# Investigations into RF-driven dielectric-loaded accelerating structures for linear collider applications

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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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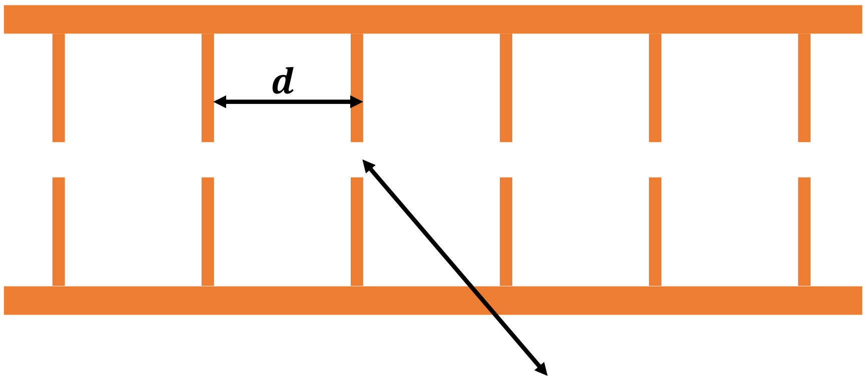
# Introduction

- **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*.

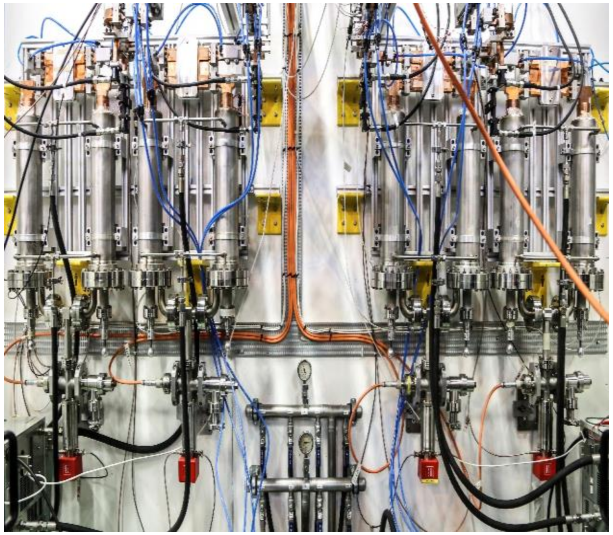
- In CLIC studies, gradient up to 100 MV/m (pulse length of 200 ns) has been demonstrated at X-band frequency with rf pulses of 100s ns.

# 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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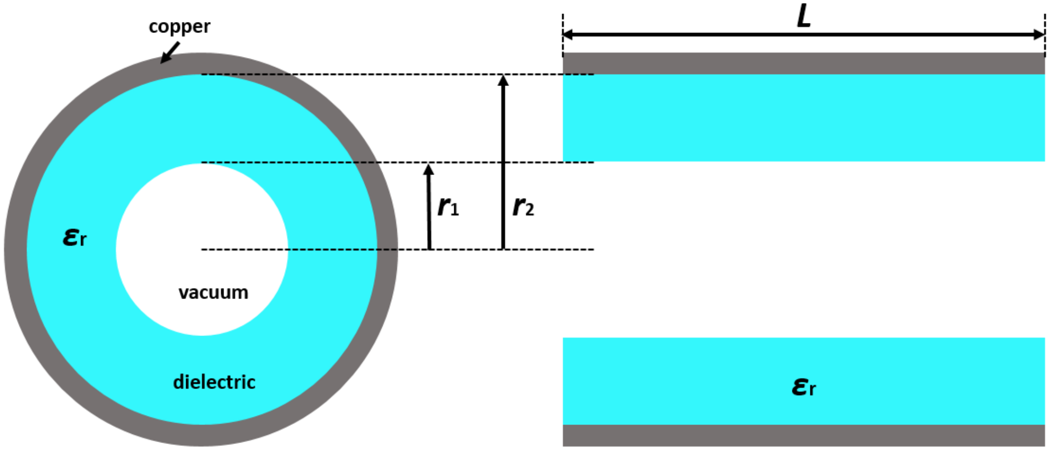
# Introduction

- **Slow wave accelerators: dielectric-lined accelerating (DLA) structures**




Advantages of DLA:

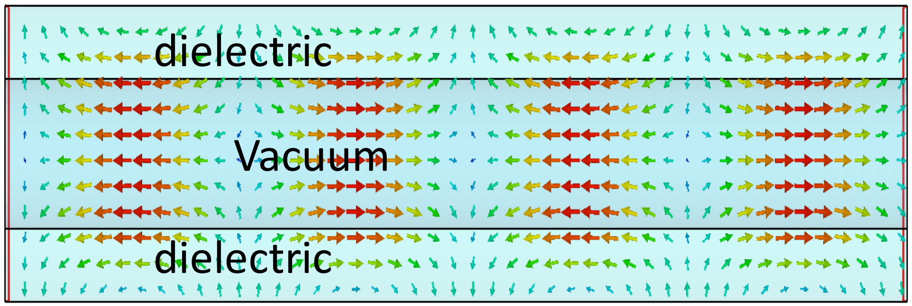
- Simple geometry for easy fabrication;
- No field enhancements on irises;
- Potential high gradient;
- Easy to damp HOMs;

Disadvantages of DLA:

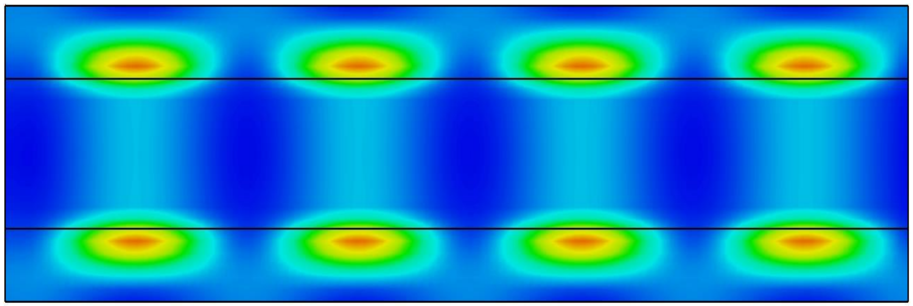
- Low power efficiency due to high group velocity >10% of *c*

# DLA Structures

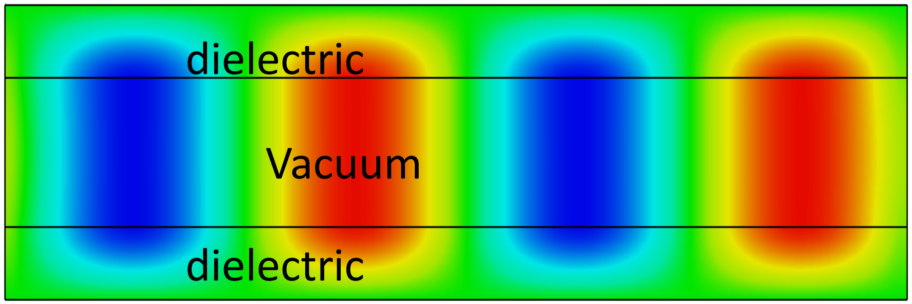
E-field of the TM01 mode ($v_{\mathrm{p}} = c$)



