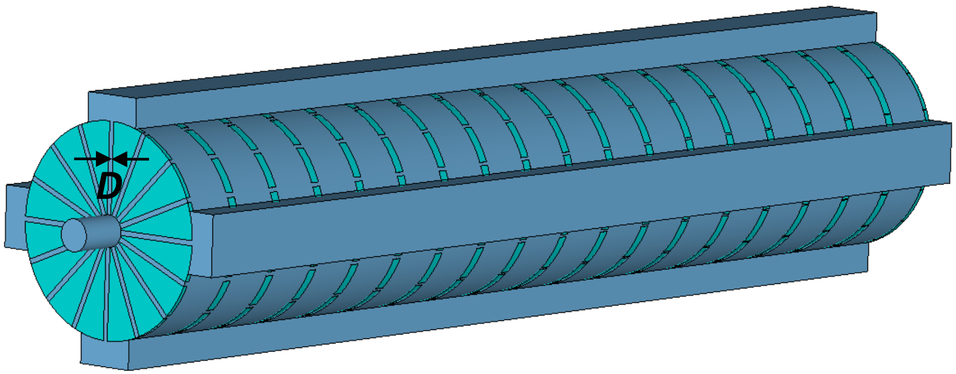


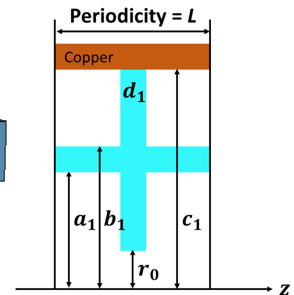
Number of dielectric slots	D[mm]	quality factor Q_0	shunt impedance r' [MΩ/m]	7 bunches			Envelope [7 bunches]		
				F_c	F_{rms}	F_{worst}	F_c	F_{rms}	F_{worst}
4	2.0	45286	193	2.1	3.5	13.4	12.3	6.2	34.7
8	1.5	95052	457	2.9	4.6	19.5	7.6	5.9	33.6
16	1.0	95450	405	1.1	1.3	2.7	1.9	1.4	4.2
BD requirement					< 2	< 5		< 2	< 5



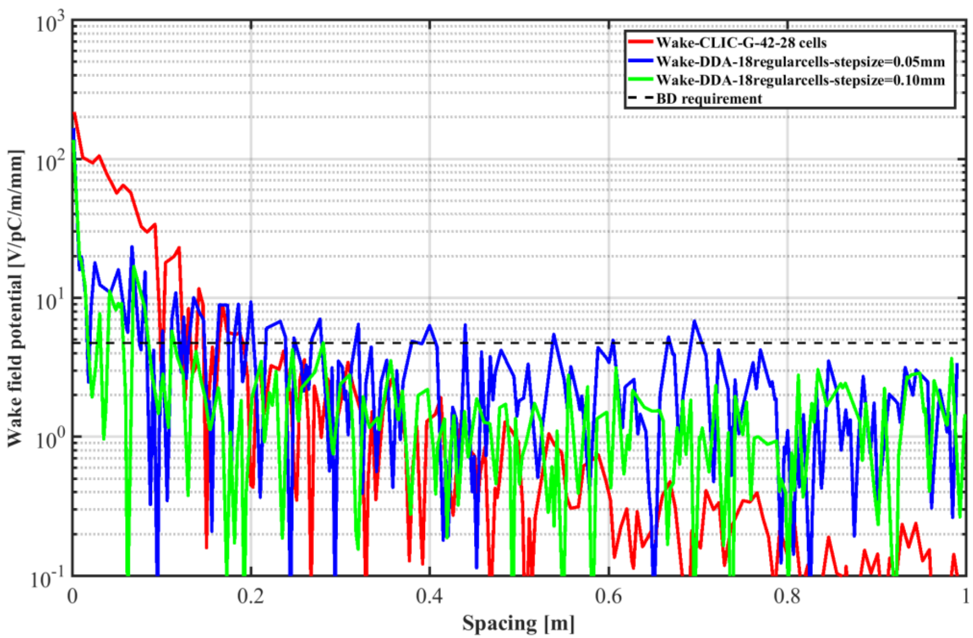
- The unloaded quality factor and shunt impedance are decreased by 30% and 50% respectively;
- Longer wakelength (> 5 m) needs to be calculated in order to get accurate F parameters.

Detuning (W=12mm, 16 dielectric slots)





- We can adjust b1 and dielectric slots width D to detune the 18-cell DDA structure;
- Each cell has a frequency of 12 GHz;
- The step size for *D* is 0.05 mm (blue line) and 0.10 mm (green line).



Number of dielectric slots	7 bunches			Envelope [7 bunches]		
	F_c	F_{rms}	F_{worst}	F_c	F_{rms}	F_{worst}
16	1.049	1.086	1.815	1.227	1.128	2.396
BD requirement		< 2	< 5		< 2	< 5

Summary and Outlook

- DLA structures with different materials and DDA structures operating at TM01 π-mode have been studied at 12 GHz;
- DDA structures operating at TM02 π-mode structure:
  - Extremely high quality factor and shunt impedance: Q_0 = 134542, r' = 819 MΩ/m;
  - High RF-to-Beam efficiency of >50%;
  - The number of acceleration cells can be up to 255 due to high bandwidth;
  - Low short-range wakefields;
  - Using waveguides, dielectric slots and detuning are promising to damp long-range wakefields.

- Further optimization and wakefield studies;
- Design of RF high power coupler;
- Fabrication and experimental studies.