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Dielectric Assist Accelerating (DAA) structures for compact linear accelerators of low energy particles in hadrontherapy treatments

P. Martinez-Reviriego^{1,3}, A. Grudiev³, D. Esperante^{1,2}, B. Gimeno¹, C. Blanch¹,
N. Fuster-Martínez¹, D. Gonzalez-Iglesias¹, P. Martín-Luna¹, E. Martinez¹,
A. Menendez¹ and J. Fuster¹

1 Instituto de Física Corpuscular (IFIC), CSIC-University of Valencia, Parque Científico, C/ Catedrático José Beltrán, 2 46980 Paterna (Valencia)

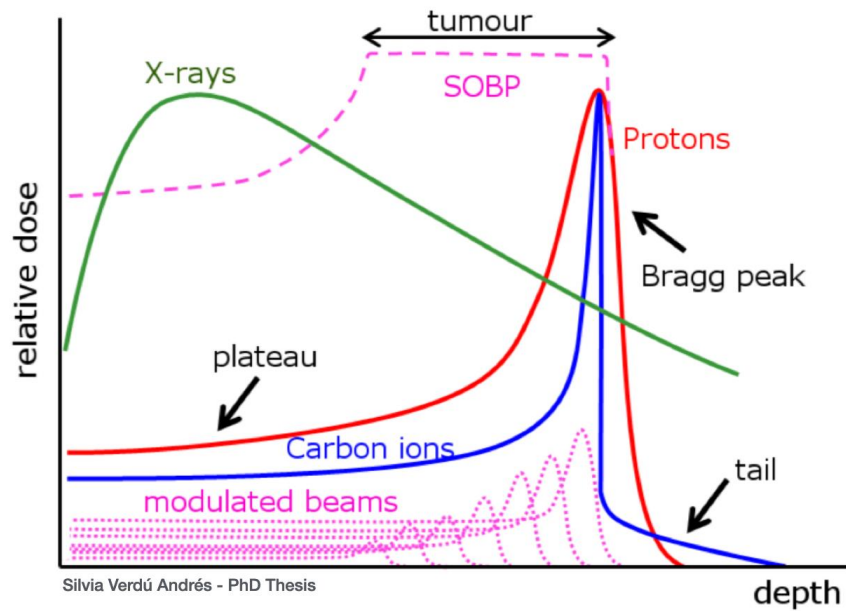
2 Electronics Engineering Department, University of València, 46100 Burjassot, Spain

3 CERN, 01631 Meyrin, Switzerland

Outline

- ❑ Linear accelerators for hadrontherapy treatments
- ❑ Dielectric Assist Accelerating (DAA) structure design procedure
- ❑ Comparison for different materials and particle velocity
- ❑ Multipactor analysis
- ❑ Electromagnetic performance

Hadrontherapy

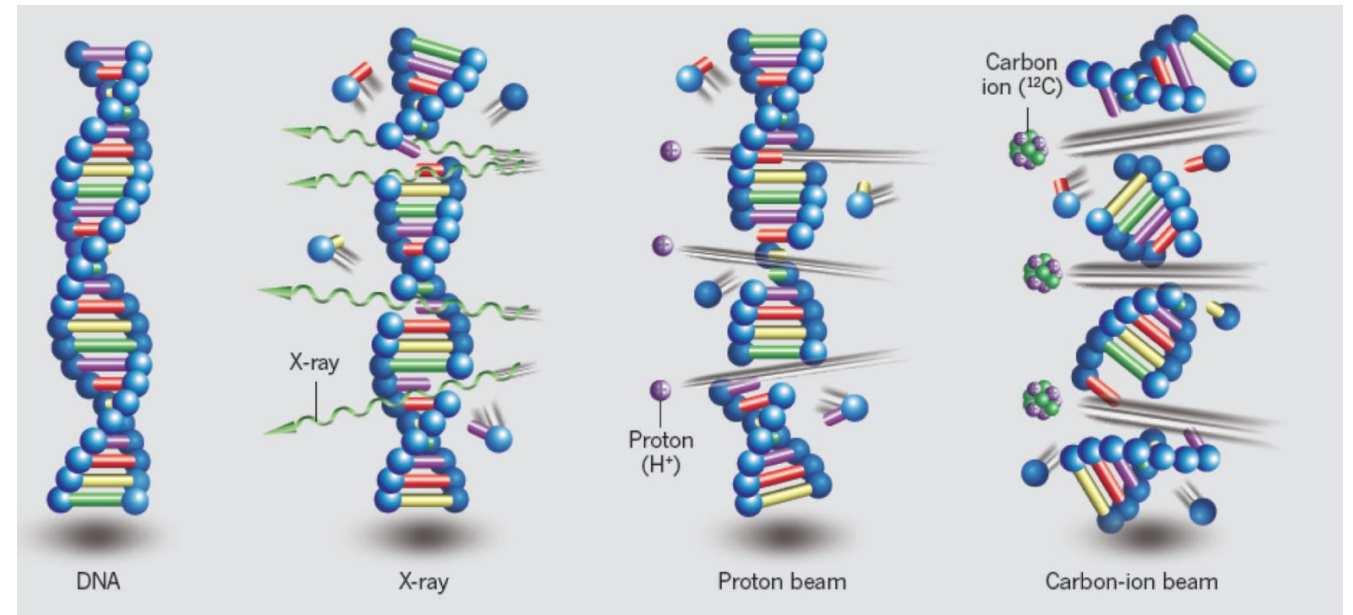


Accelerator	Beam always present during treatment?	Energy variation by electronic means?	Time needed for varying the energy
Cyclotron	Yes	No	80-100 ms (*)
Synchrotron	No	Yes	1-2 s
Linac	Yes	Yes	1-2 ms

- ❑ Relative Biological Effectiveness (RBE)
- ❑ Linear Energy Transfer (LET)

Physics challenges for linacs

- ❑ Compact and efficient accelerators

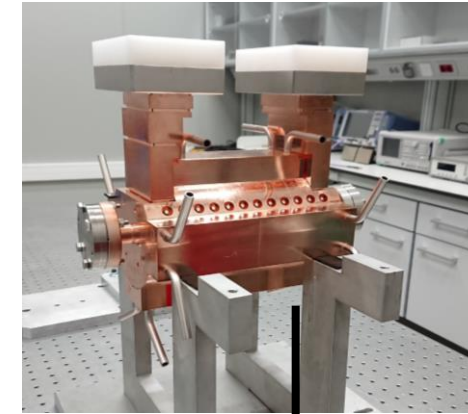
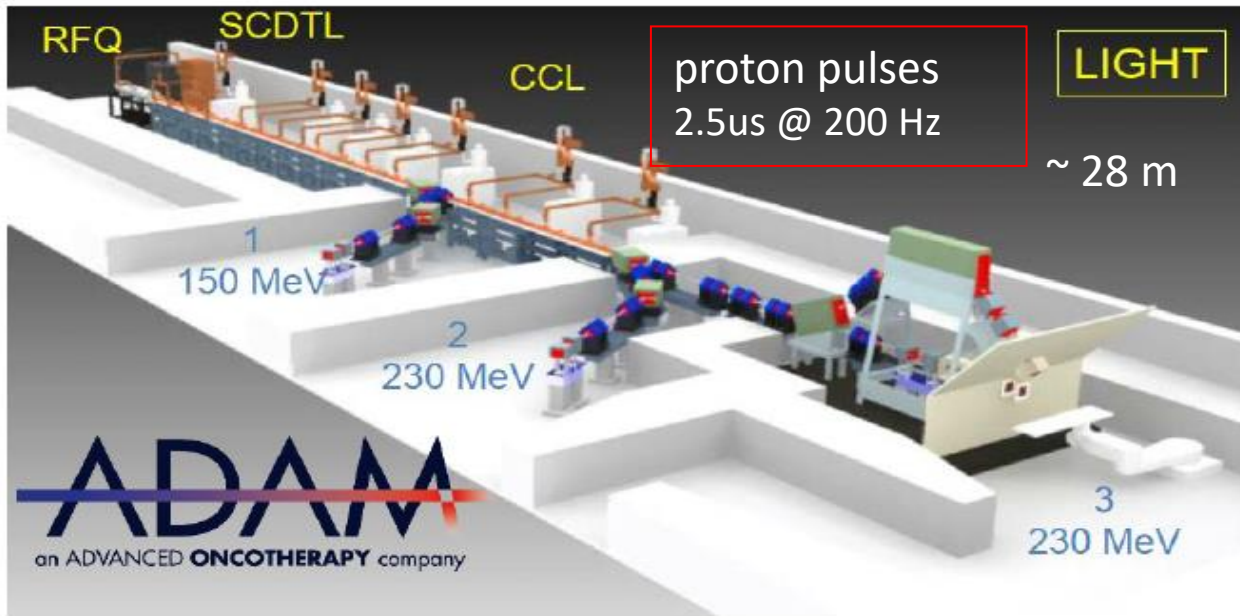


Linear Accelerators for Hadrontherapy

Normal Cavities

ADAM, spin-off of CERN and TERA foundation is developing a **proton linear accelerator** to be installed in a hospital in England

18-20 MV/m

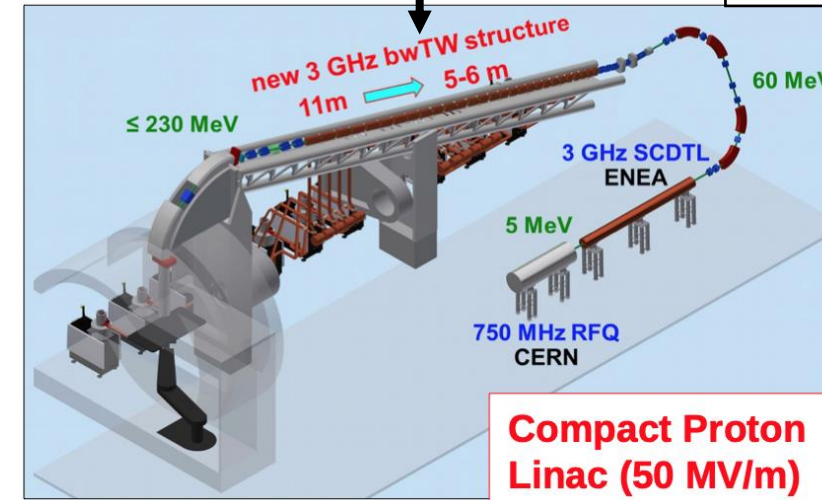


High-Gradient Cavities

Backward Travelling Wave (BTW) High Gradient cavity testing at IFIC

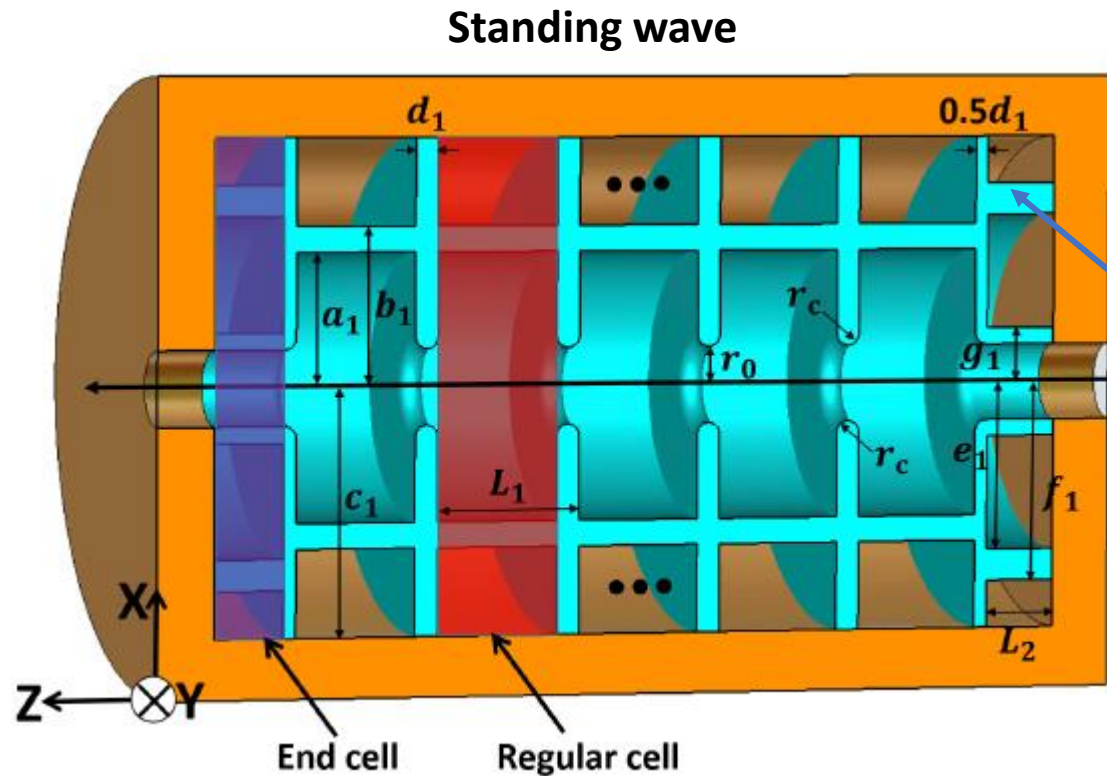
LINAC Conference 2014,
S. Benedetti et al.
RF DESIGN OF A NOVEL BACKWARD
TRAVELLING WAVE LINAC FOR PROTON
THERAPY

50 MV/m



- Limited by BDR
- High losses

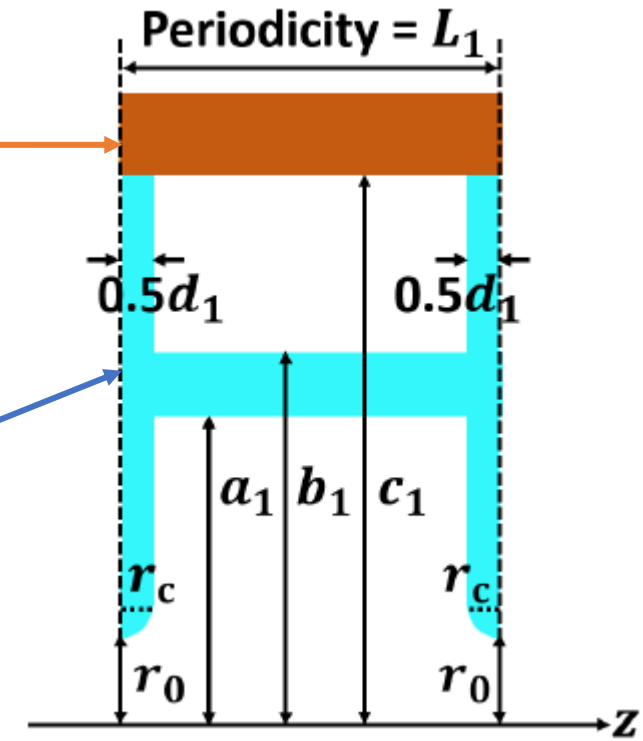
Dielectric Assist Accelerating (DAA) cavity



Copper

Dielectric:

- High ϵ_r
- Low $\tan \delta$



D. Satoh, M. Yoshida, and N. Hayashizak, "Dielectric assist accelerating structure." *Physical Review Accelerators and Beams*, vol. 19, 1, pp. 1011302, 2016
 Investigations Into X-Band Dielectric Assist Accelerating Structures for Future Linear Accelerators. Yelong Wei, Alexej Grudiev.

