Studies on X-band dielectric accelerating structures

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Outline

- **Background & Introduction**
- **Dielectric-Lined Accelerating (DLA) Structures**
- **Dielectric Disk Accelerating (DDA) Structures**
  - **TM01 operation mode**
  - **TM02 operation mode**
- **Design of an X-band DLA structure**
  - **Simulation studies**
  - **Fabrication and cold-testing of a DLA prototype**
  - **Fabrication error analysis**
- **Summary & Outlook**

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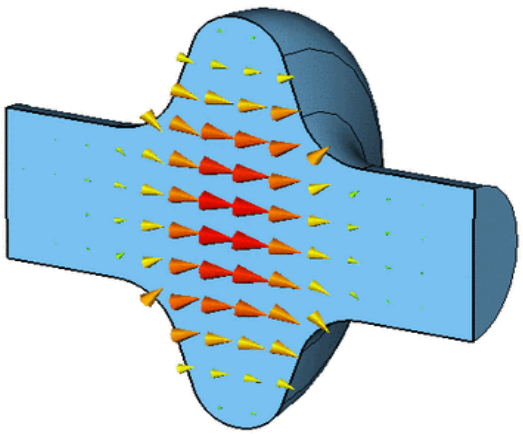
Introduction

RF Cavity Acceleration-Standing wave

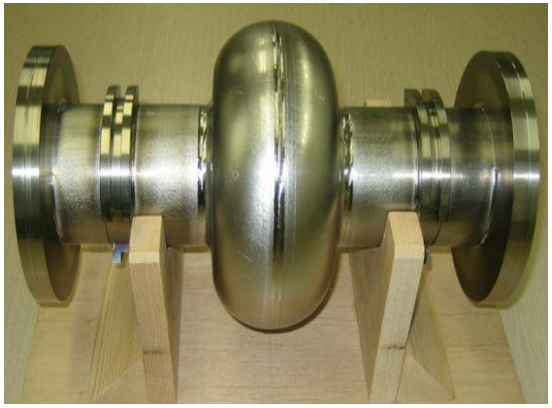


- An electron travelling close to the speed of light traverses through a cavity. During its transit it sees a time varying electric field. If we use the voltage as complex, the maximum possible energy gain is given by the magnitude,

$$\Delta E = eV_b = e\left|\int_{-L/2}^{+L/2} E_z(z,t)e^{i\omega z/c}dz\right|$$, V_b is accelerating voltage

- To receive the maximum kick with multiple cells the particle should traverse the cavity in a half RF period:

$$L = \frac{c}{2f}$$, L is length of a single cell



Acceleration gradient = $G = \frac{V_b}{L}$

Quality factor = $Q_0 = \omega \frac{U}{P_{loss}}$

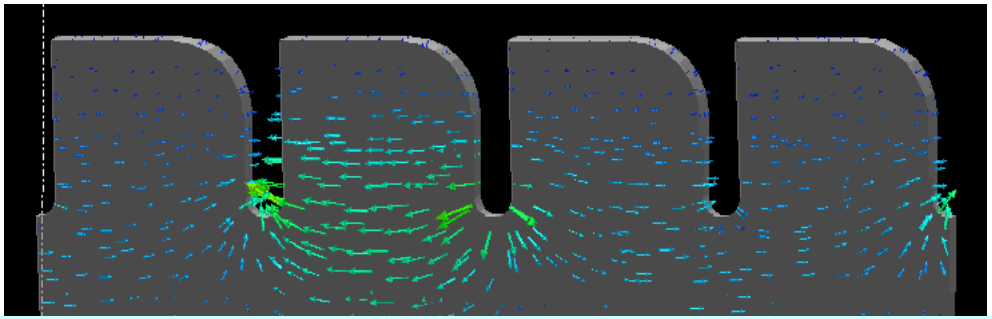
Shunt impedance = $R_{shunt} = \frac{V_b^2}{P_{loss}}$

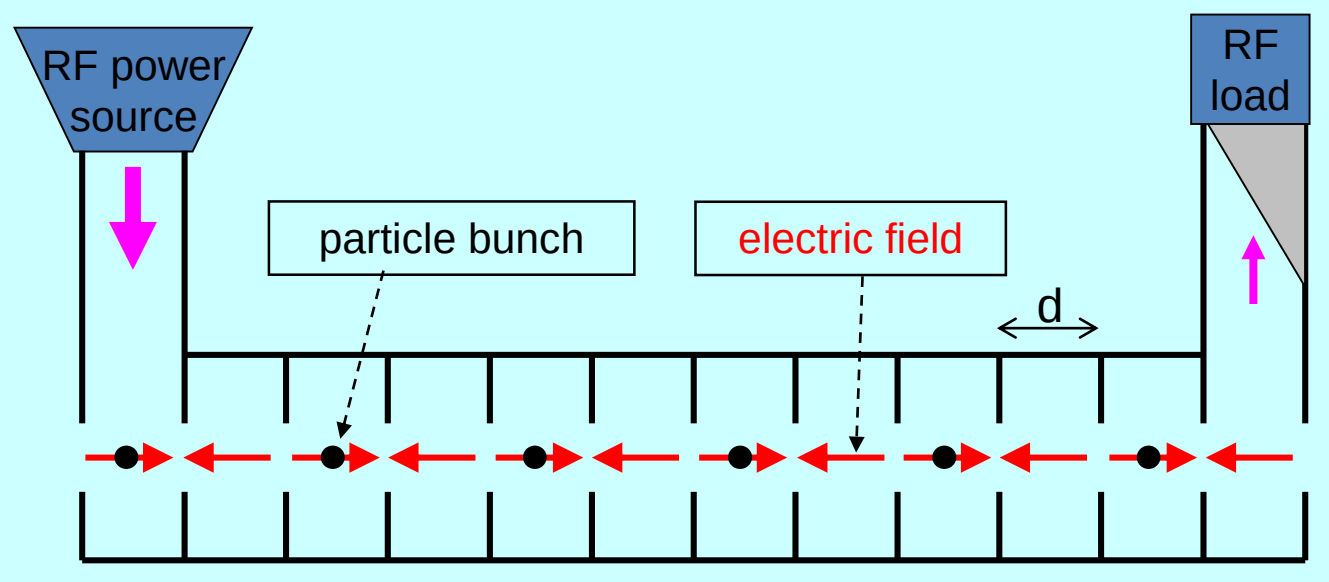
U is the stored energy, P_{loss} is the power loss on the cavity surface

Introduction

- electrons β~1 (v~c)
- short pulses
- high frequency >3 GHz
- typical 10~20 MV/m
- CLIC:
  - 12 GHz
  - 240 ns
  - 100 MV/m

RF Cavity Acceleration-travelling wave

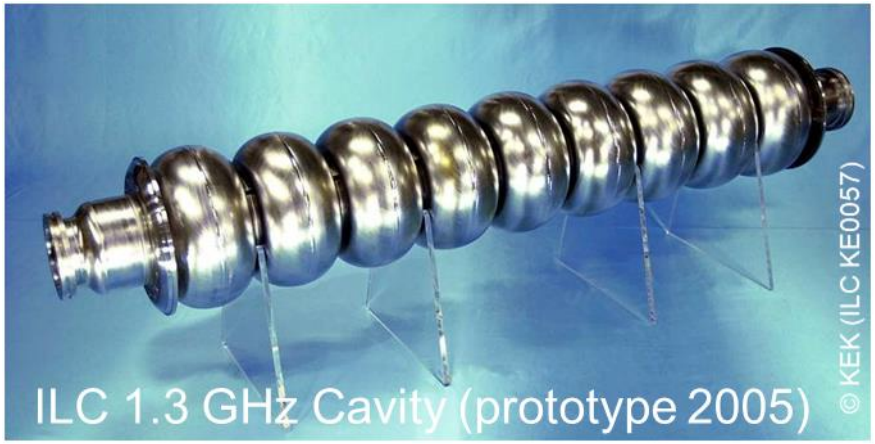




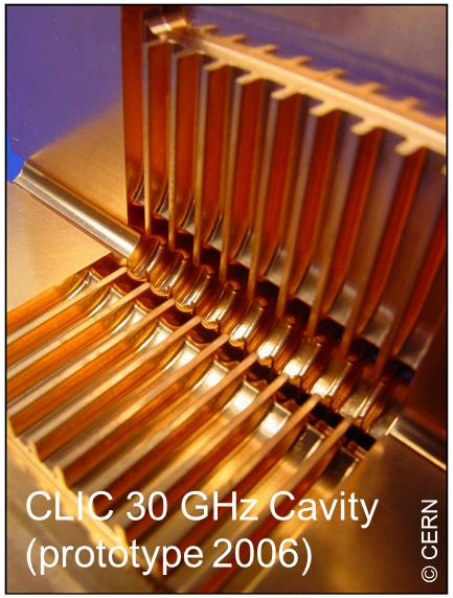
Introduction

RF Accelerating Cavities

CERN PS 19 MHz Cavity (prototype 1966)



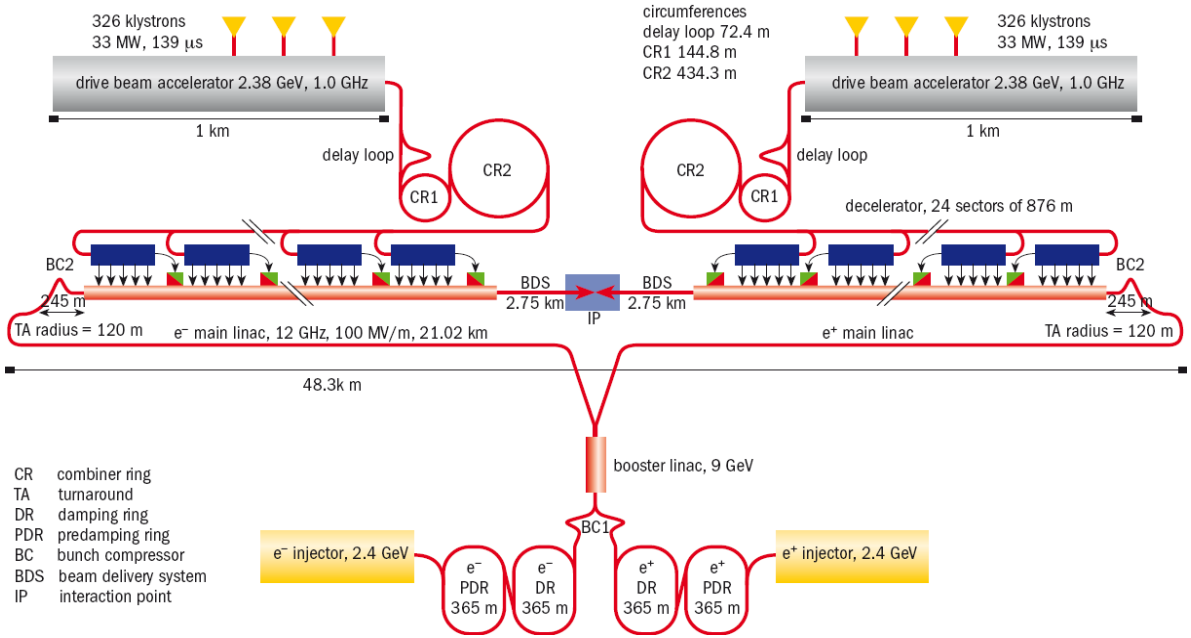
ILC 1.3 GHz Cavity (prototype 2005)



CLIC 30 GHz Cavity (prototype 2006)

Introduction

CLIC: Compact Linear Collider

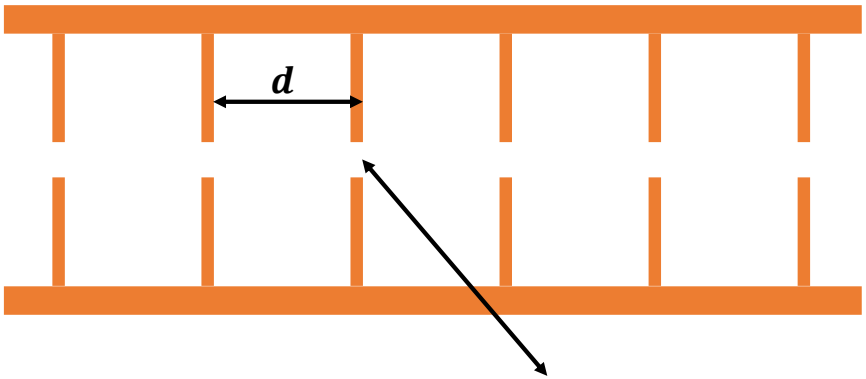


Main Linac	
C.M. Energy	3 TeV
Peak luminosity	$2x10^{34}$ $cm^{-2}s^{-1}$
Beam Rep. rate	50 Hz
Pulse time duration	156 ns
Average field gradient	100 MV/m
# accelerating cavities	2 x 71,548

The objective of the X-band activity is to develop the high-gradient, high-power X-band rf system for the CLIC main linacs. The current focus is on constructing and operating 100 MV/m prototype accelerating structures and establishing a significant high-power testing capability through klystron-based test stands. Additional activities include studies of the fundamental physics of high-gradients, the use of high-gradient technology in other applications such as XFELs and medical linacs and the design of high-efficiency and high frequency klystrons.

Introduction

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



Irises-loaded structure

X-band CLIC accelerating structure

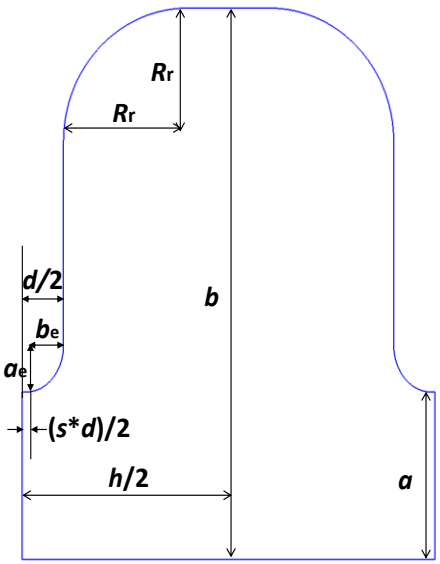
Irises form periodic structure in waveguide:

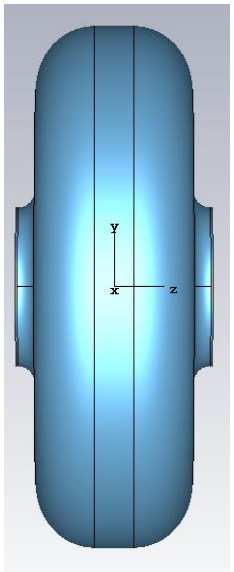
- ❖ Irises reflect part of the wave;
- ❖ Irises slow down the phase velocity so that it equals the particle velocity;
- ❖ The group velocity is usually around 1% of *c*.

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

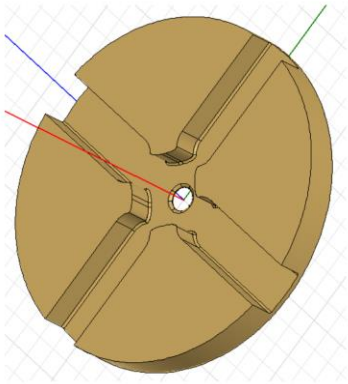
CLIC-G Accelerating Structure

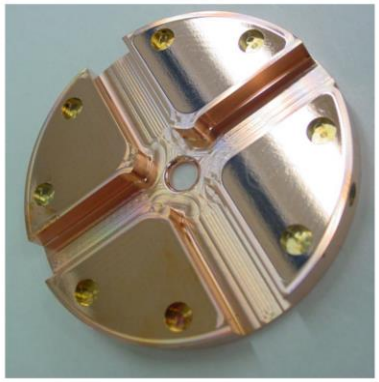
Without HOM Damping

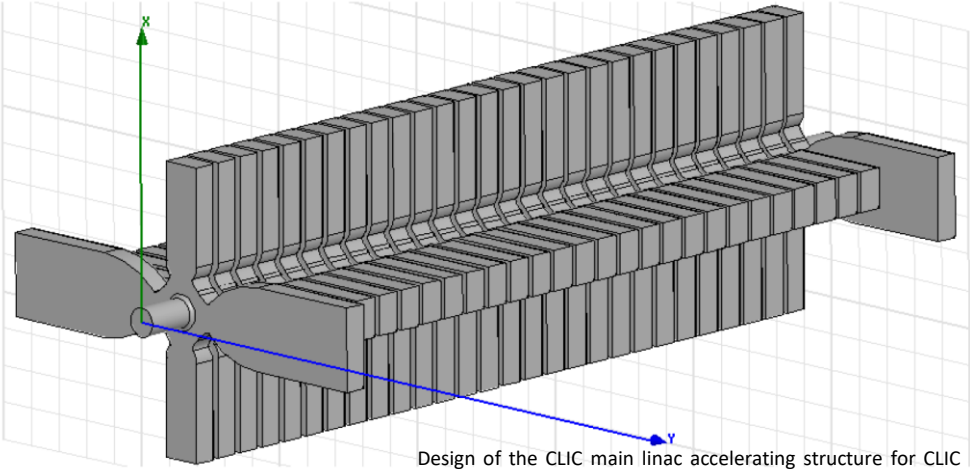




With HOM Damping







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

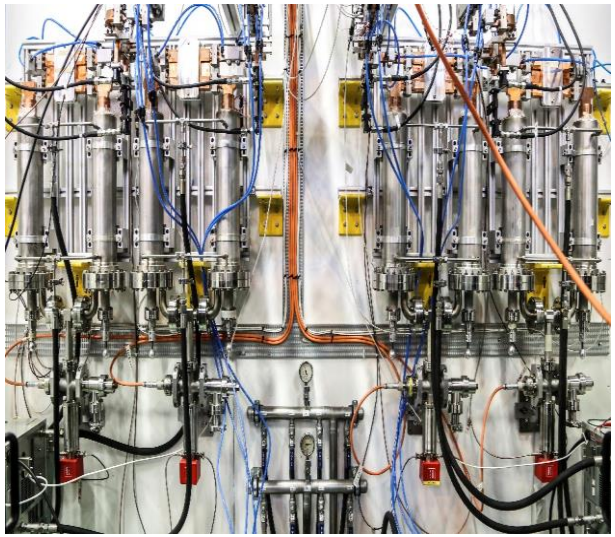
Undamped Geometry	CST	HFSS
Phase advance	120°	120°
Frequency [GHz]	11.9949	11.9943
Unloaded Q_0	7295.2	7245
r'/Q_0 [Ω/m]	15892	15924
v_g/c	0.018	0.018

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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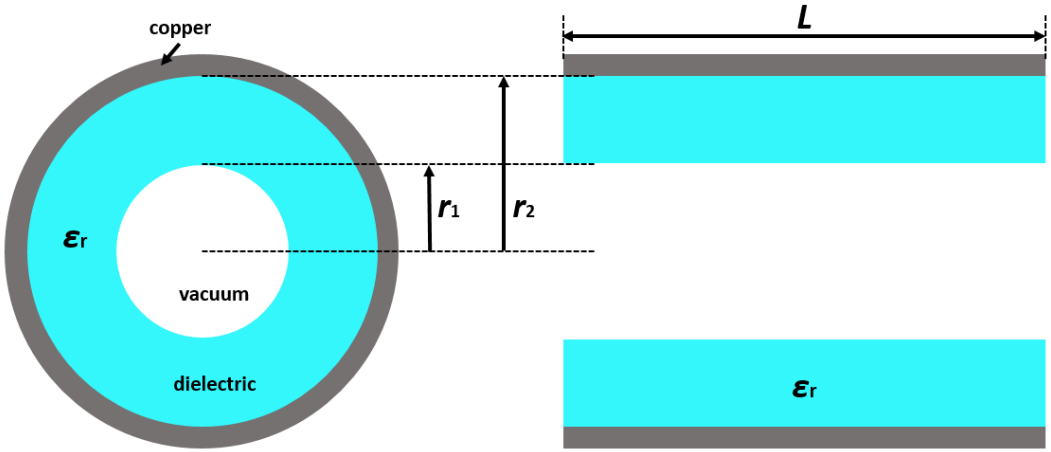
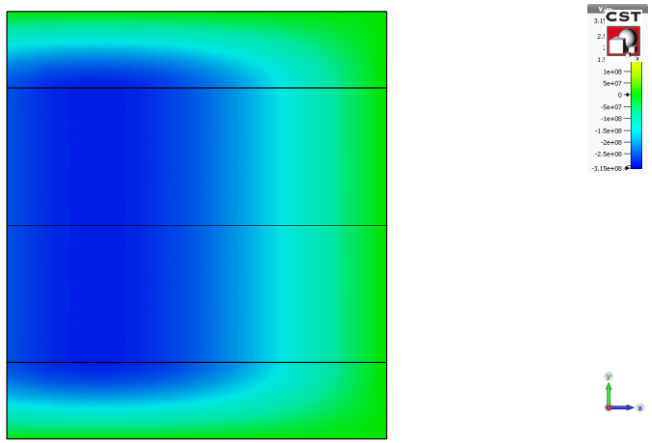


Longitudinal Electric fields



Advantages of DLA:

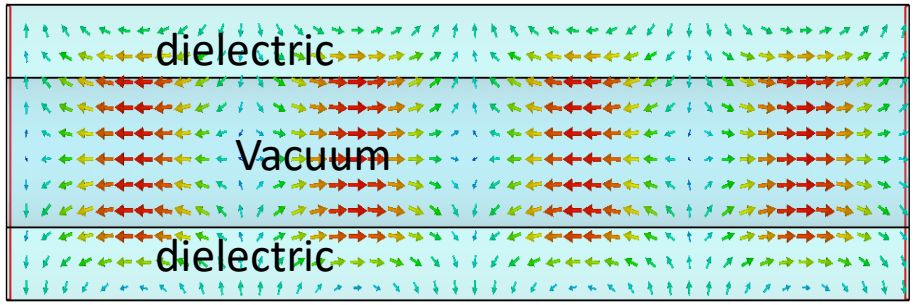
- ❖ Simple geometry for easy fabrication;
- ❖ No field enhancements on irises;
- ❖ Potential high gradient;
- ❖ Easy to damp HOMs;

Disadvantages of DLA:

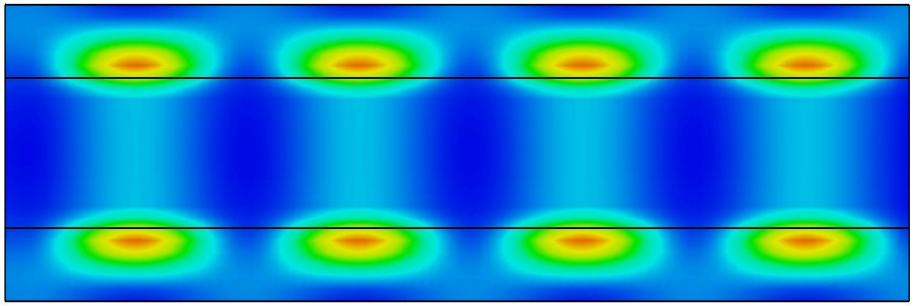
- ❖ Low power efficiency due to high group velocity >10% of *c*

DLA Structures

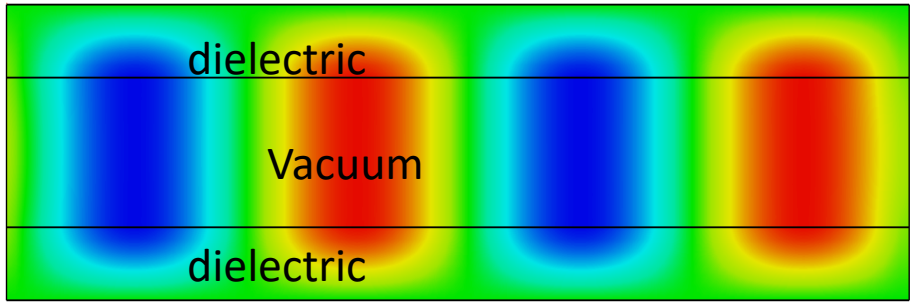
E-field of the TM01 mode ($v_p = c$)



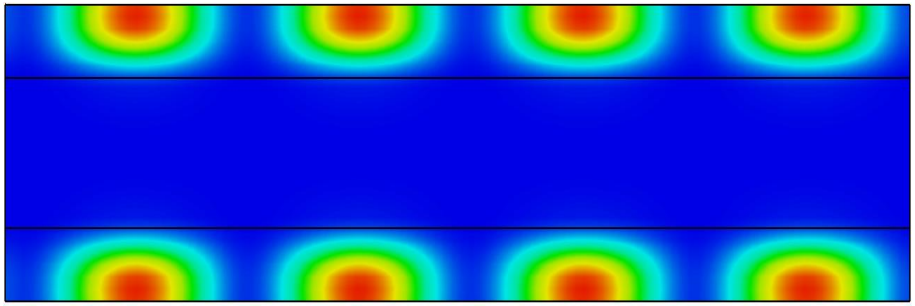
Electric energy density



*E*z of the TM01 mode ($v_p = c$)

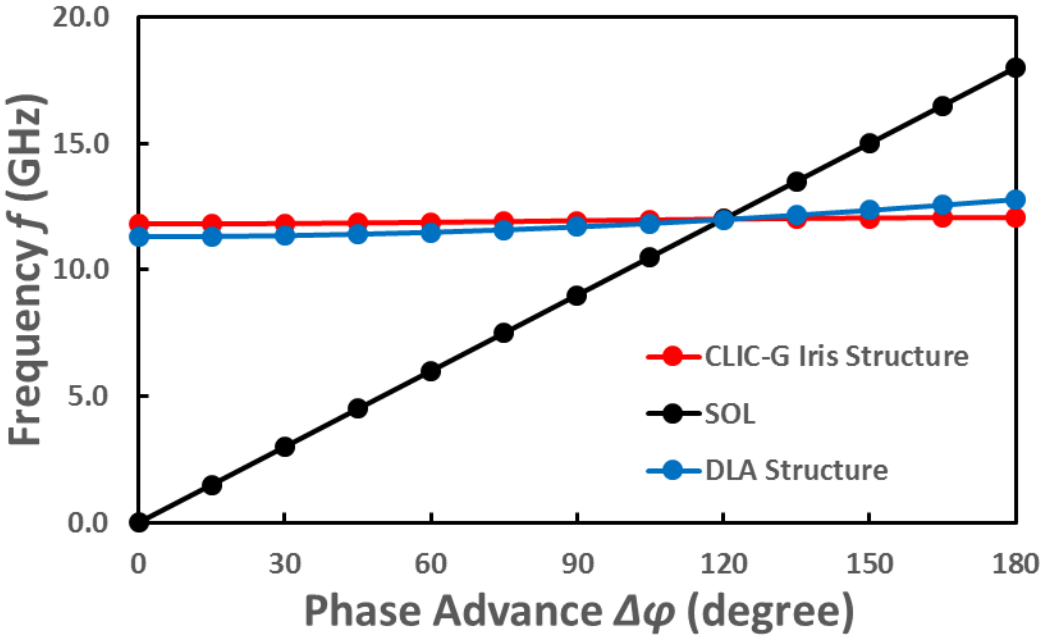


Magnetic energy density



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)	MCT-16	MgCaTi	BaTi
Dielectric constant ε_r		3.75	5.7	9.64	16	20	35
Dielectric loss tangent δ		0.00005	0.0001	0.000006	0.0001	0.0001	0.0001
Structure length [mm]	8.33	8.33	8.33	8.33	8.33	8.33	8.33
Phase advance	120°	120°	120°	120°	120°	120°	120°
Inner radius r_1 [mm]	3.15	3.15	3.15	3.15	3.0	3.15	3.15
Outer radius r_2 [mm]		7.22	6.20	5.364	4.675	4.624	4.245
Frequency [GHz]	11.9943	11.9990	11.9958	11.9966	11.9984	11.9942	11.9919
Unloaded Q_0	7245	6127	3998	4231	2468	2214	1691
r'/Q_0 [Ω/m]	15924	10719	11166	10427	9489	8463	6878
r' [MΩ/m]	115	66	45	44	23	19	12
v_g/c	0.018	0.273	0.183	0.111	0.068	0.057	0.034
Es/Ea	2.4819	1.0757	1.0755	1.0756	1.069	1.0760	1.0760
Es/Ea [dielectric]		1.0289	1.0024	1.0010	1.0	1.0152	1.0141
Power required to generate 100 MV/m [MW]	45.0	1013	652	424	287	266	197