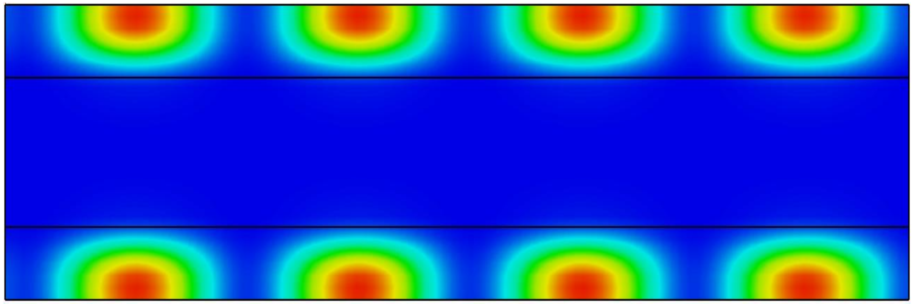

Electric energy density



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



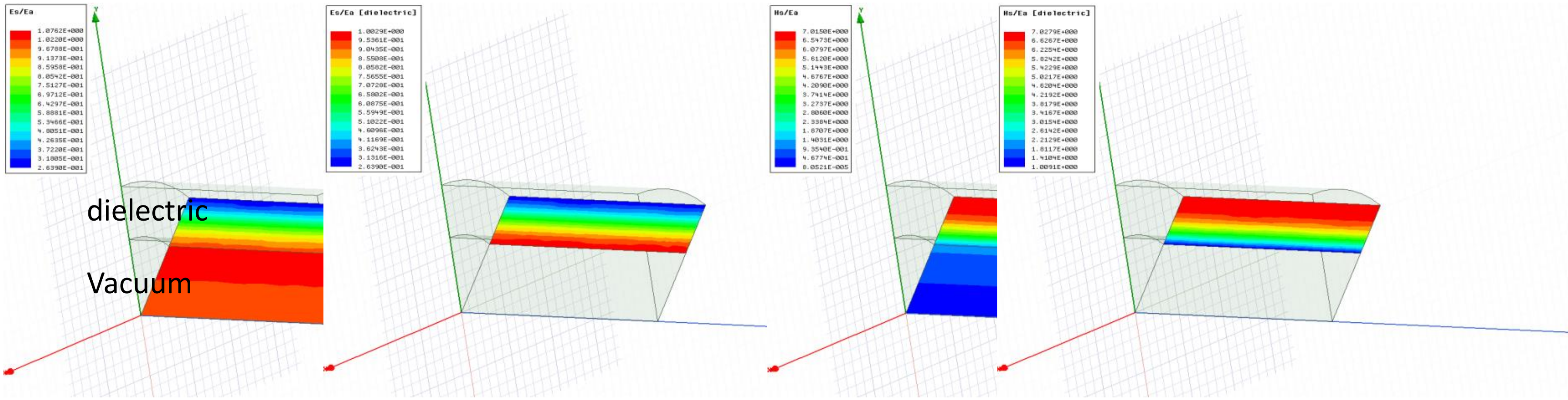

Magnetic energy density



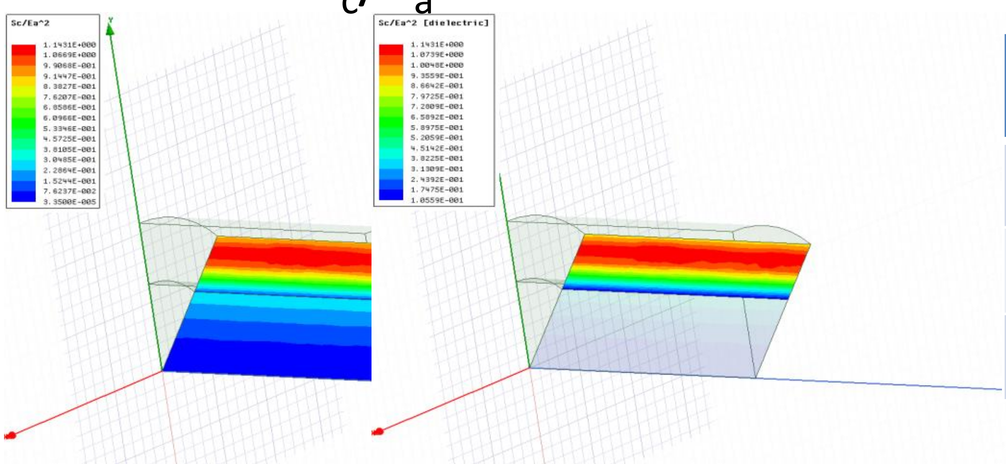
1) **The axial accelerating field is the maximum electric field in the structure;**
2) **The phase velocity of TM01 mode can be slowed down to c;**
3) **Most of energy is stored in dielectric area, resulting in low power efficiency.**

# Alumina DLA structure

$E_s/E_a$ $H_s/E_a$

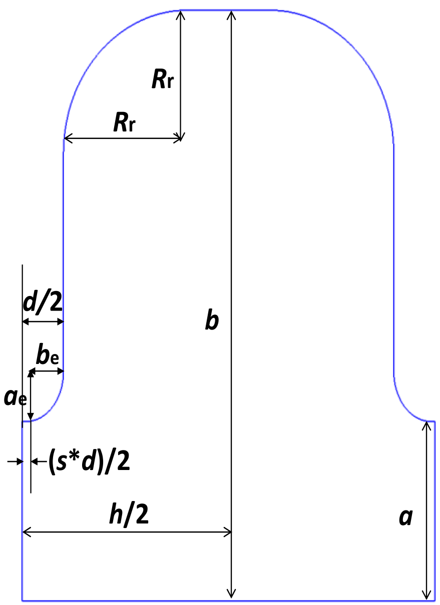



$S_c/E_a^2$



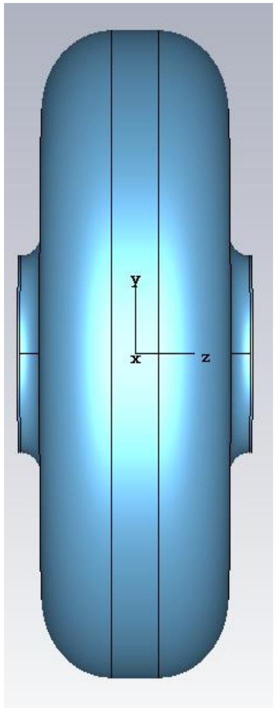
| | All area | Dielectric area |
|---|---|---|
| Es/Ea | 1.0762 | 1.0029 |
| Hs/Ea [mA/V] | 7.015 | 7.015 |
| Sc/Ea^2 [mA/V] | 1.1431 | 1.1431 |

# CLIC-G Iris structure

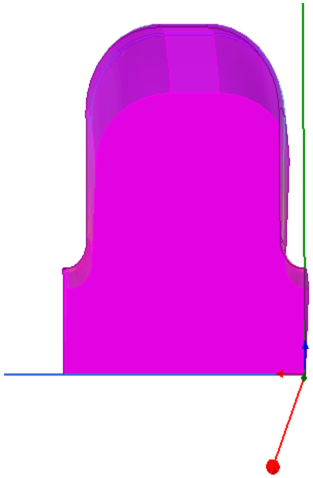



| Geometry parameters | Unit: mm |
|---|---|
| $a$ | 3.15 |
| $b$ | 10.35635 |
| $h$ | 8.332 |
| $d$ | 1.67 |
| $s$ | 0.1 |
| $a_e$ | 0.877 |
| $b_e$ | 0.7515 |
| $R_r$ | 2.5 |

| | 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 |

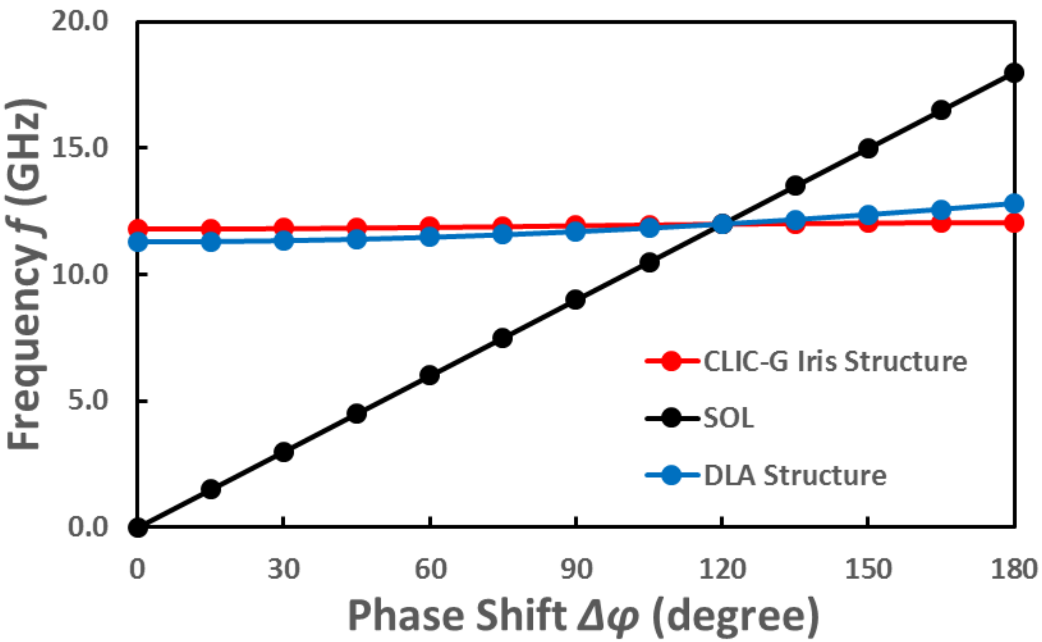


CST modelling



HFSS modelling

# 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 ($Al_2O_3$) | MgCaTi | BaTi |
|---|---|---|---|---|---|---|
| Dielectric constant $\varepsilon_r$ | | 3.75 | 5.7 | 9.64 | 20 | 35 |
| Dielectric loss tangent $\delta$ | | 0.00005 | 0.0001 | 0.000006 | 0.0001 | 0.0001 |
| Structure length [mm] | 8.33 | 8.33 | 8.33 | 8.33 | 8.333 | 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 | 5.365 | 4.624 | 4.245 |
| Frequency [GHz] | 11.9943 | 11.9990 | 11.9958 | 11.9924 | 11.9942 | 11.9919 |
| Unloaded $Q_0$ | 7245 | 6127 | 3998 | 4232 | 2214 | 1691 |
| $r'/Q_0$ [Ω/m] | 15924 | 10719 | 11166 | 10423 | 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 | 1.0762 | 1.0760 | 1.0760 |
| Es/Ea [dielectric] | | 1.0289 | 1.0024 | 1.0029 | 1.0152 | 1.0141 |
| Power required to generate 100 MV/m [MW] | 45.0 | 1013 | 652 | 424 | 266 | 197 |