Parameter	Calculation
L_1	$\beta\lambda_0/2$
d_1	$\lambda_0/(4\sqrt{\epsilon_r})$
r_c	$d_1/2$
r_0	2 mm

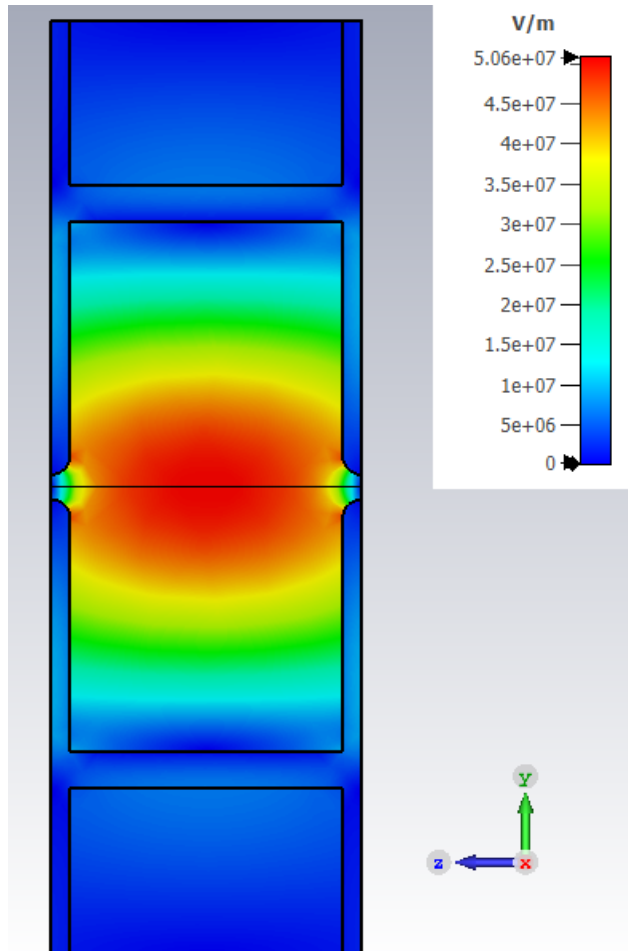
Working under $TM_{02} - \pi$ mode:

- High Q_0 .
- Dielectric helps to decrease cavity size.
- Low electric field in metal.
- Axial symmetry

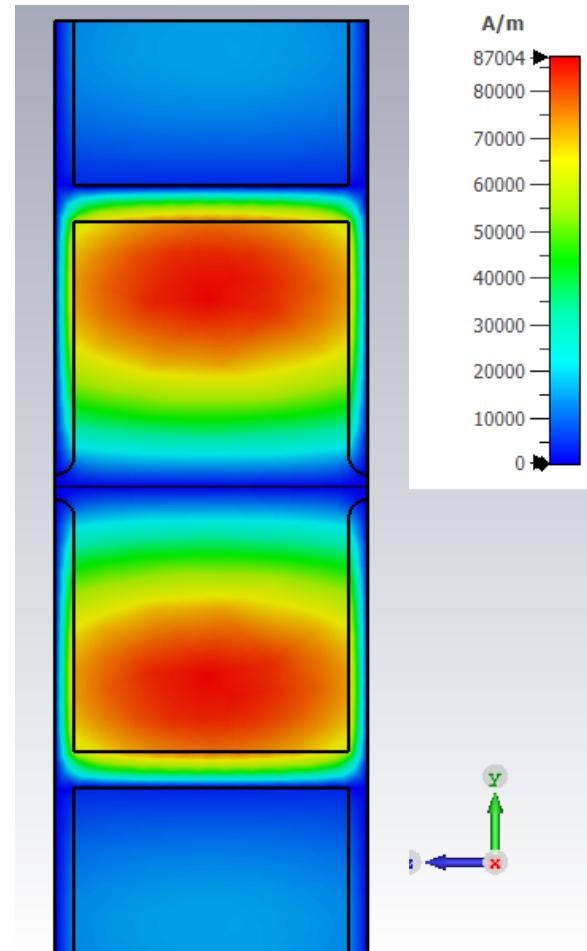
Resonant frequency for the mode depends on the combination of a_1, b_1, c_1

DAA cavity single cell solution

Electric field



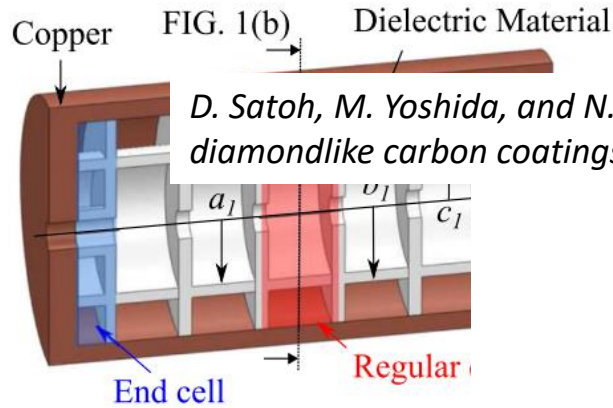
Magnetic field



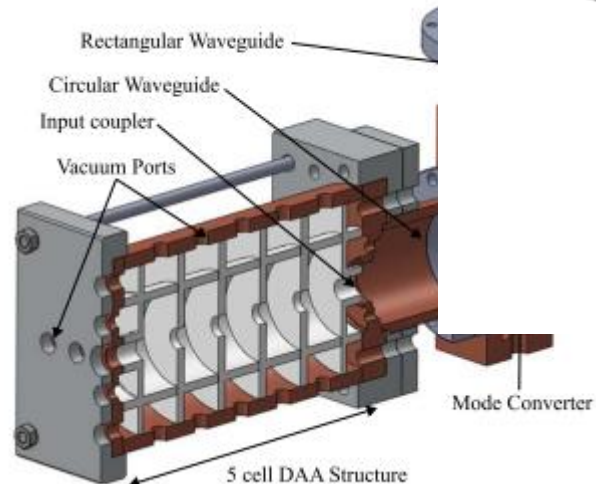
- Electric field focus on accelerating area.
 - Low field on metallic surface:
High breakdown limit
- Magnetic field concentrated on vacuum.
 - Low losses on metal:
High Q_0

Dielectric Assist Accelerating cavity

D. Satoh, M. Yoshida, and N. Hayashizak, "Dielectric assist accelerating structure." *Physical Review Accelerators and Beams*, vol. 19, 1, pp. 1011302, 2016

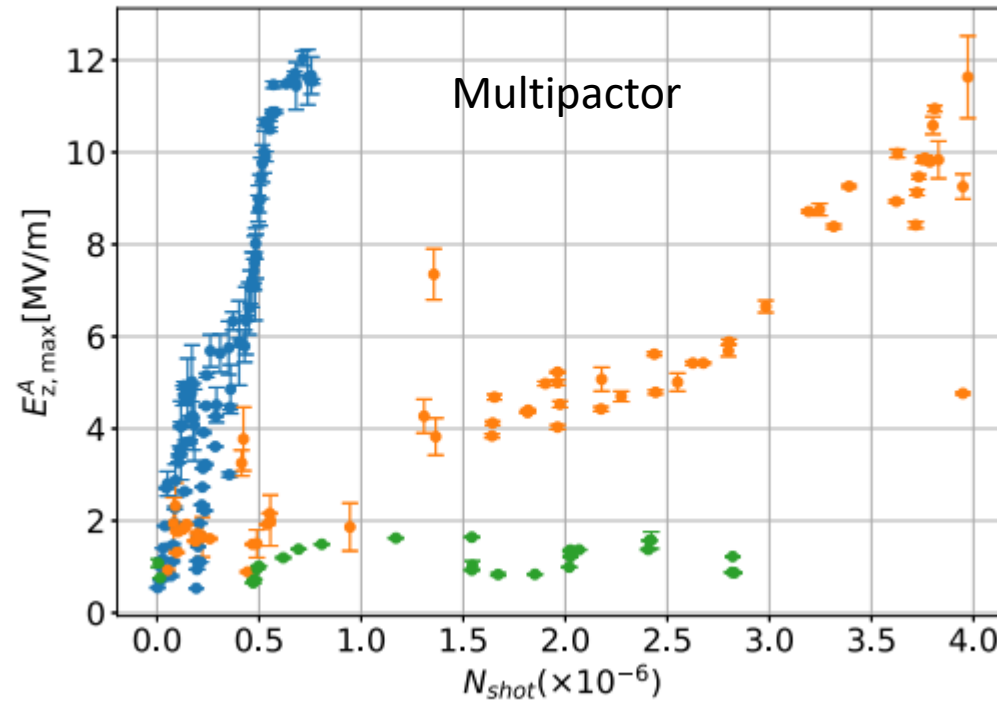


D. Satoh, M. Yoshida, and N. Hayashizak, "Multipactor suppression in dielectric-assist accelerating structures via diamondlike carbon coatings." *Physical Review Accelerators and Beams*, vol. 19, 1, pp. 1011302, 2016



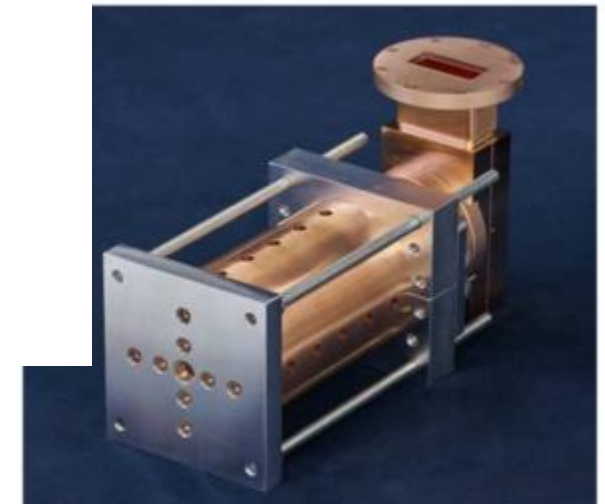
Dielectric Disk

Dielectric Cylinder



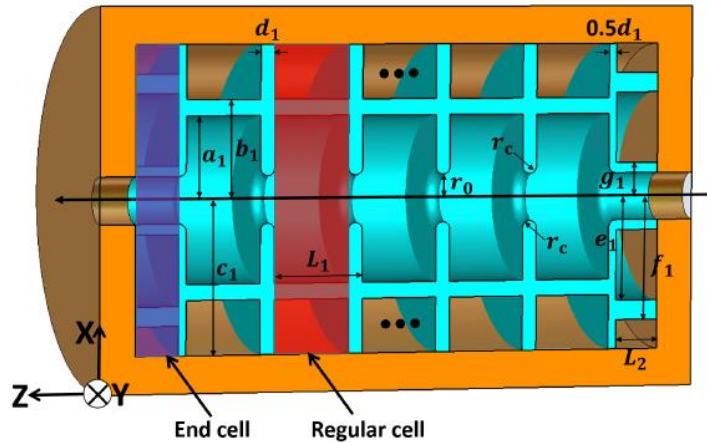
- $\beta = 1$
- $Q_0 \sim 120\,000$
- $Z_{eff} \sim 650\text{ M}\Omega/\text{m}$

Physical Review Accelerators and Beams, vol. 20,



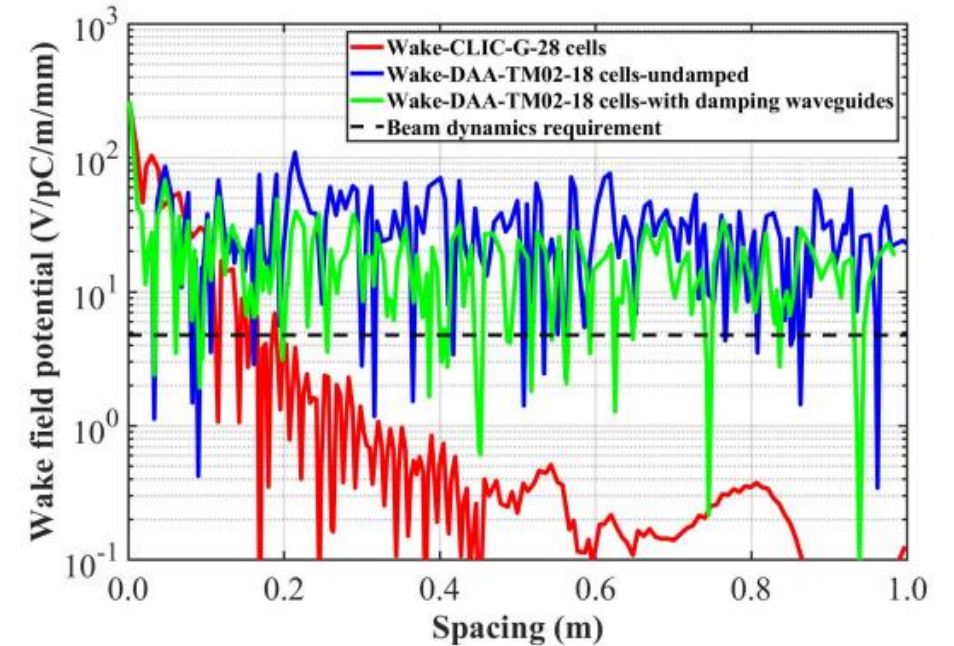
Dielectric Assist Accelerating cavity for CLIC

Investigations Into X-Band Dielectric Assist Accelerating Structures for Future Linear Accelerators. Yelong Wei, Alexej Grudiev



- MgO
- X-band
- $\beta = 1$
- $Q_0 \sim 134\,525$
- $Z_{eff} \sim 781\text{ M}\Omega/\text{m}$

Wakefields are too high



Dielectric assist accelerating structures for compact linear accelerators of low energy particles in hadrontherapy treatments. P Martinez-Reviriego et al.

- S-band
- Low β particles
- Optimize d_1
- Study of different ceramics

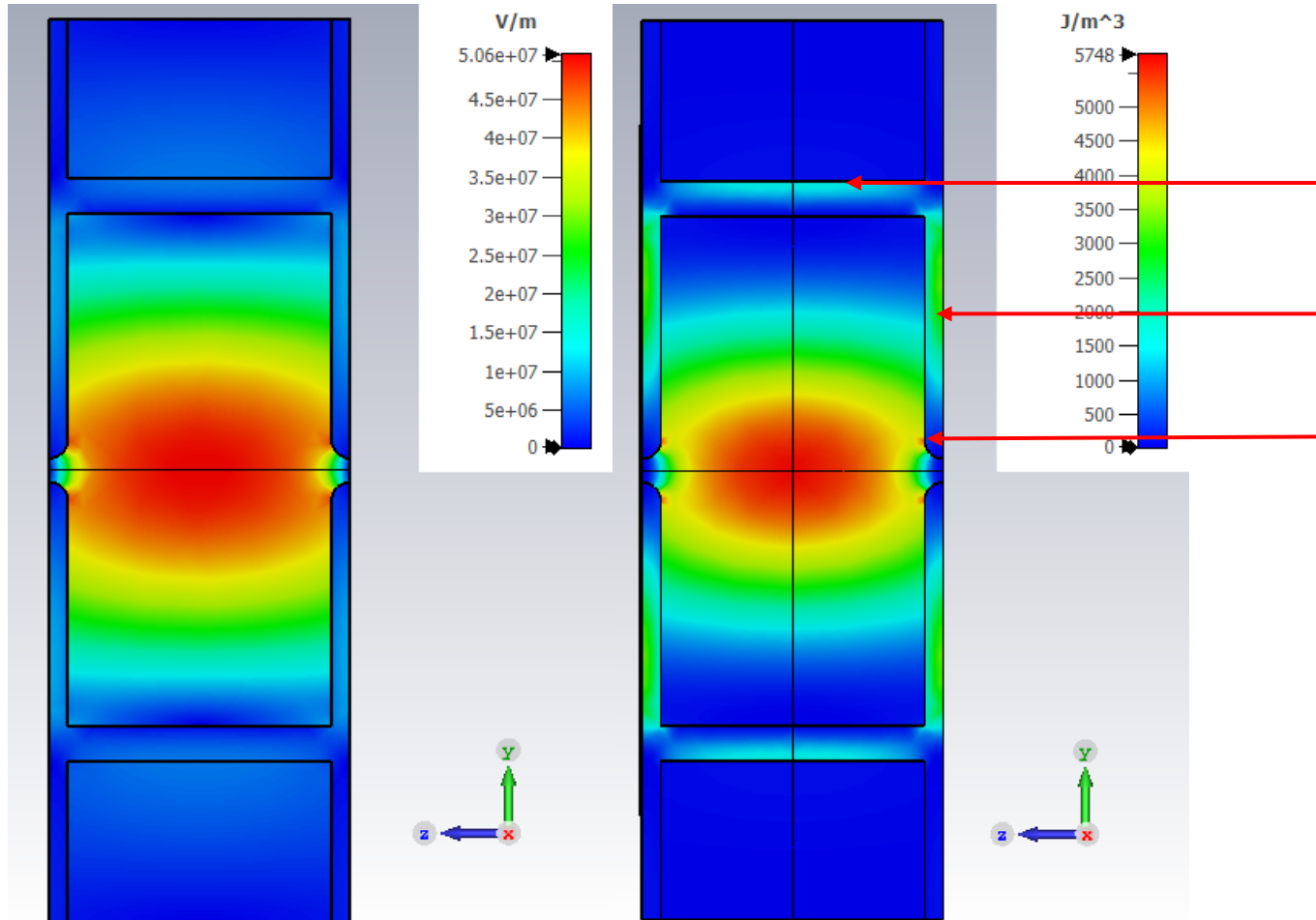


Linear accelerators for hadrontherapy (low current)