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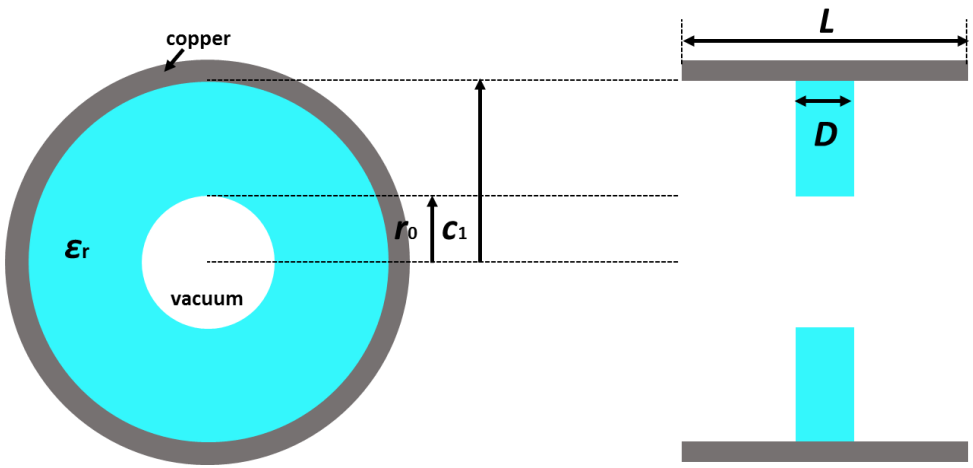
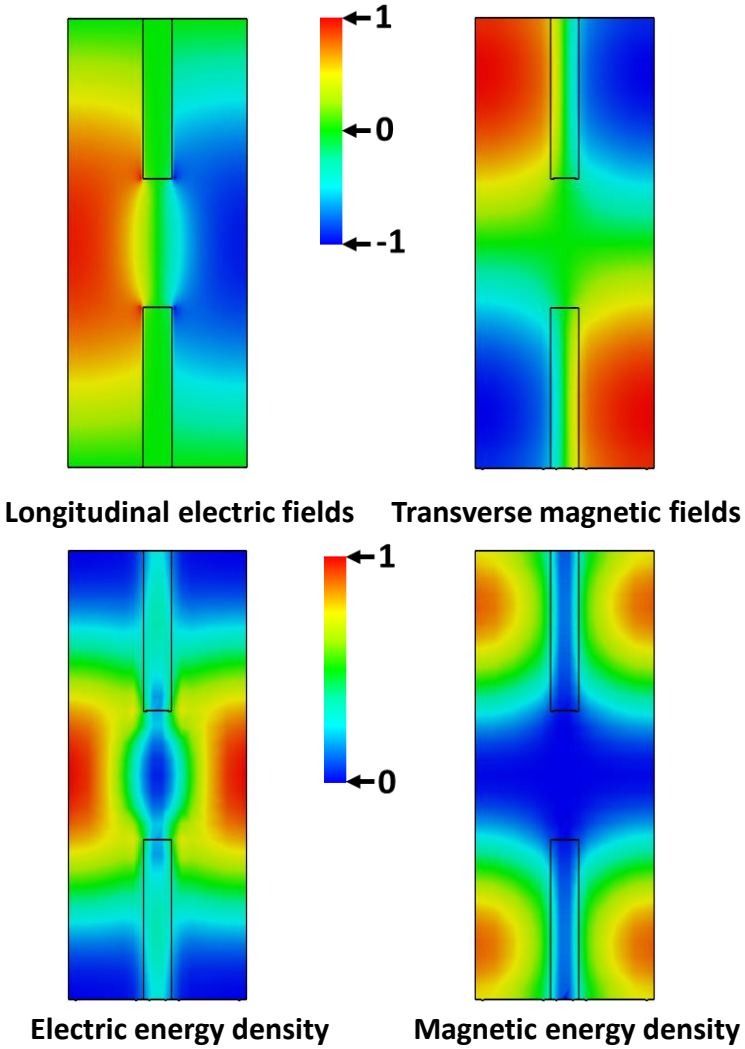
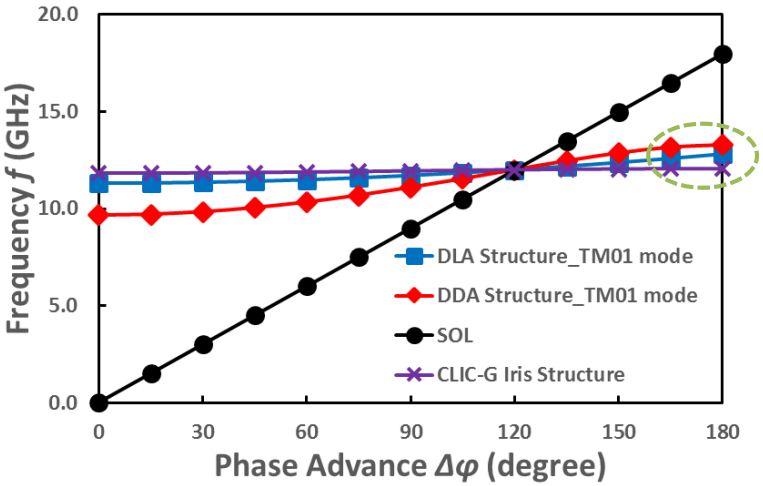
DDA Structures-TM01 mode

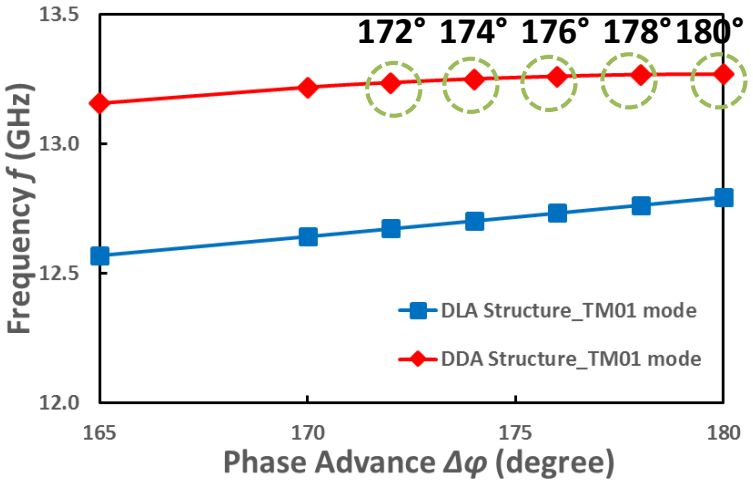




- We can adjust r_0, c_1, D and ε_r to get the desired frequency of 12 GHz.
- Such a structure has a periodicity L which can be used to slow down the group velocity of accelerating mode.

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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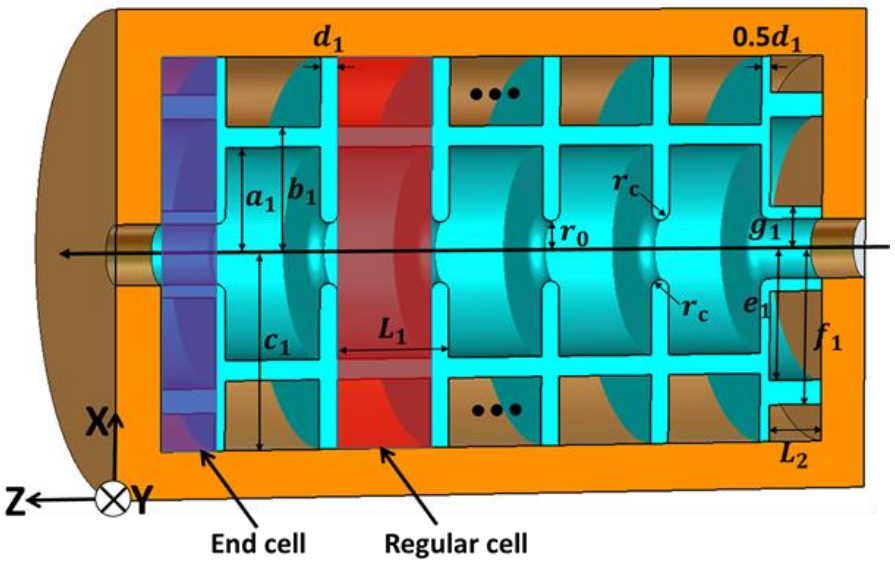
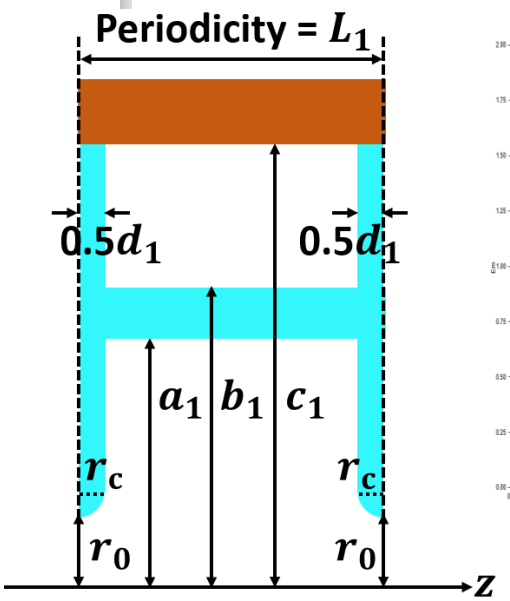
DDA Structures-TM02 π-mode

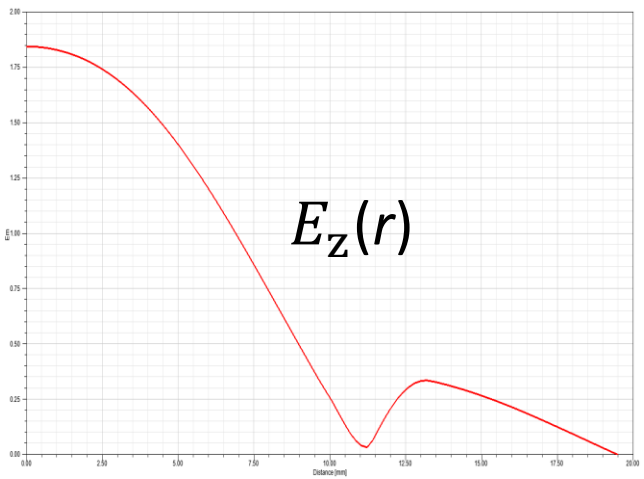


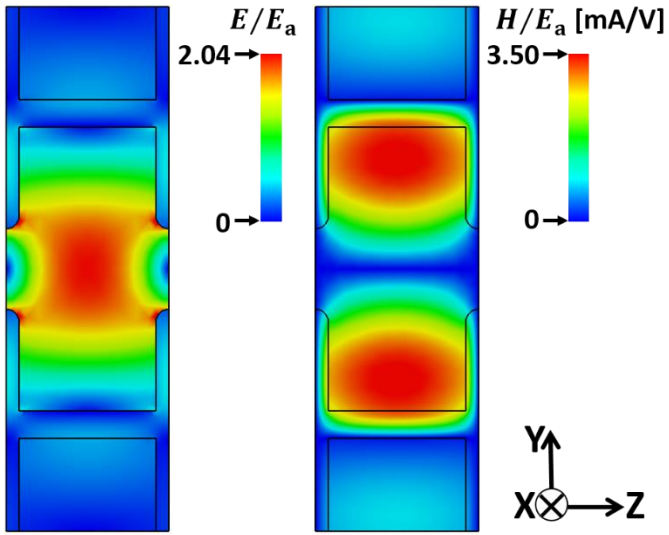
- High order mode operation reduces the surface fields;
- The electromagnetic fields can be controlled by dielectric parts;
- Very high power efficiency;
- X-band frequency potentially generates a high accelerating gradient.

Y. Wei and A. Grudiev, IEEE Transactions on Nuclear Science 68, 1062-1071, May 2021, doi: 10.1109/TNS.2021.3069110.

Regular cell



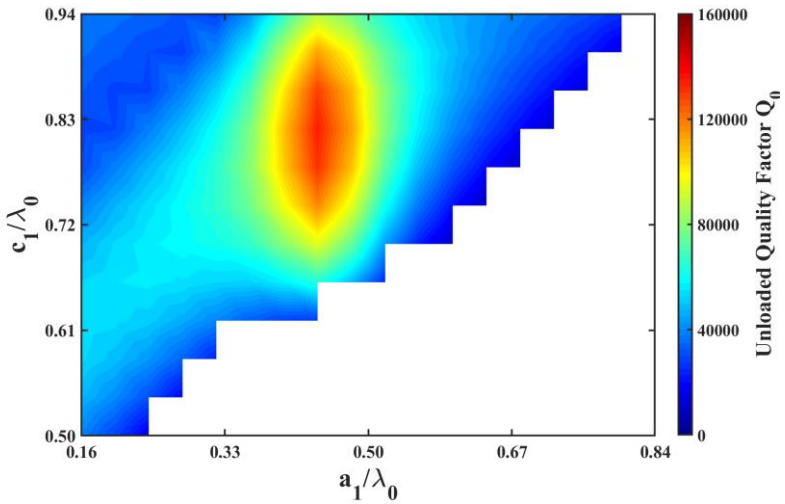


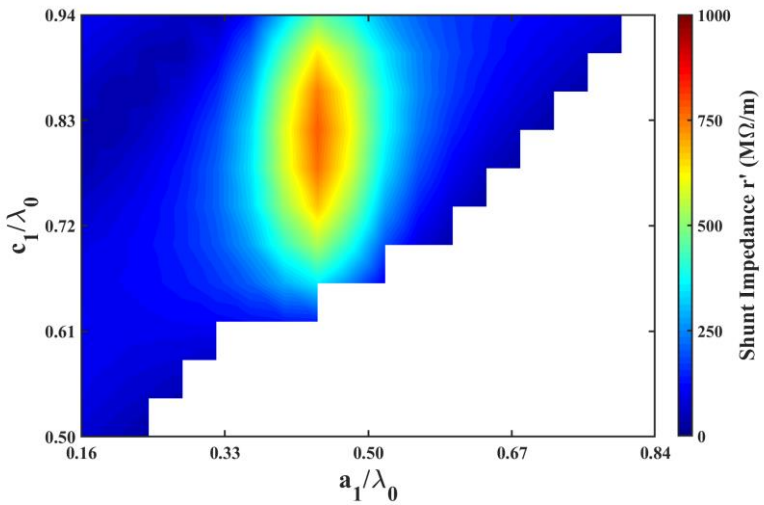


Electric fields magnetic fields

- 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.

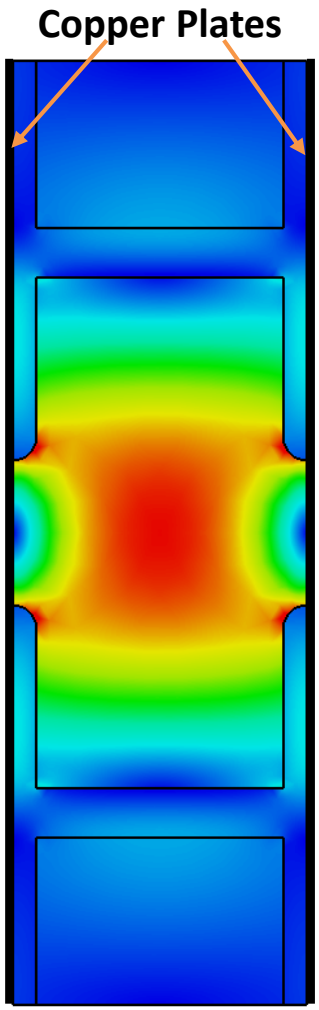
Optimization on a regular cell





Optimum parameters	
Dielectric constant ε_r	9.64
Dielectric loss tangent δ	6E-6
Iris radius r_0 [mm]	3.15
Corner fillet radius r_c [mm]	1.0
Inner radius a_1 [mm]	11.10
Inner radius b_1 [mm]	13.22
Copper radius c_1 [mm]	20.5
Disk thickness d_1 [mm]	2.0
Periodical length L_1 [mm]	12.50
Phase advance	180°
Acceleration mode	TM02 π-mode
Frequency [GHz]	11.9940
Unloaded Q_0	134542
r' [MΩ/m]	781

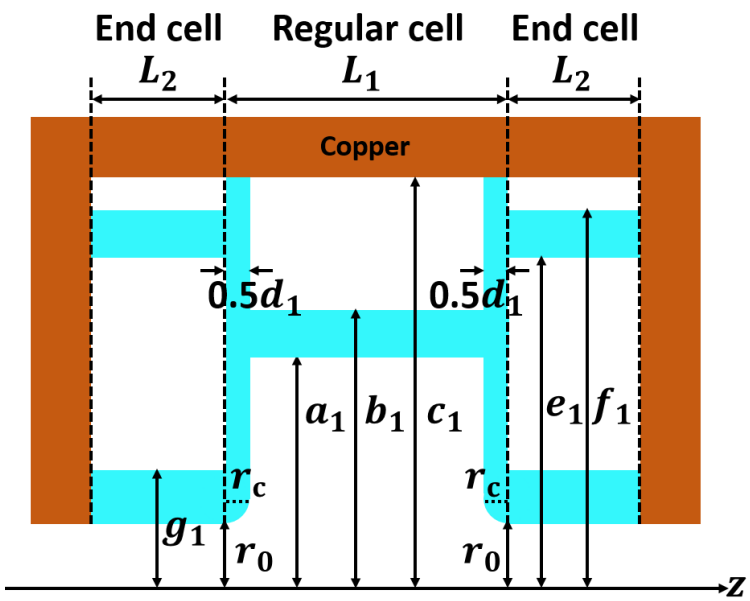
Regular cell with copper plates

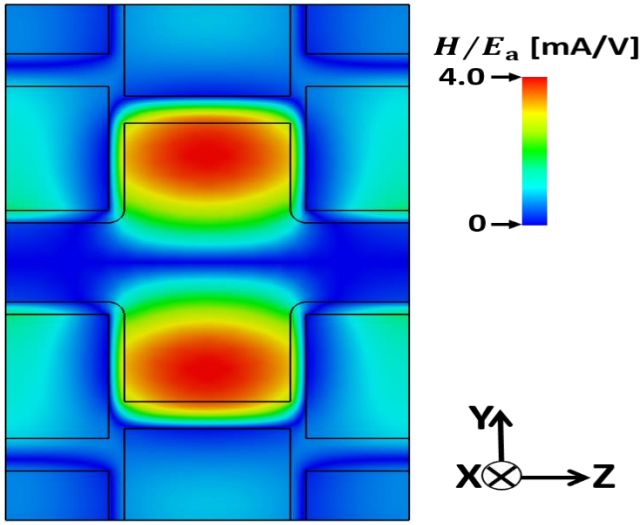


- Copper plates: 2.8% RF loss comes from dielectric loss, 97.2% RF loss comes from copper wall loss;
- Periodic boundary: 27.2% RF loss comes from dielectric loss, 72.8% RF loss comes from copper wall loss;

End cell is added to reduce the wall loss

Optimization on end cells

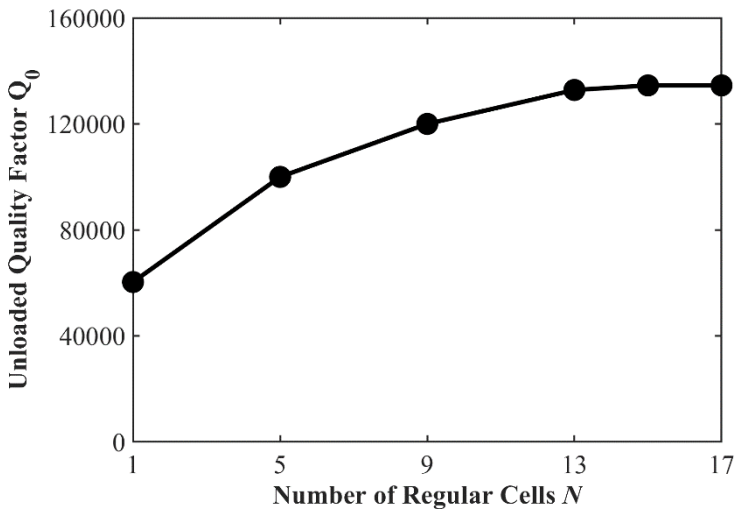


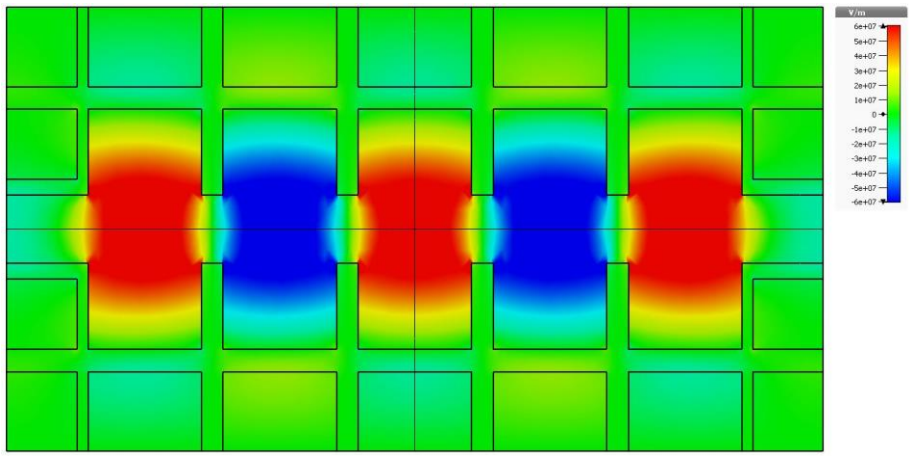


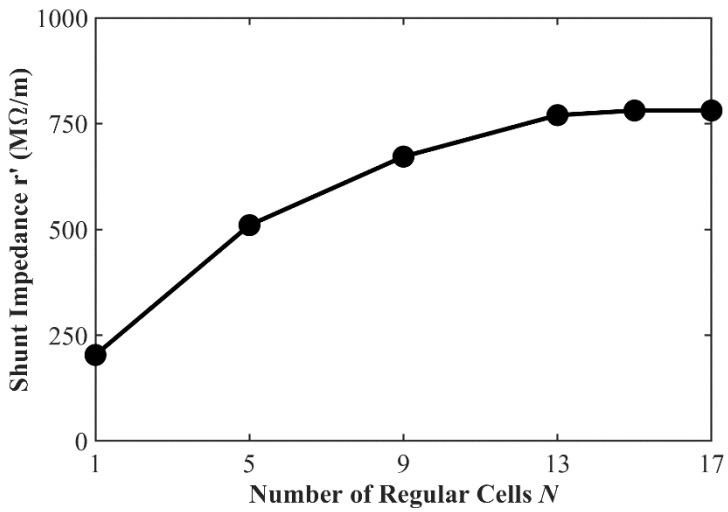
e_1 [mm]	14
L_2 [mm]	6.5
f_1 [mm]	16.58
g_1 [mm]	4.15
Frequency [GHz]	11.9942
Unloaded Q_0	60323
r' [MΩ/m]	203

- The ratio of copper wall loss to total power loss is reduced from 97.2% to 87.75%;
- The total power loss in a DDA structure with end cells is about 76% lower than that of a DAA structure without end cells.

Multi-cell DDA structure



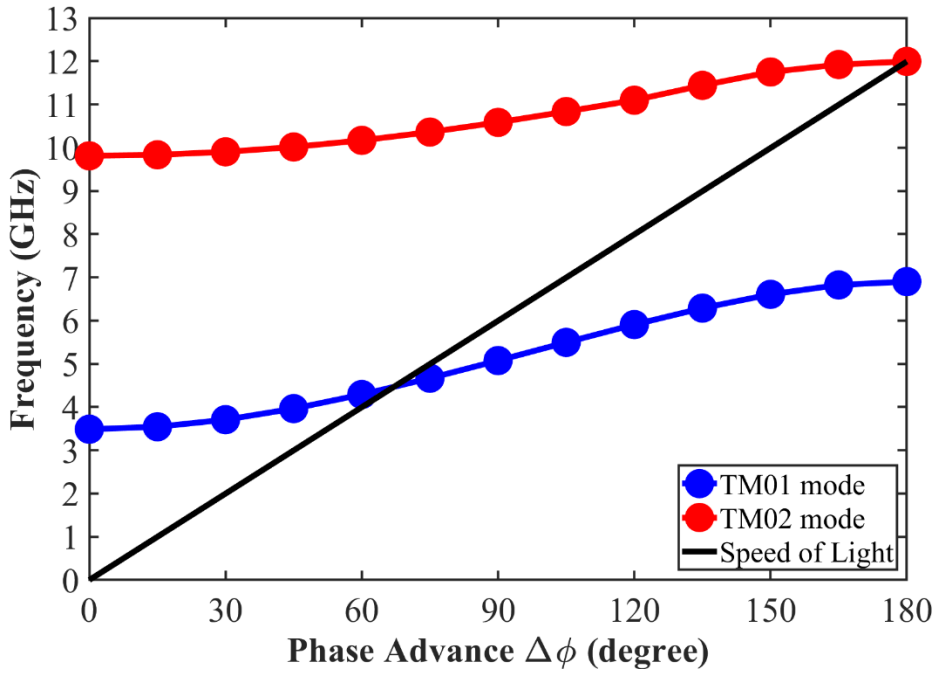




- Quality factor Q_0 = 100000, shunt impedance r' = 510 MΩ/m for a 5-cell cavity with same dielectric material;
- Quality factor and shunt impedance increase with the number of cells and become saturated when the number of regular cells reaches 13.