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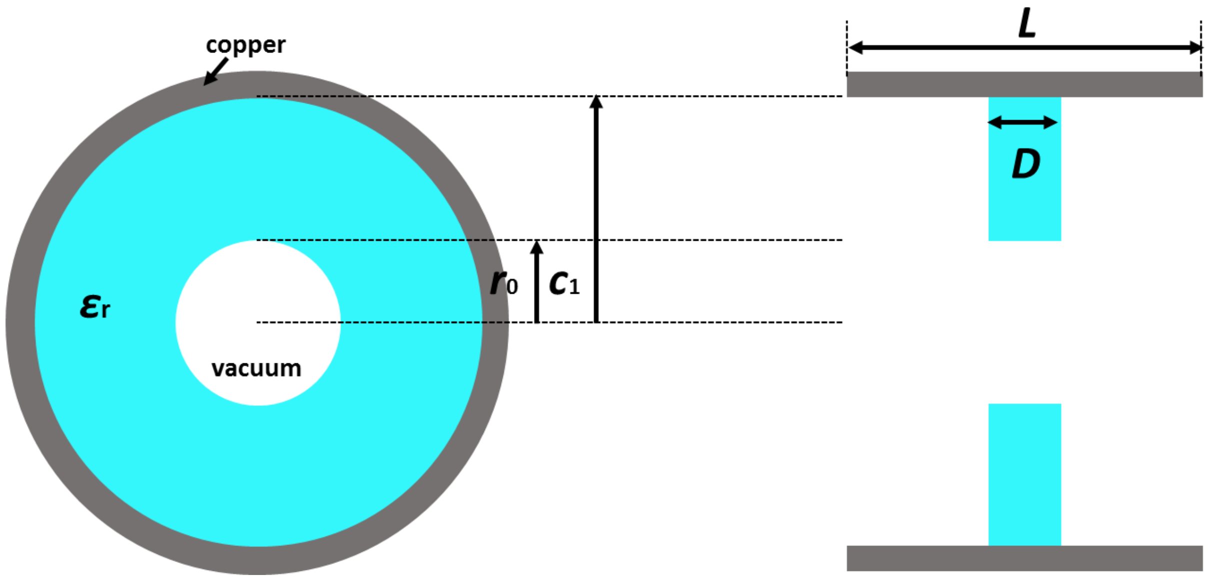
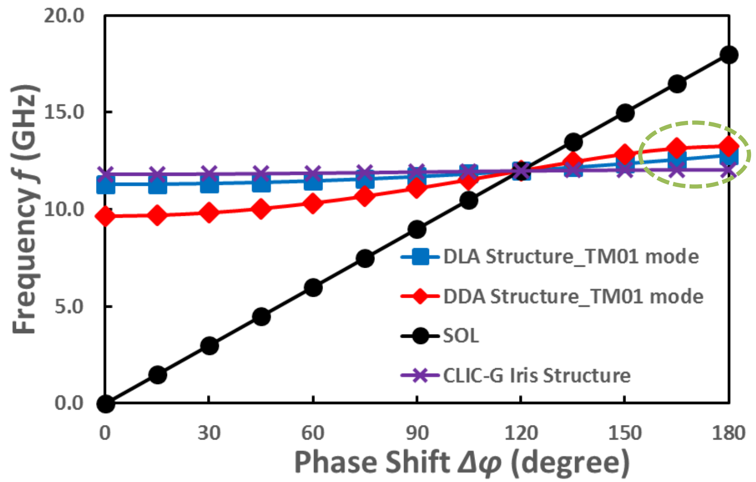
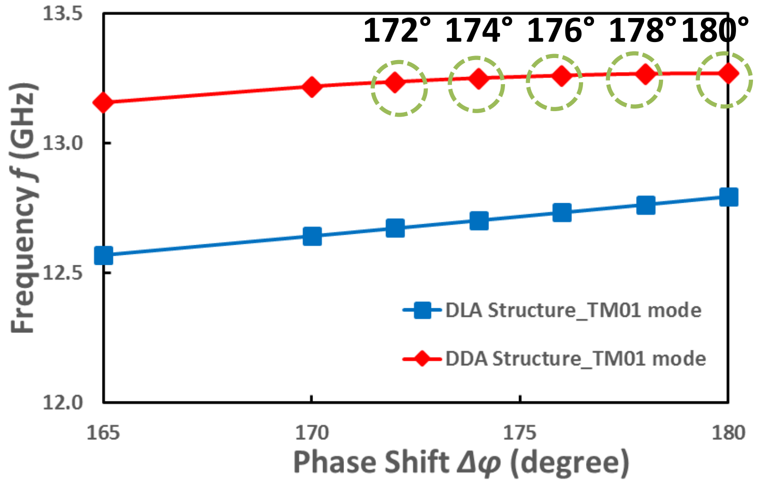
# DDA Structures-$TM_{01}$ mode




- We can adjust $r_0$, $c_1$, $D$ and $\varepsilon_r$ 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

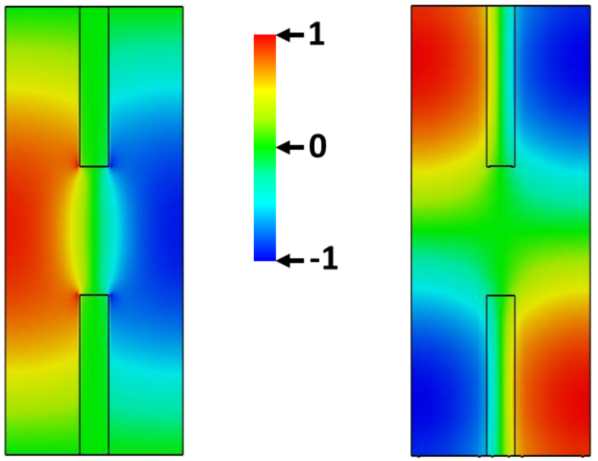


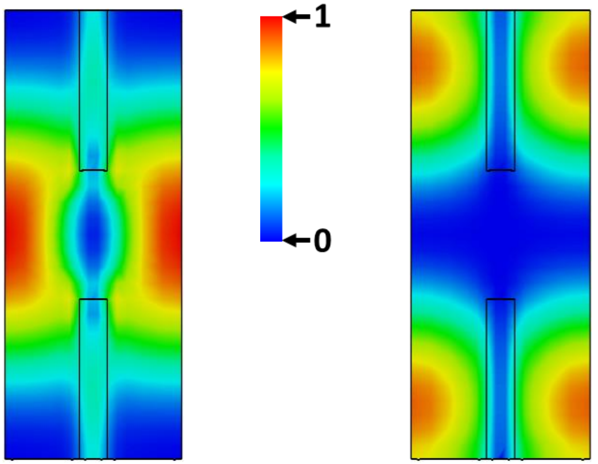

| Geometry parameters | DDA_TM01 mode |
|---|---|
| Dielectric constant $\varepsilon_r$ | 9.64 |
| Dielectric loss tangent $\delta$ | 6e-6 |
| Structure length $L$ [mm] | 8.333 |
| $r_1$ [mm] | 3.15 |
| $r_2$ [mm] | 10.59 |
| $D$ [mm] | 2 |

- 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.

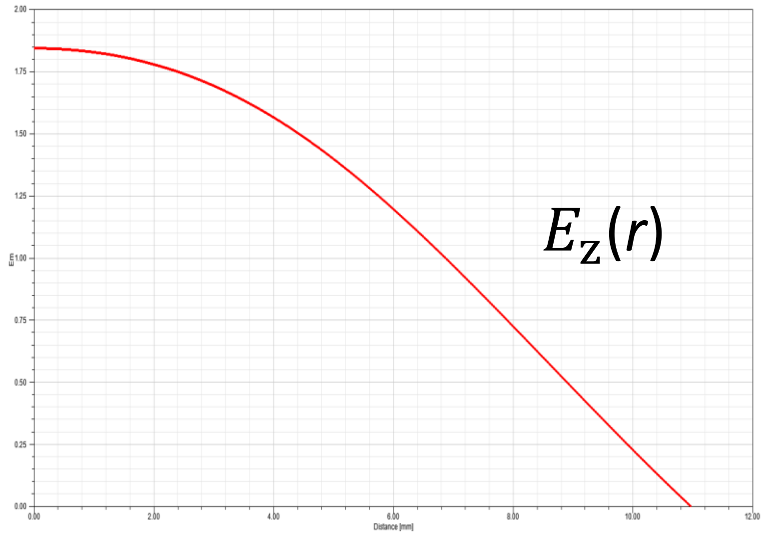
# Fields distributions for $TM_{01}$ π-mode