DAA cavity single cell solution

Electric field

Electric Energy



$$D = \epsilon E$$

$$E_{\parallel,1} = E_{\parallel,2}$$

$$D_{\perp,1} = D_{\perp,2}$$

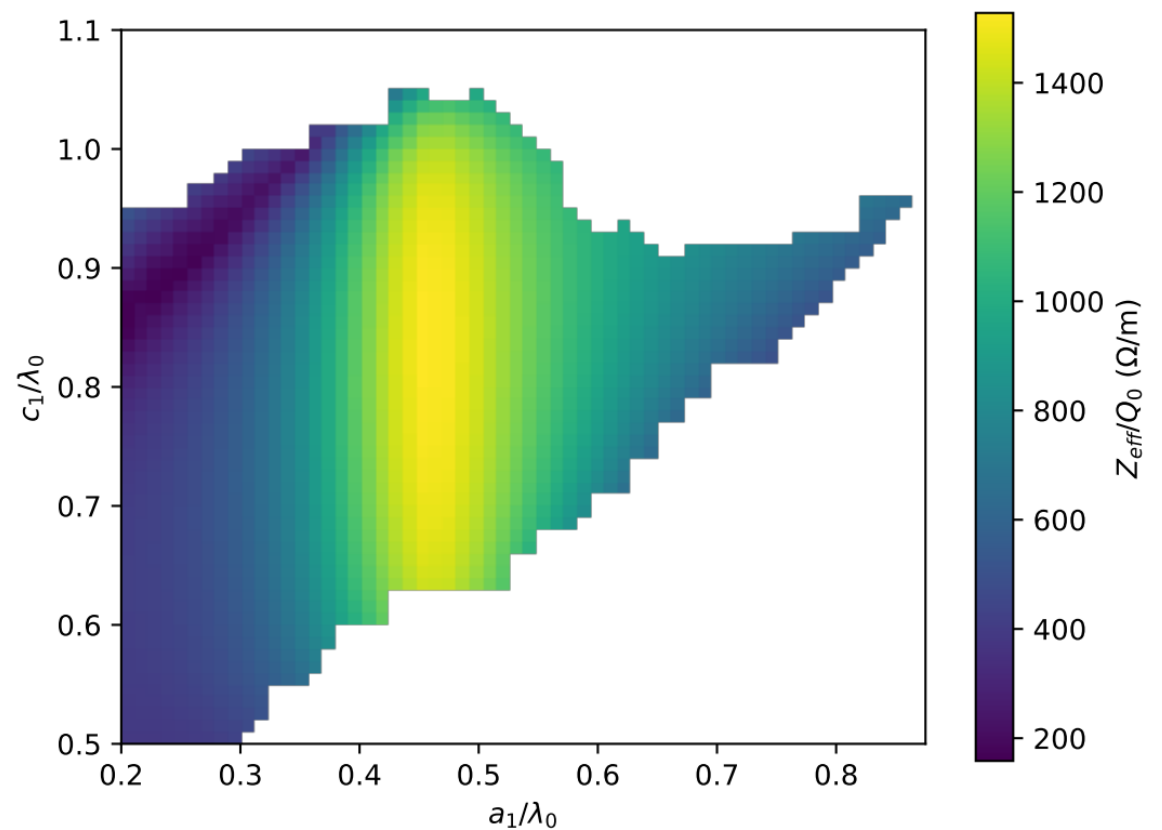
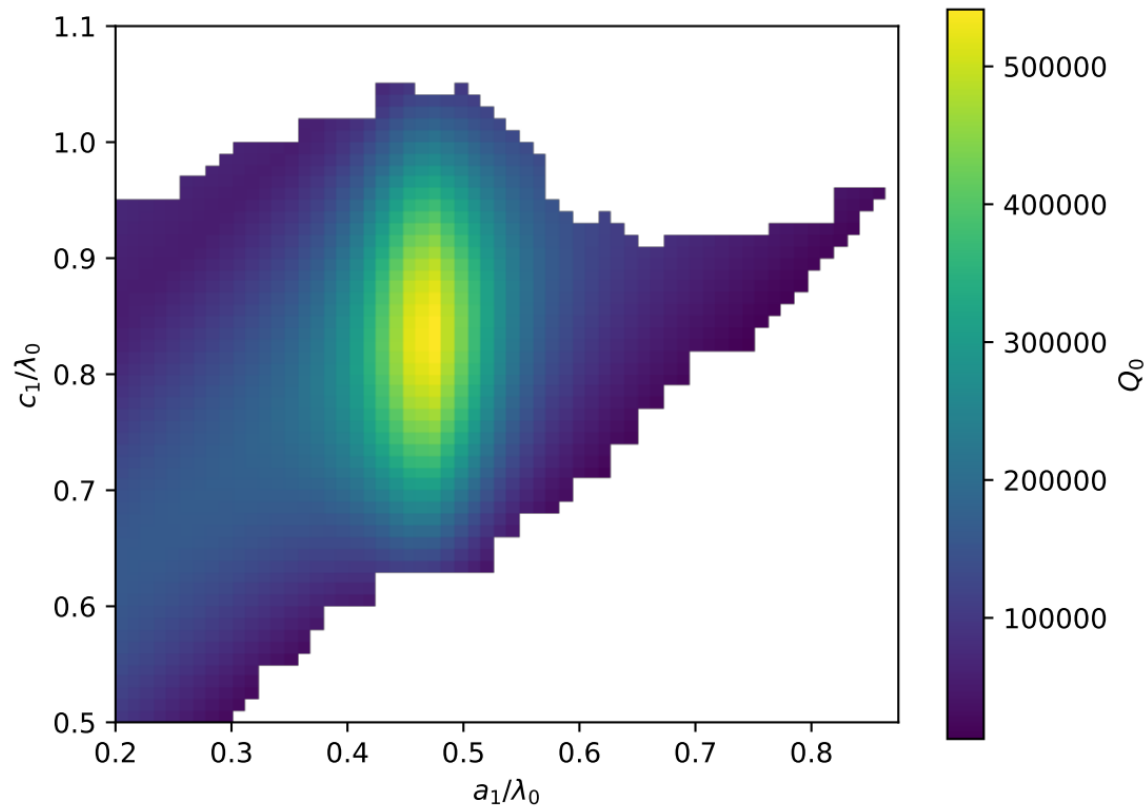
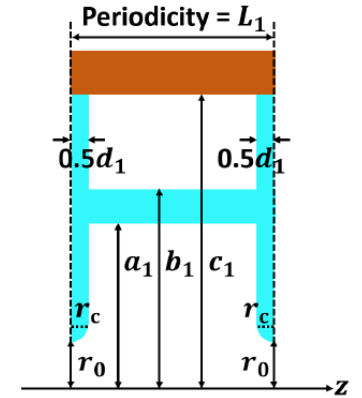
- 1st: Parallel boundary $\left\{ \begin{array}{l} E \text{ is constant} \\ \text{High } D \text{ inside dielectric} \end{array} \right.$
- 2nd: D is conserved along the dielectric
- 3rd: Perpendicular boundary $\left\{ \begin{array}{l} D \text{ is constant} \\ \text{High } E \text{ in vacuum} \end{array} \right.$

DAA cavity single cell design

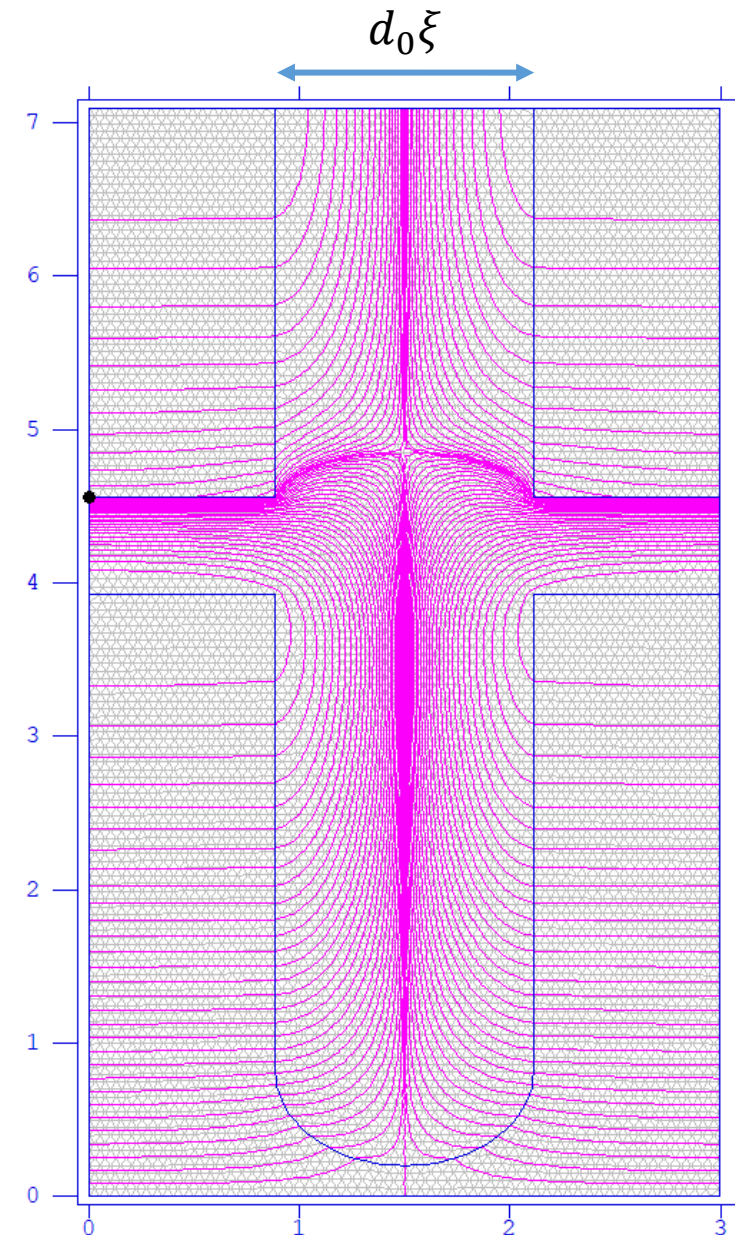
Resonant frequency for the mode depends on the combination of a_1, b_1, c_1 :

- ❑ Scan for a_1, c_1 and we look for the value of b_1 that makes $f = (3000 \pm 2)$ MHz.
- ❑ Look for the values of a_1, b_1, c_1 that maximizes Z_{eff}, Q_0

Example for ideal material: $\epsilon_r = 16.66$, $\tan \delta = 0$ and $\beta = 0.6$



DAA cavity single cell iris optimization



$$\epsilon_r = 16.66, \beta = 0.6$$

Scan in iris thickness: $d_0 = \lambda_0 / (4\sqrt{\epsilon_r})$

Iris thickness = $d_0 \xi$

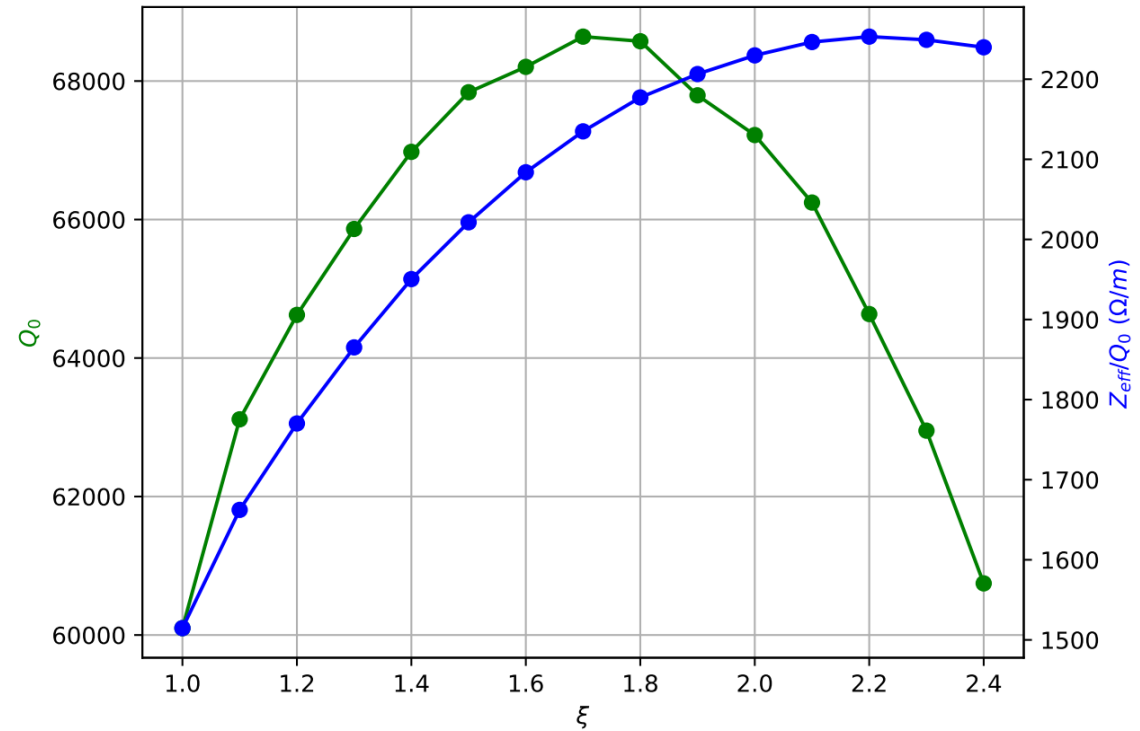
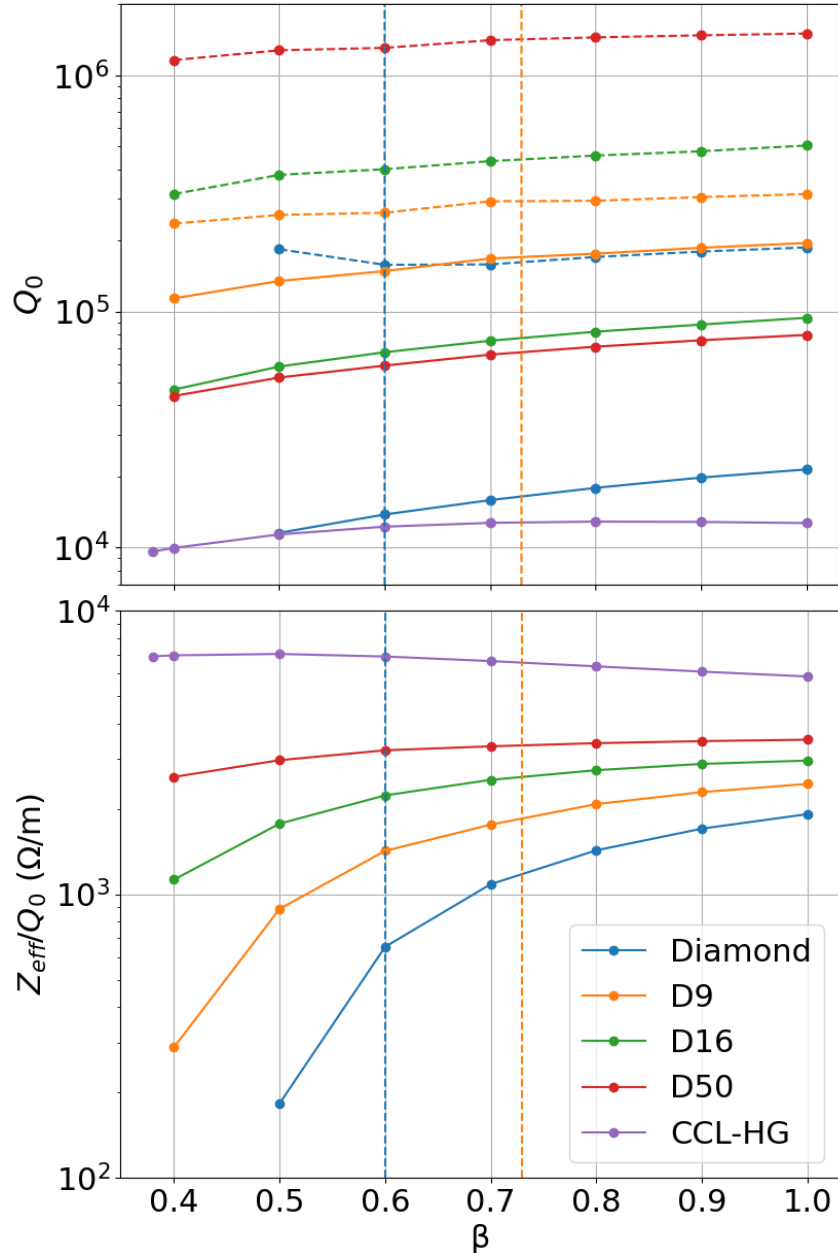