Considerations on the maximum number of cells

Reference: Nagle, Knapp and Knapp, 1964 and 1968



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

$$f_r = \frac{\sqrt{2} f_\pi f_0}{\sqrt{f_\pi^2 + f_0^2}} = 10.74\ \text{GHz}$$

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

Bandwidth $BW = f_r k = 2.13\ \text{GHz}$

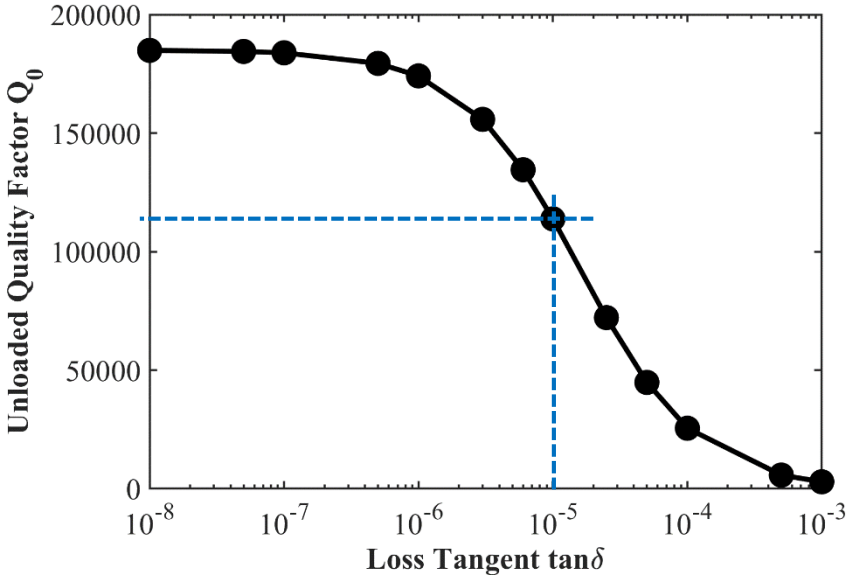
To avoid mode overlapping: $N < \sqrt{\frac{Q_\pi \pi^2 k}{4}} = 256$; $N < \frac{Q_{\pi/2}\pi k}{2} = 39221$

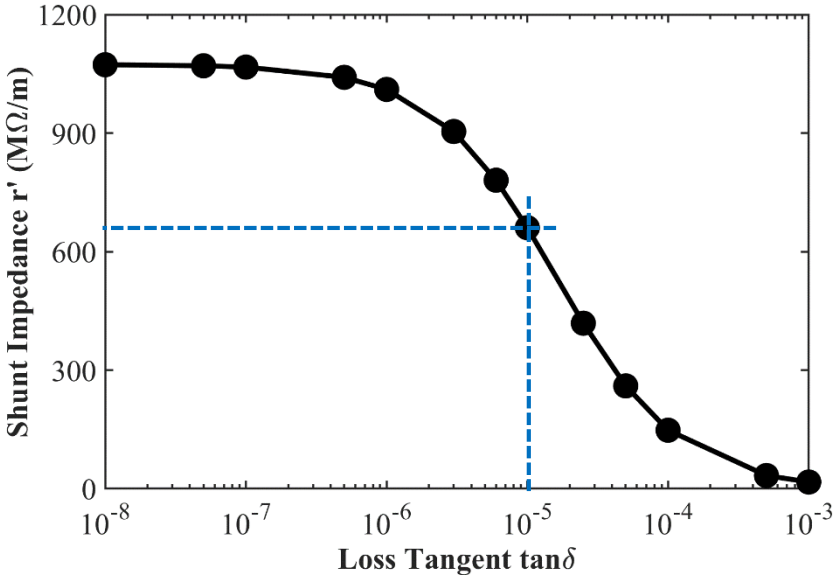
The frequency separation for modes: $\Delta f_{N-1,N}^{\pi} = f_r \frac{k\pi^2}{4N^2} = 1.0\ \text{MHz}$;

$\Delta f_{N-1,N}^{\pi/2} = f_r \frac{k\pi}{4N} = 23.5\ \text{MHz}$

Maximum number of cells can be 72

DDA structures with different dielectric loss tangent





- Dielectric loss tangent δ affects quality factor Q_0 and shunt impedance r';
- The highest quality factor and shunt impedance: $Q_0 = 184000, r' = 1070$ MΩ/m;
- When loss tangent δ = 1E-5, $Q_0 = 113818$, $r' = 660.5$ MΩ/m. This can be achievable in a relative simpler manufacturing process.

RF Properties

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

$N = 18 \qquad L = 12.5\ \text{mm}$

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

$V_{\text{acc}} = NLE_{\text{acc}}^{\text{Load}} = 22.5\ \text{MV}$

$$P_{\text{dis}} = \frac{V_{\text{acc}}^2}{r'NL} = 2.881\ \text{MW}$$

$$P_{\text{b}} = V_{\text{acc}} I_{\text{b}} = 26.775\ \text{MW}$$

$$P_0 = P_{\text{dis}} + P_{\text{b}} = 29.656\ \text{MW}$$

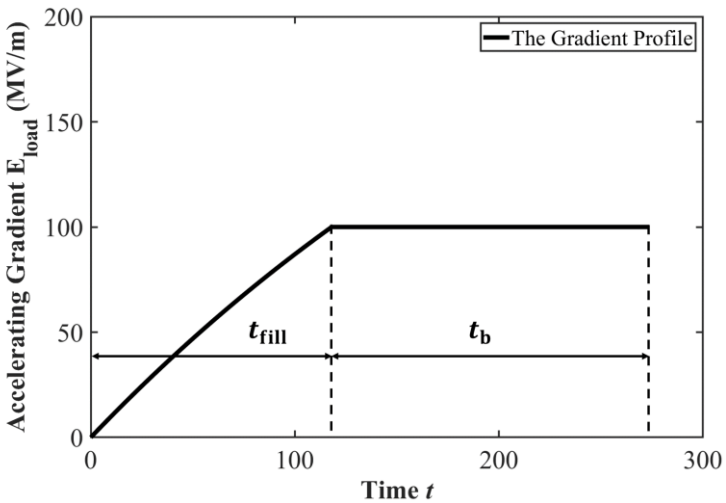
$$\beta = \frac{P_0}{P_{\text{dis}}} = 10.294$$

$$\tau = \frac{2Q_0}{\omega(1+\beta)} = 316\ \text{ns}$$

$$E_{\text{acc}}^{\text{Unload}} = \sqrt{\frac{P_0 r'}{NL}} = 320.84\ \text{MV/m}$$

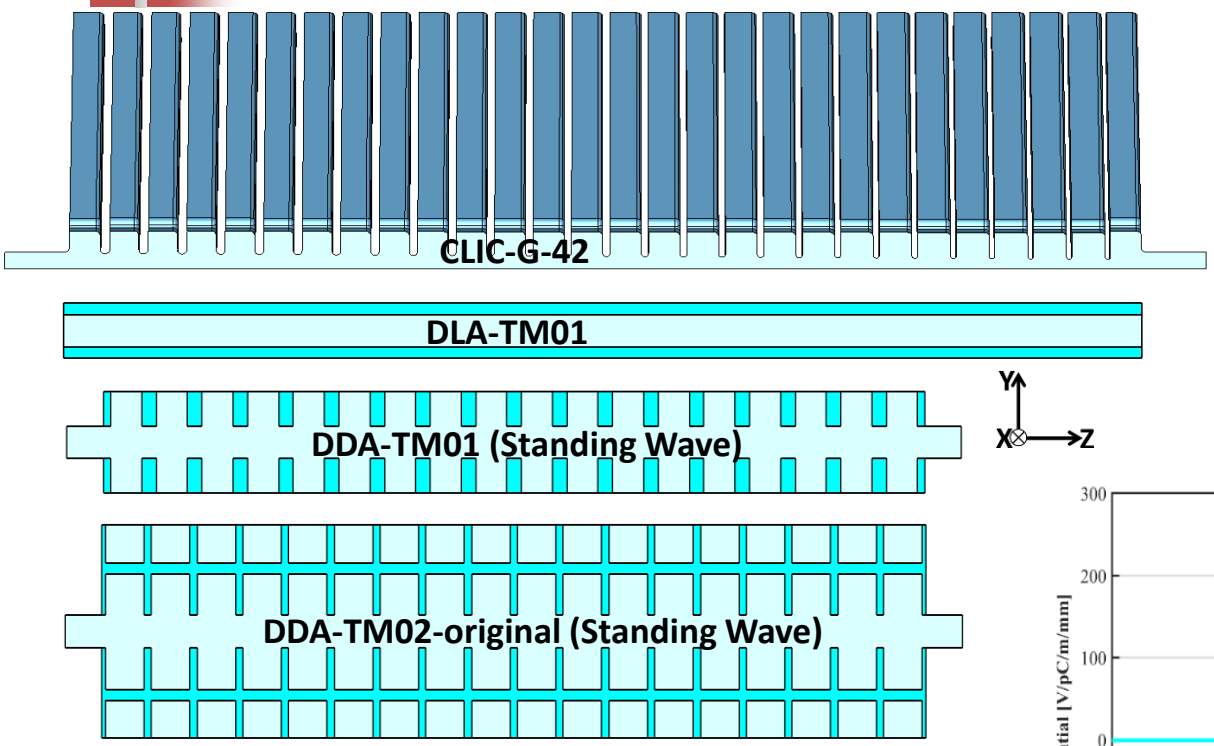
$$E_{acc}^{\text{load}} = E_{\text{acc}}^{\text{Unload}}\left(1 - e^{-\frac{t}{\tau}}\right)$$

RF properties	CLIC-G (28 cells)	DDA (18 regular cells)	DDA (18 regular cells)
Dielectric loss tangent δ		6E-6	1E-5
Acceleration mode	2π/3	TM02 π-mode	TM02 π-mode
Shunt impedance r' [MΩ/m]	92	781	660.5
Peak input power [MW]	61.3	29.7	30.2
Loaded gradient $E_{\text{acc}}^{\text{Load}}$ [MV/m]	100	100	100
Filling time t_{fill} [ns]	67	118	125.4
t_{b} [ns]	155.6	155.6	155.6
RF to beam efficiency	28.5%	51%	49%

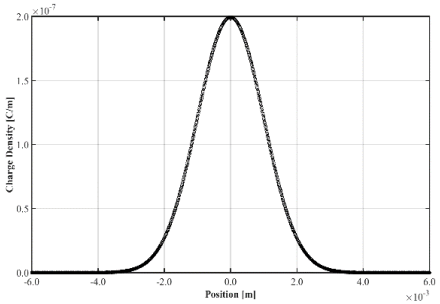


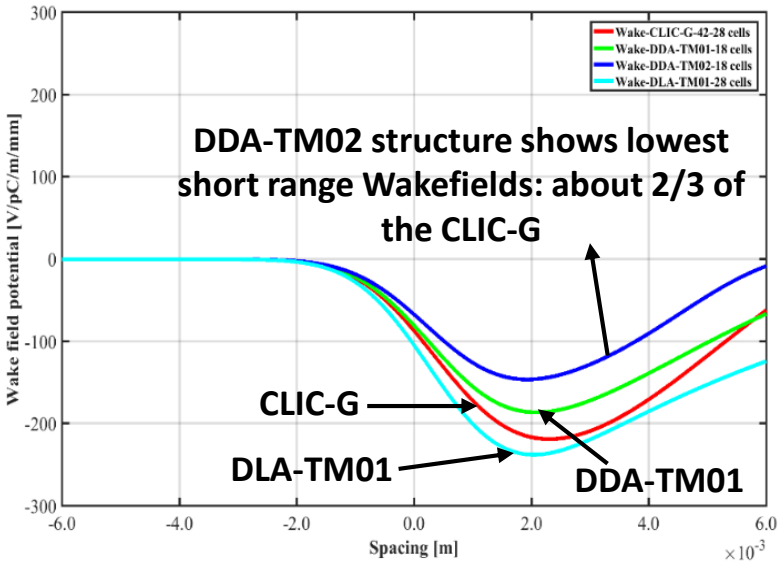
The average powers dissipated in the dielectrics are 21.5 W and 26 W with different loss tangents of 6E-6 and 1E-5, respectively, at these powers and pulse lengths with a repetition rate of 100 Hz

Short-range Wakefields



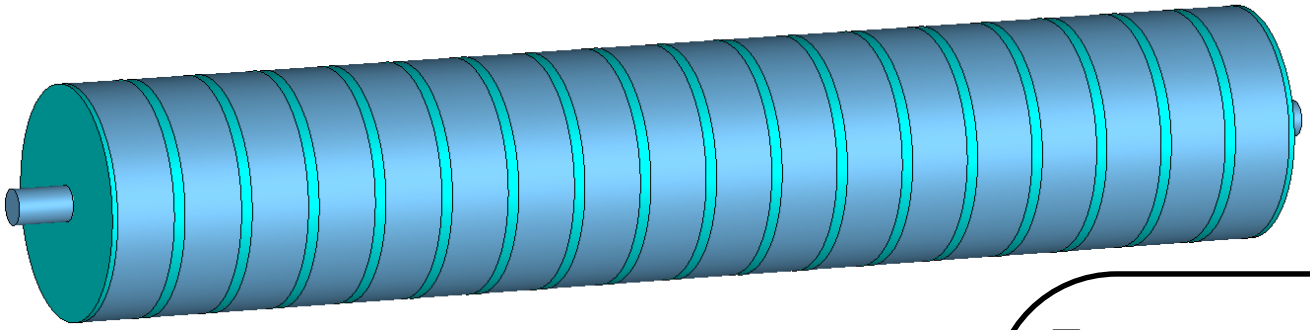
Charge Density

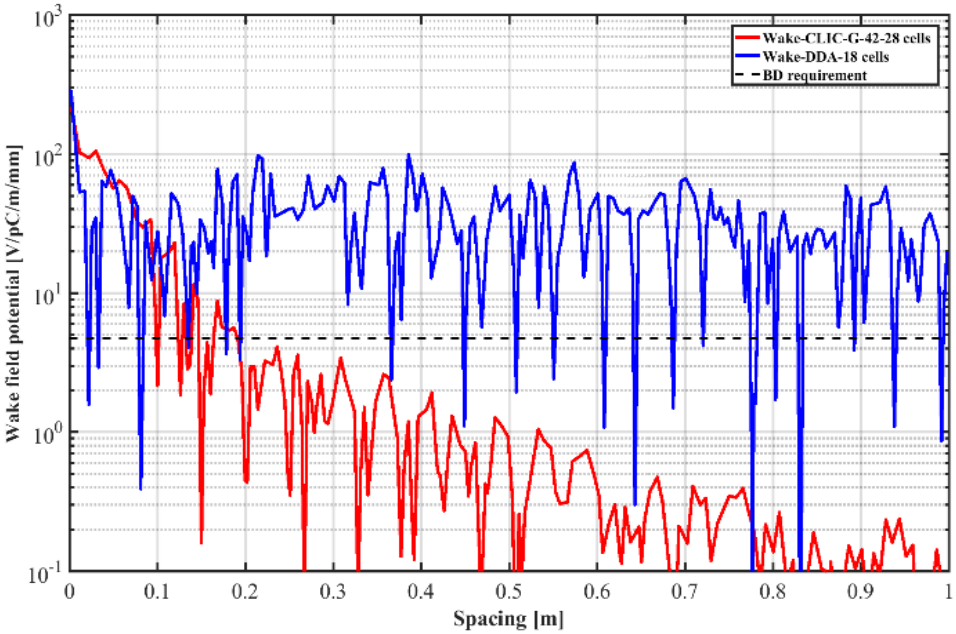




- CLIC-G: 28*8.332 ↔ DDA TM02-π: 18*12.5, so the number of regular cell is 18, no end cells are included;
- Convergence studies: dx = dy = dz = 0.05 mm;
- Bunch charge *Q* = 1.0 nC, bunch sigma = 1.0 mm, offset = 0.5 mm.

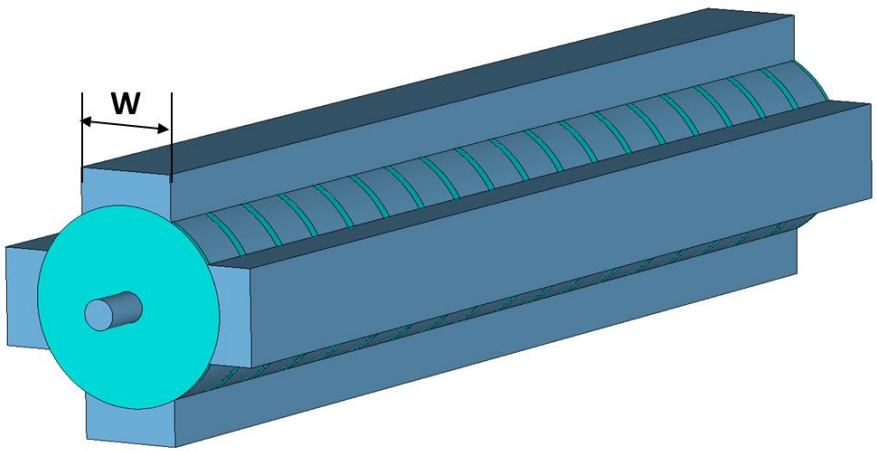
Long-range Wakefields



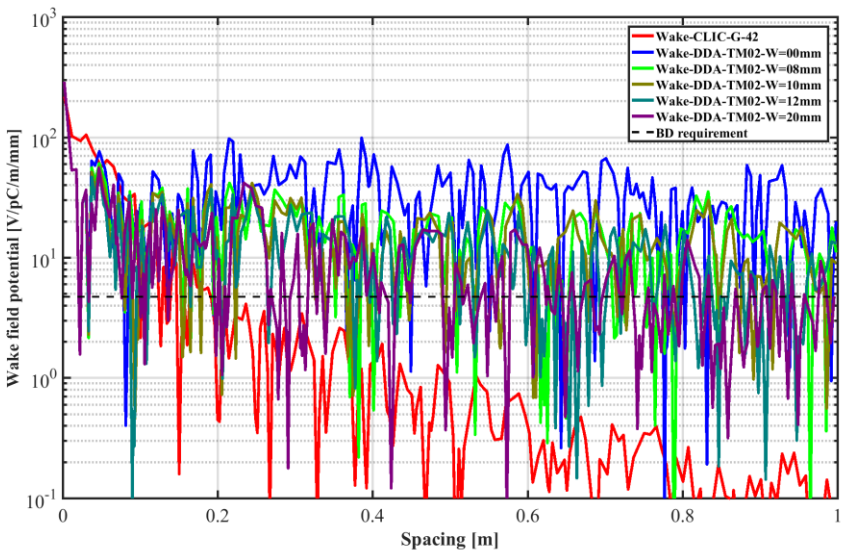


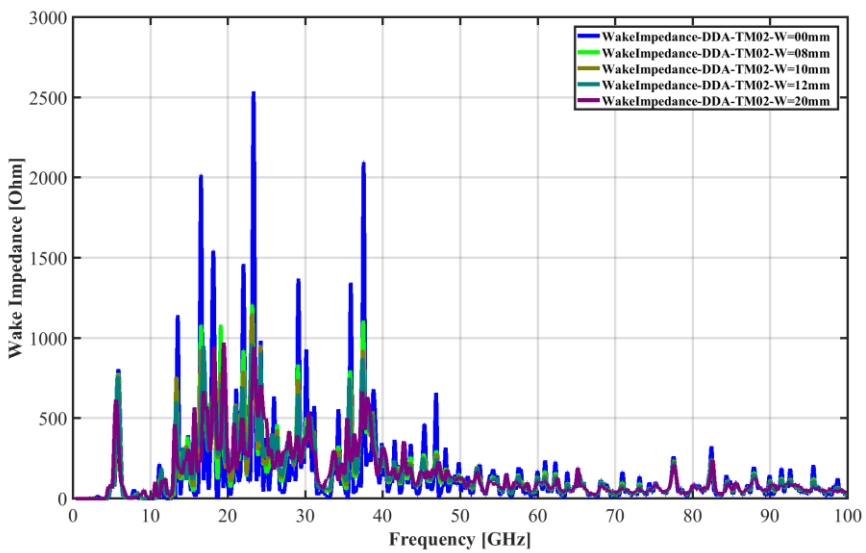
- The same bunch and structure parameters are used for Gdfidl simulations: dx = dy = dz = 0.05 mm, bunch charge *Q* = 1.0 nC, bunch sigma = 1.0 mm, offset = 0.5 mm;
- The envelope of transverse wakefields oscillate with the wakelength due to high order modes trapped inside the DDA;
- Damping schemes

Adding Damping Waveguide

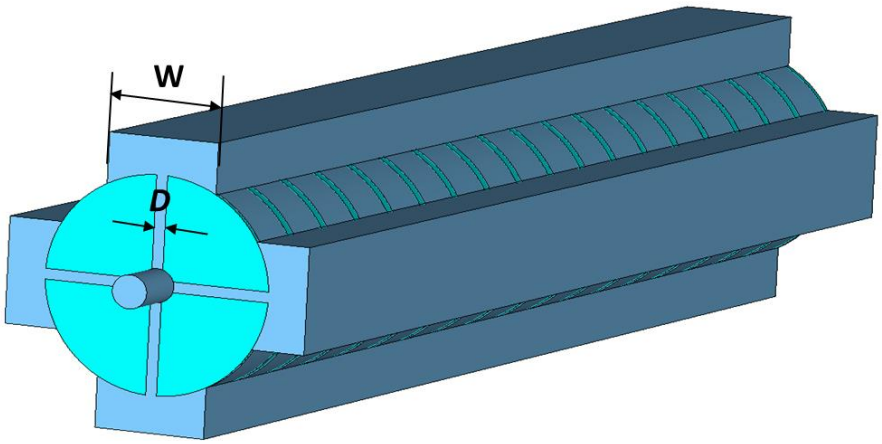


W [mm]	quality factor Q_0	shunt impedance r' [MΩ/m]	7 bunches			Envelope [7 bunches]		
			F_c	F_{rms}	F_{worst}	F_c	F_{rms}	F_{worst}
0	134542	819	149	752	5051	4086	2836	19483
8	113810	680	6	37	174	213	149	999
10	103330	612	8	67	408	269	211	1420
12	84336	489	6	26	149	123	101	661
20	< 40000	< 200	15	54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

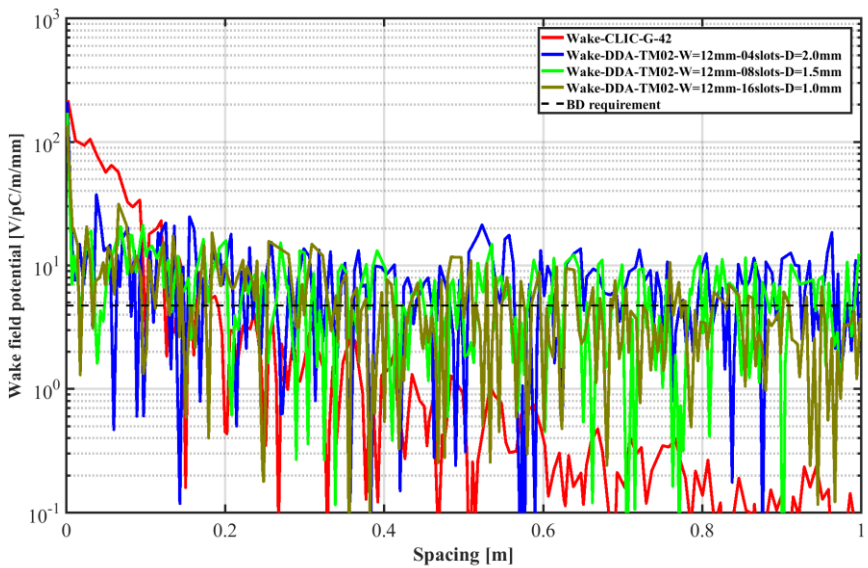




Adding Dielectric Slots (W=12 mm)

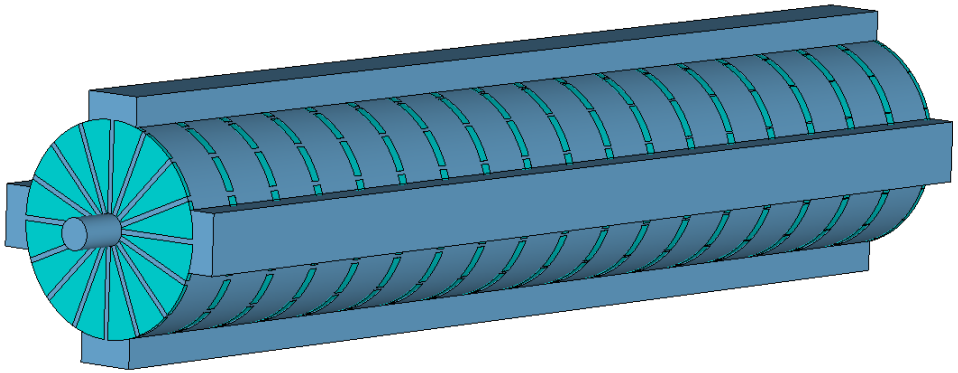


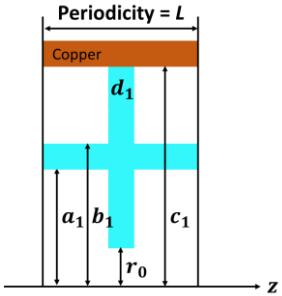
Number of dielectric slots	D[mm]	quality factor Q_0	shunt impedance r' [MΩ/m]	7 bunches			Envelope [7 bunches]		
				F_c	F_{rms}	F_{worst}	F_c	F_{rms}	F_{worst}
4	2.0	45286	193	2.1	3.5	13.4	12.3	6.2	34.7
8	1.5	95052	457	2.9	4.6	19.5	7.6	5.9	33.6
16	1.0	95450	405	1.1	1.3	2.7	1.9	1.4	4.2
BD requirement									



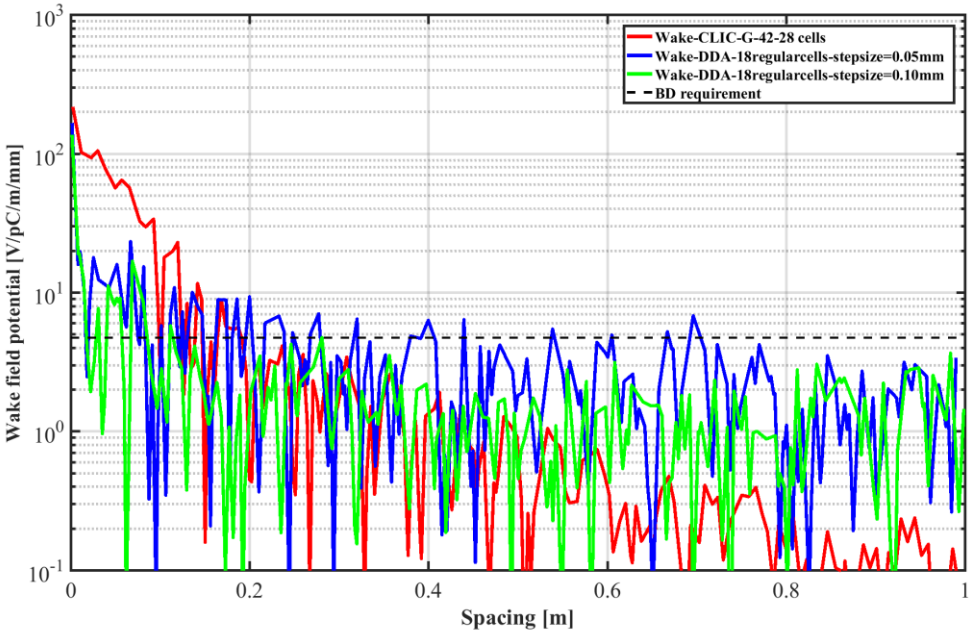
- The unloaded quality factor and shunt impedance are decreased by 30% and 50% respectively;
- Longer wakelength (> 5 m) needs to be calculated in order to get accurate F parameters.