Longitudinal electric fields    Transverse magnetic fields

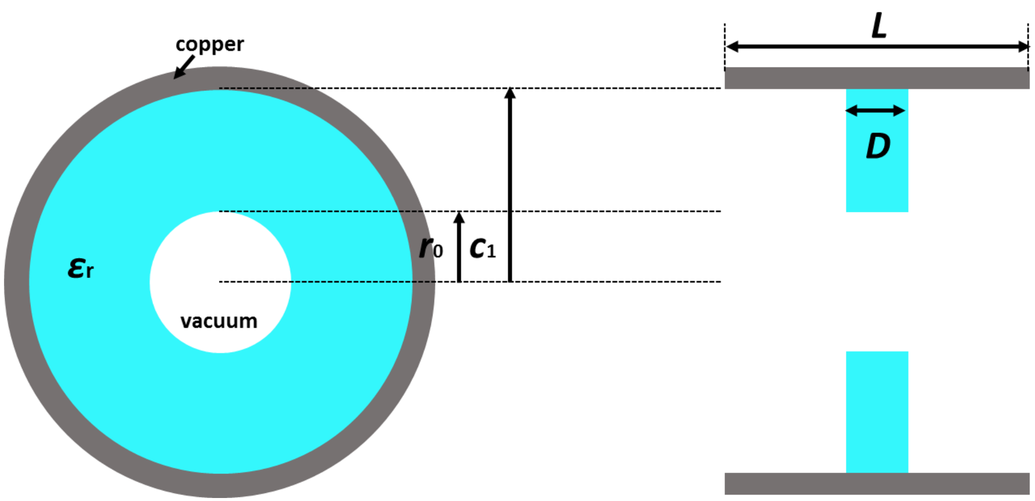


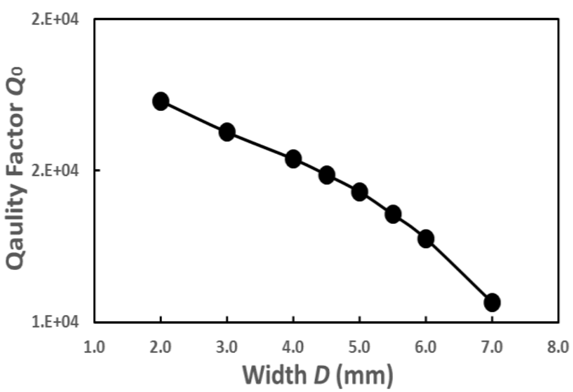

Electric energy density    Magnetic energy density

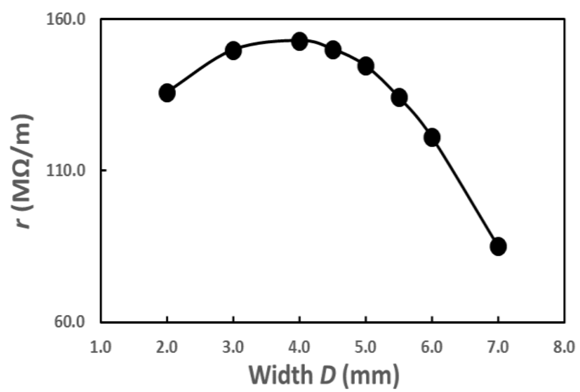



- Most of the RF energy is stored in the vacuum region;
- The total RF loss including both the wall loss on the conducting cylinder and dielectric loss in the DDA structure can be reduced, thereby resulting in both a high quality factor and shunt impedance at room temperature.

# Optimum geometry for DDA TM01 $\pi$-mode




| Optimum parameters | |
|---|---|
| Dielectric constant $\varepsilon_r$ | 9.64 |
| Dielectric loss tangent $\delta$ | 6E-6 |
| Inner radius $r_0$ [mm] | 3.15 |
| Outer radius $c_1$ [mm] | 9.925 |
| D [mm] | 4.0 |
| Structure period length L [mm] | 12.50 |
| Phase advance | 180° |
| Acceleration mode | TM01 π-mode |
| Frequency [GHz] | 11.9926 |
| Unloaded $Q_0$ | 15392 |
| $r'/Q_0$ [Ω/m] | 9931 |
| $r'$ [MΩ/m] | 153 |

# Comparisons

| | CLIC-G | DLA | DDA_TM01_0.96$\pi$-mode | DDA_TM01_0.99$\pi$-mode | DDA_TM01_$\pi$-mode |
|---|---|---|---|---|---|
| Dielectric constant $\varepsilon r$ | | 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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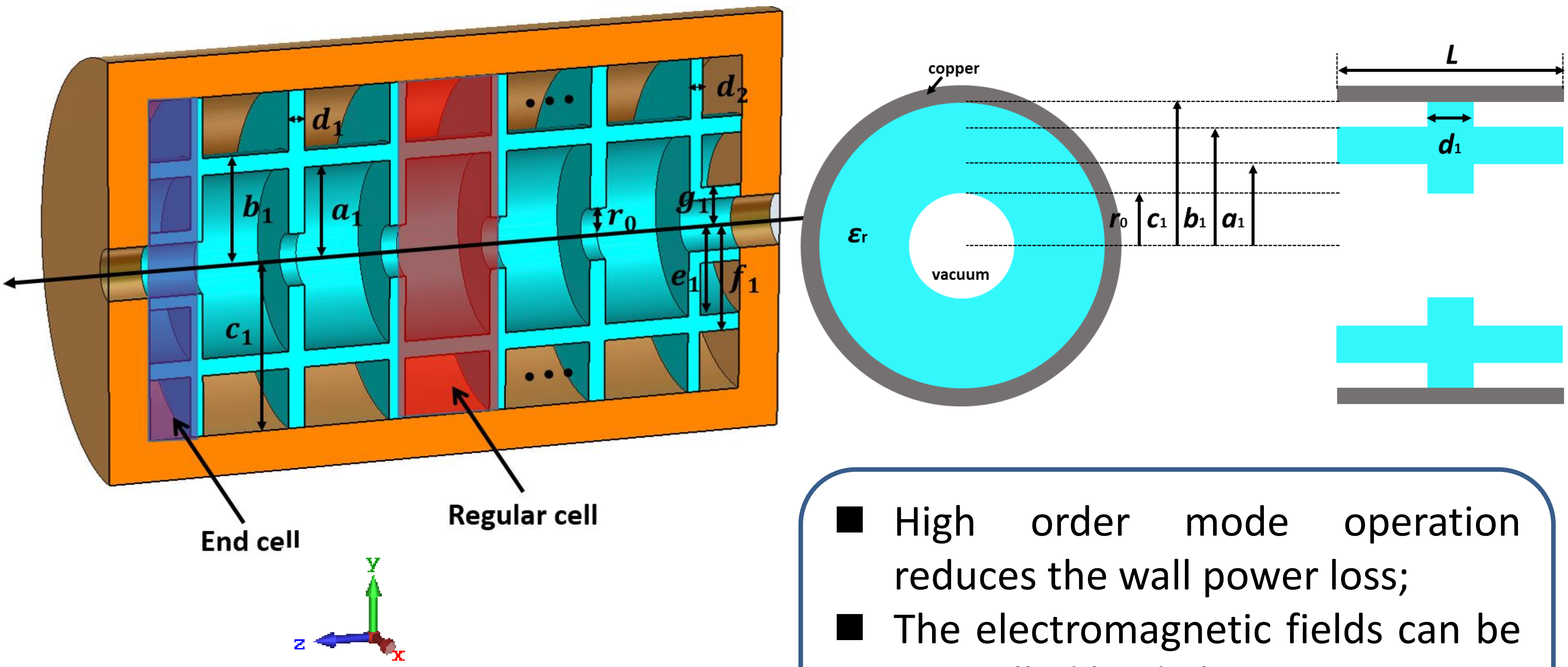
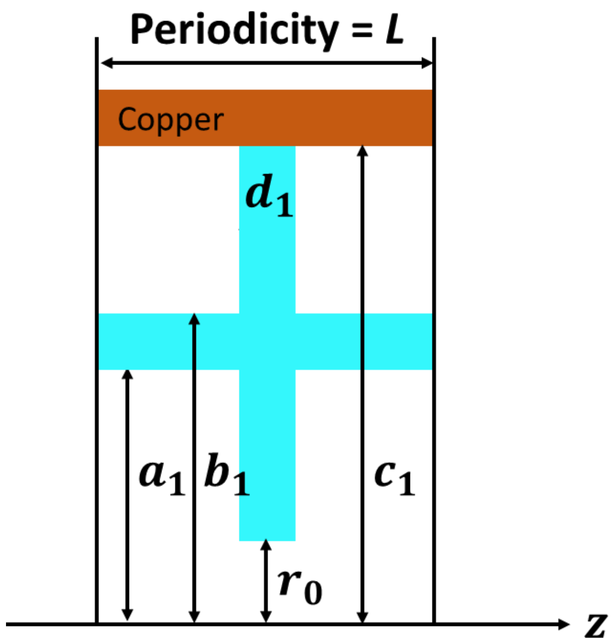
# DDA Structures-$TM_{02}$ π-mode




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

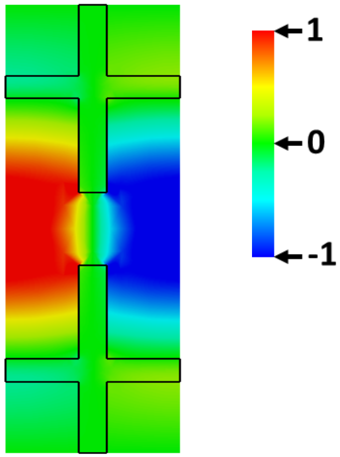
D. Satoh, et al. Phys. Rev. Accel. Beams 19, 011302 (2016)

# Regular cell

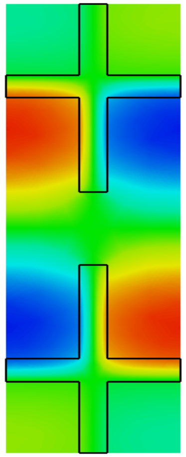



- Both types generate the same RF parameters;
- Different boundary conditions generate different modes due to different fields distribution.