TABLE I
LIST OF DIELECTRICS STUDIED IN THE OPTIMIZATION

Material	Acronym	ϵ_r	$\tan \delta$
CVD Diamond	Diamond	5.7	10^{-4}
MgO	D9	9.64	6×10^{-6}
MgTiO ₃	D16	16.66	3.43×10^{-5}
BaTiO _x	D50	50.14	8×10^{-5}

$$\beta = \{0.4, 0.5, \dots, 1\}$$

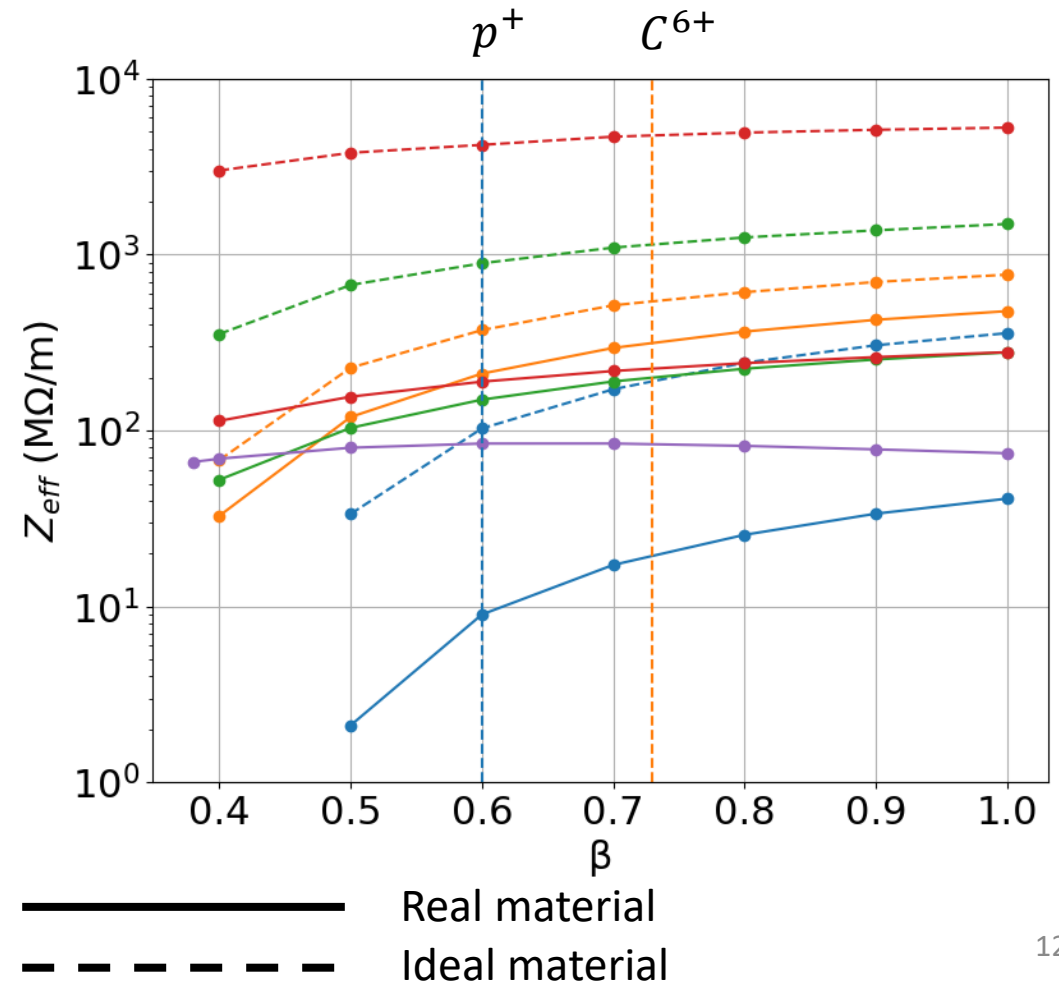
Energy range for hadrontherapy



○ Protons: 70 – 230 MeV $\rightarrow \beta : 0.37 - 0.6$

○ $^{12}\text{C}^{6+}$: 100 – 430 MeV/u $\rightarrow \beta : 0.43 - 0.73$

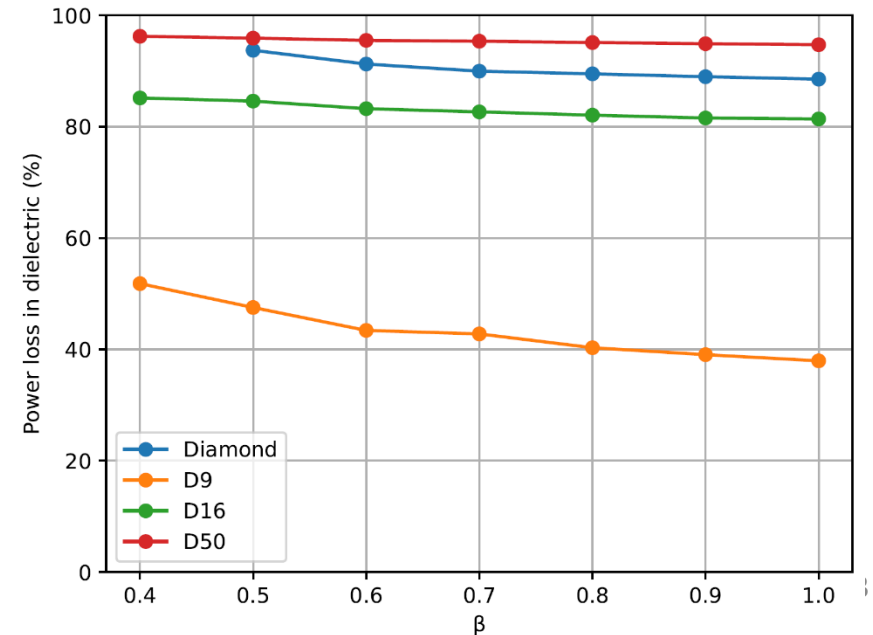
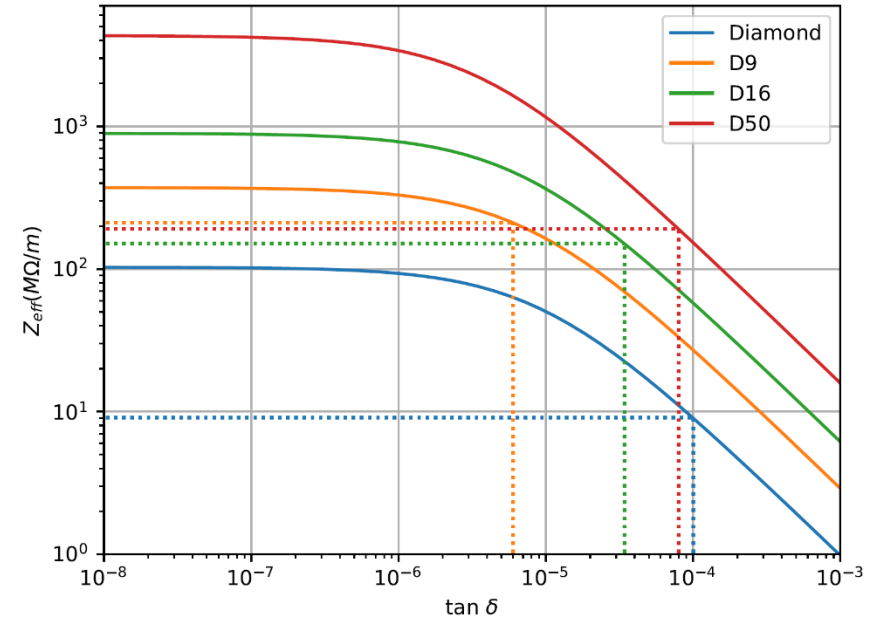
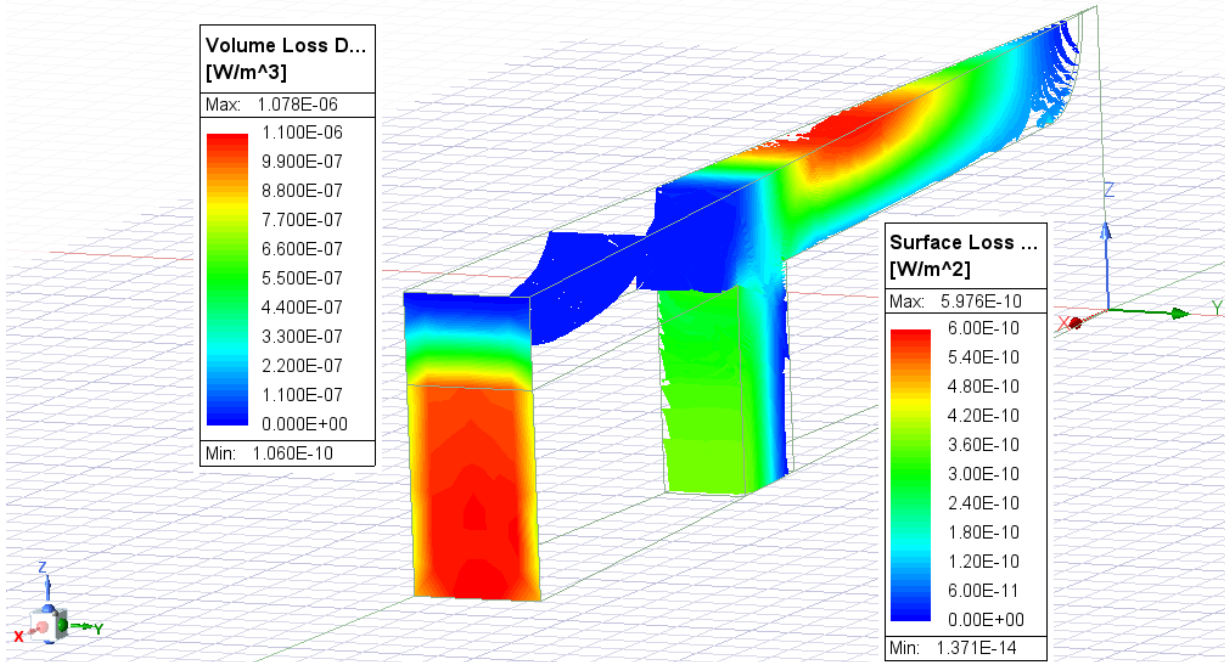
Bencini, V. (2020). *Design of a novel linear accelerator for carbon ion therapy* (Doctoral dissertation, Rome U.).



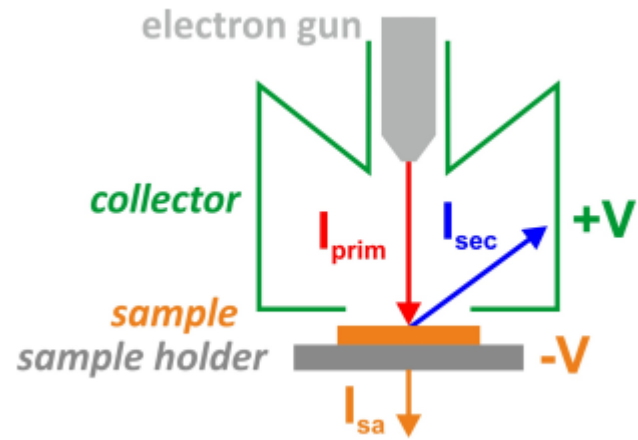
Scan in losses

Conductor: $P_c = \frac{R_s}{2} \int |\hat{n} \times \vec{H}|^2 dS$ $R_s = \sqrt{\frac{\omega\mu_0}{2\sigma_c}}$

Dielectric: $P_d = \frac{1}{2} \omega \tan \delta \epsilon_0 \epsilon_r \int |\vec{E}|^2 dV$