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).

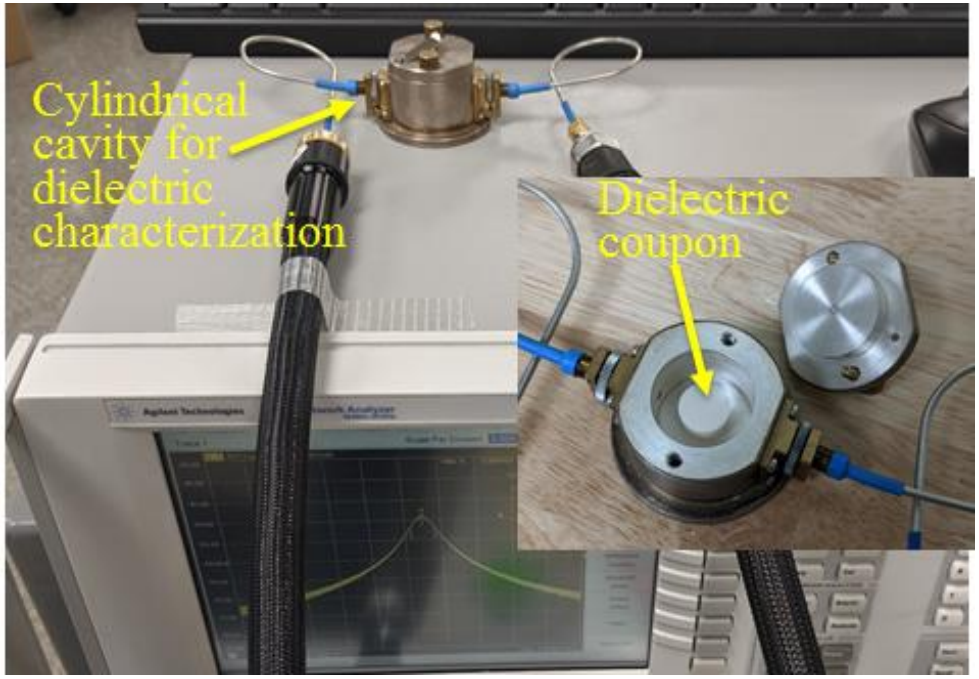


Number of dielectric slots	7 bunches			Envelope [7 bunches]		
	F_c	F_{rms}	F_{worst}	F_c	F_{rms}	F_{worst}
16	1.049	1.086	1.815	1.227	1.128	2.396
BD requirement						

Outline

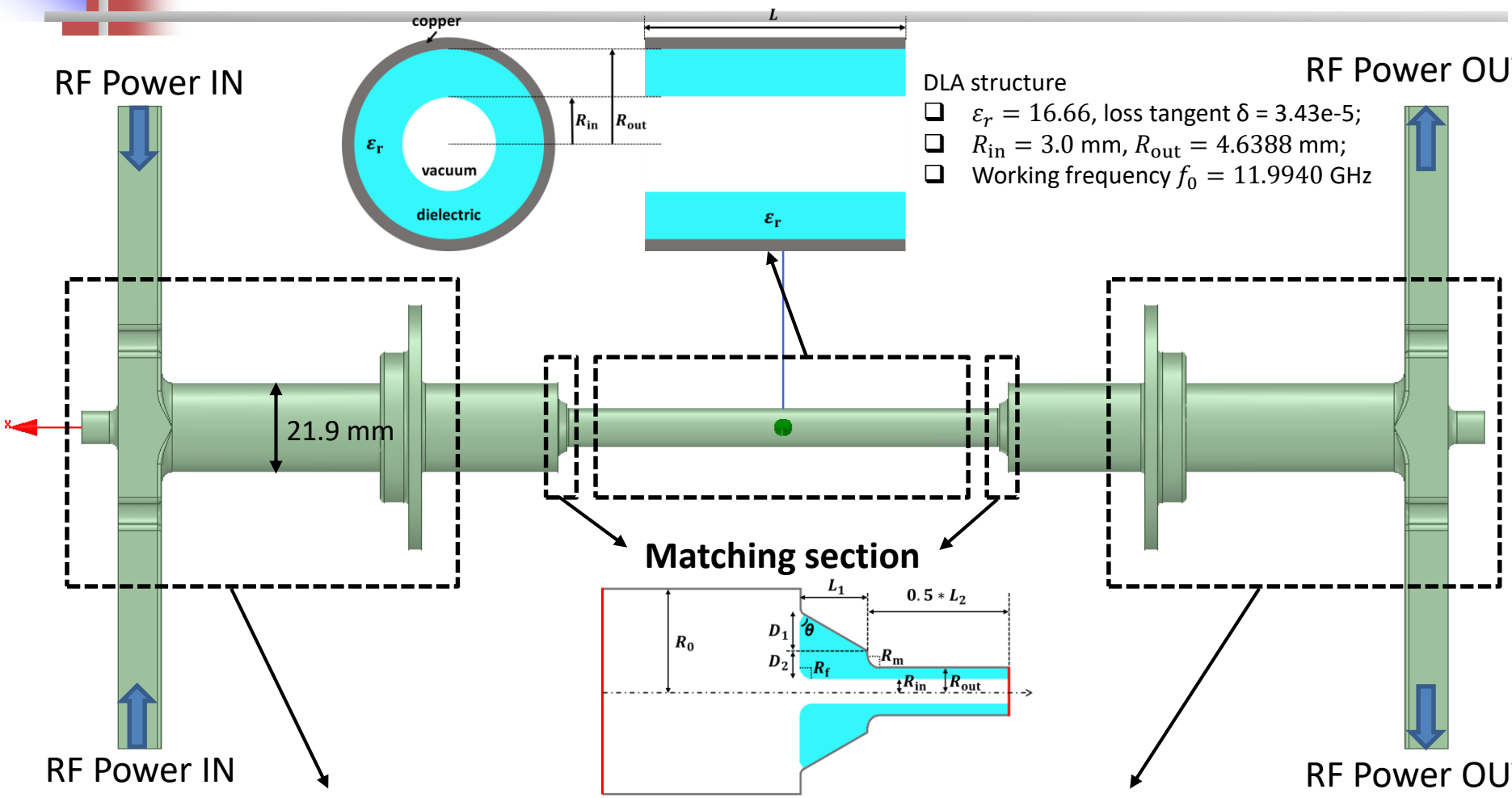
- Background & Introduction
- Dielectric-Lined Accelerating (DLA) Structures
- Dielectric Disk Accelerating (DDA) Structures
  - TM01 operation mode
  - TM02 operation mode
- **Design of an X-band DLA structure**
  - **Simulation studies**
  - Fabrication and cold-testing of a DLA prototype
  - Fabrication error analysis
- Summary & Outlook

Dielectric RF property



- A $TE_{01\delta}$ silver-plated resonator with a high quality factor, which is designed for testing ceramics at an X-band frequency, is used to measure the dielectric constant ε_r and loss tangent $\tan\delta$ of sample coupons.
- Four dielectric coupons made from the same dielectric rods as for the fabrication of the DLA structure are measured.
- A dielectric constant $\varepsilon_r = 16.66$ and an ultralow loss tangent $\tan\delta = 3.43 \times 10^{-5}$ (having error bars 0.6% of the nominal value) are obtained for the RF design of the DLA structure and matching sections which follows.

An X-band DLA structure

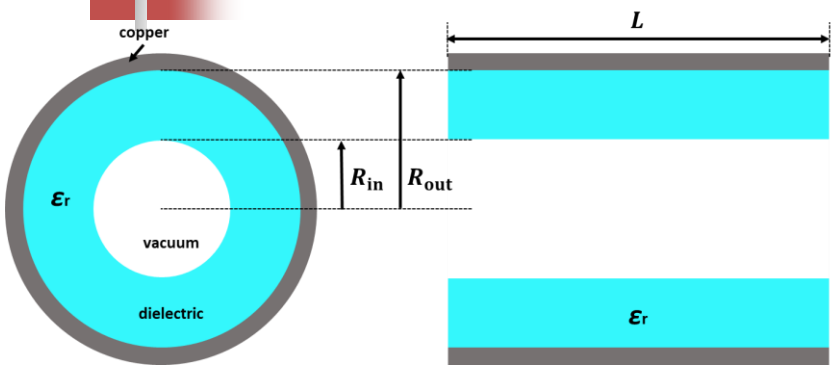


DLA structure

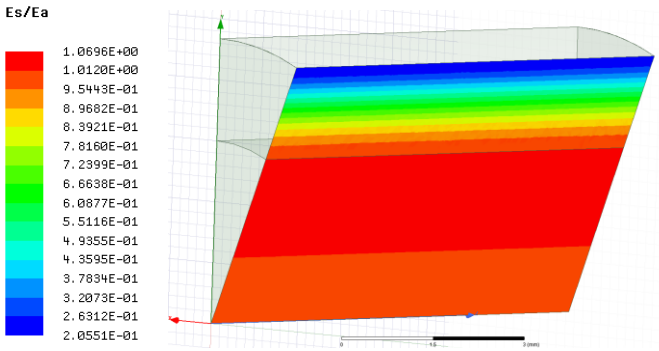
- $\varepsilon_r = 16.66$, loss tangent δ = 3.43e-5;
- $R_{in} = 3.0$ mm, $R_{out} = 4.6388$ mm;
- Working frequency $f_0 = 11.9940$ GHz

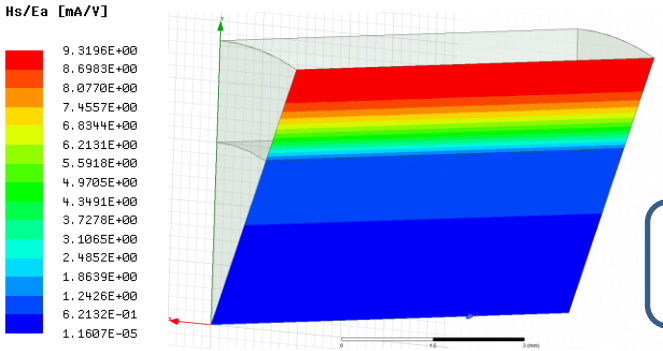
- An X-band mode converter (Converting TE10 mode into TM01 mode)
- A choke geometry is added to remove the contact issue and bonding joints for assembling two copper parts together

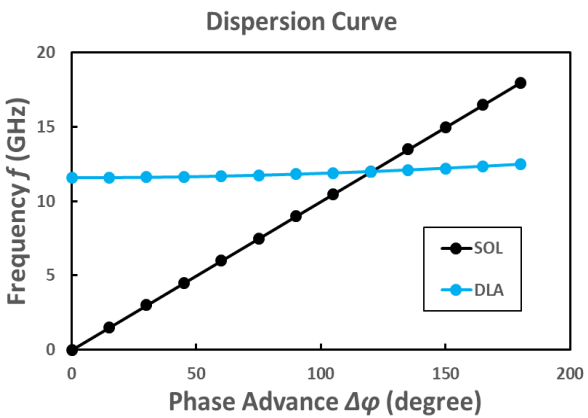
RF parameters for a DLA



E_{s_vacuum}/E_a	1.07
$E_{s\_dielectric}/E_a$	1.00
E_{s_metal}/E_a	0.206
H_{s_vacuum}/E_a [mA/V]	1.00
$H_{s\_dielectric}/E_a$ [mA/V]	9.32
H_{s_metal}/E_a [mA/V]	9.09



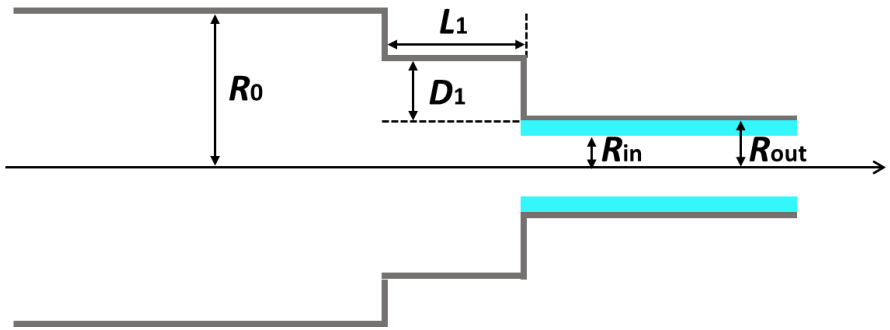




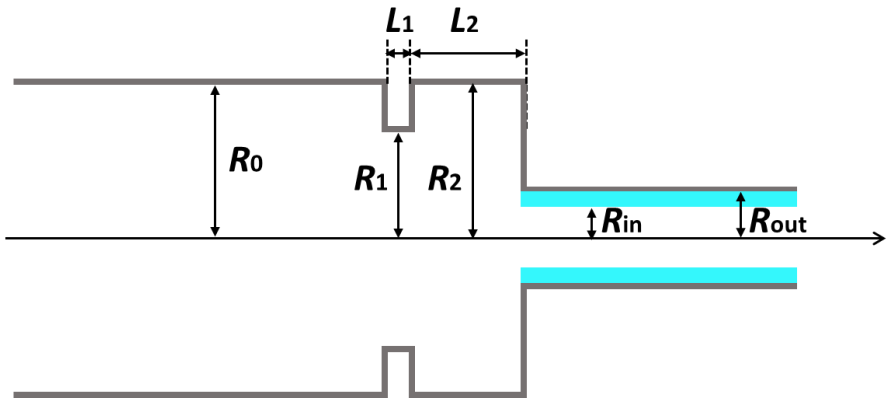
- A DLA with a length of 100 mm is used for fabrication studies.

	MCT-16
Dielectric constant ε_r	16.66
Dielectric loss tangent δ	3.43e-5
Periodical length L [mm]	8.3333
Phase advance	120°
Inner radius R_{in} [mm]	3.0
Outer radius R_{out}[mm]	4.6388
Frequency [GHz]	11.9940
Unloaded Q_0	2829
r'/Q_0 [Ω/m]	9368
r' [MΩ/m]	26.5
v_g/c	0.066
E_s/E_a	1.07
H_s/E_a [mA/V]	9.32
Power required to generate 100 MV/m [MW]	280

Standard methods for matching between a DLA structure and a circular waveguide



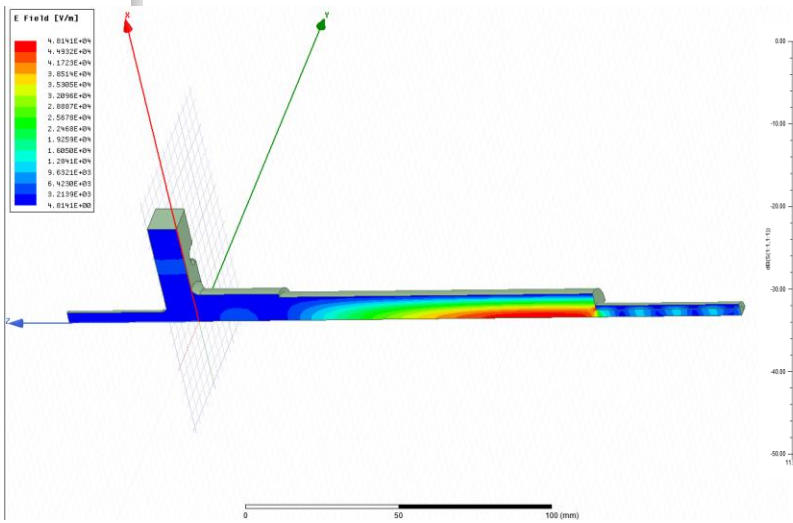
(1) Quarter wavelength waveguide

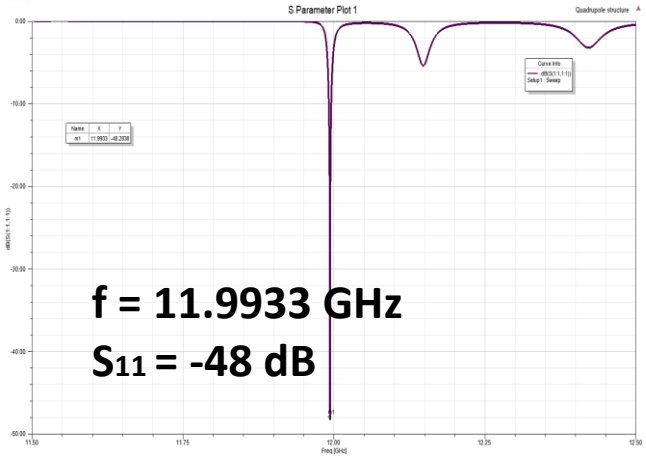


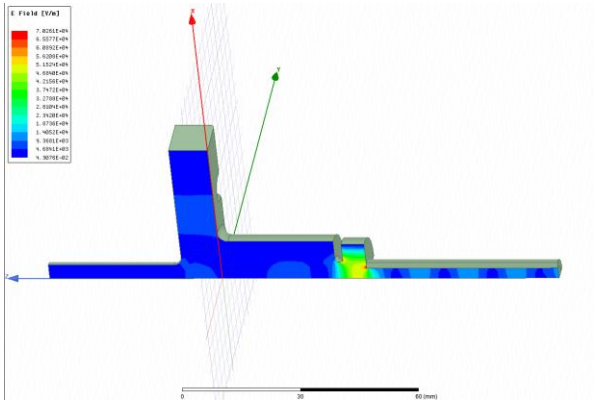
(2) A matching cell

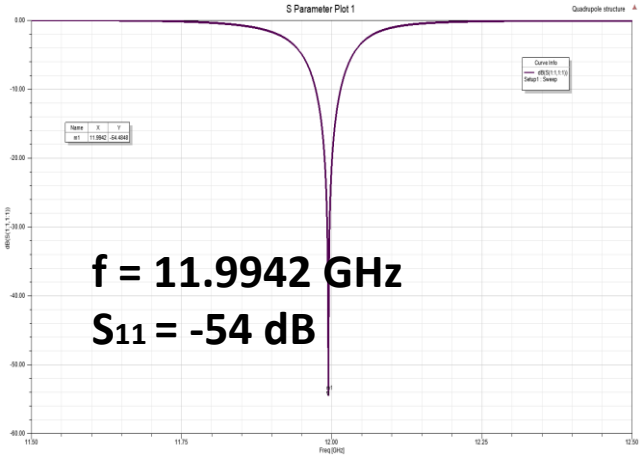
- Circular waveguide has a radius of $R_0 = 10.95$ mm;
- DLA has a inner radius $R_{\text{in}} = 3.0$ mm and outer radius $R_{\text{out}} = 4.675$ mm;
- Two methods are being used:
  1) Quarter wavelength waveguide;
  2) A matching cell.

S Parameter Simulation



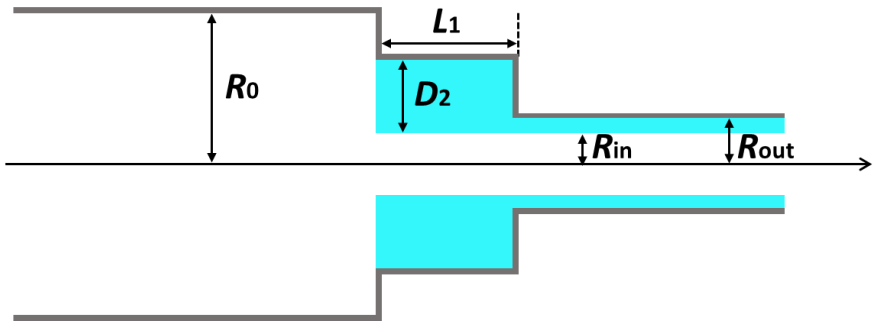


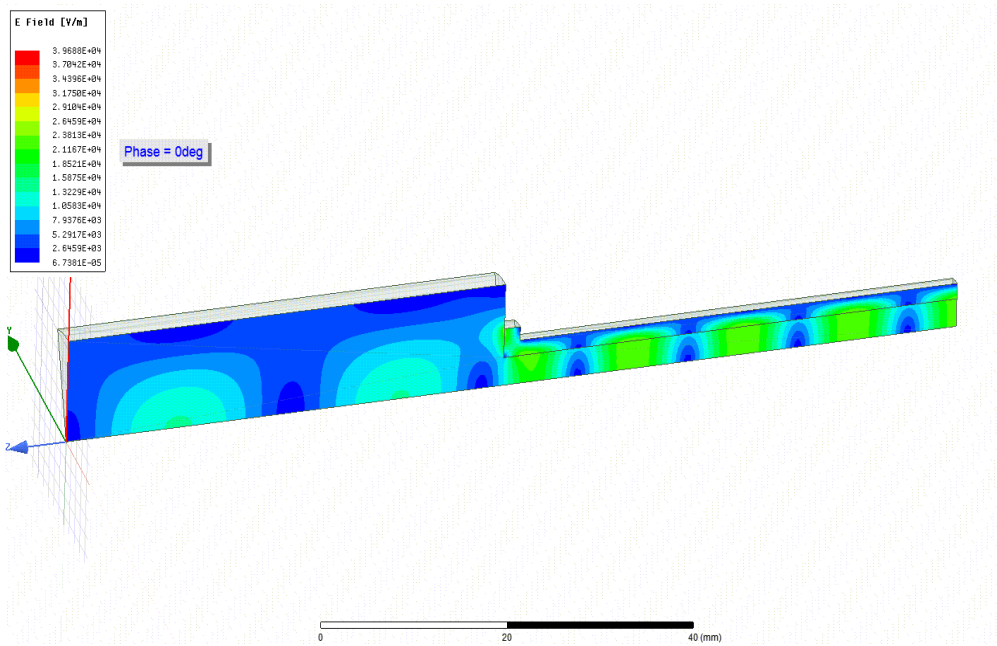


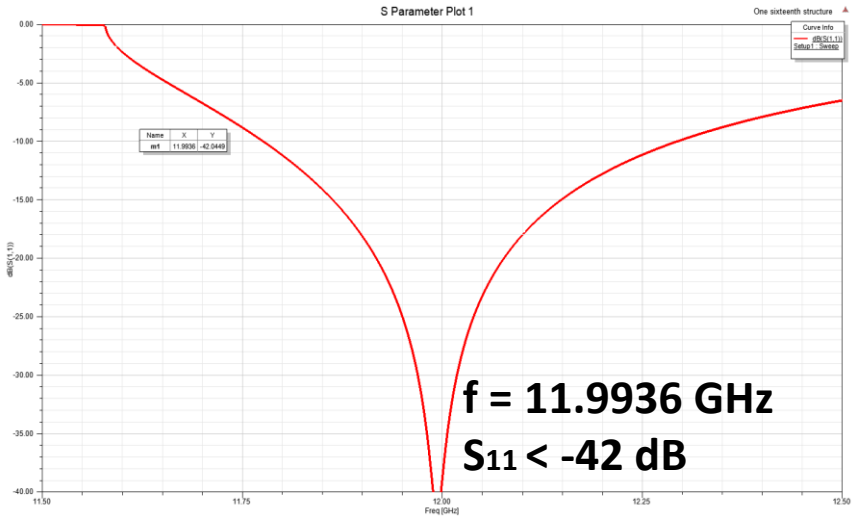


- Good S_{11} can be achieved;
- Further simulation studies are needed to reduce the maximum field in the matching sections.