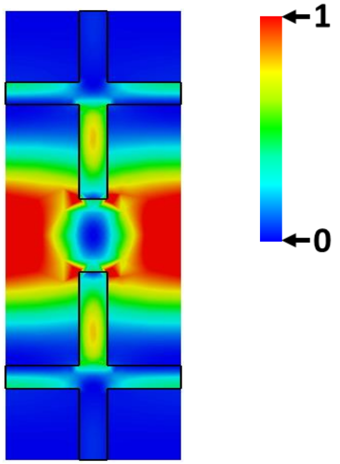
# Field distributions in a regular cell



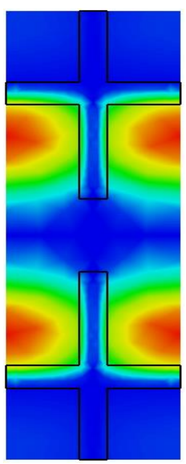

Longitudinal electric fields



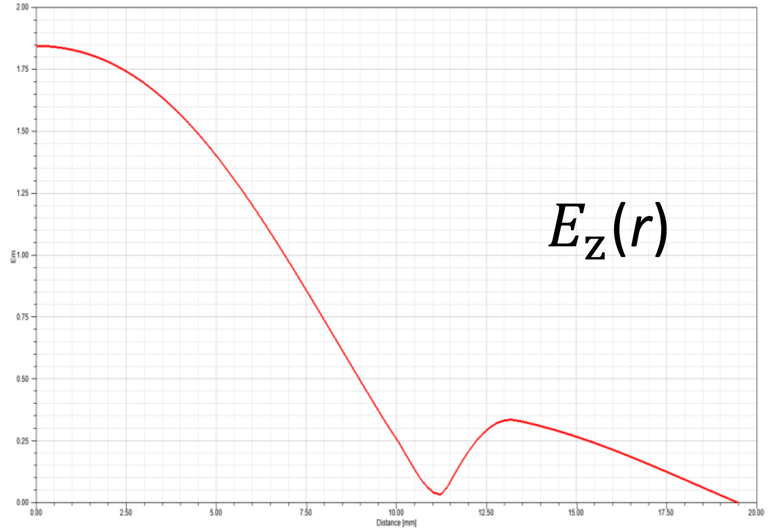
Transverse magnetic fields




Electric energy density

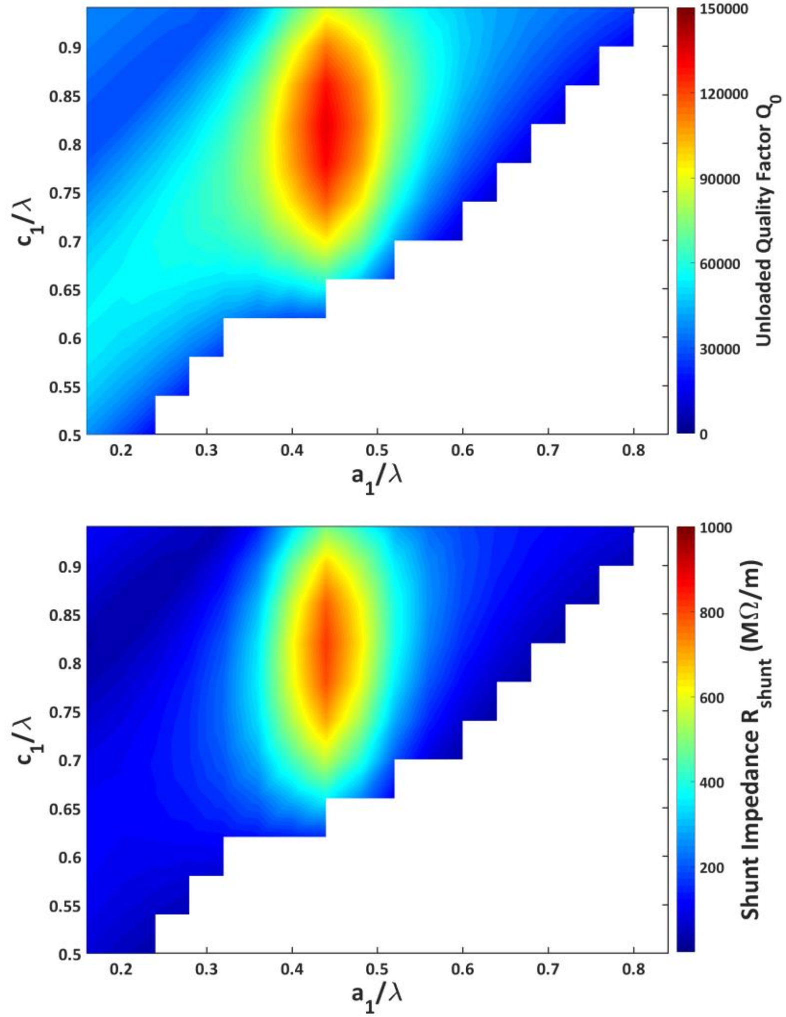


Magnetic energy density



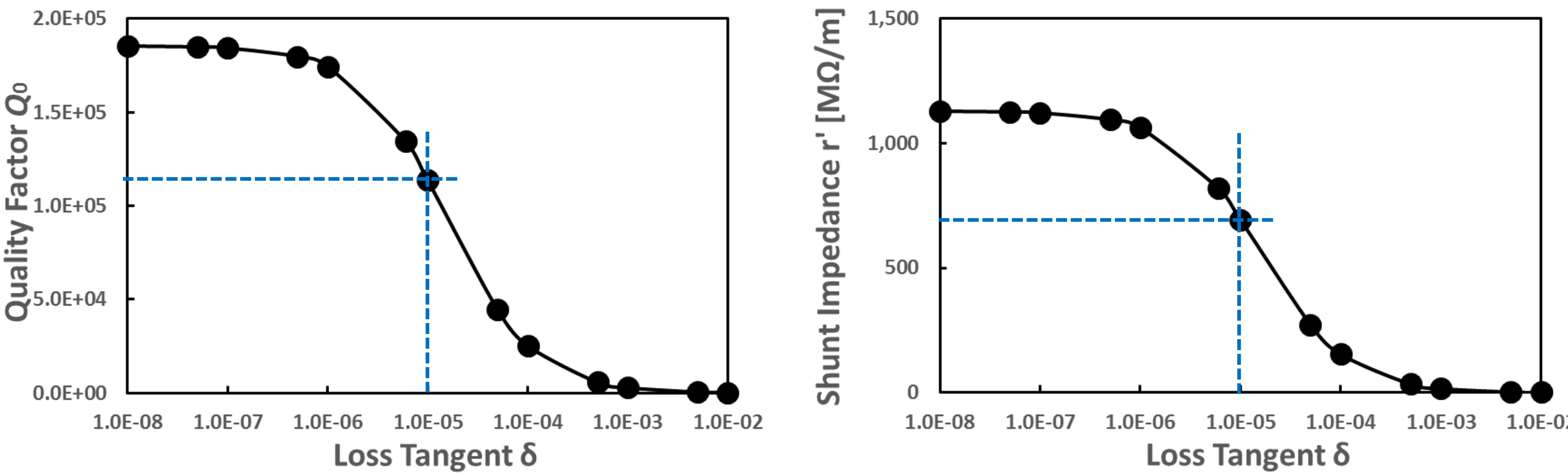

- Most of the RF energy is stored in the vacuum region;
- The total RF loss including both the wall loss on the conducting cylinder and dielectric loss in the DDA structure can be drastically reduced, thereby resulting in both an extremely high quality factor and a very high shunt impedance at room temperature.

# Optimization for a regular cell




| Optimum parameters | |
|---|---|
| Dielectric constant εr | 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 |

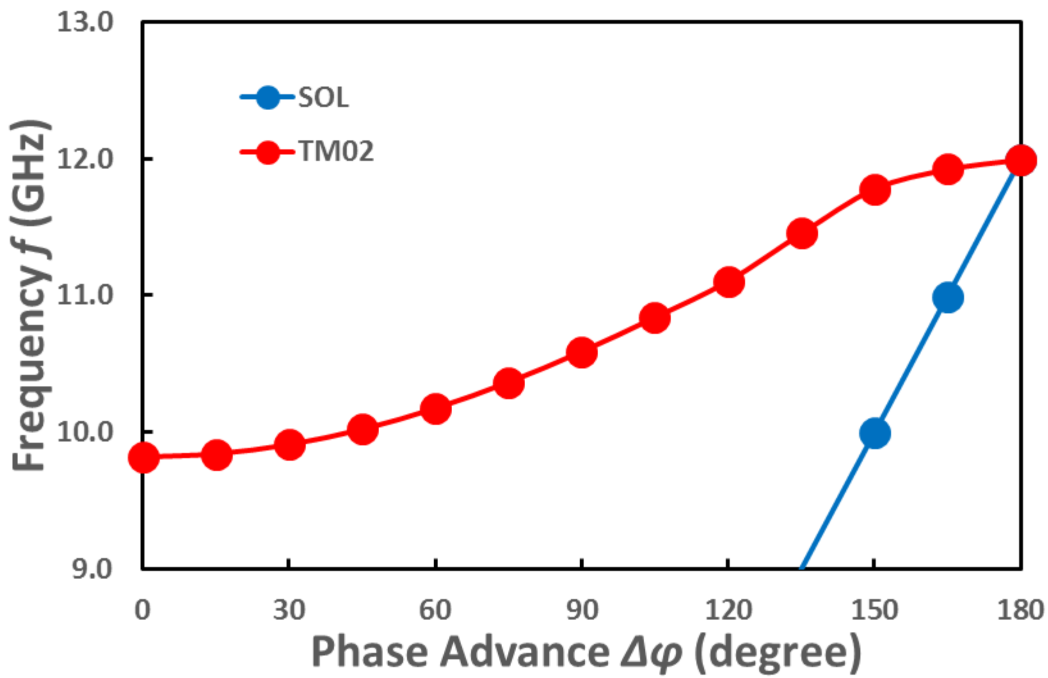
# Regular cell with different loss tangent




- 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.