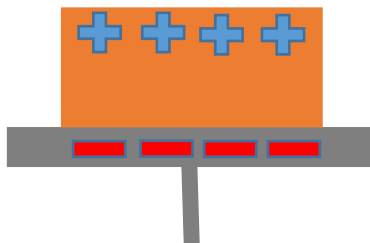
SEY Measurements



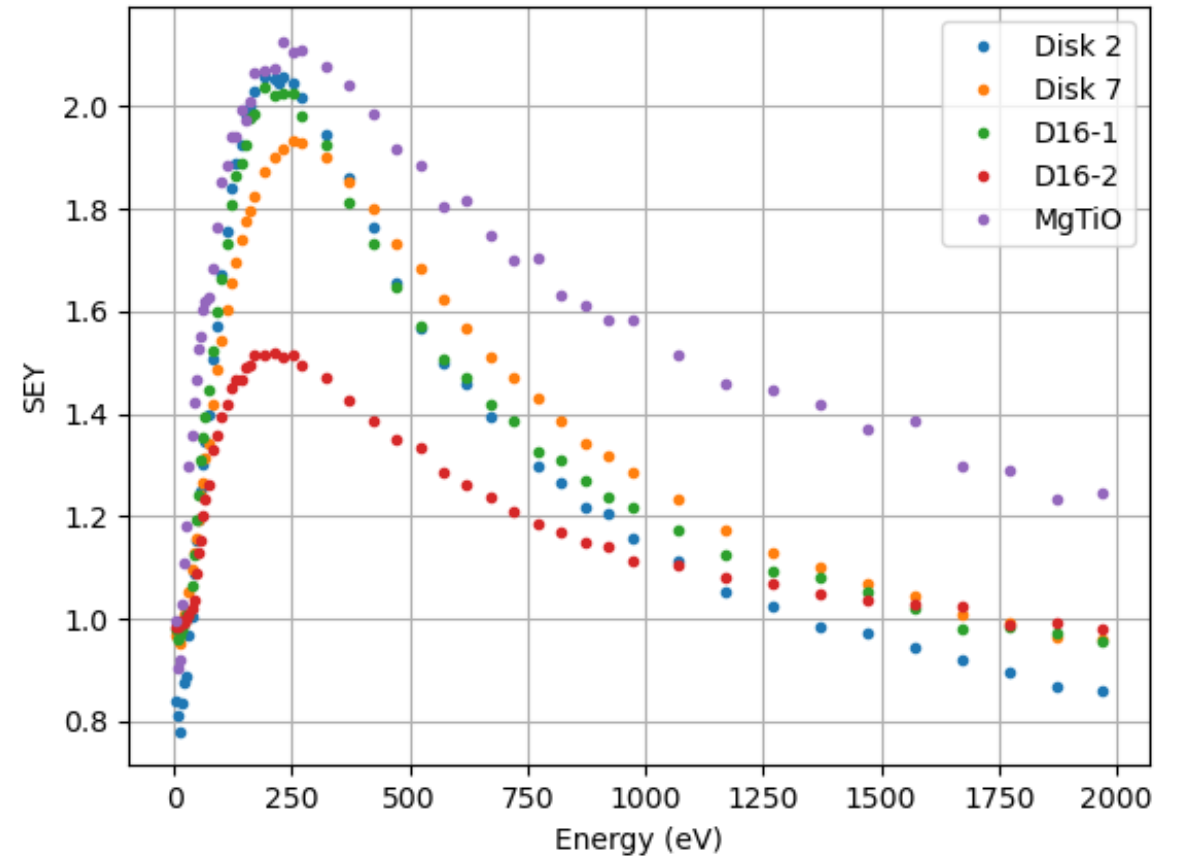
Metals

$$Q = VC$$

$$C = \frac{\epsilon_r \epsilon_0 S}{d}$$

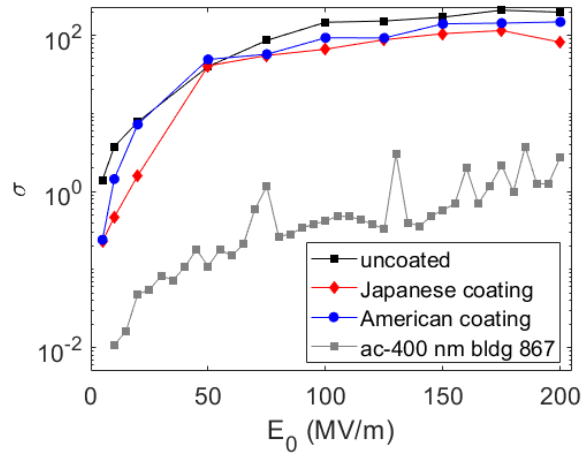
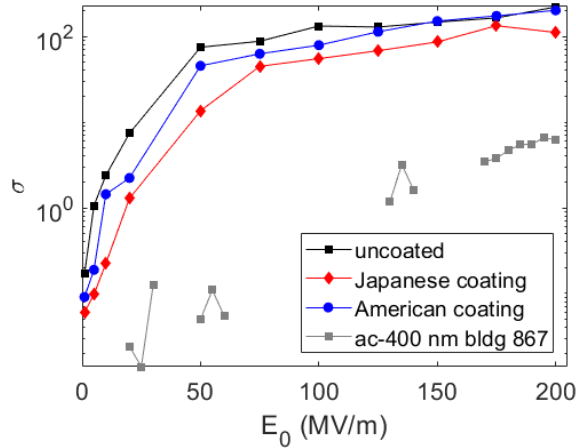


Dielectric



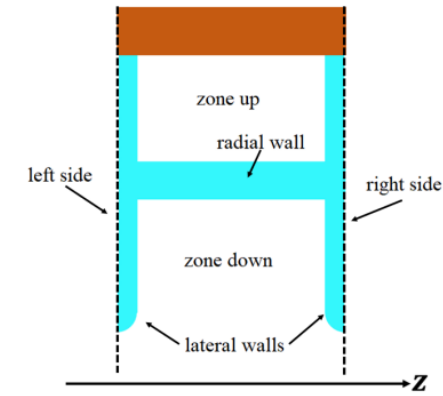
Multipactor in the DAA structure

Some of the main results of the multipactor simulations in the DAA cell are summarized on this slide



$$N_e(t/T) = N_0 e^{\sigma T}$$

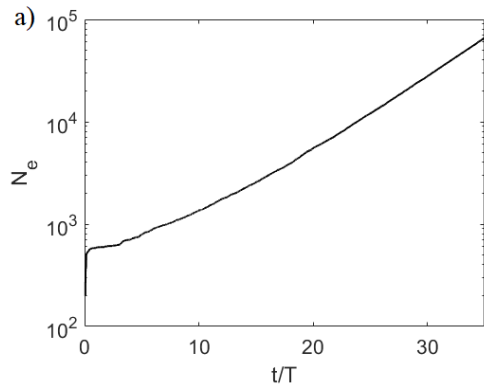
N_e , number of electrons
 N_0 , initial electron number
 growth factor



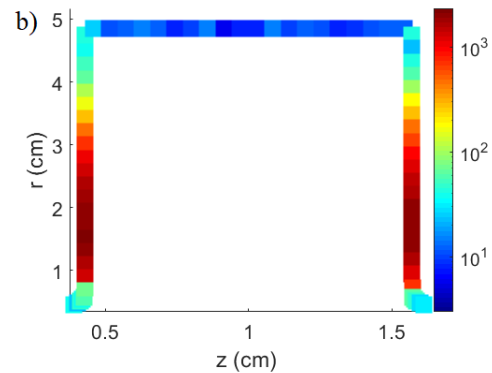
Courtesy of Daniel Gonzalez-Iglesias

Multipactor growth factor σ as a function of the RF electric field amplitude at the cell axis in the down zone (left) and up zone (right)

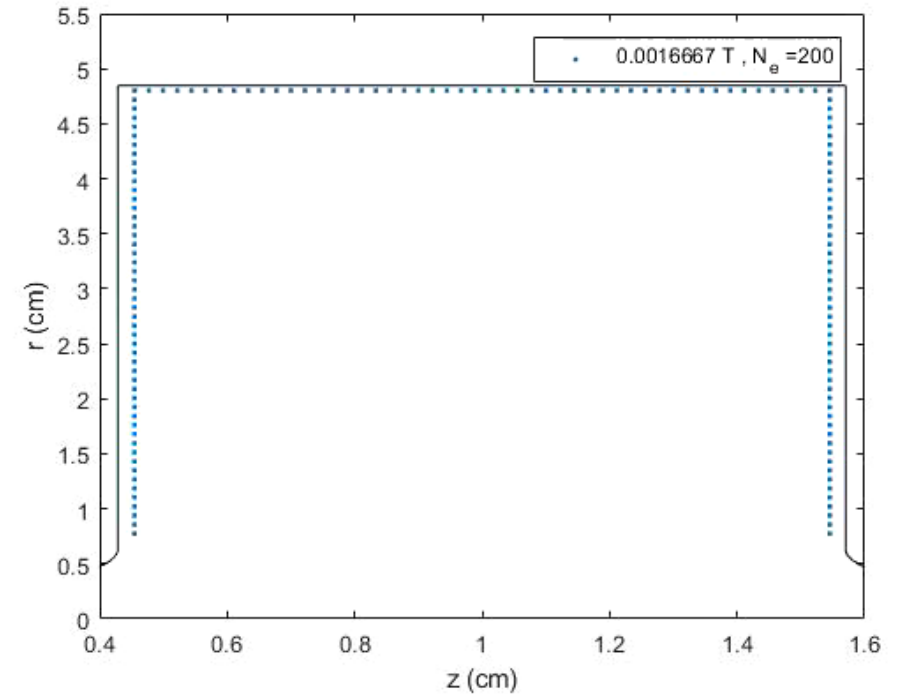
Results for $E_0 = 1$ MV/m (down zone)



a) Number of electrons in the structure as a function of time normalised to the period of the RF signal.



b) Colour map with the number of electrons impacting at each wall position being able to generate two or more secondary electrons.

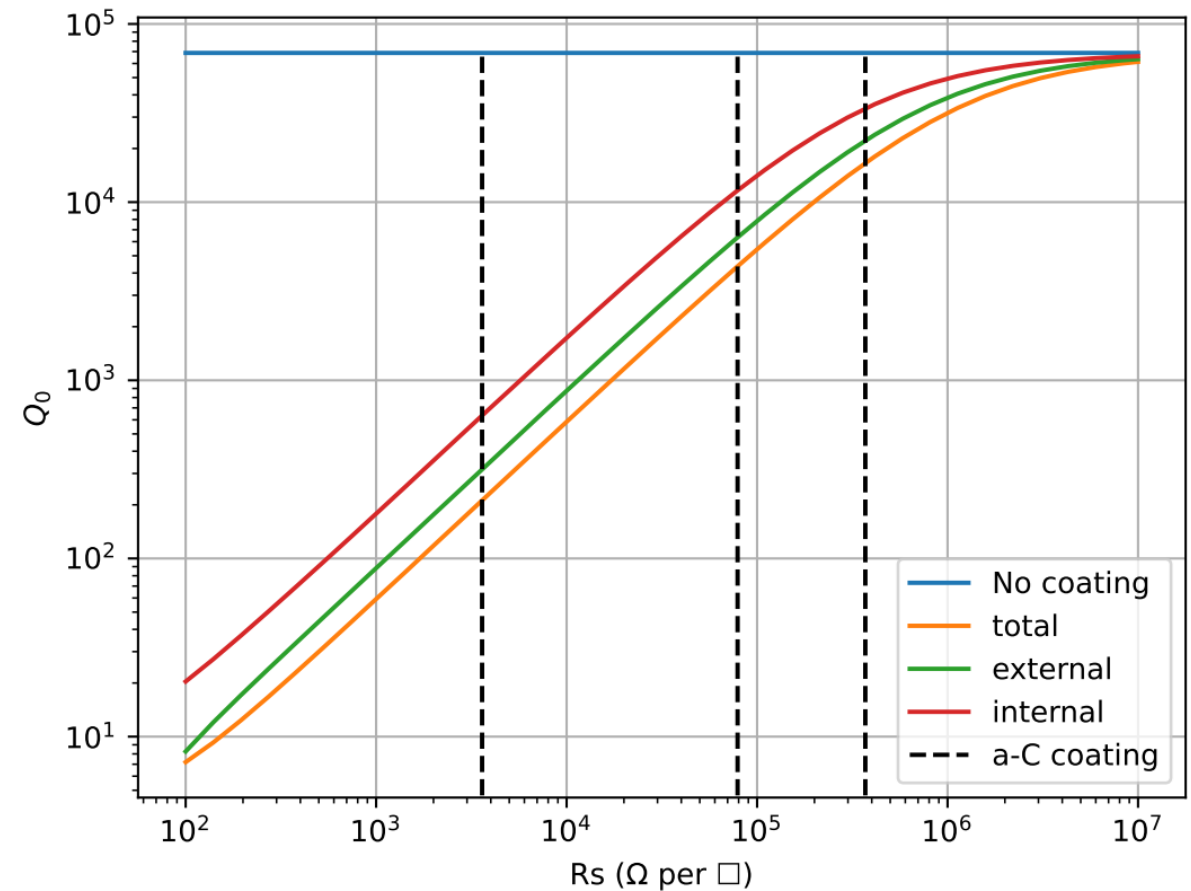
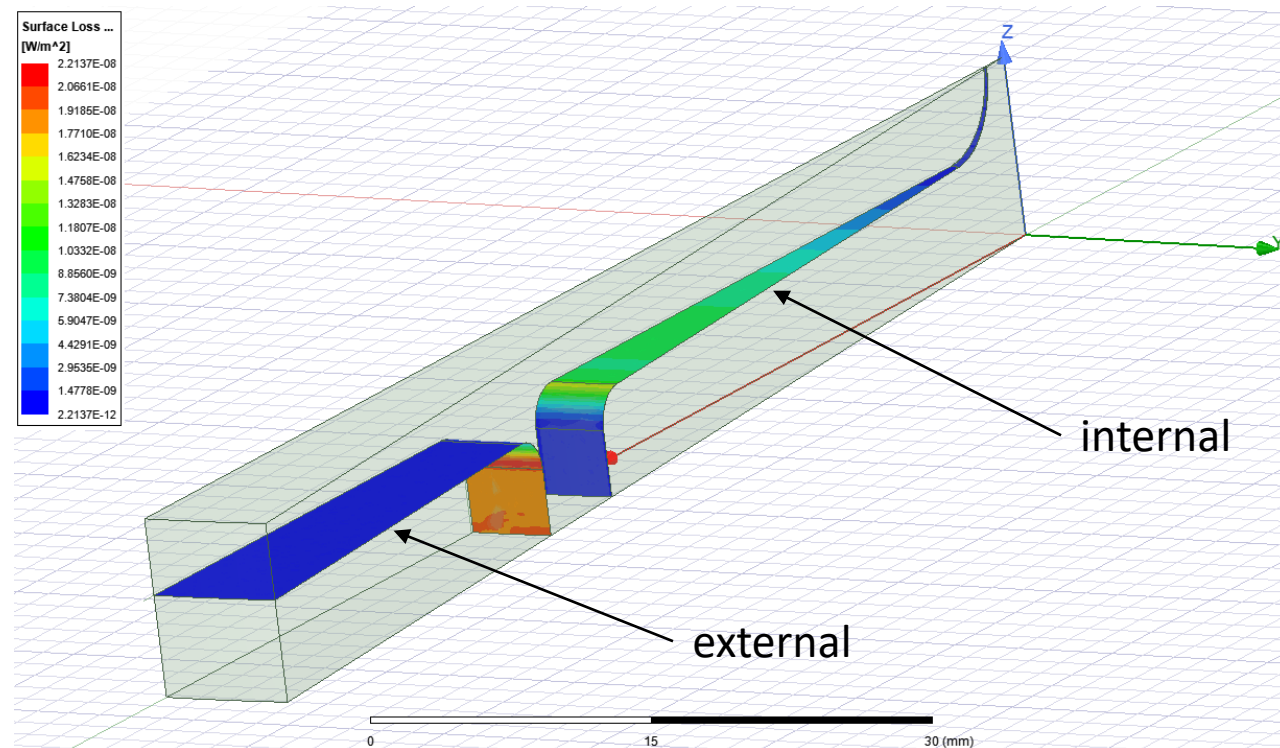


Multipactor simulation in the down zone for $E_0 = 1$ MV/m

Coating losses

- a-C coating can reduce multipactor but it has an impact on electromagnetic performance

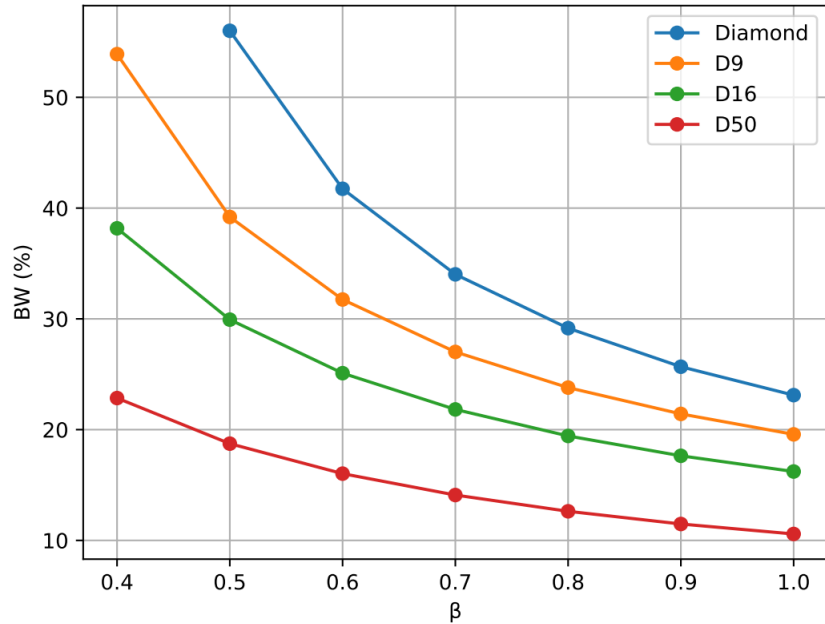
Coating losses:
$$P_s = \frac{1}{2R} \int |\hat{n} \times \vec{E}|^2 dS$$