Adding dielectrics into matching section

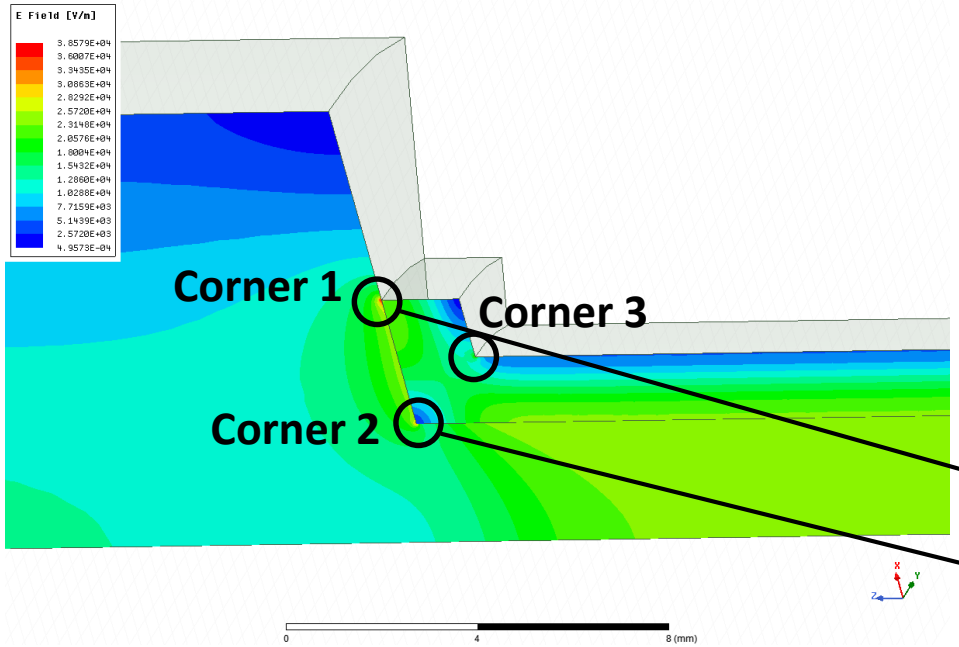


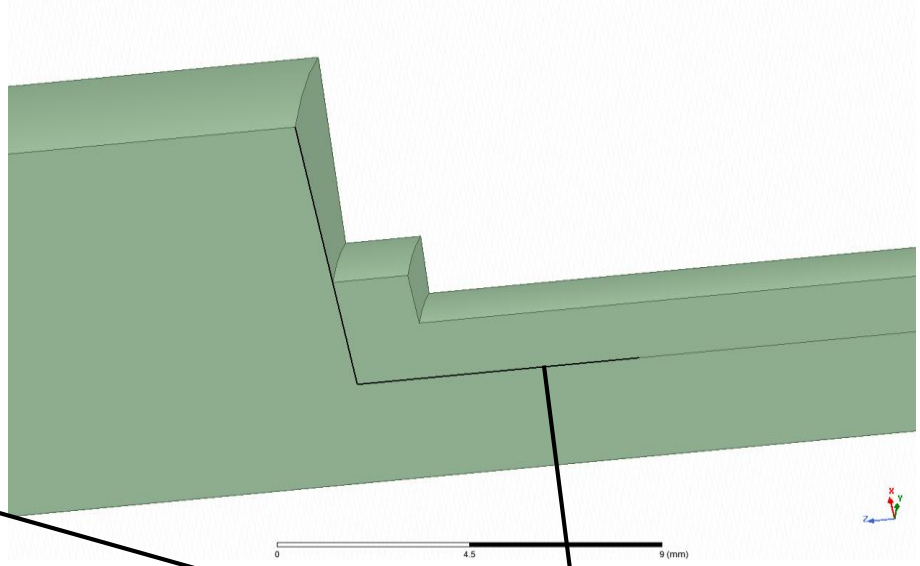


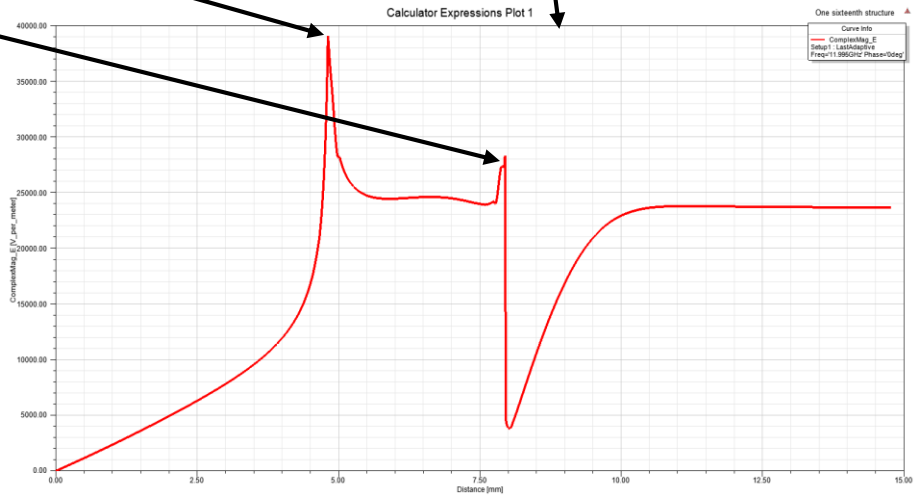


- L1 = 1.82 mm, D2 = 3.135 mm;
- The maximum field in the matching section is lower than in the DLA, but still pay special attention to the fields in the corners.
- Bandwidth is much larger and it is limited by the waveguide cut-off frequency

Electric fields in the corners

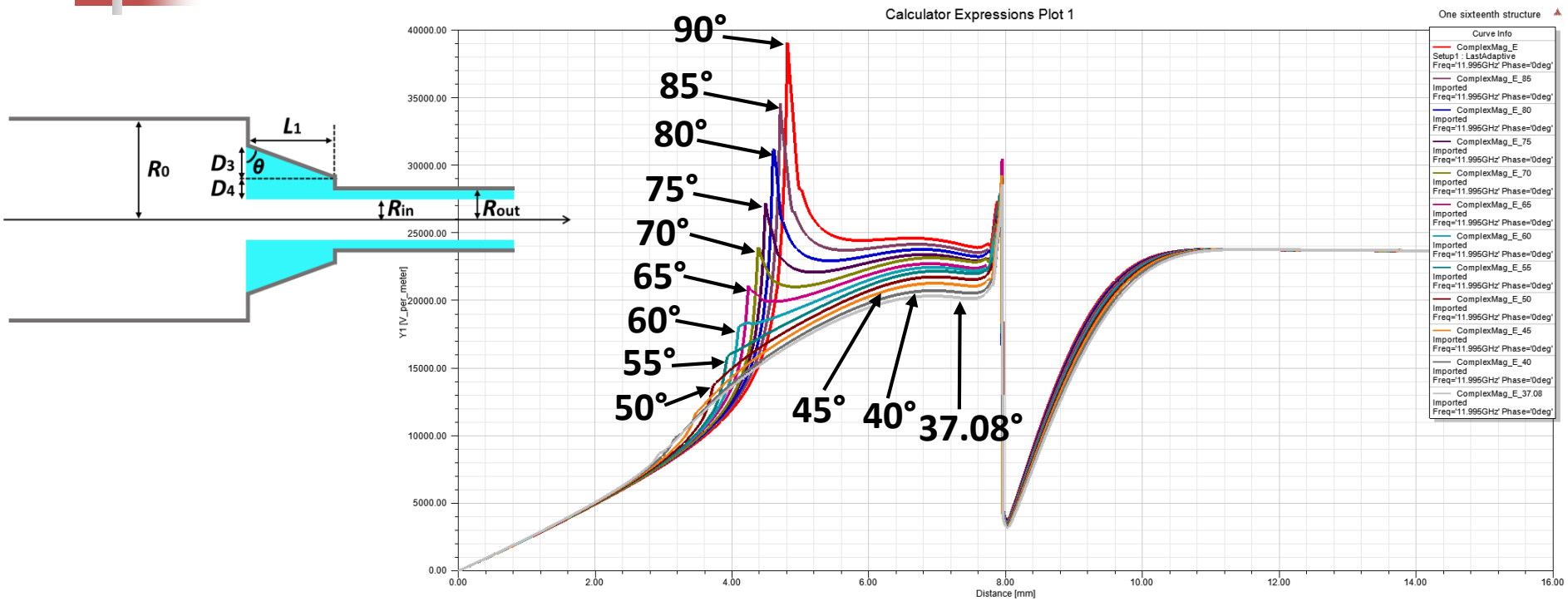






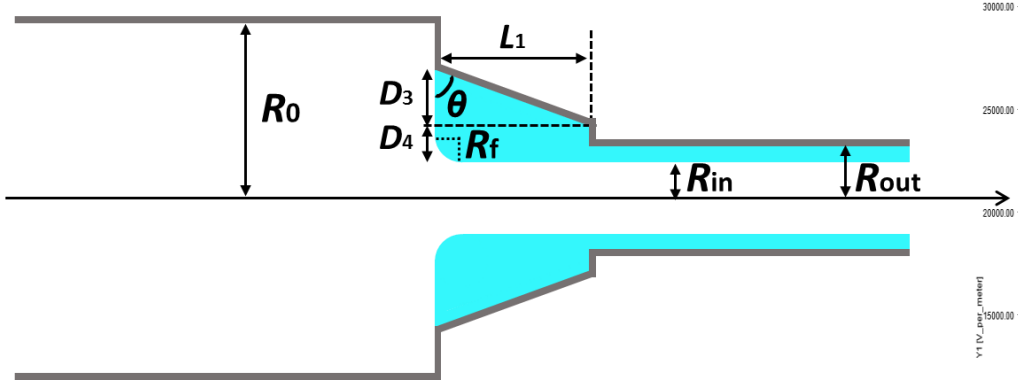
- There are two peak fields in the corner 1 and dielectric corner 2, respectively;
- We need to reduce these two peak fields;

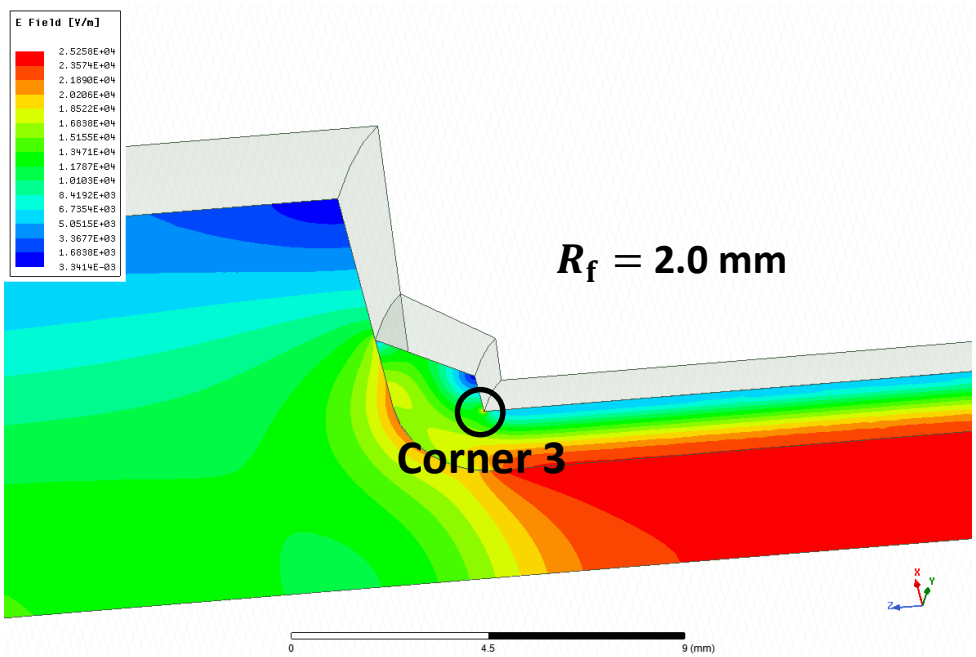
Adding a skew angle θ for Corner 1

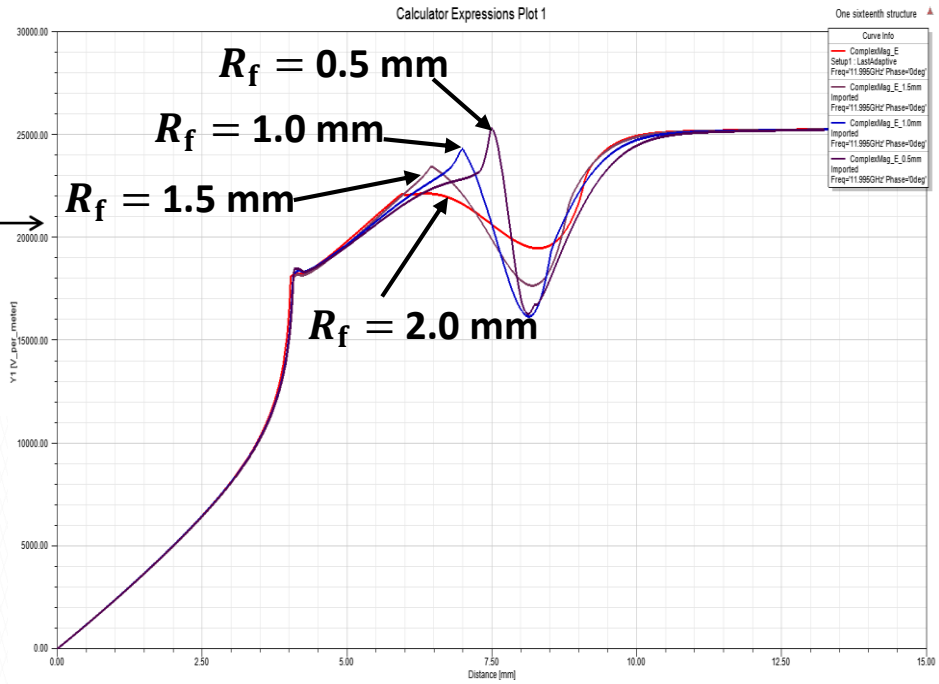


- For each skew angle, it is perfectly matched with a S_{11} < -40 dB;
- The peak fields in the corner 1 are decreased with a smaller skew angle θ;
- When $\theta = 70^0$, the peak fields in the corner 1 equal to the accelerating fields in the DLA structure; 70^0 is a critical skew angle;
- $\theta = 60^0$ is chosen for the following optimization.

Fillet Corner 2 at a skew angle of 60°

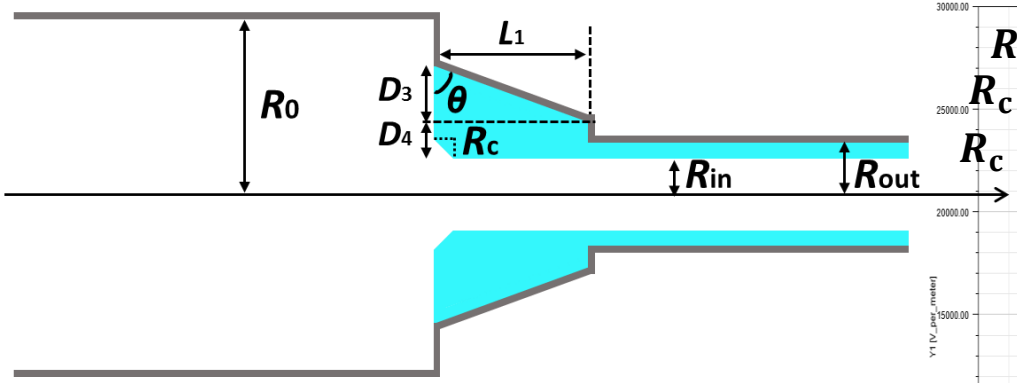


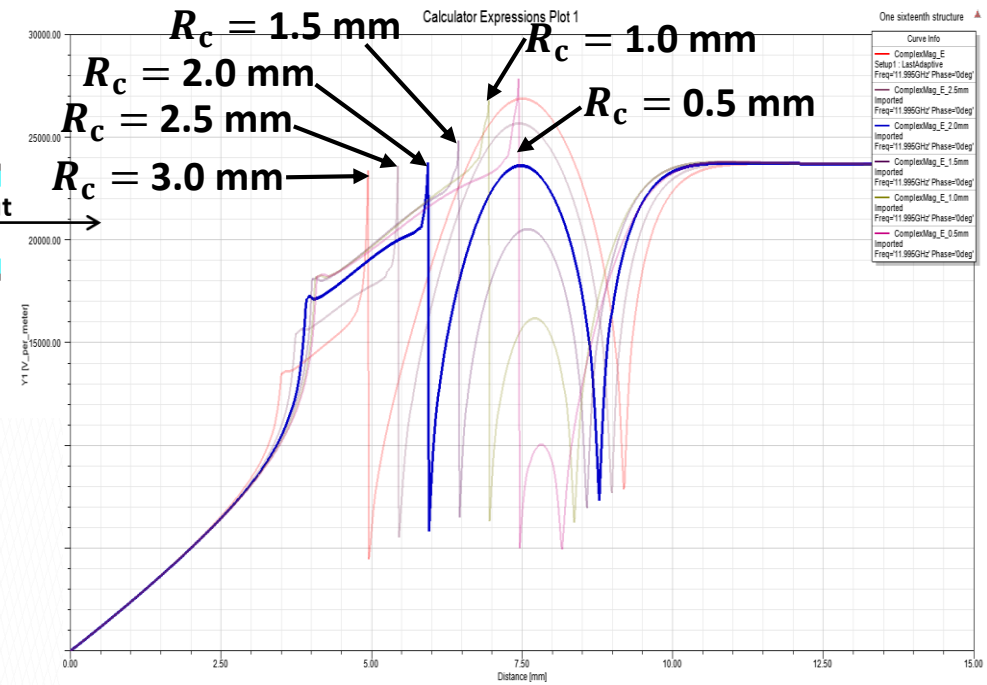


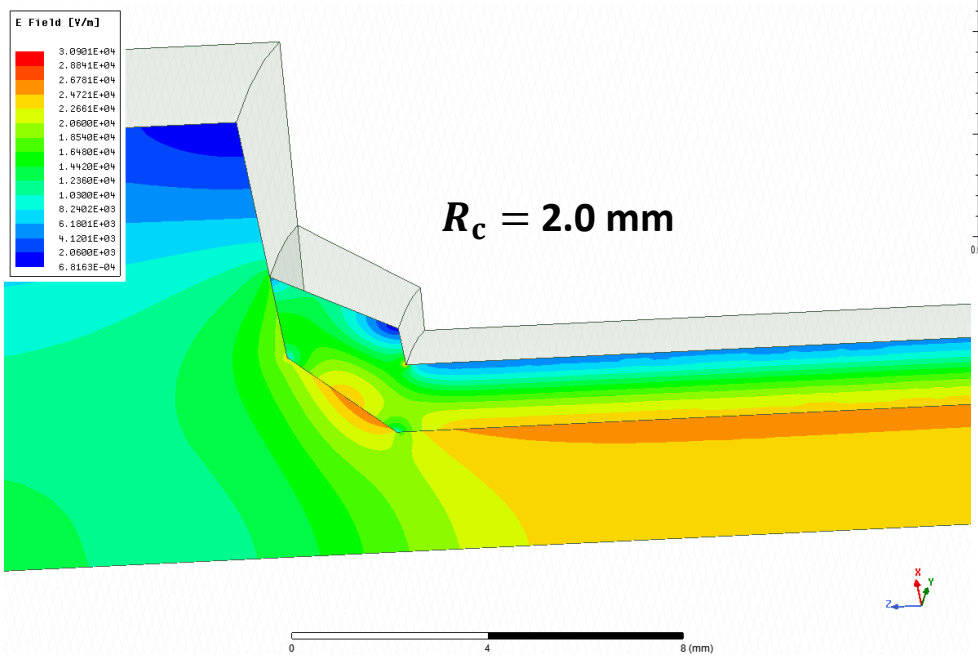


- For each curve, it is perfectly matched with a S_{11} < -40 dB;
- The peak fields in the corner 1 are decreased with a larger fillet radius R_f;
- $R_f = 2.0$ mm is chosen for the following optimization.

Chamfer Corner 2 at a skew angle of 60°

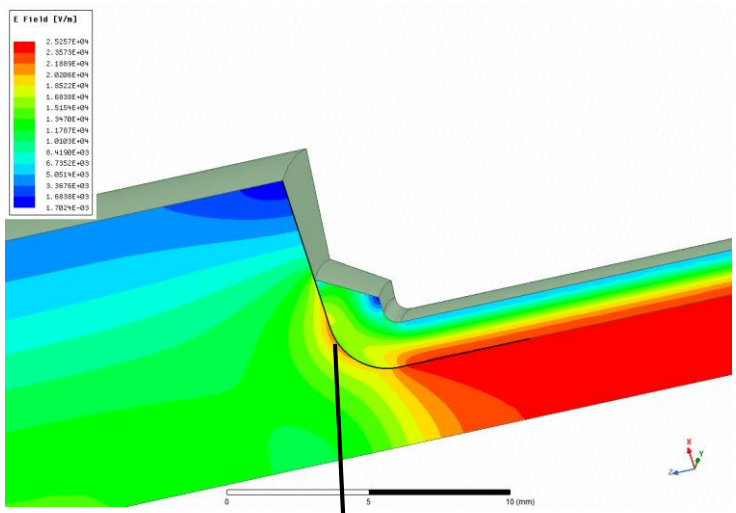


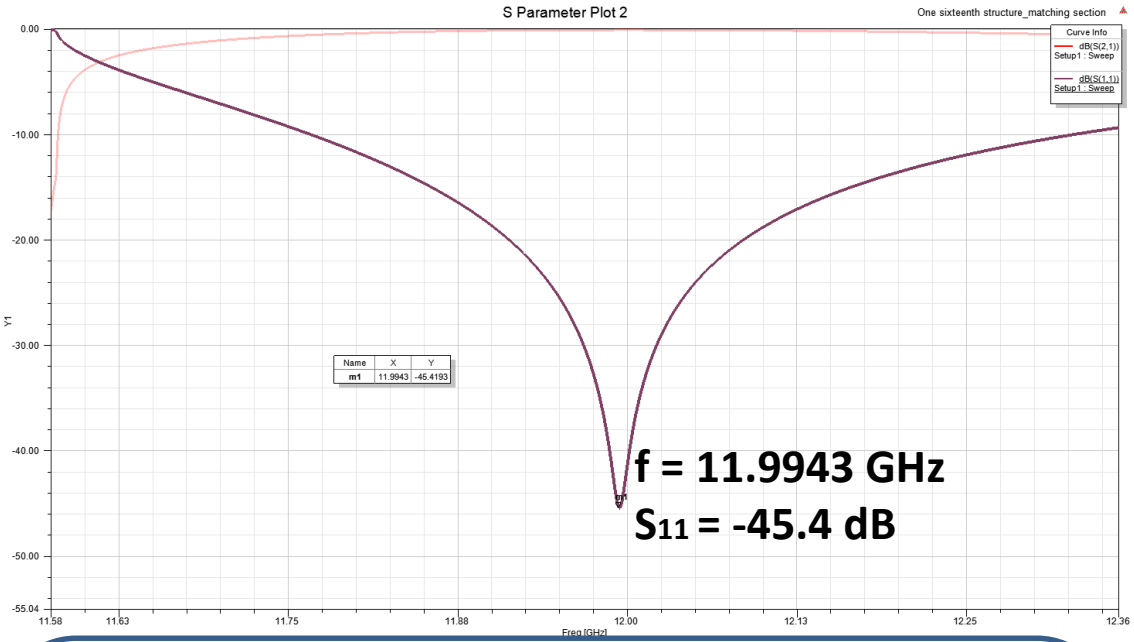


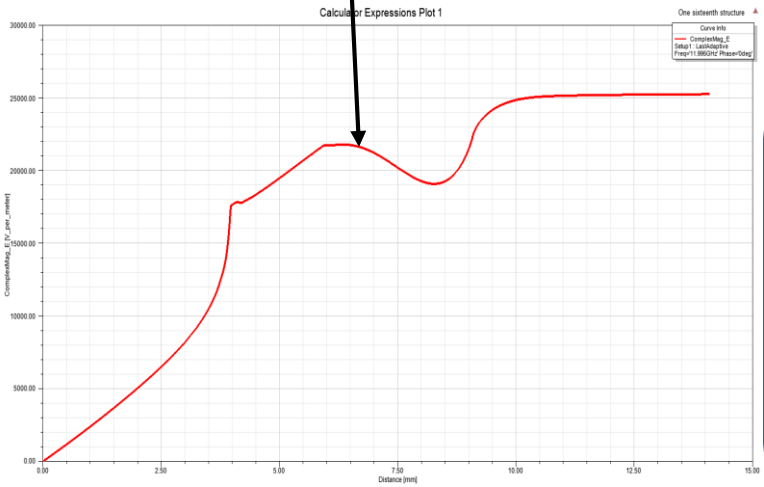


- For each curve, it is perfectly matched with a S_{11} < -40 dB;
- Only when $R_c = 2.0$ mm, the peak fields in the corner 2 equal to the accelerating fields in the DLA structure.

Skew angle $\theta = 60°$, Fillet Corner 2 with a radius R_f = 2.0 mm



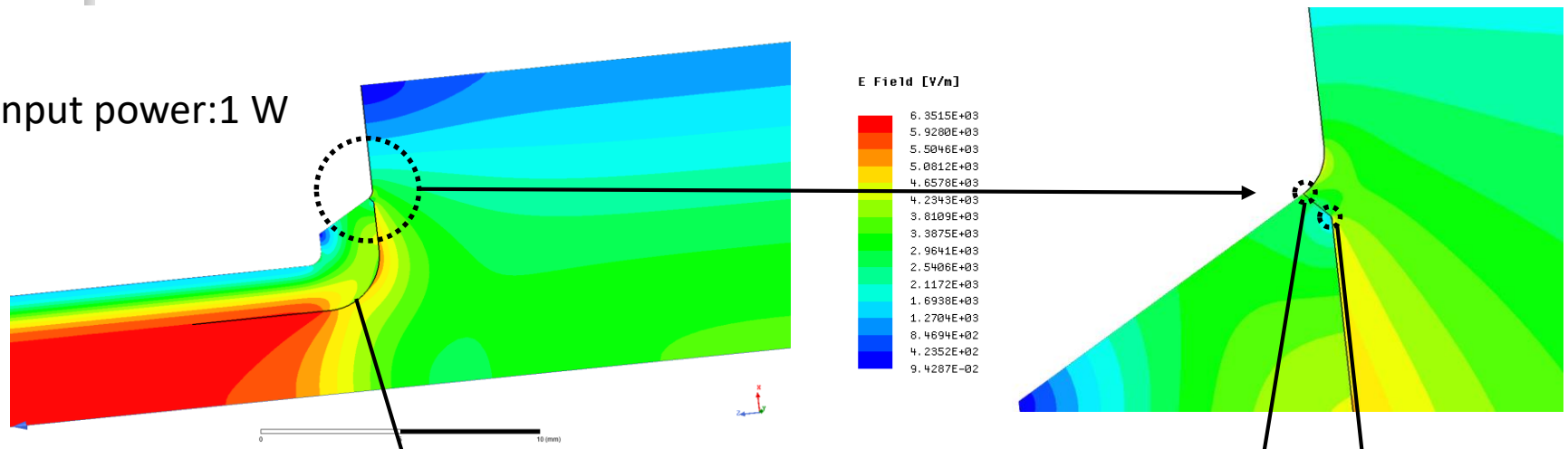


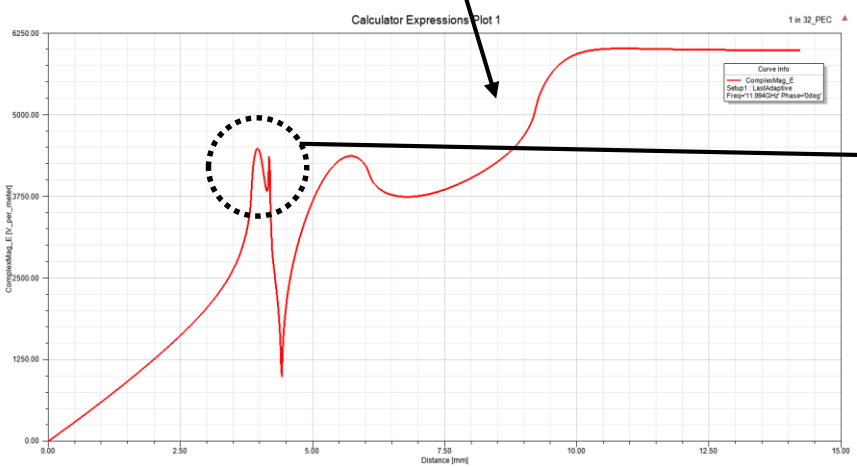


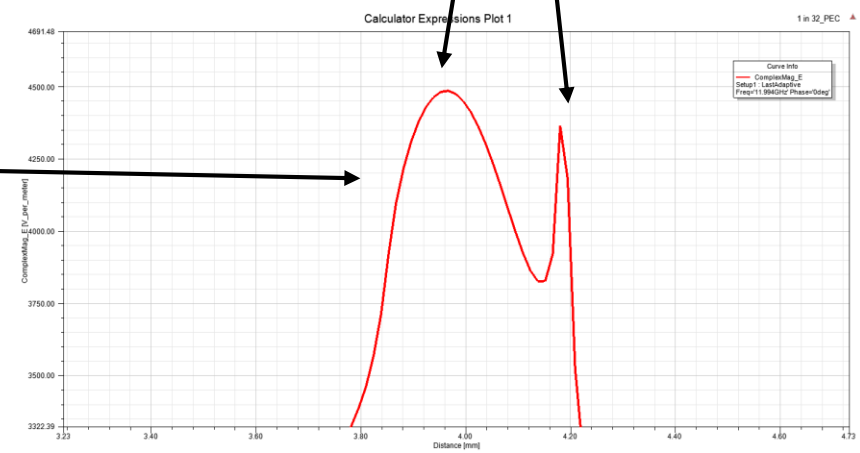
- Fillet Corner 3 with a radius of 0.5 mm;
- The peak fields in the Corner 1, Corner 2 and Corner 3 are greatly reduced so that the maximum fields are located in the DLA structure;
- For S_{11} < -30 dB, the bandwidth Δ = 12.0216 GHz - 11.9680 GHz = 53.6 MHz;
- For S_{11} < -20 dB, the bandwidth Δ = 12.0855 GHz - 11.9131 GHz = 172.4 MHz

Chamfer the dielectric corner considering robust fabrication on the dielectric corner