# 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 $BW = f_r k = 2.17$ GHz

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

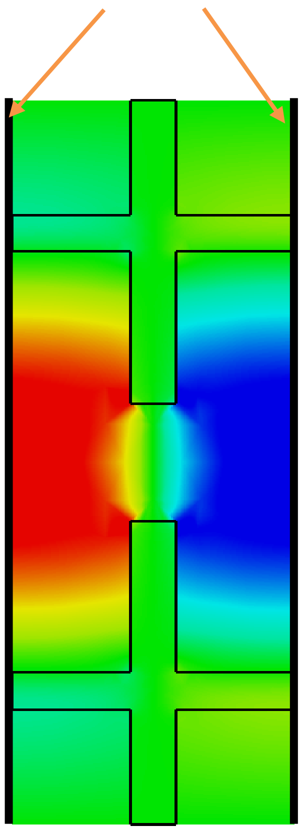
The frequency separation for modes: $\Delta f_{N-1,N}^{\pi} = f_r \frac{k\pi^2}{4N^2} = 21$ MHz;

$\Delta f_{N-1,N}^{\pi/2} = f_r \frac{k\pi}{4N} = 6.7$ MHz

;

***N* = 250 structures**

# Regular cell with copper plates

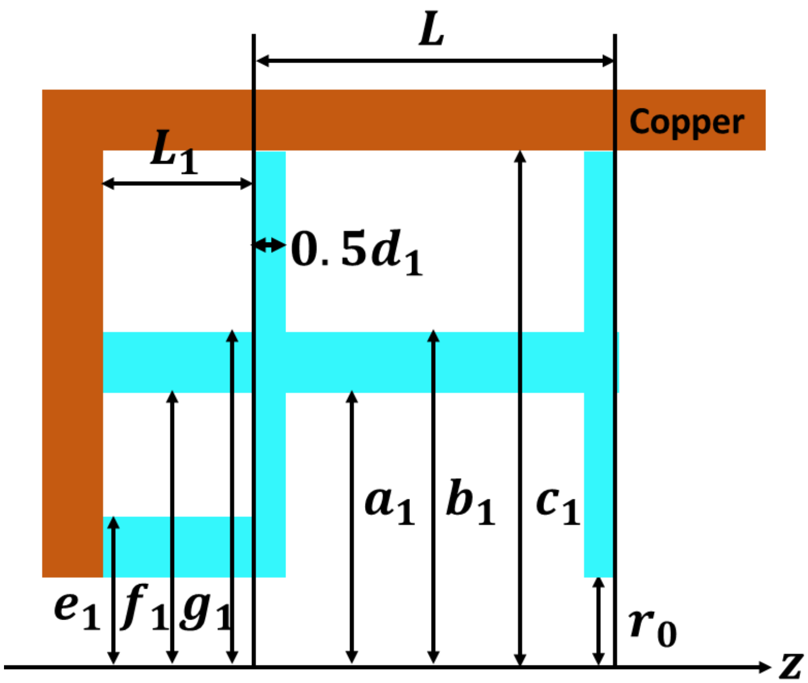


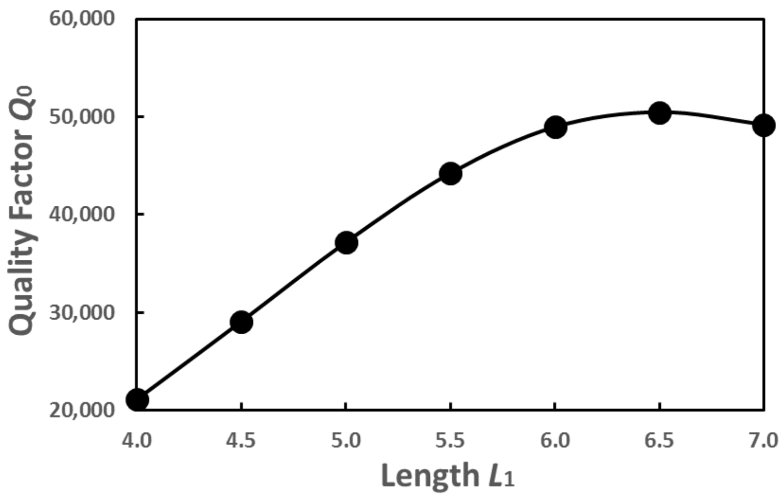

- Copper plates: 2.8% RF loss comes from dielectric loss, 97.2% RF loss comes from copper wall loss;
- Periodic boundary: 27.4% RF loss comes from dielectric loss, 72.6% RF loss comes from copper wall loss;

| | |
|---|---|
| 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

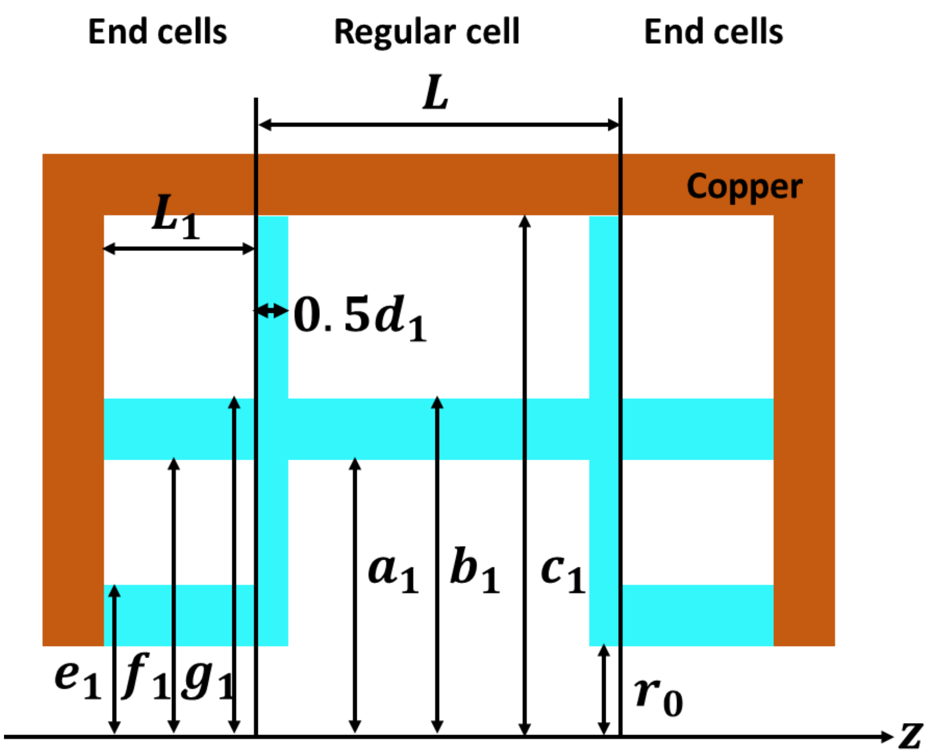



| | |
|---|---|
| $e_1$ [mm] | 4.6 |
| $L_1$ [mm] | 6.5 |
| $f_1$ [mm] | 11.1 |
| $g_1$ [mm] | 13.16 |
| Frequency [GHz] | 11.9942 |
| Unloaded $Q_0$ | 50464 |
| $r'$ [MΩ/m] | 181 |

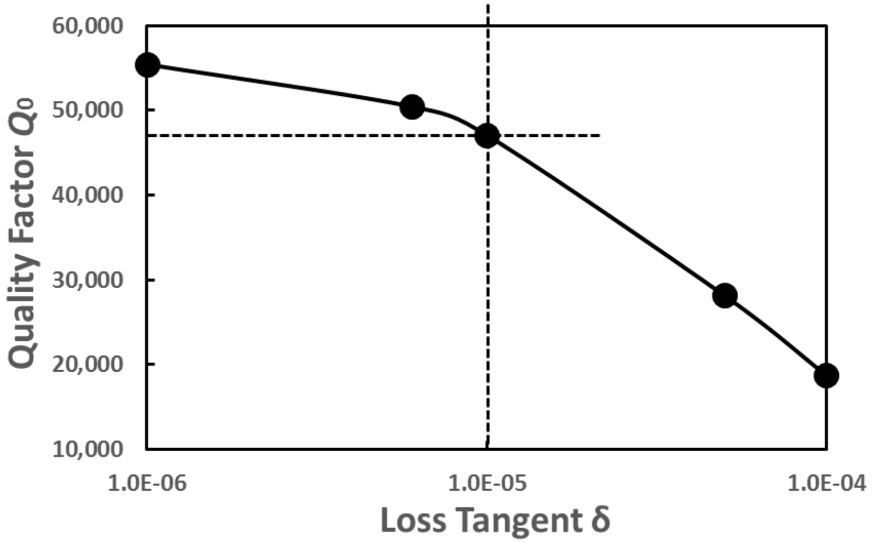
- Frequency is sensitive to $e_1$ and $L_1$;
- The ratio of copper wall loss to total power loss is reduced from 97.2% to 89.3%