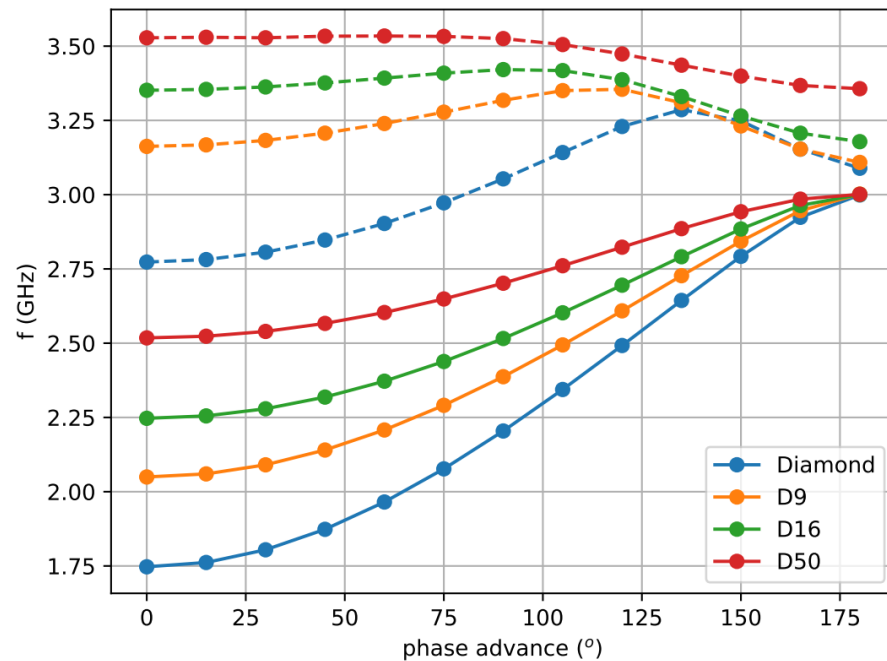
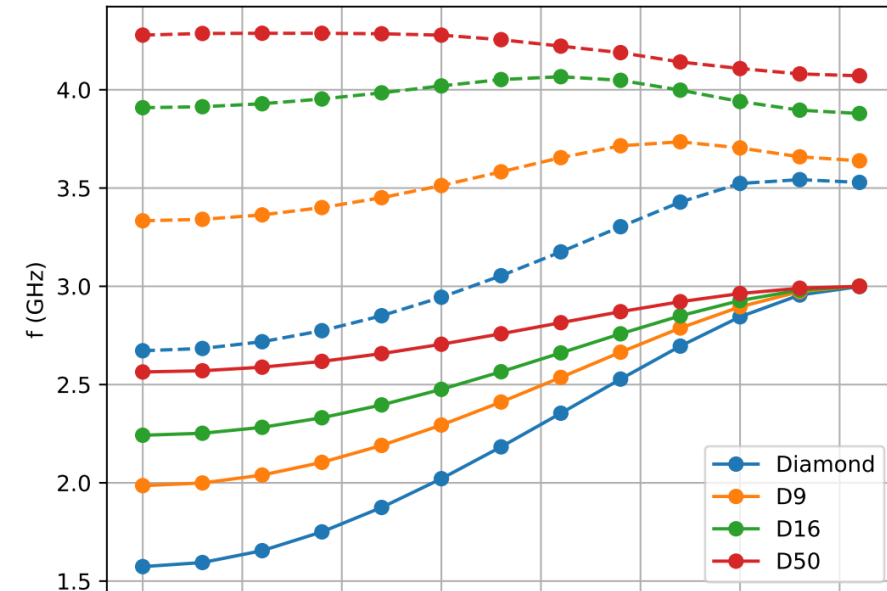
Coupling and dispersion curve

$$BW = \frac{f_{\pi} - f_0}{f_{\pi}} 100(\%)$$

D16, $\beta = 0.6$



- High electrical coupling between cells.
 - No need for coupling cells
- Low ϵ_r leads to dispersion curves crossing.
- Thicker irises lead to mode overlapping.



Thermal simulation

Thermal load:

- Heat flux: Surface losses in copper.
- Heat generation: Volumetric losses in dielectric.

Electromagnetic normalization:

- $G * T = 50 \text{ MV/m}$
- $\text{DUT} = 0,075 \times 10^{-3}$

$\beta = 0.6$

Boundary condition: 22 °C

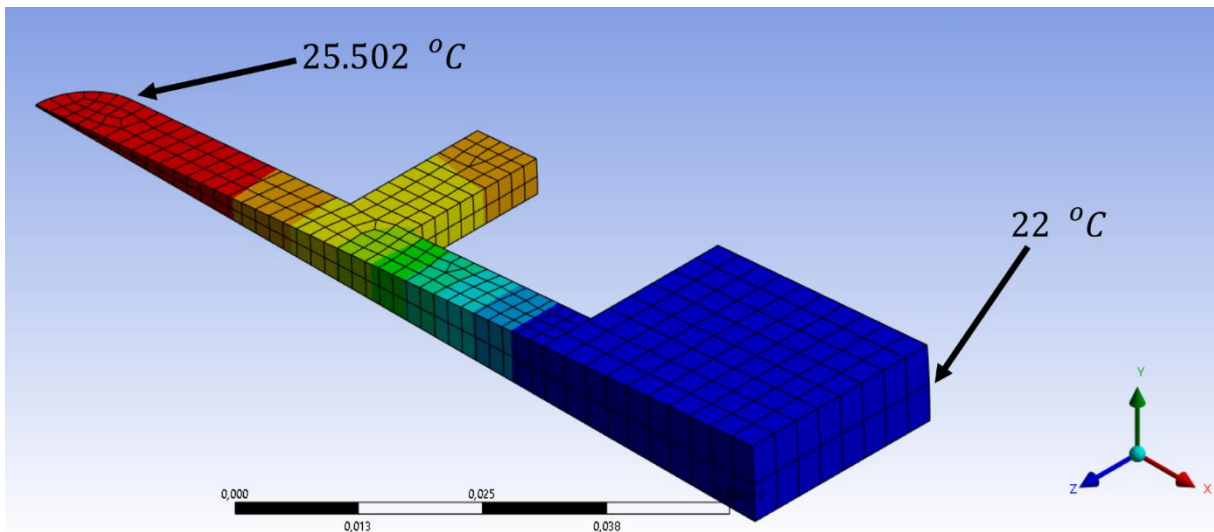


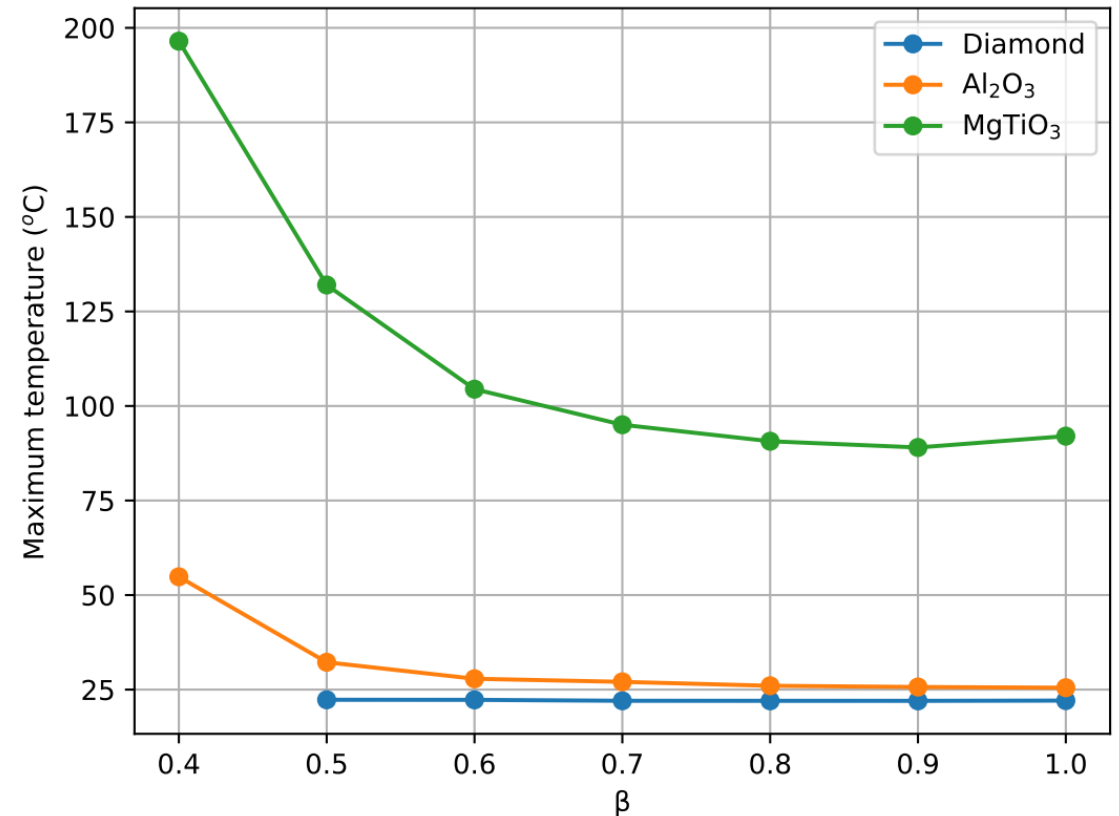
TABLE II
LIST OF DIELECTRICS USED FOR THERMAL SIMULATIONS

Material	ϵ_r	$\tan \delta$	$\kappa \text{ W}\cdot\text{m}^{-1}\cdot\text{K}^{-1}$
CVD Diamond	5.7	10^{-4}	2000
Al ₂ O ₃ 99.99%	9.8	10^{-5}	30
MgTiO ₃	16.66	3.43×10^{-5}	3.8

<https://www.americanelements.com/magnesium-titanate-12032-30-3>

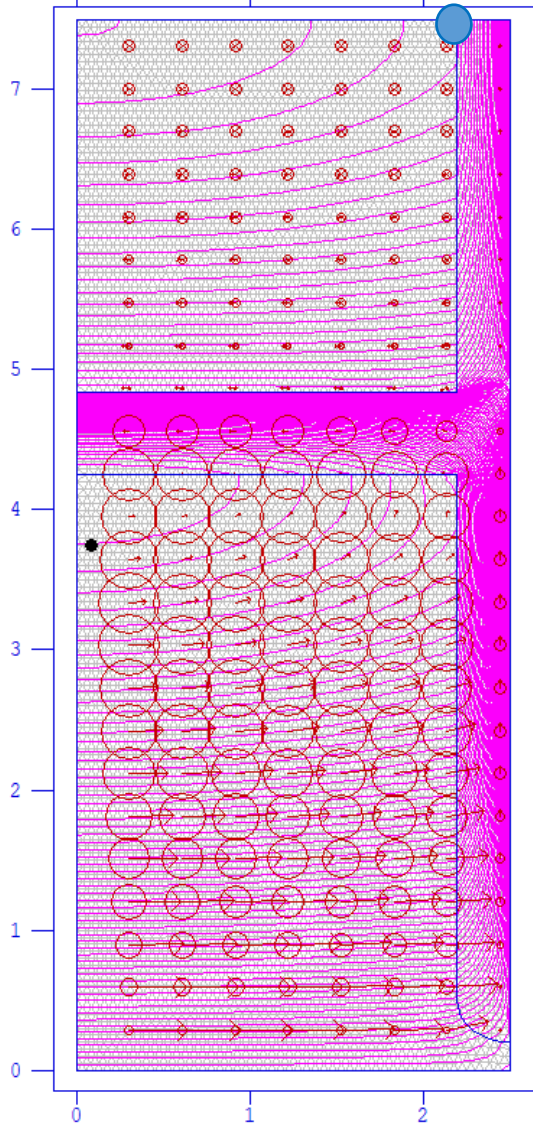
<https://www.makeitfrom.com/material-properties/Magnesium-Titanate-IEC-60672-Type-C-320>

<https://accuratus.com/alumox.html>

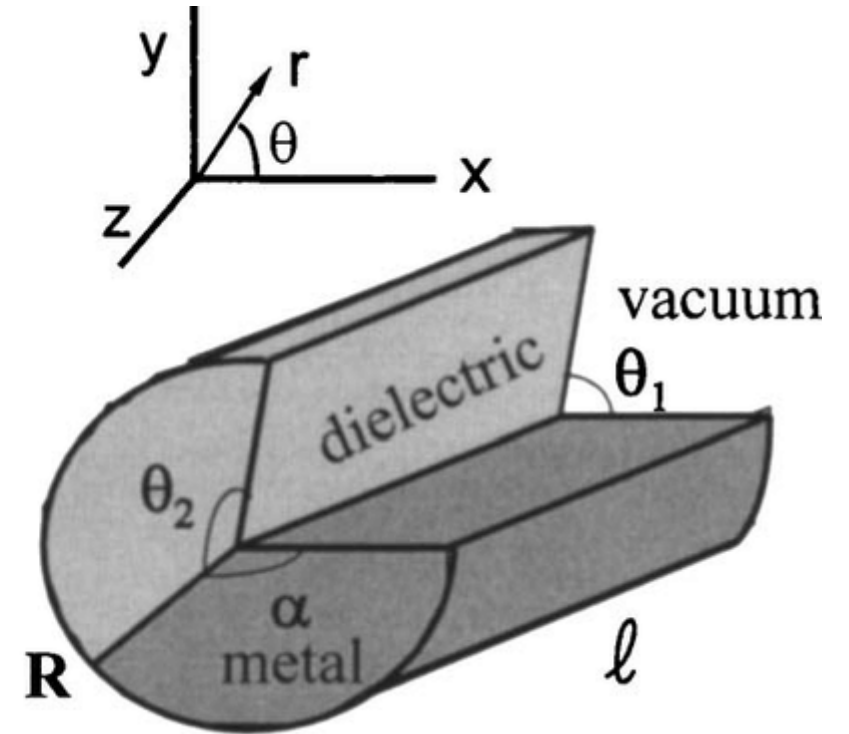
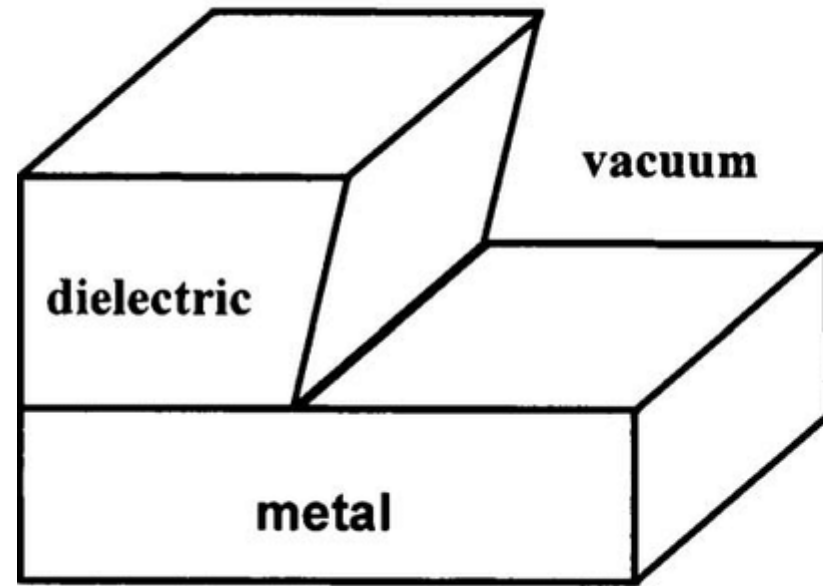


Critical points

DAA cavity $F = 3001.5979$ MHz

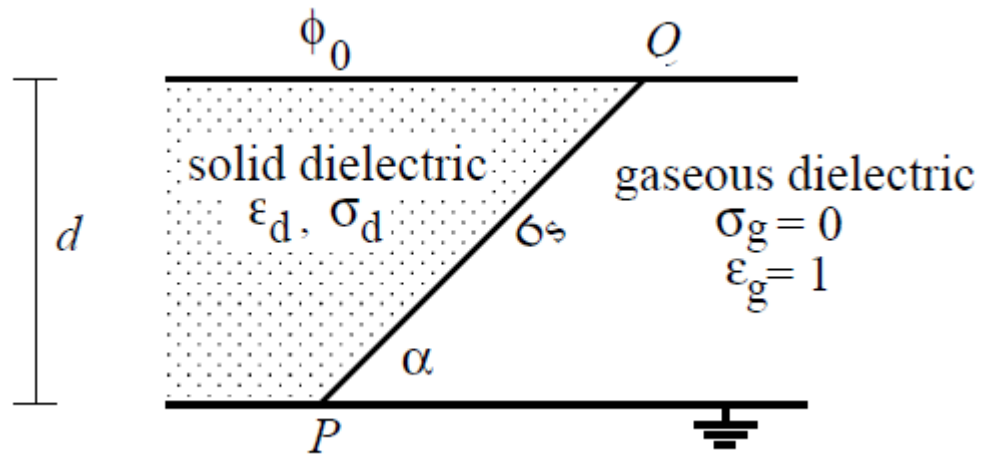


Triple junction points can lead to **instabilities and singularities** in electric field in the neighborhood of the point



In the surroundings of the junction, $\lambda \gg L$ so we can use a 2D constant field approach.