Input power:1 W

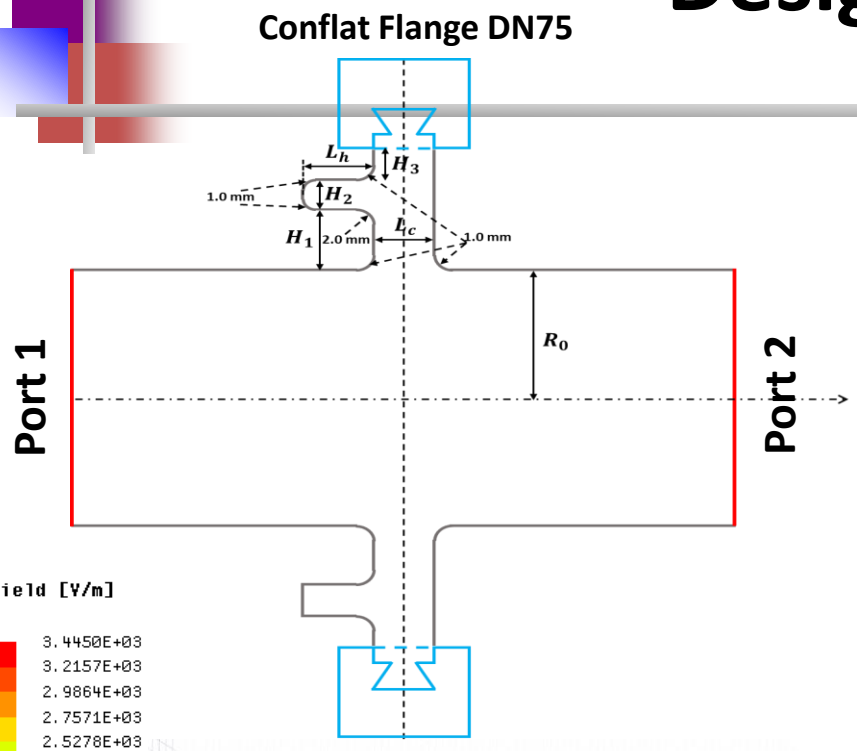




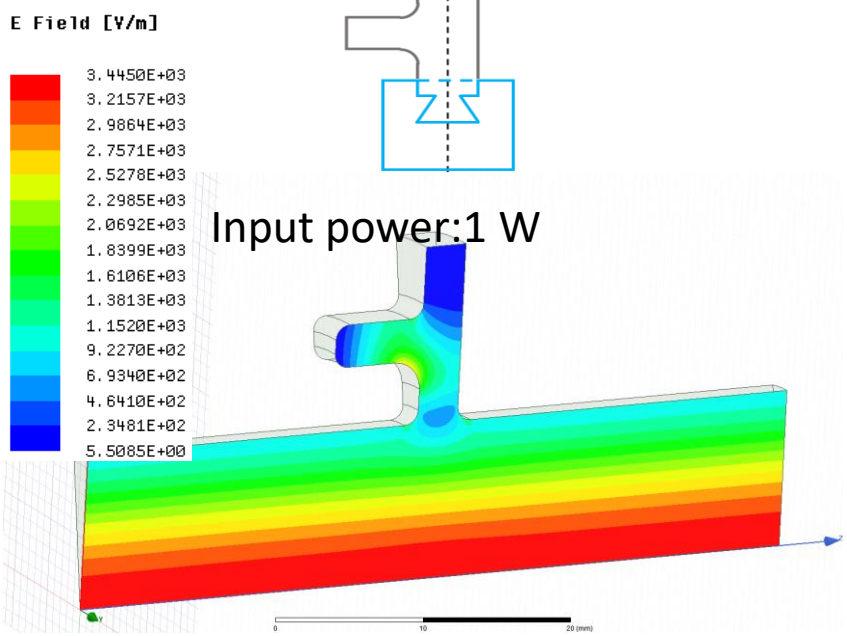


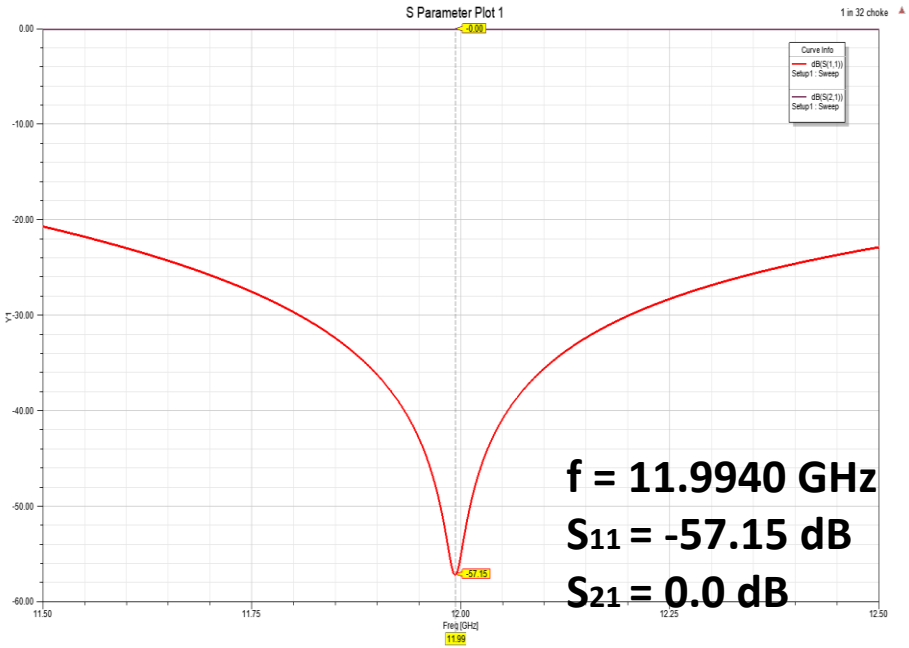
- **The fields in the matching section are still weaker than those of DLA.**

Design of a choke



Dimensions	Unit: mm
H_1	4.5
H_2	3.0
H_3	≥5.0
L_c	3.0
L_h	6.535



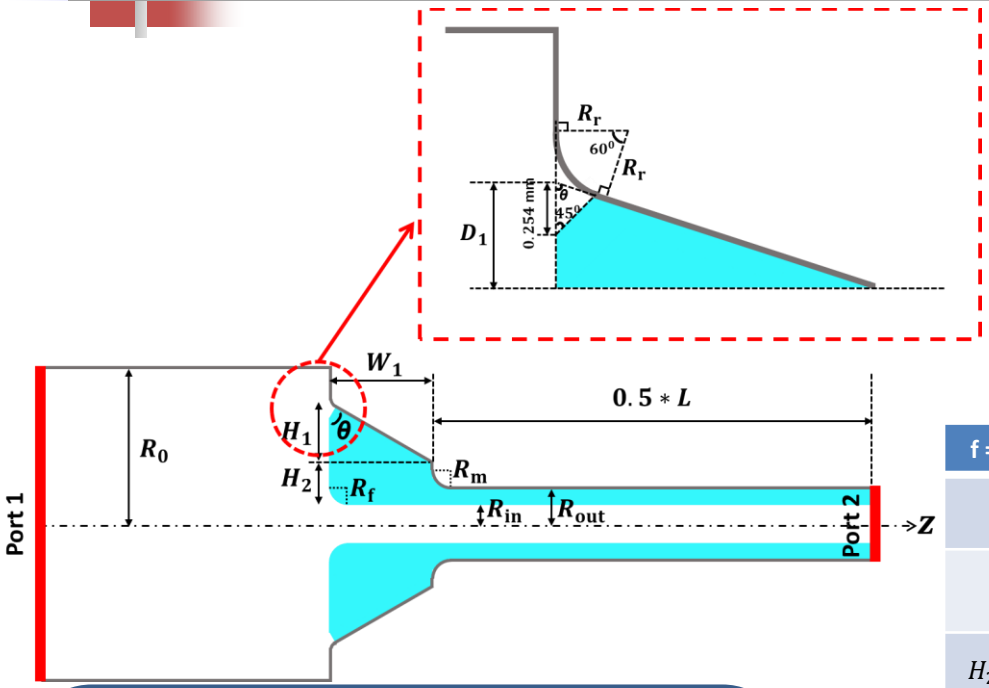


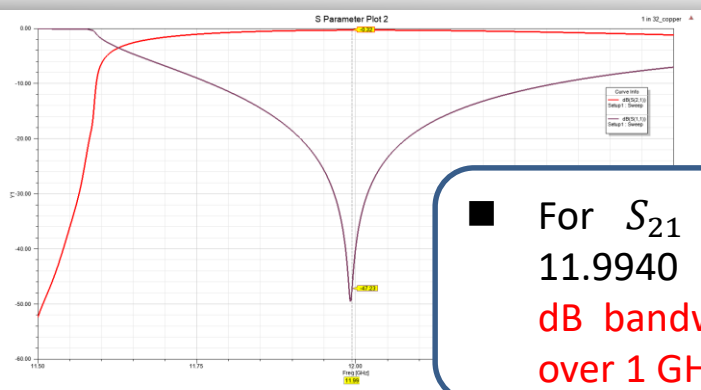
f = 11.9940 GHz

S_{11} = -57.15 dB

S_{21} = 0.0 dB

Tolerance studies



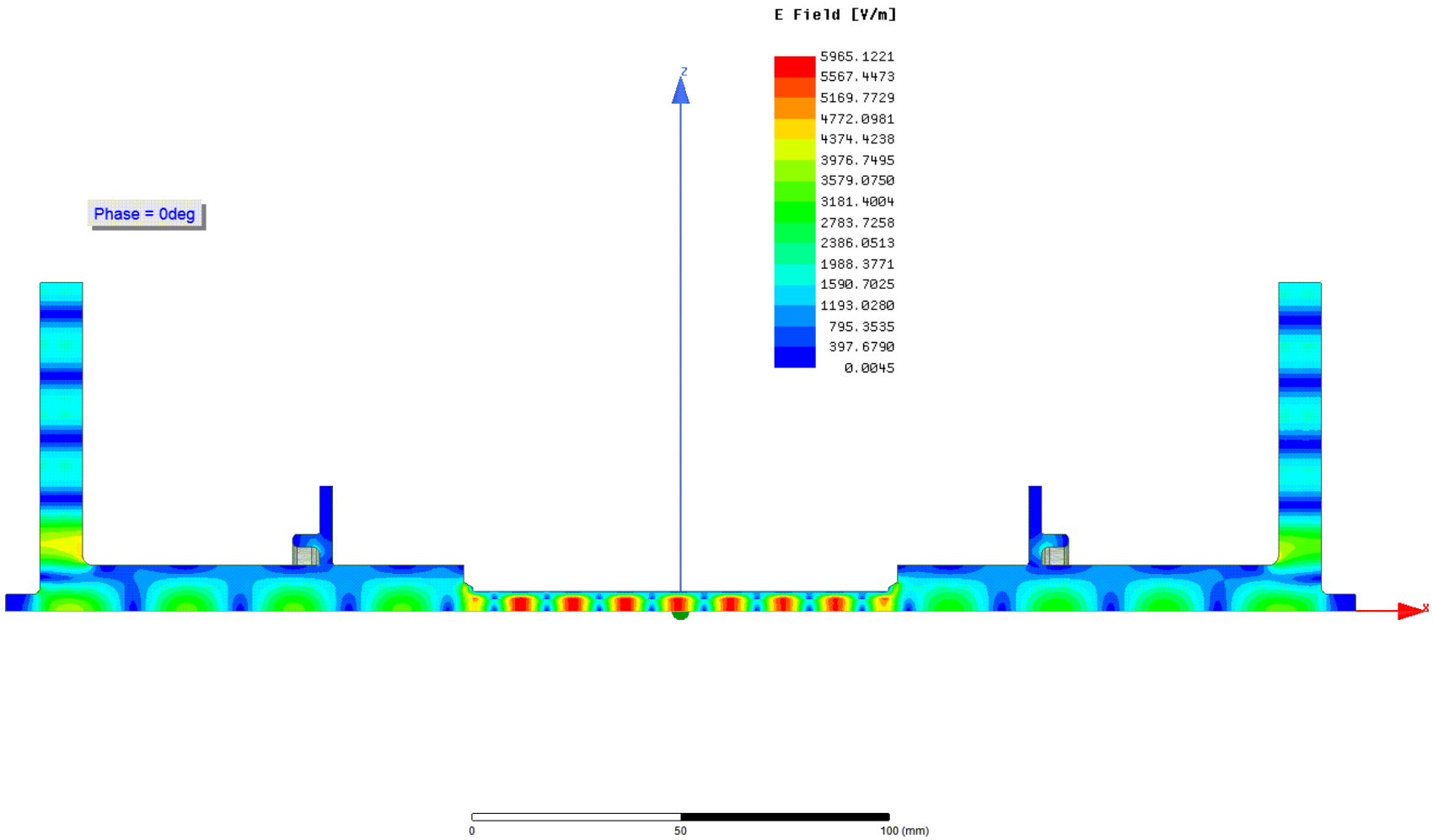


- For S_{21} at f = 11.9940 GHz, 3 dB bandwidth is over 1 GHz.

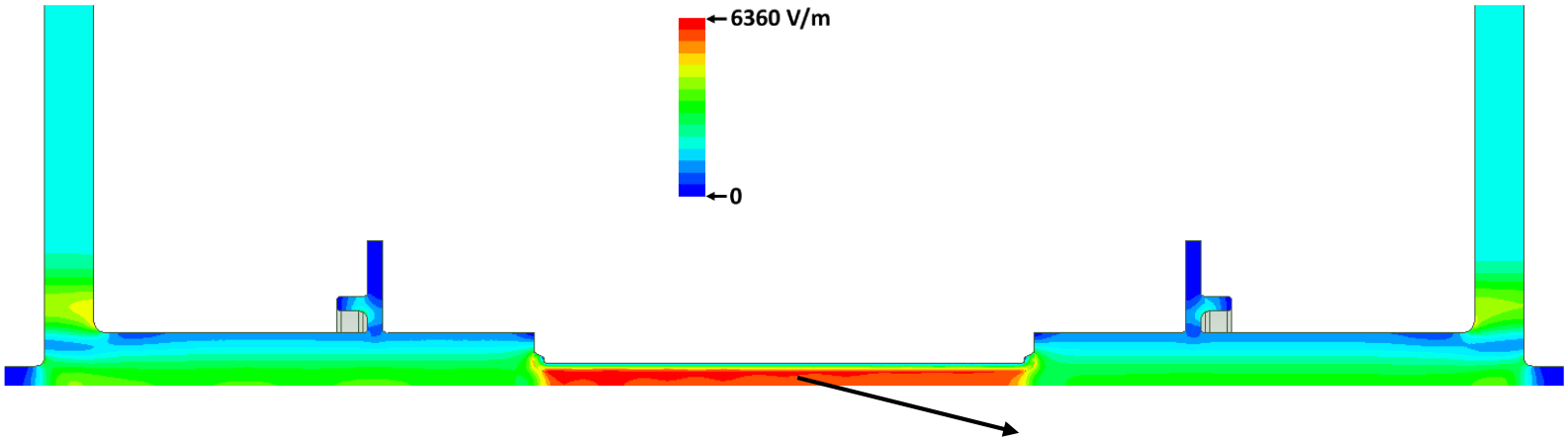
f = 11.9940 GHz	$S_{11} \leq -30$ dB	$S_{11} \leq -25$ dB	$S_{11} \leq -20$ dB
$\varepsilon_r = 16.66$	[-0.079, +0.081]	[-0.139, 0.148]	[-0.24, +0.27]
$W_1 = 2.035$ [mm]	[-0.007, +0.007]	[-0.012, +0.012]	[-0.022, +0.022]
$H_2 = 2.74$ [mm]	[-0.015, +0.017]	[-0.027, +0.030]	[-0.051, +0.054]
$\theta = 60^0$	[-2.5^0, +2.0^0]	[-4.3^0, +3.7^0]	[-7.3^0, +7.0^0]
$R_f = 2.0$ [mm]	[-0.042, +0.040]	[-0.076, +0.068]	[-0.140, +0.120]
$R_m = 0.5$ [mm]	[-0.061, +0.049]	[-0.118, +0.090]	[-0.245, +0.151]
$R_{out} = 4.6388$ [mm]	[-0.0076, +0.0065]	[-0.0123, +0.0127]	[-0.020, +0.025]
$R_{in} = 3.0$ [mm]	[-0.006, +0.007]	[-0.012, +0.012]	[-0.024, +0.020]

- S_{11} is most sensitive to W_1, R_{out}, and R_{in};
- S_{11} is least sensitive to H_2, θ, R_f, R_m, ε_r;
- Fabrication accuracy should be better than $\pm$ 0.02 mm in order to realize a $S_{11} \leq -20$ dB.

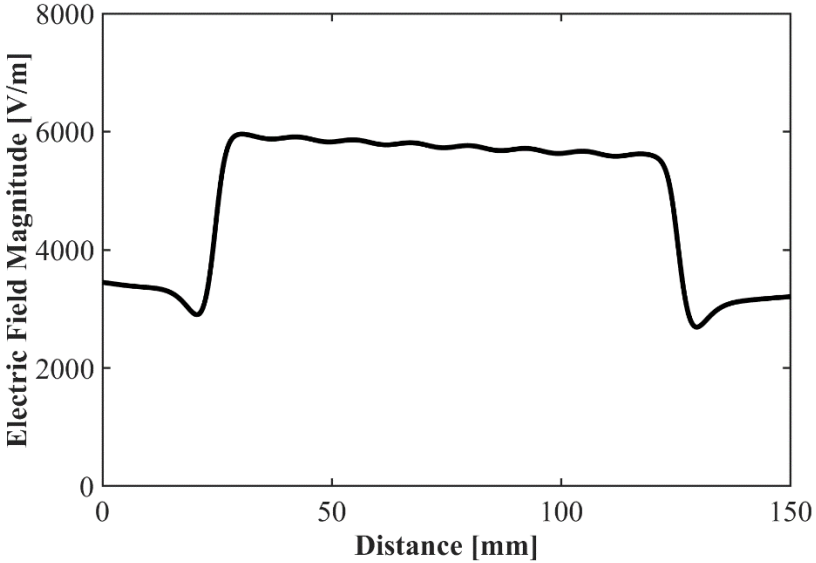
E-field propagation



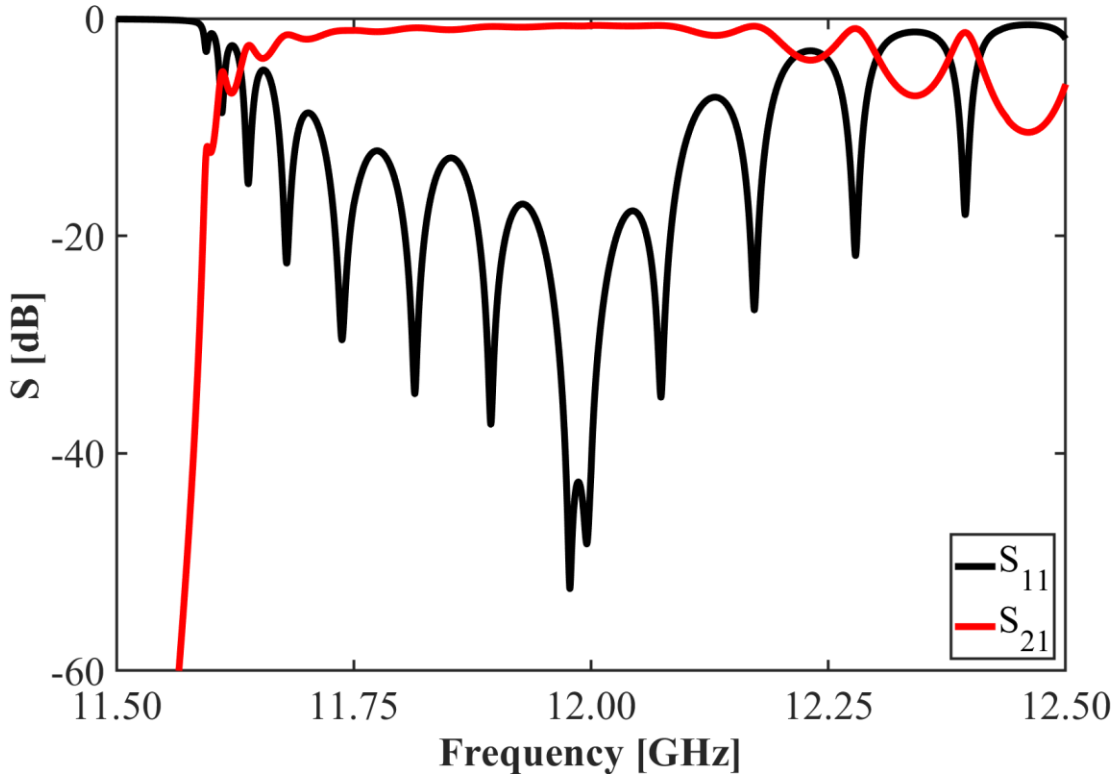
Accelerating field



Whole structure	
A DLA Length	100 mm
Voltage @ 1W	577.3 V
Average Gradient @ 1W	5773 V/m
Average Gradient @ 40 MW	36.5 MV/m



Simulated S-parameters



For an input power of 40 MW, a pulse width of 1.5 µs, and a repetition rate of 50 Hz	
S_{11}	< -40 dB
S_{21}	-0.67 dB
Power loss in dielectrics	36 W
Power loss in copper surface	390 W

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  - Simulation studies
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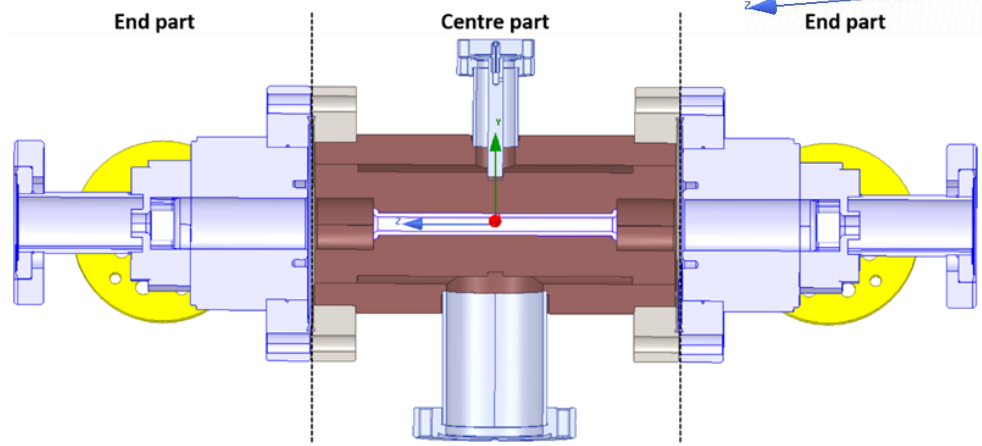
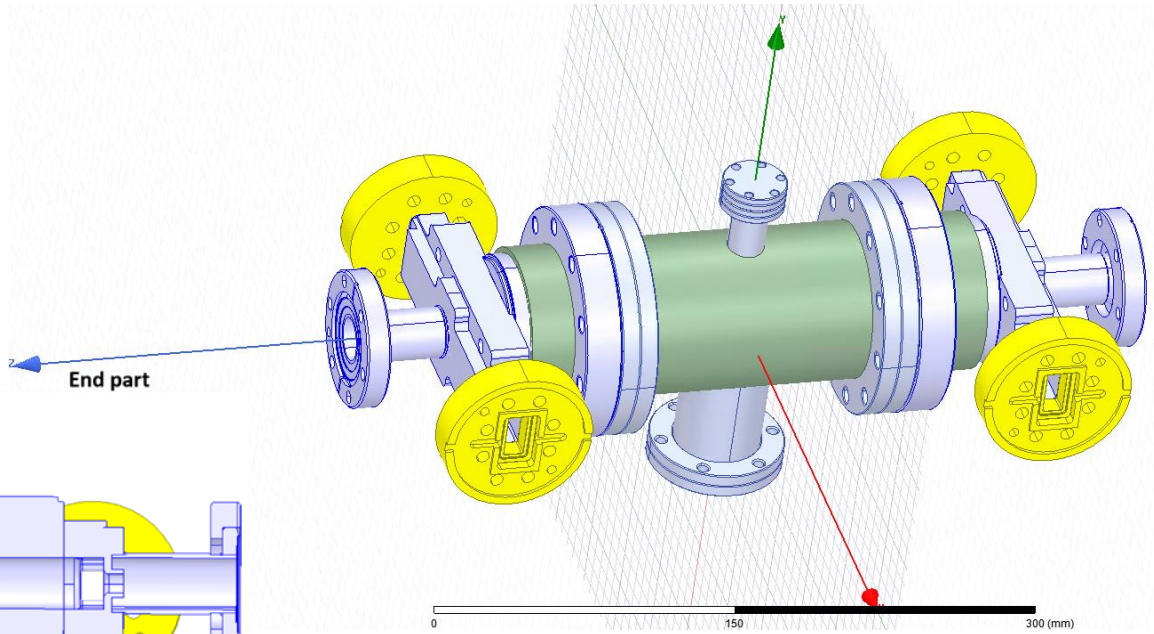
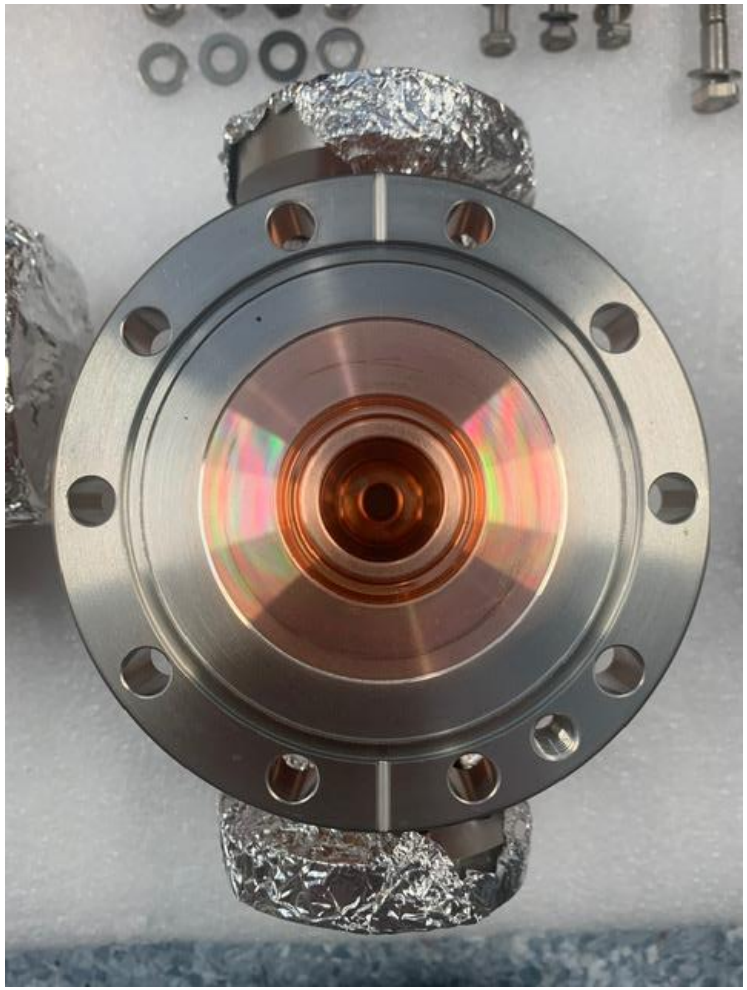
Mechanical modelling