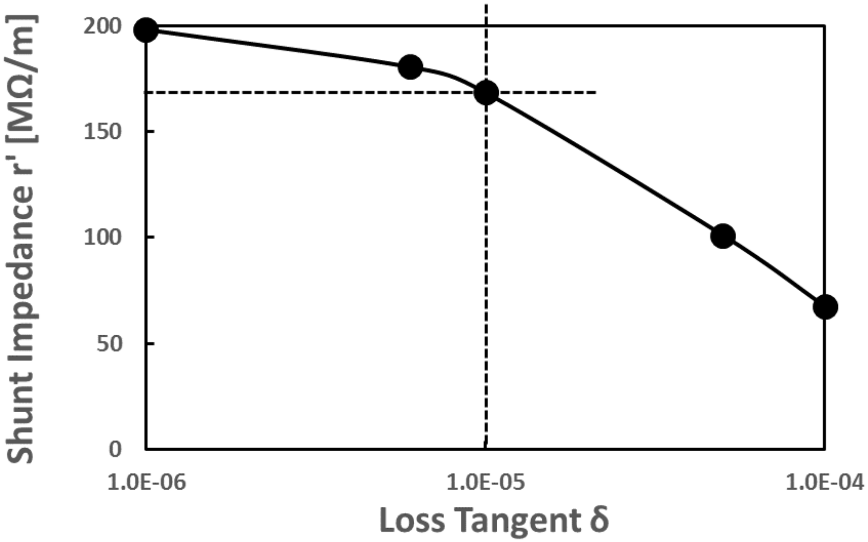
# Single-cell DDA structure




| | |
|---|---|
| Dielectric constant $\varepsilon_r$ | 9.64 |
| Dielectric loss tangent $\delta$ | 6E-6 |
| Inner radius $r_0$ [mm] | 3.15 |
| Outer radius $c_1$ [mm] | 20.5 |
| $a_1$, $f_1$ [mm] | 11.1 |
| $b_1$, $g_1$ [mm] | 13.16 |
| $d_1$ [mm] | 2.0 |
| $e_1$ [mm] | 4.6 |
| Operation temperature | 20 ℃ |
| Acceleration mode | TM02 π-mode |
| Frequency [GHz] | 11.9942 |
| Unloaded $Q_0$ | 50464 |
| $r'/Q_0$ [Ω/m] | 3578 |
| $r'$ [MΩ/m] | 181 |

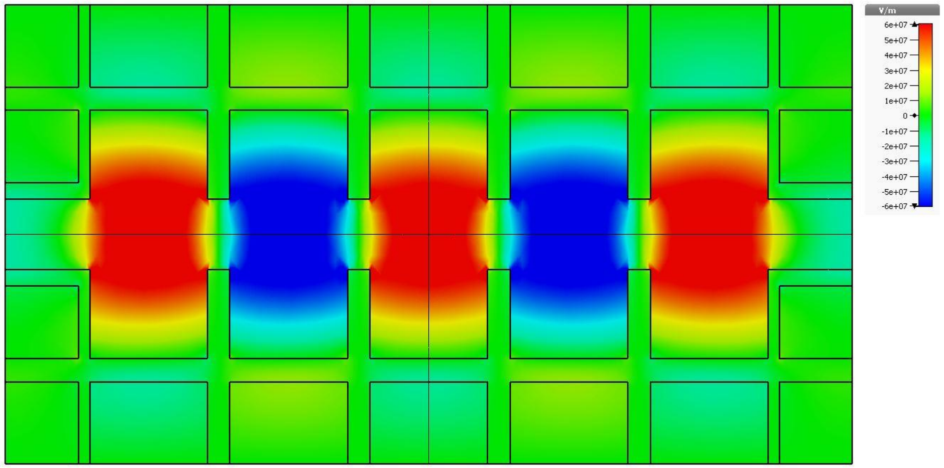
# Different loss tangent $\delta$



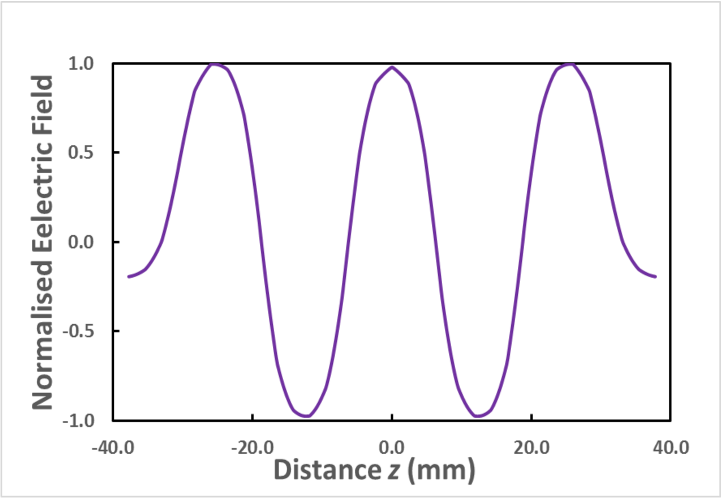



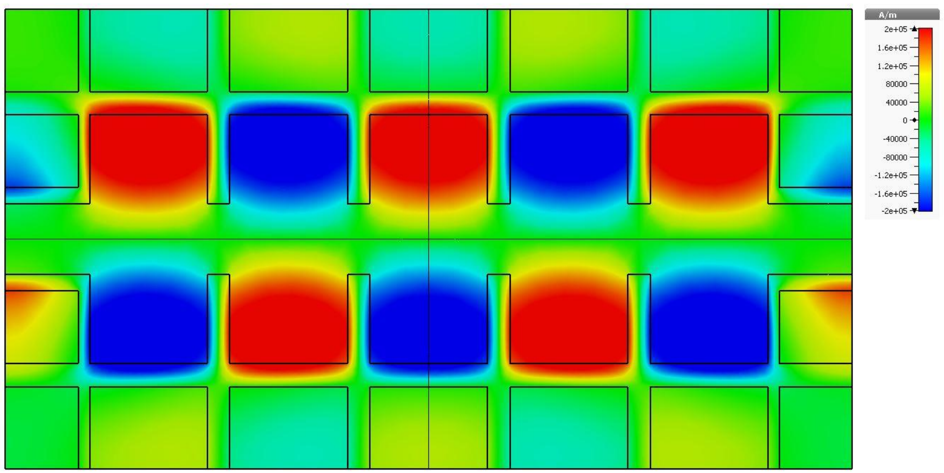

- ❑ The dielectric loss tangent 6E-6 is really challenging in the reality; It really depends the materials process;
- ❑ For a single-cell DDA structure, loss tangent δ is 1E-5, which is achievable from other labs;
- ❑ The quality factor is 47093 and shunt impedance is 169 MΩ/m, which are still better than those of CLIC accelerating structures.

# Multi-cell DDA structure



Longitudinal electric fields



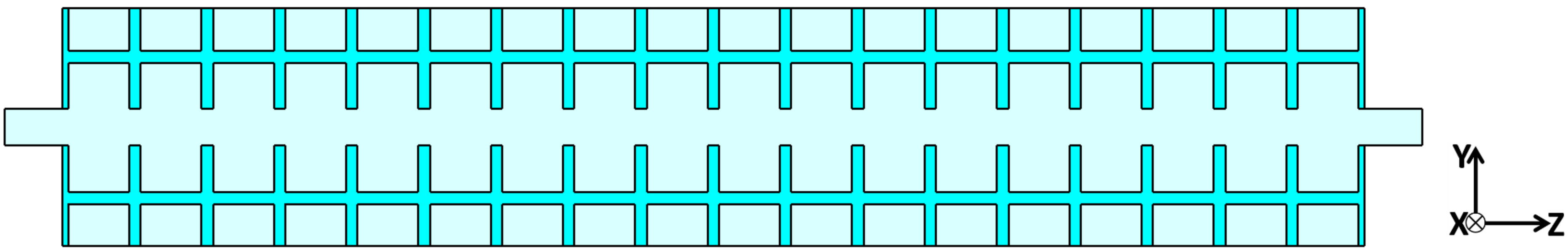
Transverse magnetic fields

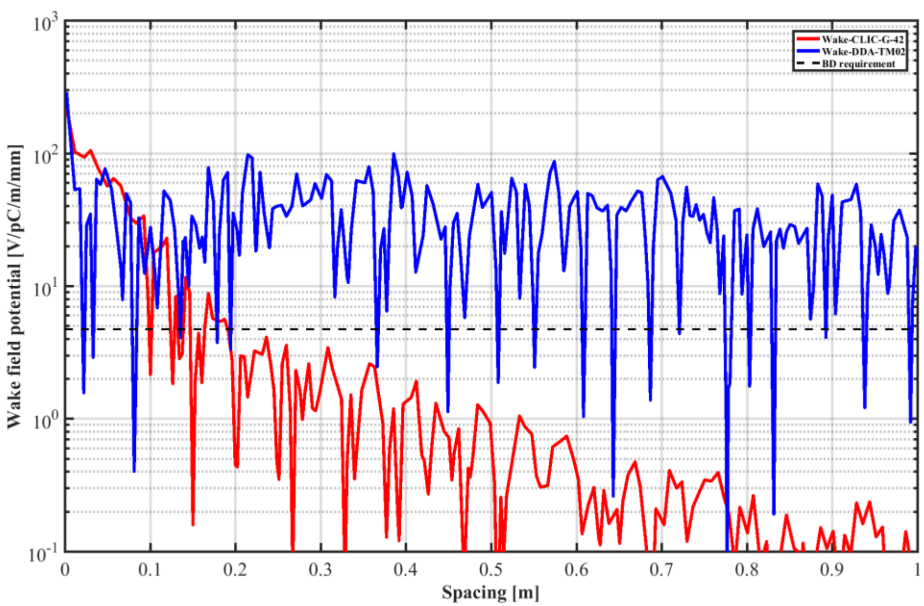
- Quality factor $Q_0$ = 97146, shunt impedance r’ = 508 MΩ/m for a 5-cell cavity with same dielectric material;
- $Q_0$ and r’ can be increased to 110840 and 695 MΩ/m for a 9-cell cavity;
- Quality factor and shunt impedance increase with the number of cells.