Analytical approach



Techaumnat, B., Hamada, S., & Takuma, T. (2002). Effect of conductivity in triple-junction problems. *Journal of electrostatics*, 56(1), 67-76

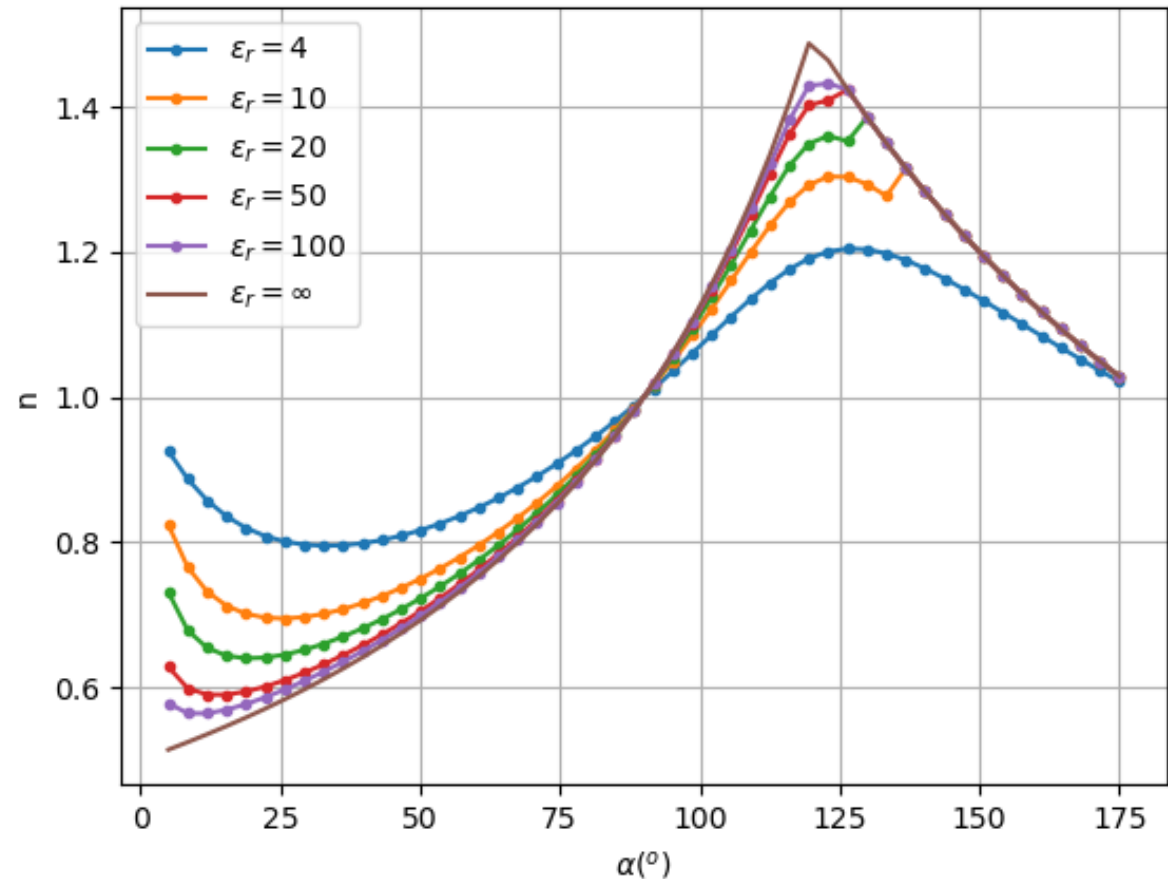
$$\phi_g \approx ar^z \sin z\theta$$

$$\phi_d \approx br^z \sin z(\pi - \theta)$$

$$z = n + jm$$

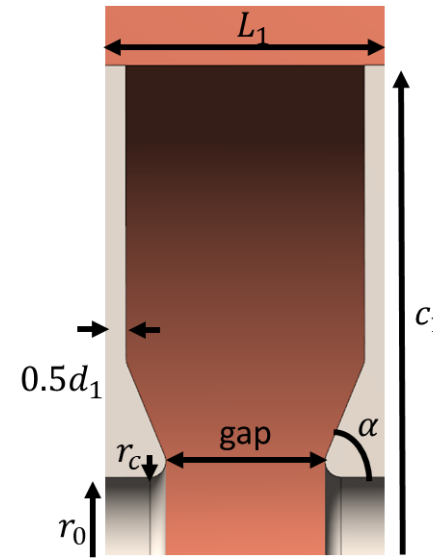
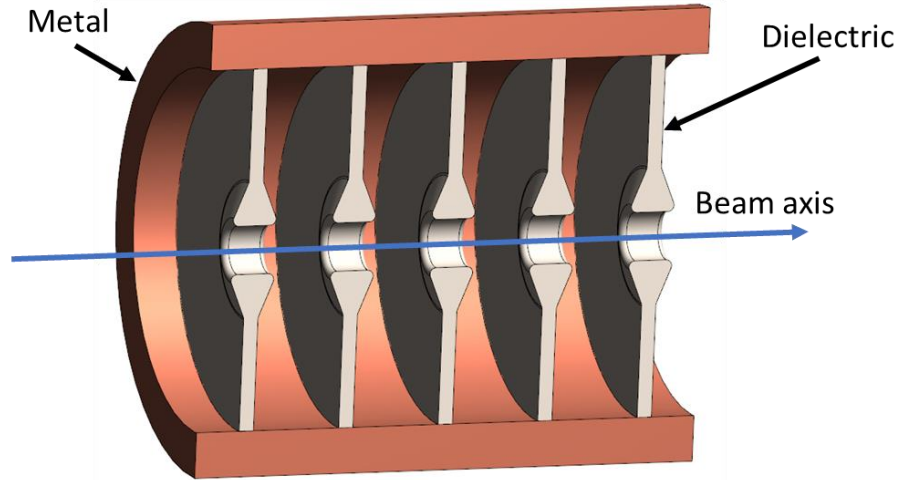
The contact-point electric field will be **infinitely large** if $n < 1$ and will be **zero** if $n > 1$. A non-zero and non-singular value will exist only if $n = 1$.

$$\cot n\alpha + \varepsilon_d \cot n(\pi - \alpha) = 0$$



Dielectric Disk Accelerating (DDA) cavity

□ **Goal:** design a prototype to test dielectric cavities.

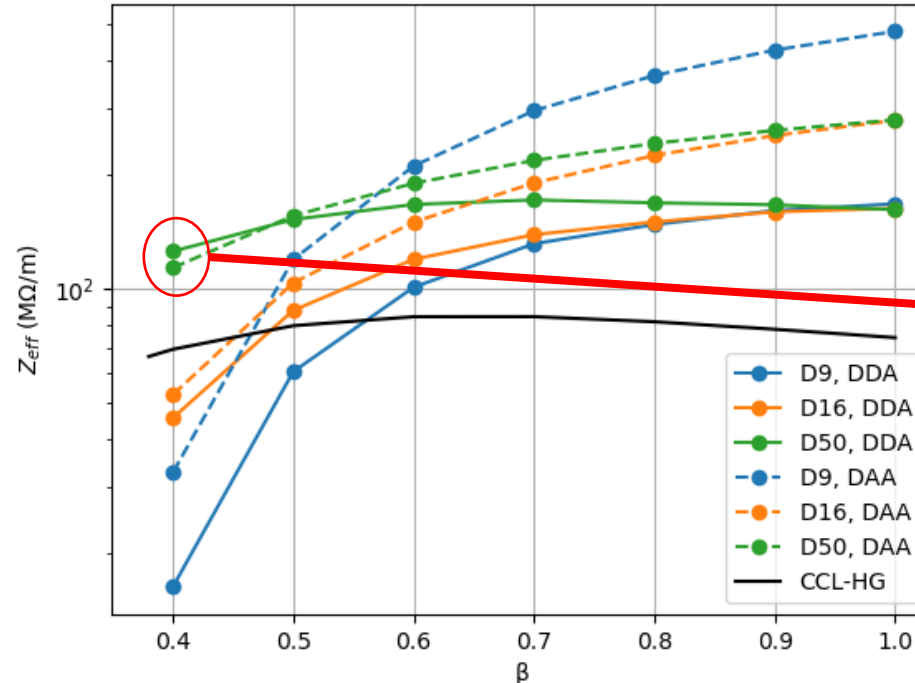
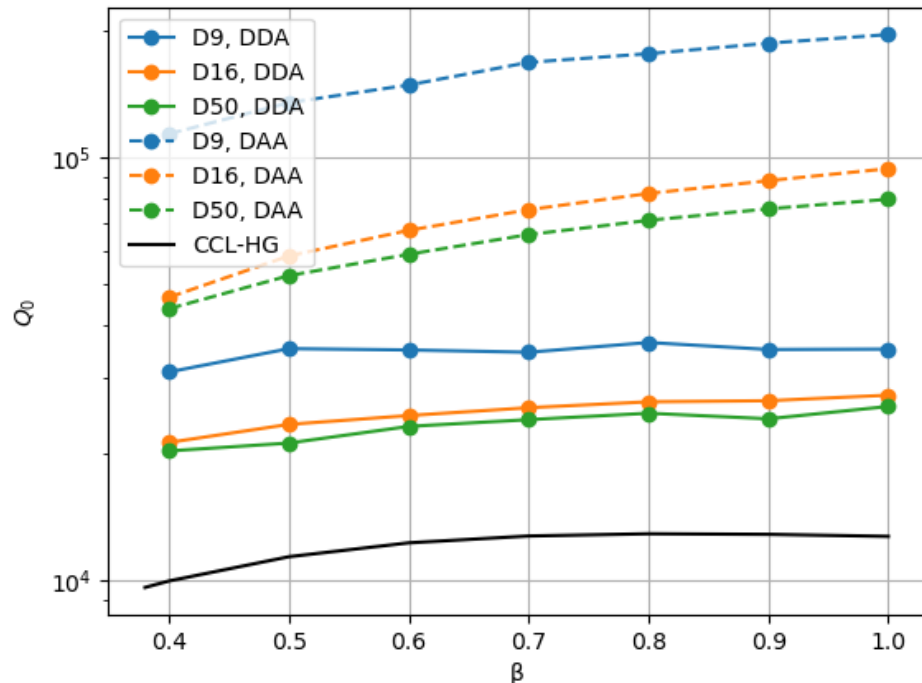


Advantages:

- Simpler geometry
- Less sensitive to material

Challenges:

- Multipactor
- Fabrication



DDA structure with **D50** material for $\beta = 0.4$ is a promising solution.

Conclusions

- ❑ DAA have extremely high Q_0 and Z_{eff} :
 - Results are better for high ϵ_r and β
 - Lower input power needed.

- ❑ Z_{eff}/Q_0 worse than copper structures
 - Higher total energy needed.

- ❑ Iris length is an important parameter to add in the optimization process.

- ❑ Multipactor must be suppressed by coatings with high sheet resistivity.

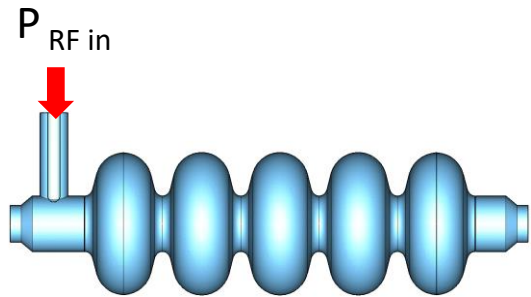
- ❑ Very high coupling between cells
 - Modes overlapping can be a problem for low ϵ_r and β .

- ❑ Very low thermal conductivity can be a source of mechanical problems.

- ❑ Triple junction point and sharp corners must be carefully studied to avoid singularities and instabilities.

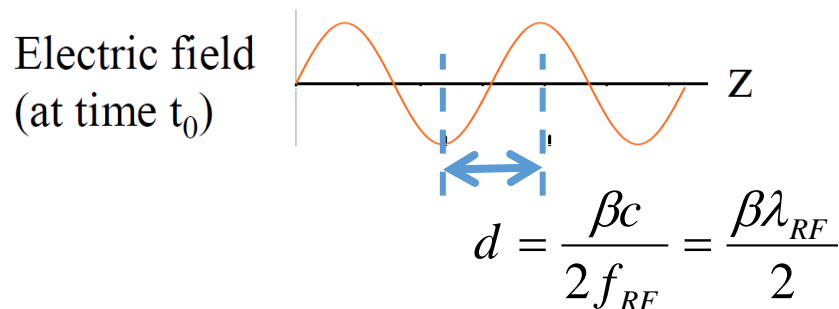
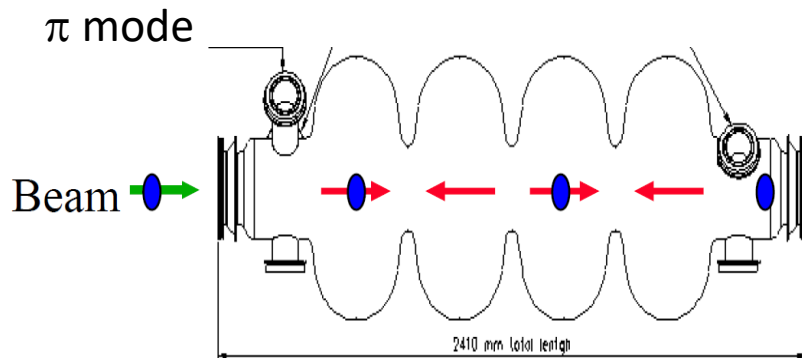
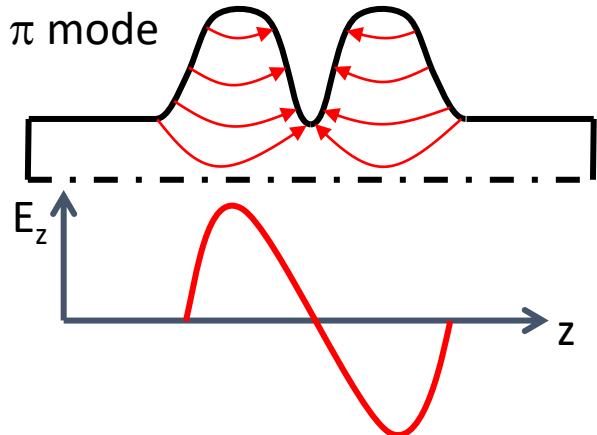
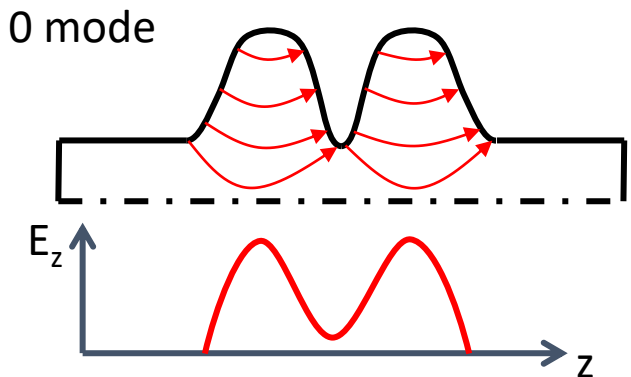
Back up