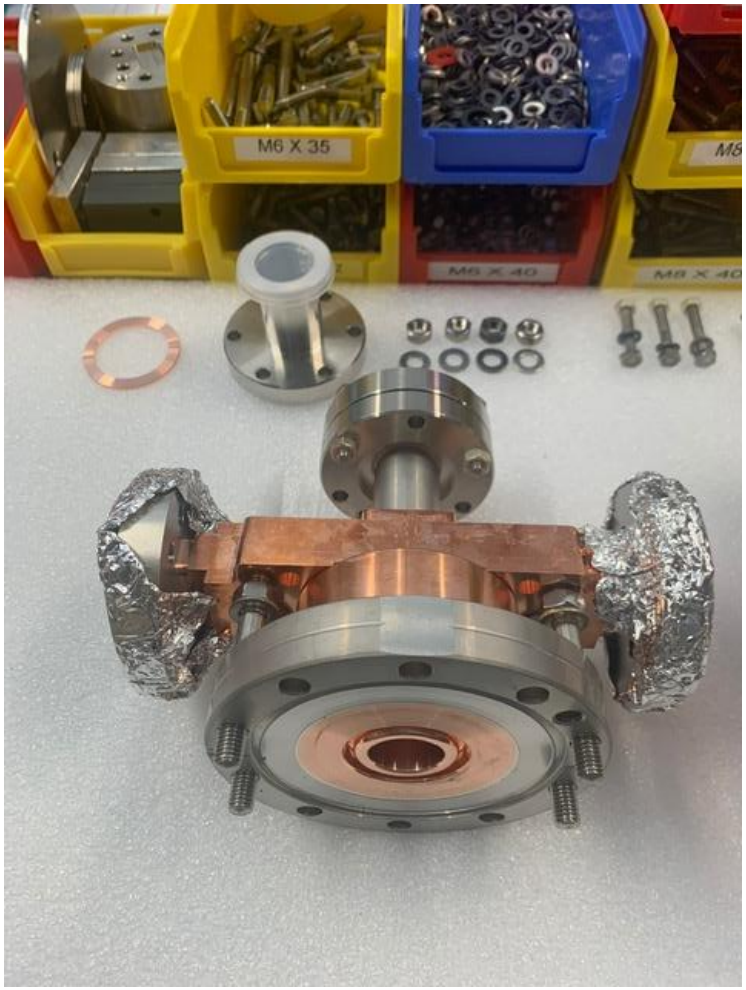




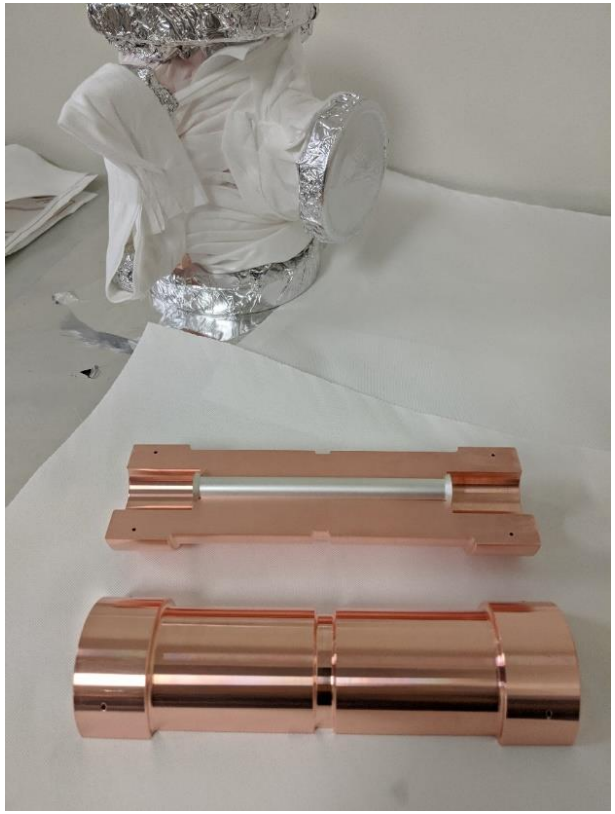
- Centre part is the DLA structure while two end parts are mode converters which are also used for coupling RF power into the DLA structure;
- Centre part is connected with end parts through the choke geometry with a Conflat Flange DN75.

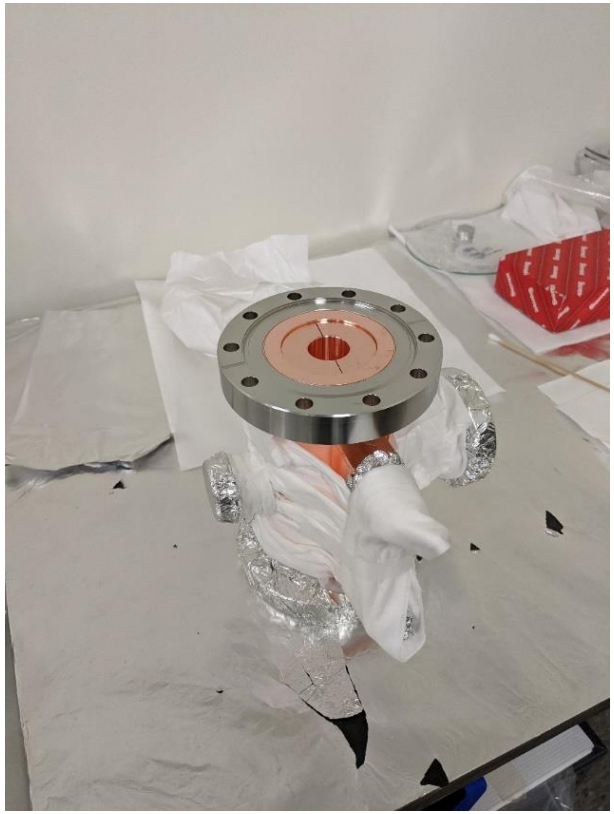
Mode converters with a choke





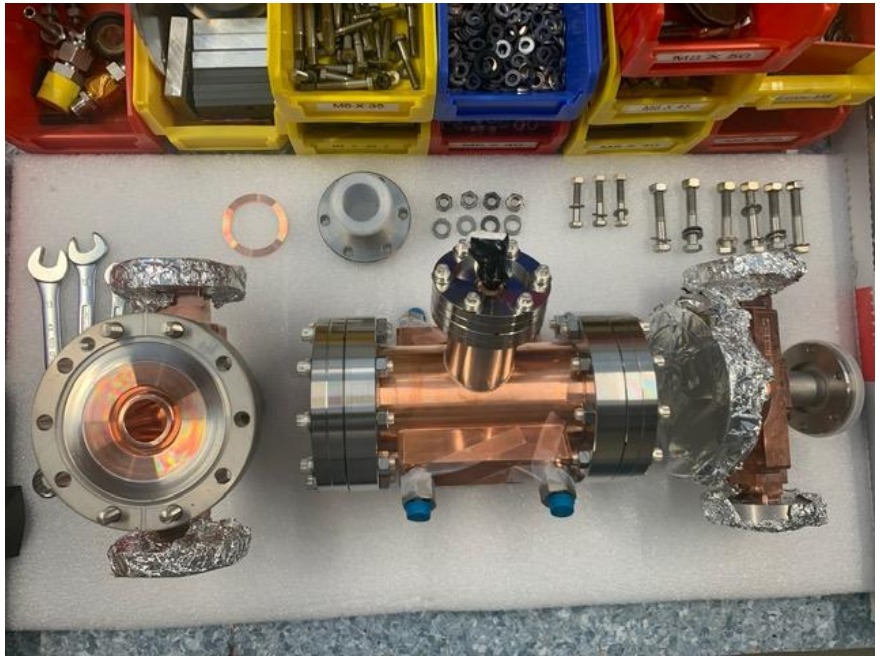
DLA structure

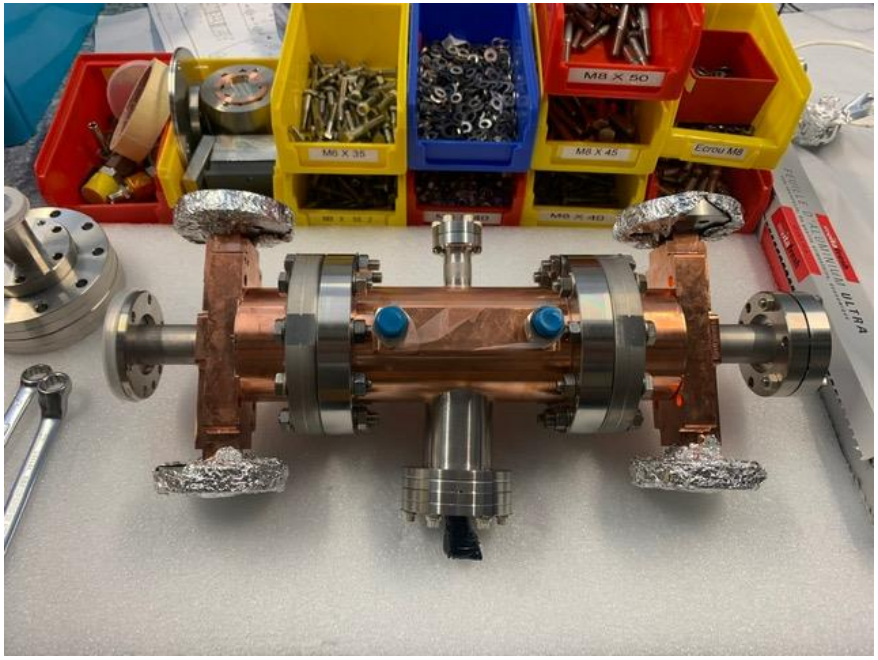




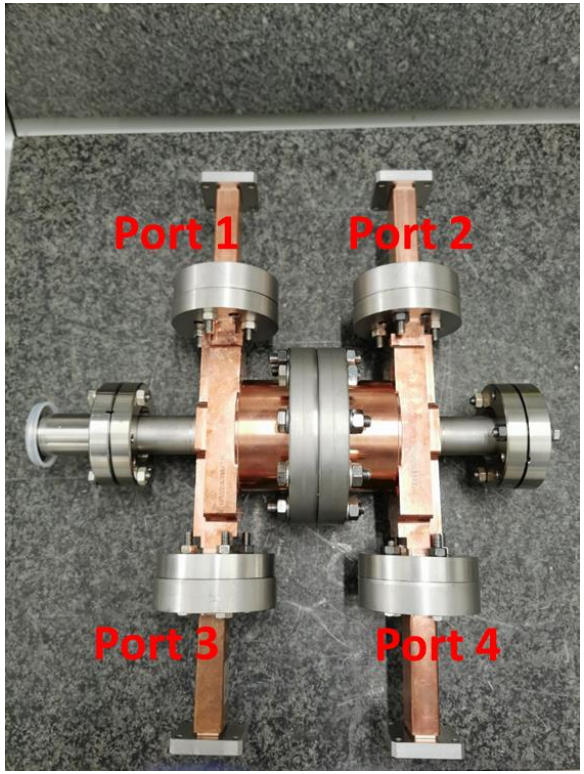
Courtesy of photos from Dr. Chunguang Jing, Euclid Techlabs.

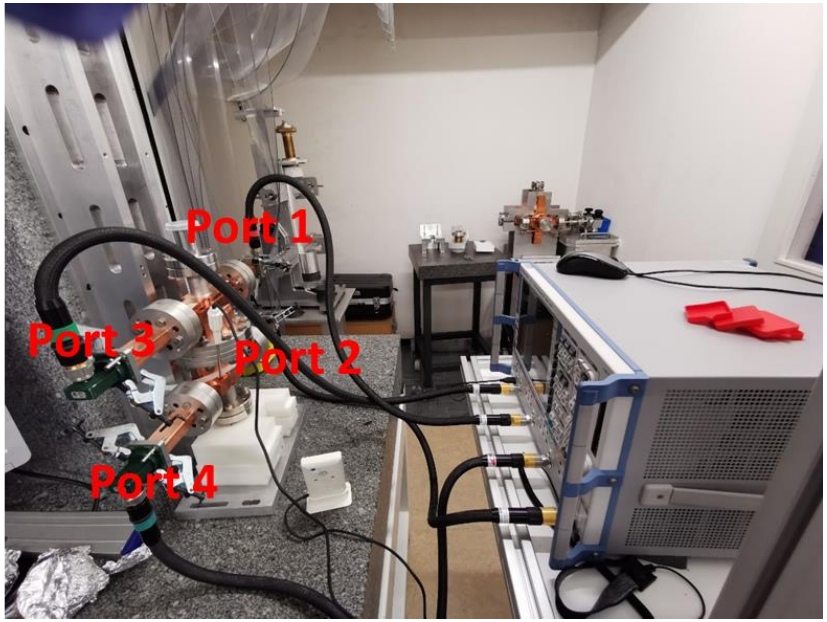
Assembly of mode converters and the DLA structure





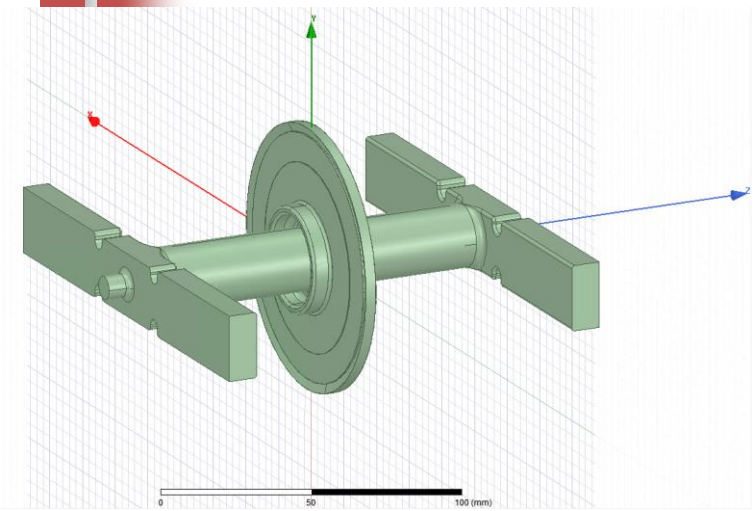
Fabricated mode converters

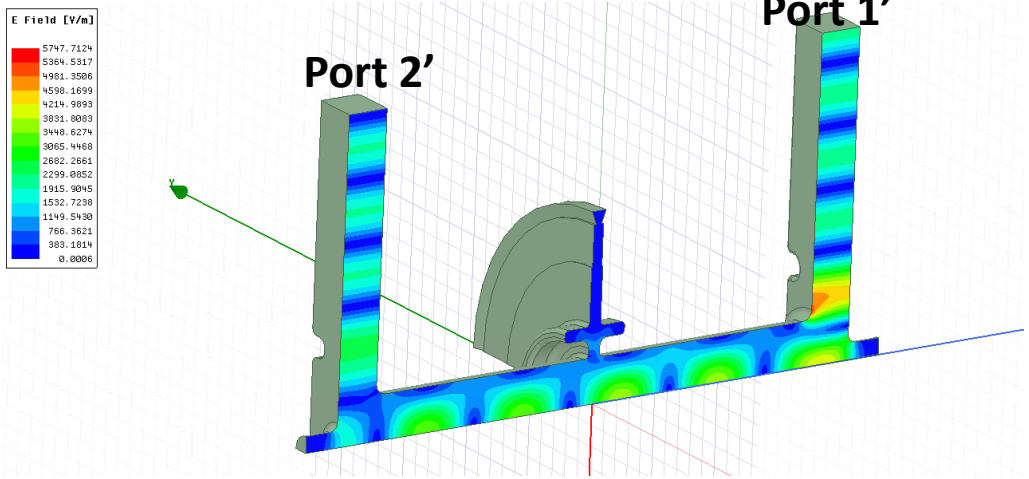


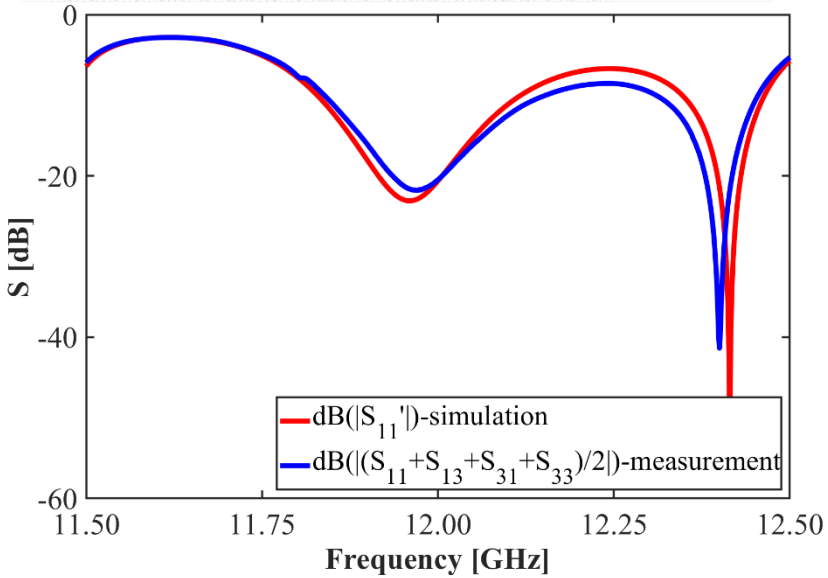


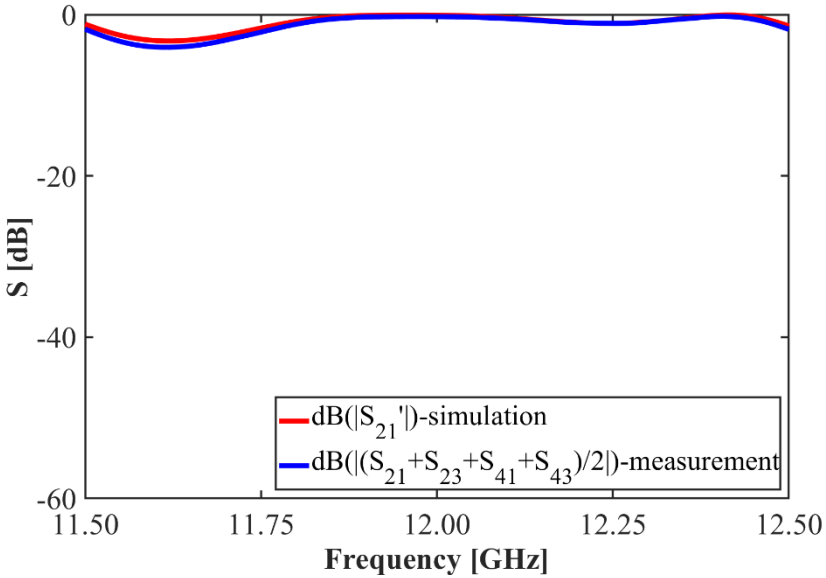
- The 4-port mode converters are used to convert a TE10 mode from a rectangular waveguide to a TM01 mode in the circular waveguide;
- The choke structure is designed to remove the contact issue for assembling two parts together. In this case, the copper disks have no bonding joints.

RF Measurement on assembly of two TE10-TM01 mode converters

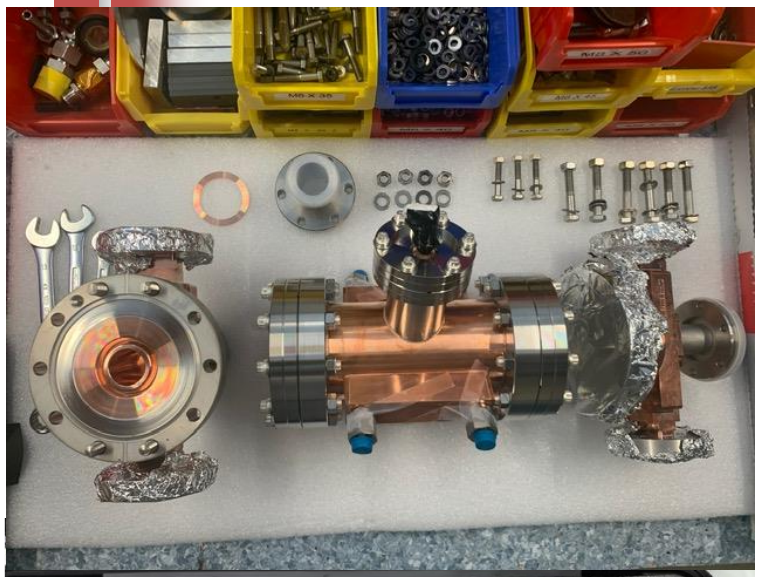


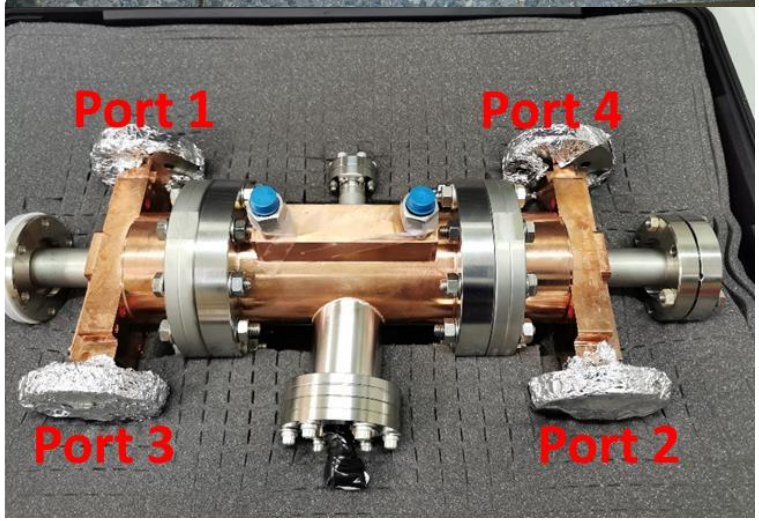


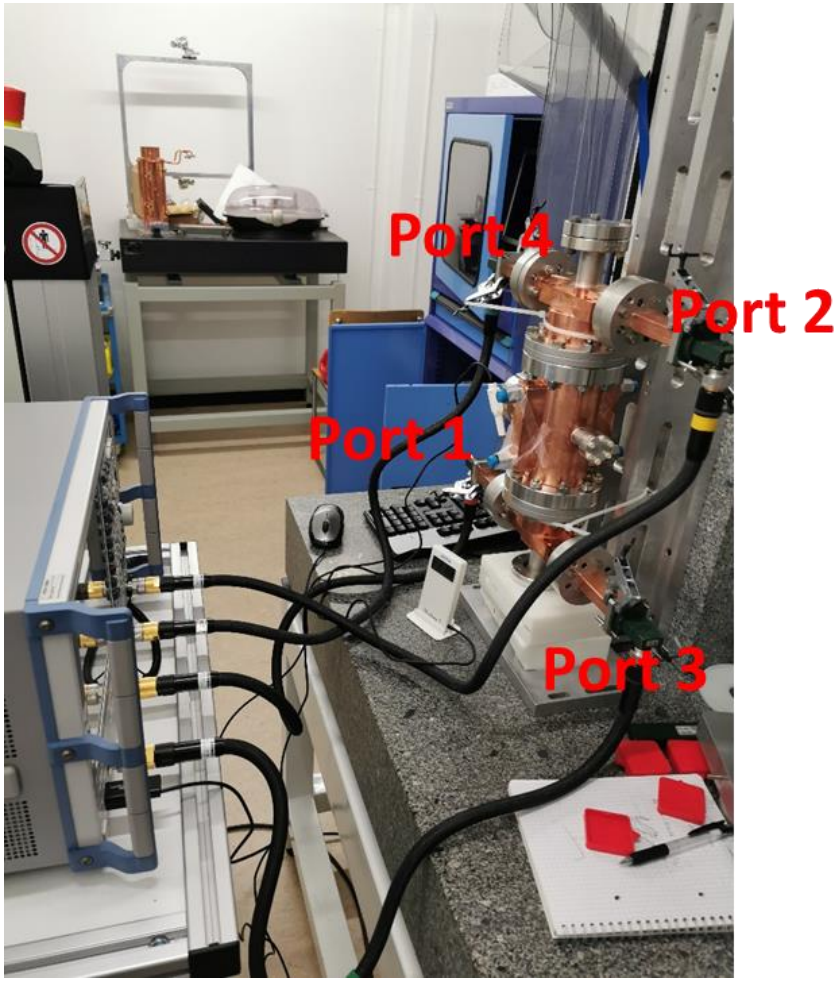




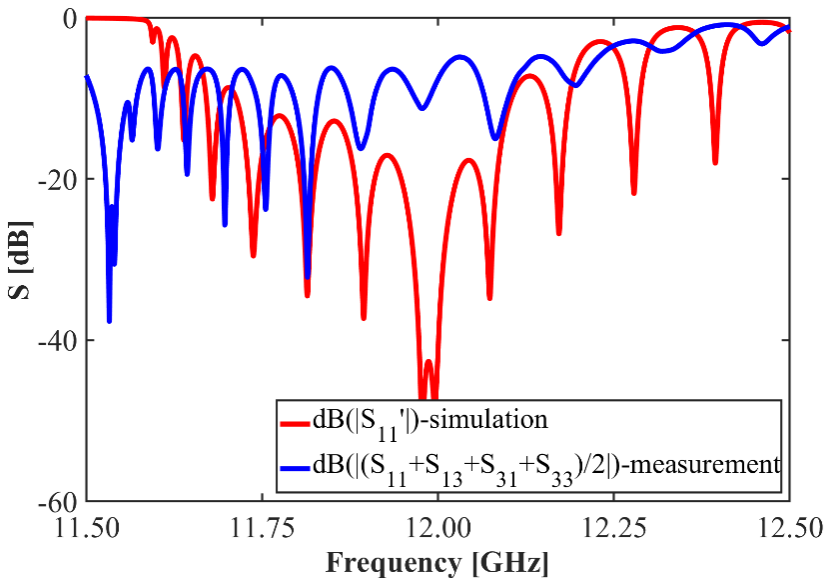
RF Measurement on assembly of two TE10-TM01 mode converters and the DLA structure