# 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

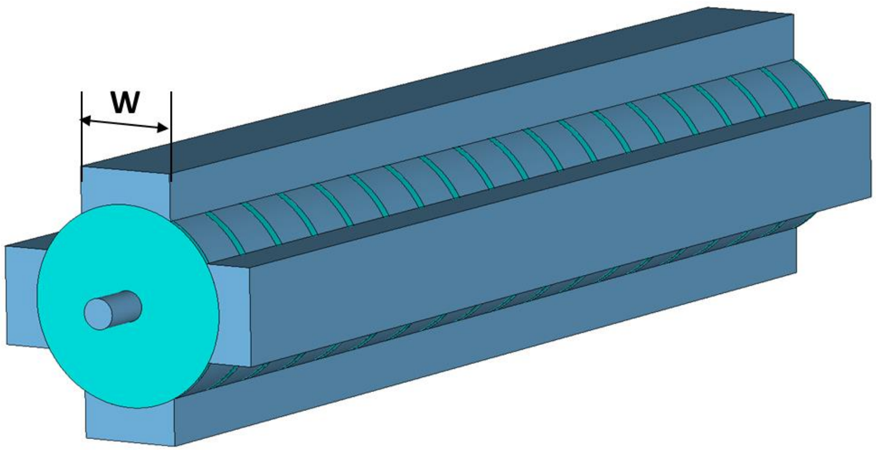
# Wakefield Studies



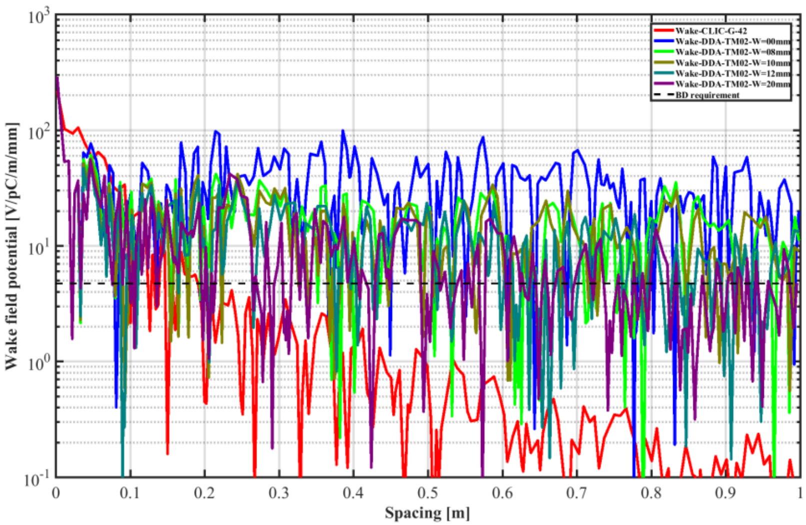



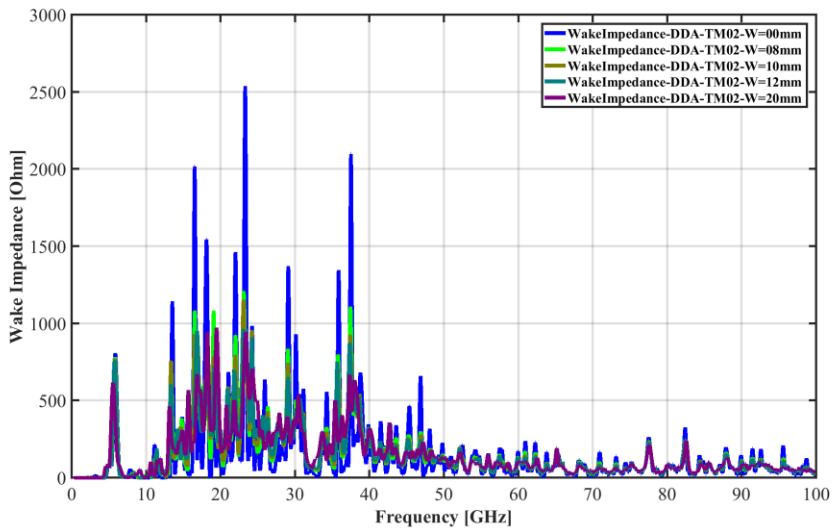

CLIC-G: 28*8.333 ↔ DDA TM02-π: 18*12.5, so the number of regular cell is 18, no end cells are included; Gdfild modelling for a DDA TM02-π-mode structure: dx=dy=dz=0.05 mm, bunch charge *Q* = 1.0 nC, bunch sigma = 1.0 mm, offset = 0.5 mm.

# Adding Damping Waveguide

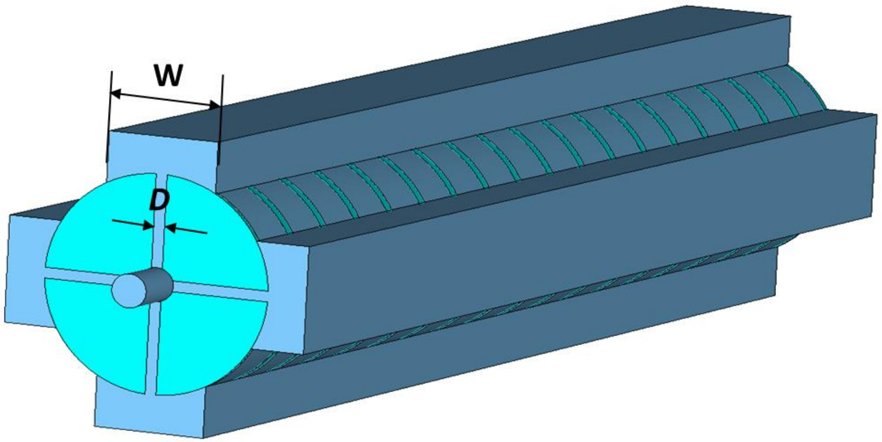



| W [mm] | quality factor $Q_0$ | shunt impedance r' [MΩ/m] | 7 bunches | | | Envelope [7 bunches] | | |
|---|---|---|---|---|---|---|---|---|
| | | | $F_c$ | $F_{rms}$ | $F_{worst}$ | $F_c$ | $F_{rms}$ | $F_{worst}$ |
| 0 | 134542 | 819 | 149 | 752 | 5051 | 4086 | 2836 | 19483 |
| 8 | 113810 | 680 | 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 |

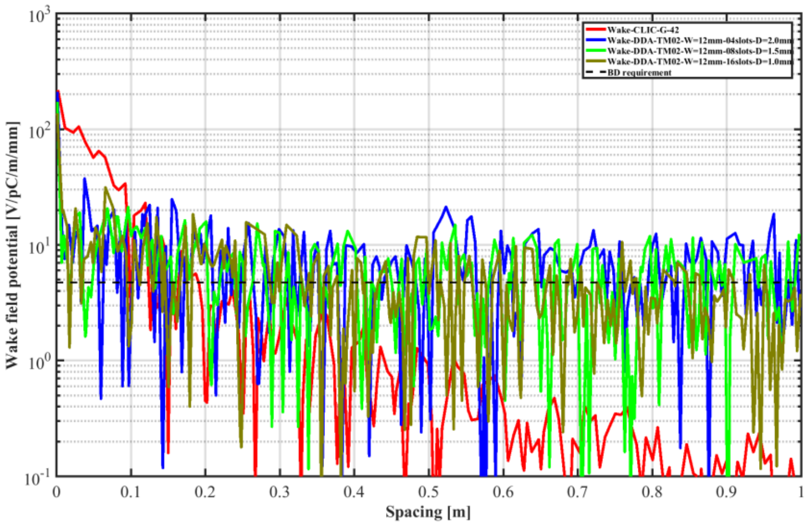


# Adding Dielectric Slots ( W=12 mm )




| 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.

# Summary and Outlook

- ❑ Different DLA structures have been studied at 12 GHz; High group velocity;
- ❑ DDA TM01 π-mode structures: $Q_0$ = 15392, r'/$Q_0$ = 9931 Ω/m, r' = 153 MΩ/m;
- ❑ DDA TM02 π-mode structure: $Q_0$ = 134542, r'/$Q_0$ = 6089 Ω/m, r' = 819 MΩ/m;
  - The number of acceleration cells can be up to 250 due to high bandwidth;
  - Optimization for a single-cell structure including regular and end cells: $Q_0$ = 50464, r'/$Q_0$ = 3578 Ω/m, r' = 181 MΩ/m;
  - Preliminary wakefield studies using damping waveguides and dielectric slots.

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