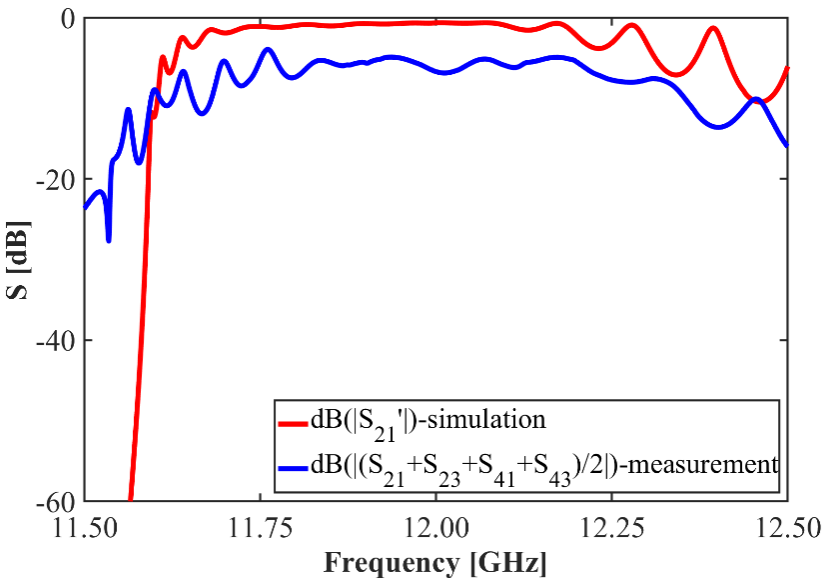


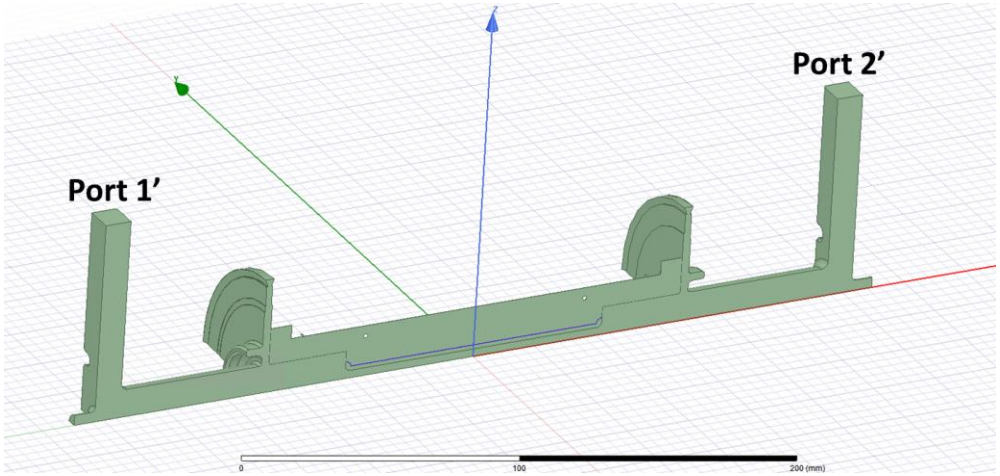




S-parameters comparison

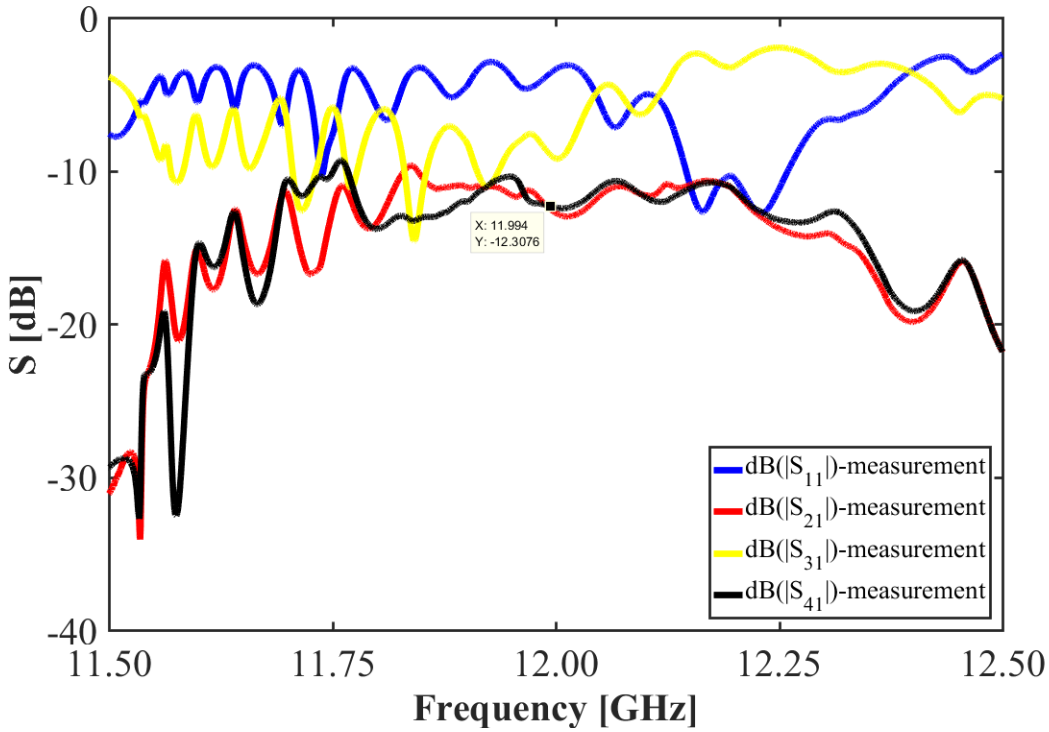






- From the measurement blue line at the frequency of 11.994 GHz, $S'_{11} = -11.35$ dB, $S'_{21} = -6.34$ dB;
- There is a big discrepancy between the measured and simulated S-parameters.

Power losses calculations from the measured S-parameters



At the designed frequency of 11.994 GHz:

S11 = -3.624 dB

S21 = -12.51 dB

S31 = -8.95 dB

S41 = -12.31 dB

For an input power of 1 W at port 1,

Reflected power at port 1 is 0.434 W

Output power at port 2 is 0.056 W

Output power at port 3 is 0.127 W

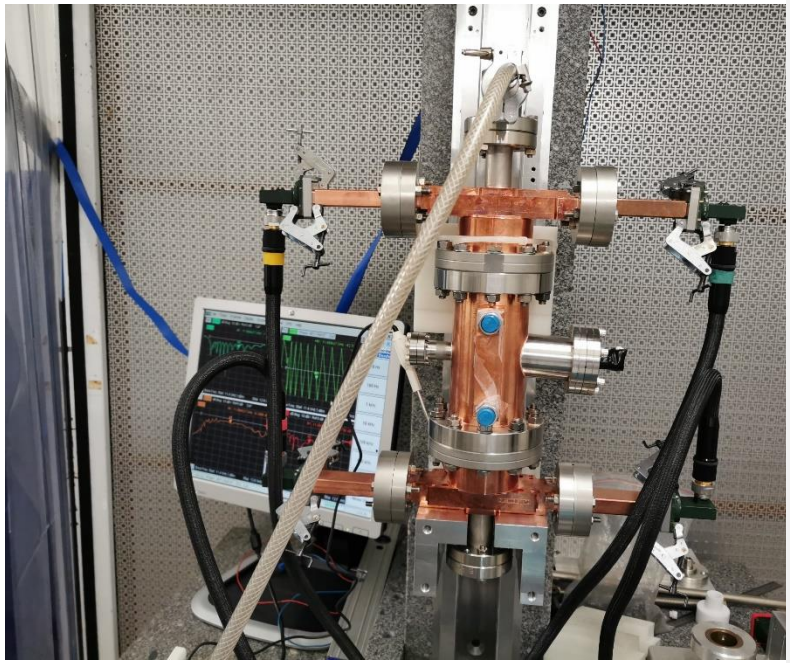
Output power at port 4 is 0.059 W

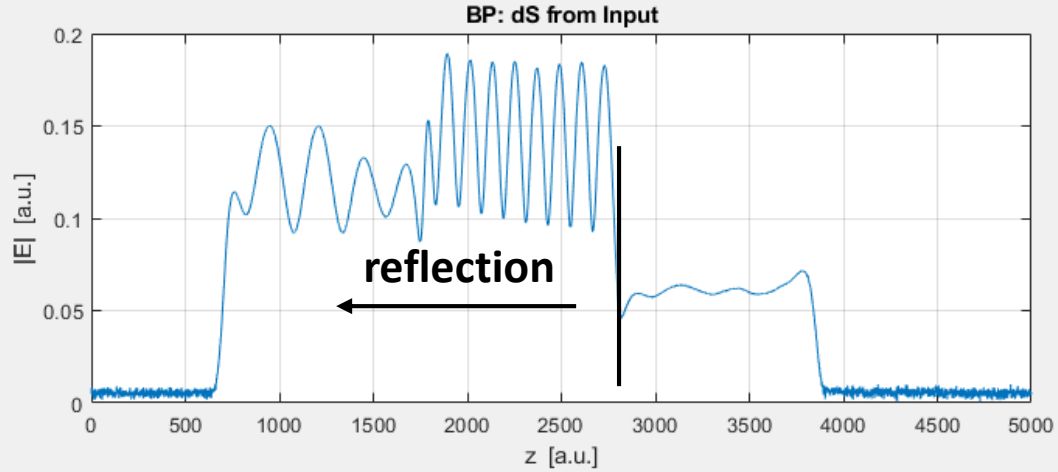
The total power loss is 1 – 0.434 – 0.056 – 0.127 – 0.059 = 0.324 W

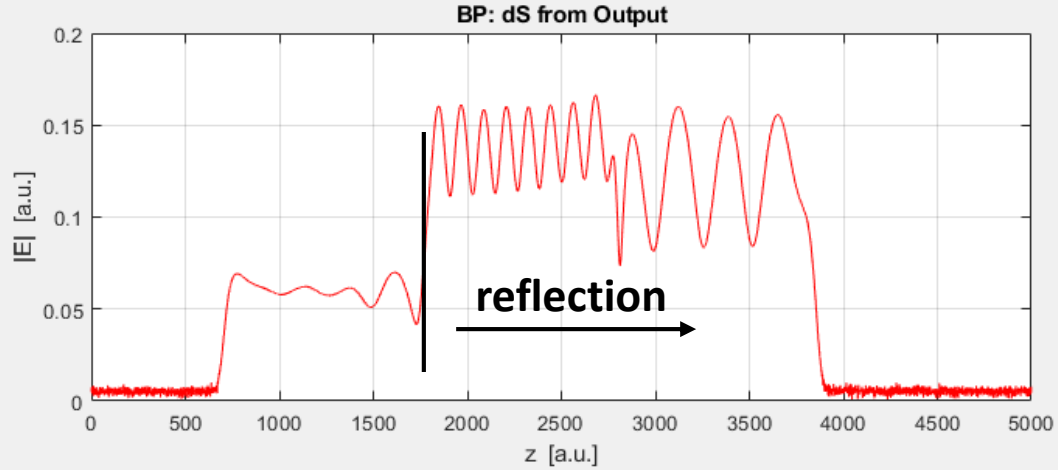
It seems that most of RF power can't travel to Port 2 and Port 4.

Bead-pull measurement (Single frequency f = 11.994 GHz)

$$S_{11} = (\text{Complex\_}S_{11} + \text{Complex\_}S_{13} + \text{Complex\_}S_{31} + \text{Complex\_}S_{33})/2$$







$$\Delta S_{11} \sim E^2$$

$$\Delta S_{11} = S_{11} - S_{11}^0$$

$$S_{11} = (\text{Complex\_}S_{22} + \text{Complex\_}S_{24} + \text{Complex\_}S_{42} + \text{Complex\_}S_{44})/2$$

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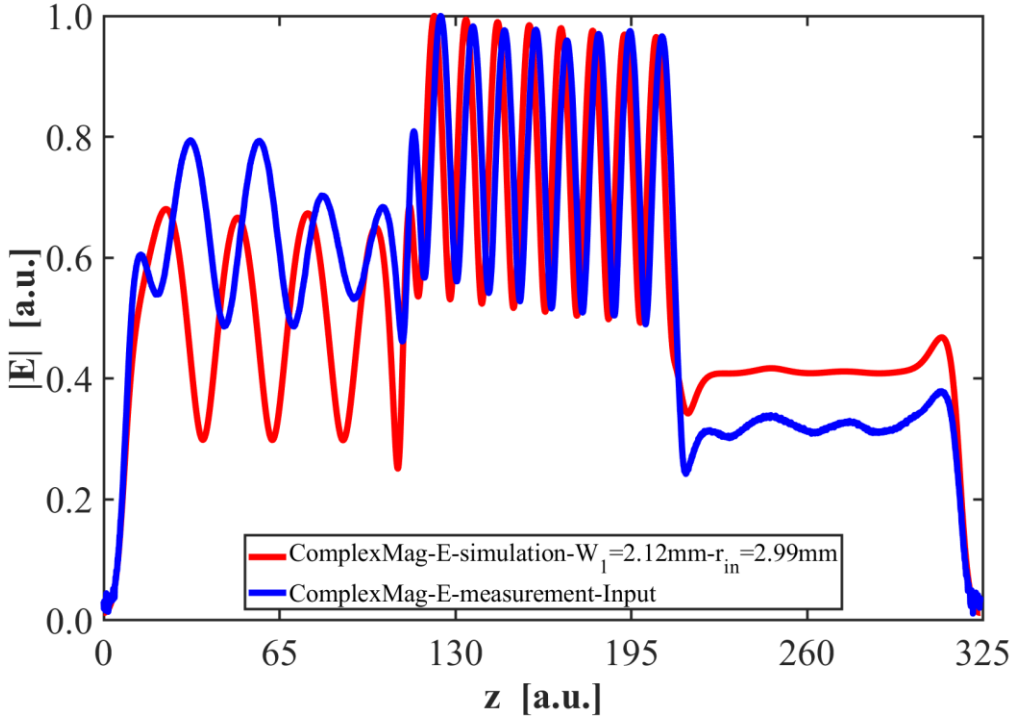
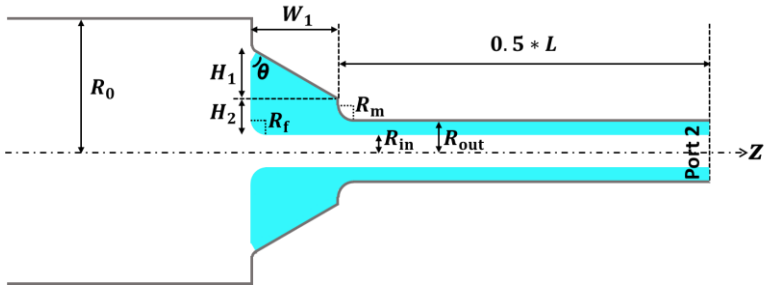
Geometrical error analysis

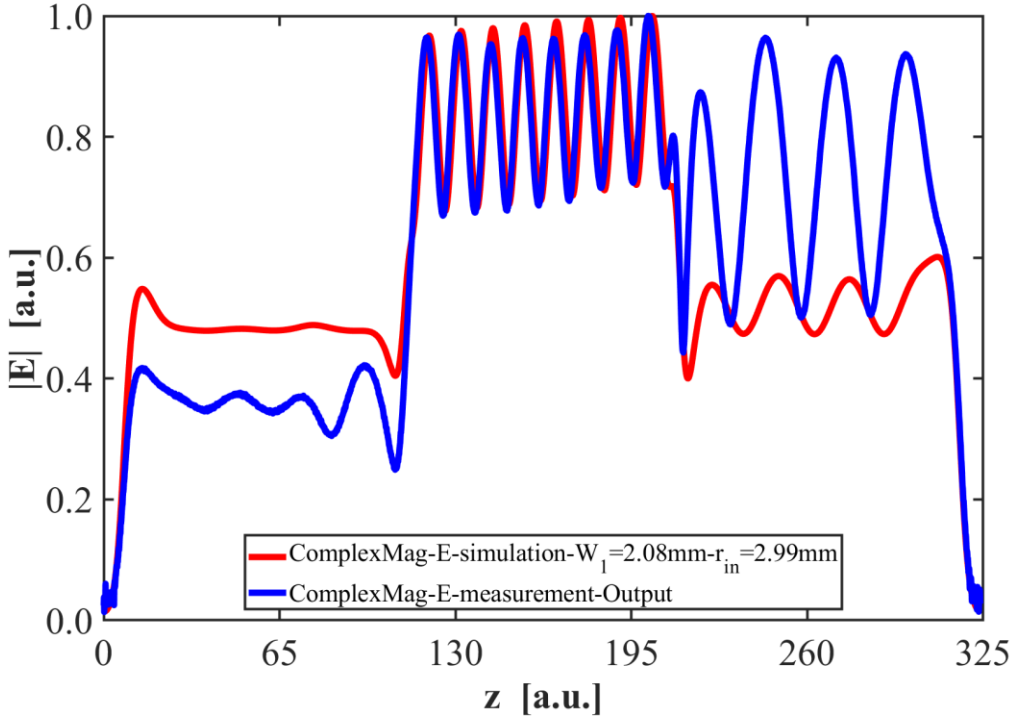


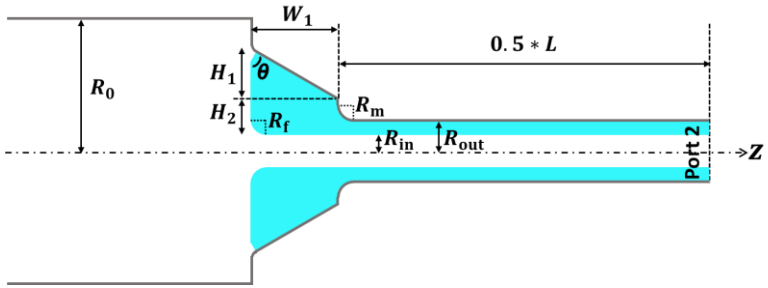


- R_{in} and W_1 denote the number of E-field peaks and magnitude of E-field in the DLA structure.
- $R_{\text{in}} = 2.99$ mm, $W_1 = 2.12$ mm for the input side (port 1 and port 3).

Designed geometry:
$R_{\text{in}} = 3.0$ mm, $W_1 = 2.035$

Geometrical error analysis

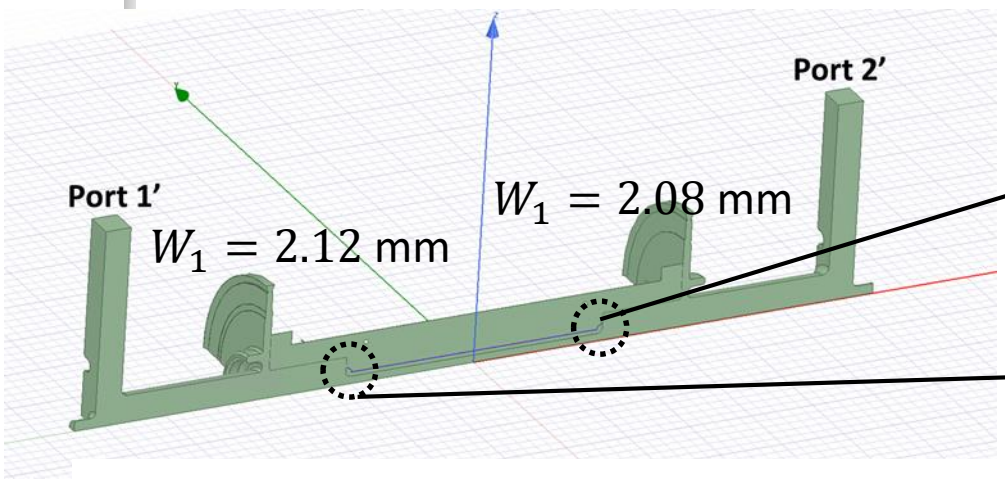


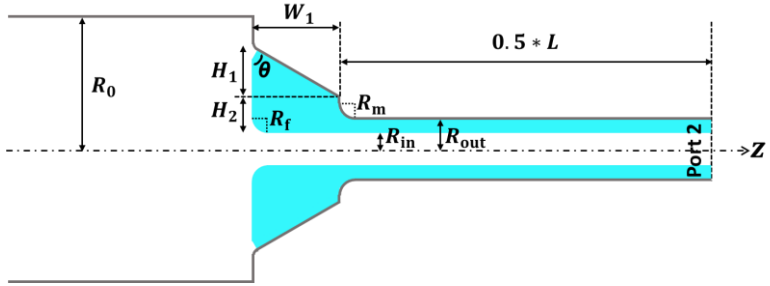


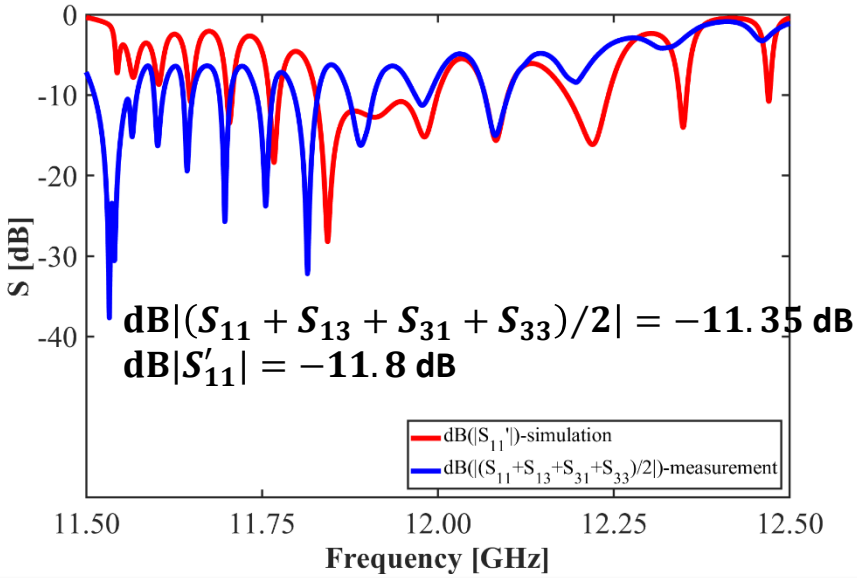
Designed geometry:
$R_{\text{in}} = 3.0$ **mm,** $W_1 = 2.035$

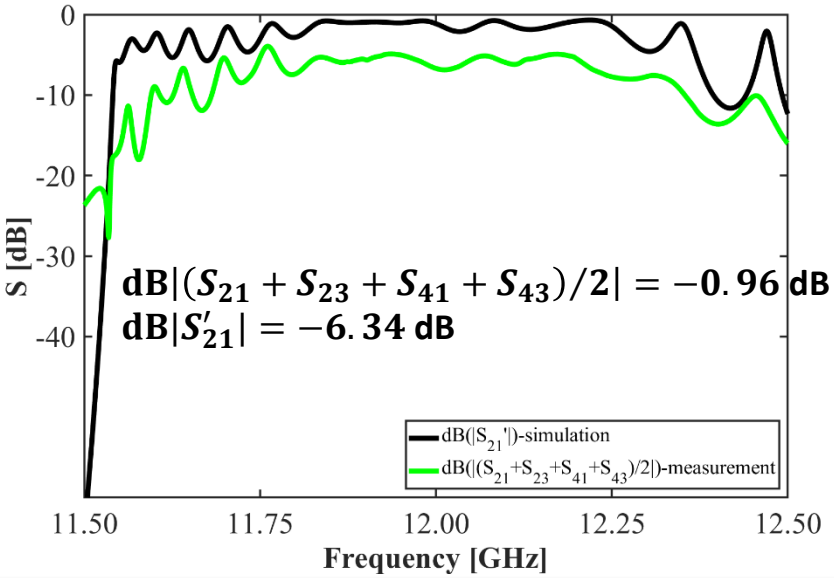
- R_{in} and W_1 denote the number of E-field peaks and magnitude of E-field in the DLA structure.
- $R_{\text{in}} = 2.99$ mm, $W_1 = 2.08$ mm for the output side (port 2 and port 4).

S-parameters of $W_1 = 2.12$ mm and $W_1 = 2.08$ mm for both matching sections, $r_{in} = 2.99$ mm

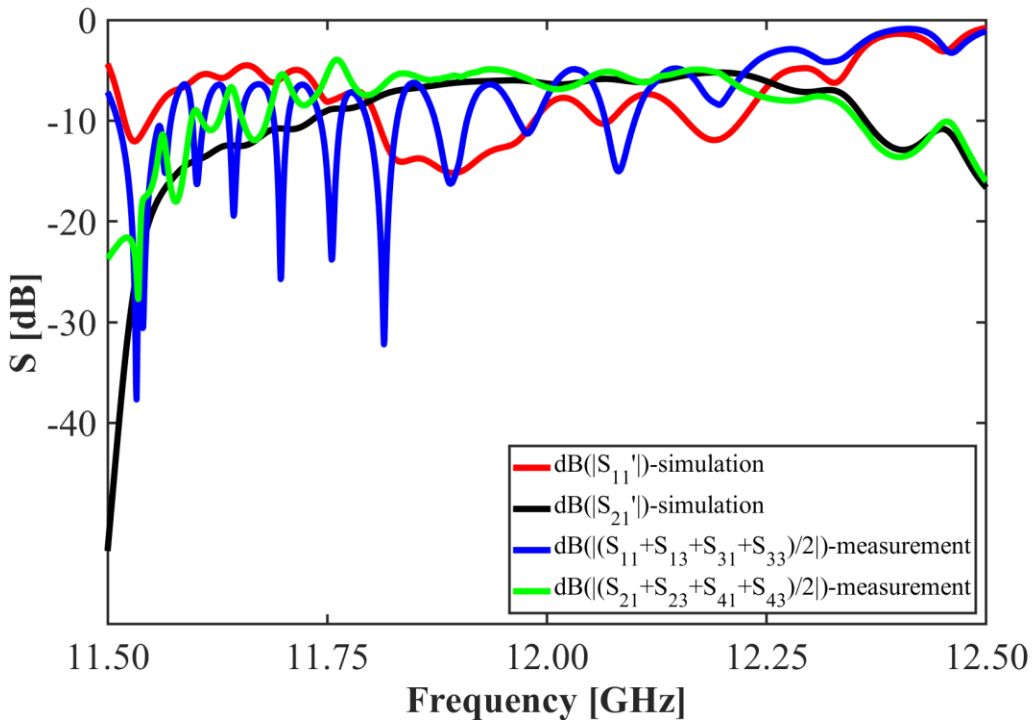








Changing conductivity of coating silver



- For the simulation modelling, asymmetrical matching sections with $W_1 = 2.12$ mm and $W_1 = 2.08$ mm for both sides, $r_{\mathrm{in}} = 2.99$ mm are used.

- At the designed frequency of 11.994 GHz, when the conductivity of thin coating metal is $\sigma = 5.5 \times 10^5$, $S'_{11} = -10$ dB, $S'_{21} = -6.25$ dB, which are similar to those of measurement.

Outline

- Background & Introduction
- Dielectric-Lined Accelerating (DLA) Structures
- Dielectric Disk Accelerating (DDA) Structures
  - TM01 operation mode
  - TM02 operation mode
- Design of an X-band DLA structure
  - Simulation studies
  - Fabrication and cold-testing of a DLA prototype
  - Fabrication error analysis
- **Summary & Outlook**

Summary & Outlook

- DLA structures and DDA structures operating at TM01 π-mode have been studied;
- DDA structures operating at TM02 π-mode:
  - Extremely high quality factor and shunt impedance: Q_0 = 134525, r' = 781 MΩ/m;
  - High RF-to-Beam efficiency of ~50%;
  - The number of acceleration cells can be up to 72 due to high bandwidth;
  - Low short-range wakefields.
- An X-band DLA structure with matching sections and the TE10-TM01 mode converters is designed, fabricated, and cold-tested.
  - The mode converters work well;
  - The fabrication error may cause the big discrepancy between the measured and simulated S-parameters.

- Further optimization and wakefield studies on DDA TM02 π-mode structure;
- Investigations into possible reasons for the discrepancy are ongoing.