Standing Wave Acceleration Cavities



Cylindrical single (or multiple cavities) working on the TM_{010} -like mode are used

Synchronization condition



β : particle velocity
 d : distance between cells
 f_{RF} : RF frequency
 c : speed of light in vacuum

Figures of merit:

- Shunt impedance: efficiency of the acceleration mode.

$$R = \frac{\hat{V}_{acc}^2 T^2}{P_{diss}} \quad [\Omega]$$

NC cavity $R \sim 1M\Omega$ SC cavity $R \sim 1T\Omega$

- Quality factor: efficiency to store RF energy .

$$Q = \omega_{RF} \frac{W}{P_{diss}}$$

NC cavity $Q \sim 10^4$ SC cavity $Q \sim 10^{10}$

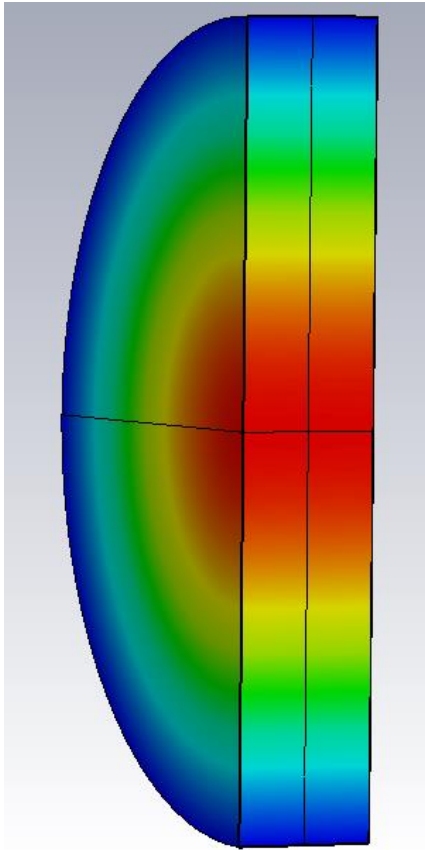
- R/Q: pure geometric qualification factor.

$$\frac{R}{Q} = \frac{\hat{V}_{acc}^2 T^2}{\omega_{RF} W} \sim 100 \Omega$$

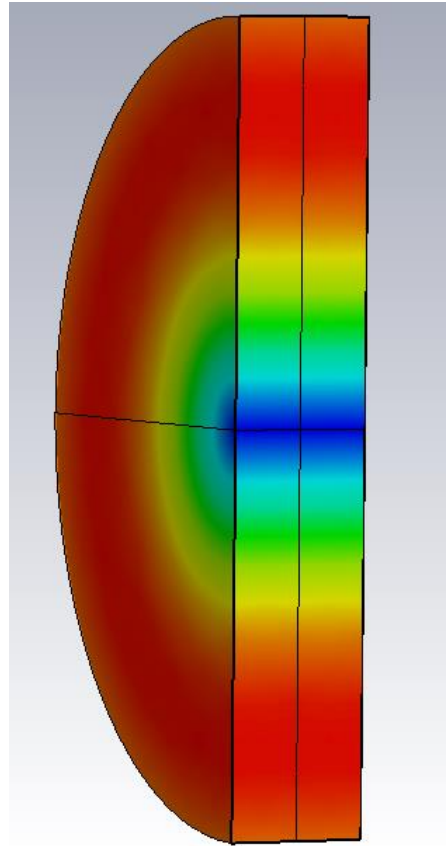
HG-CCL Copper structure single cell

Pillbox cavity TM_{010}

Electric field



Magnetic field

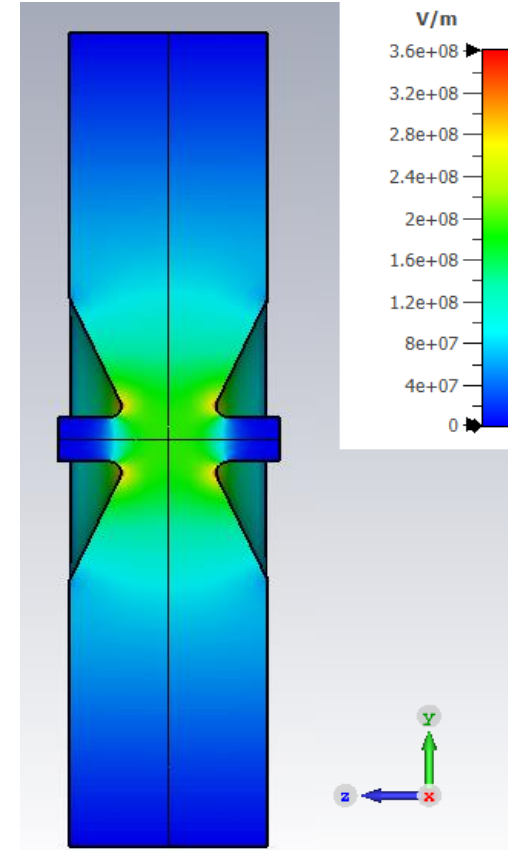


Optimization

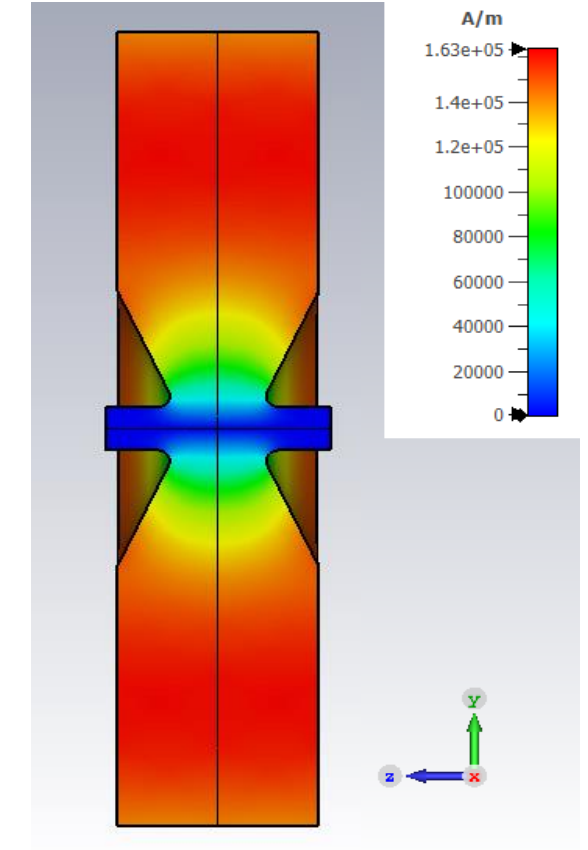


$\beta = 0.38$, mode $TM_{01} - \pi$

Electric field



Magnetic field

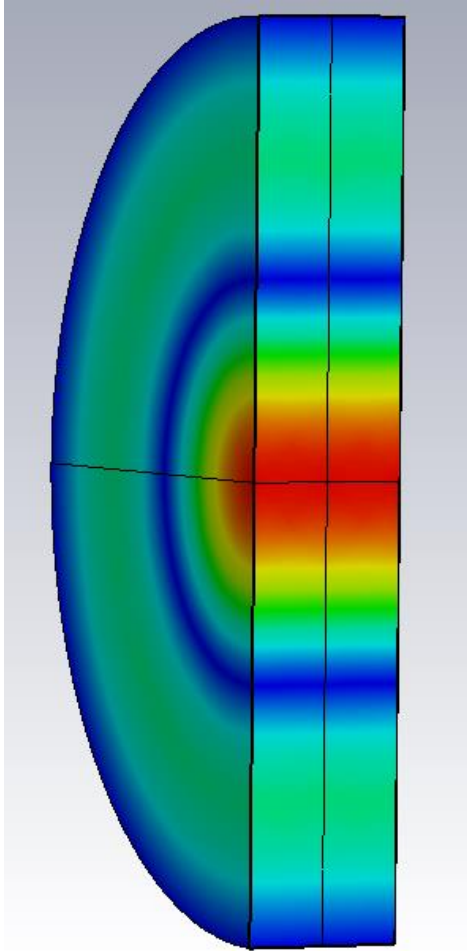


- High losses in metallic walls: low RF efficiency.
- High peak electric field in metal: field emission and RF breakdown.

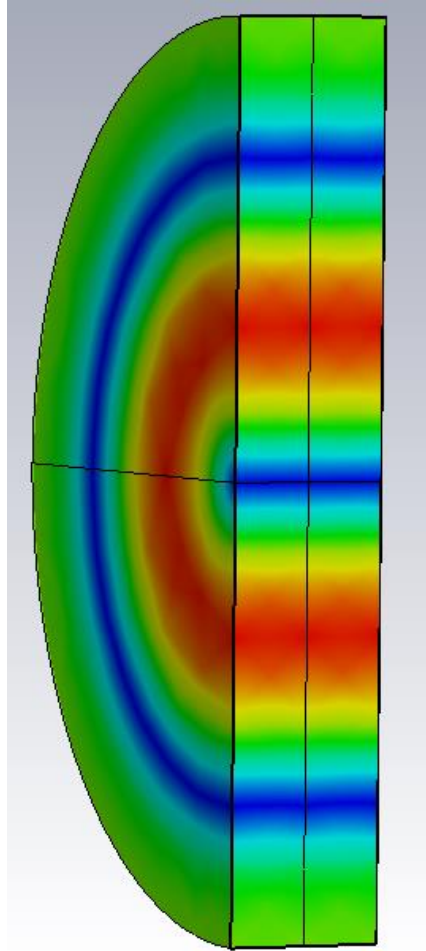
DAA cavity single cell solution

Pillbox cavity TM_{020}

Electric field



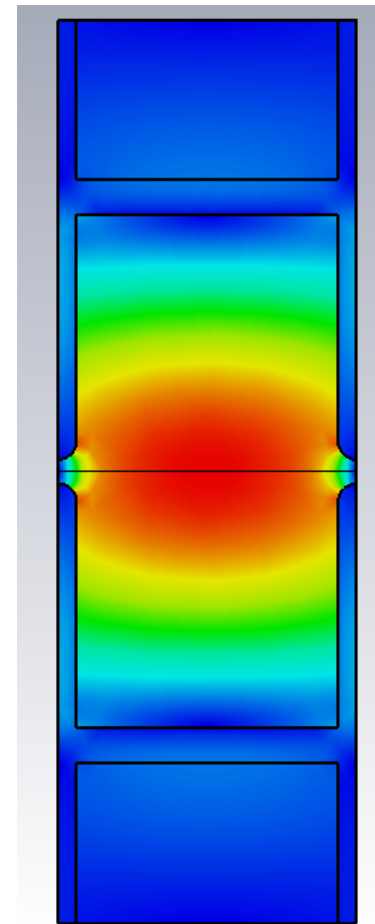
Magnetic field



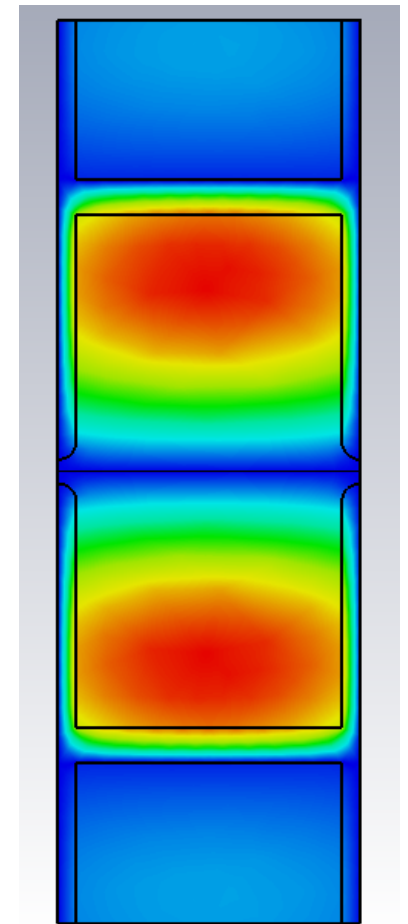
Dielectric and
Optimization
→

DAA mode $TM_{02} - \pi$

Electric field



Magnetic field



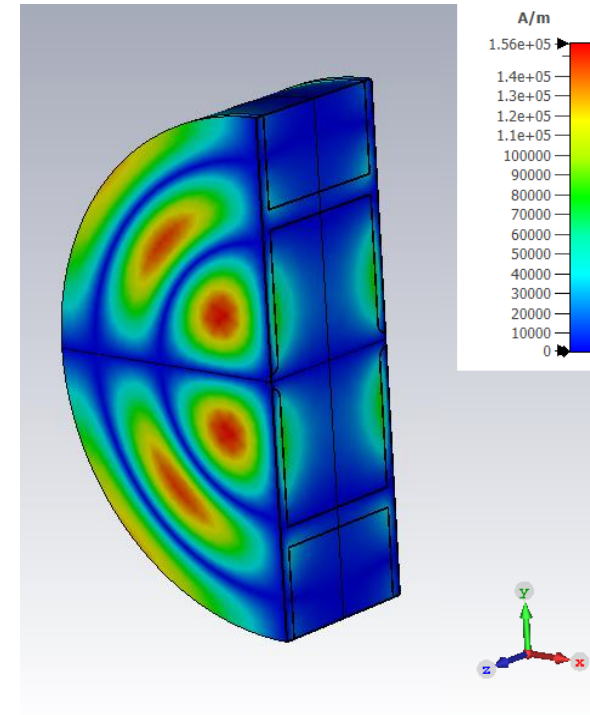
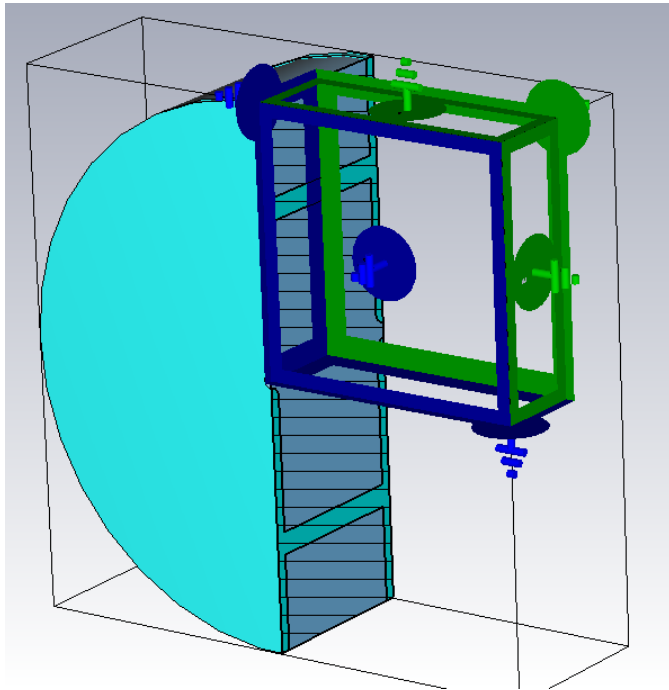
- Low losses in metallic walls
- Low peak electric field in metal.

DAA cavity single cell CST

Resonant frequency for the mode depends on the combination of a_1, b_1, c_1 :

- ❑ Scan for a_1, c_1 and we look for the value of b_1 that makes $f = (3000 \pm 2)$ MHz.
- ❑ Look for the values of a_1, b_1, c_1 that maximize ZTT, Q_0

In CST the minimum volume to simulate is 1/8 of the total volume using symmetry planes in XY, XZ, YZ. Then the mode we are interested in is mixed with many modes with no revolution symmetry



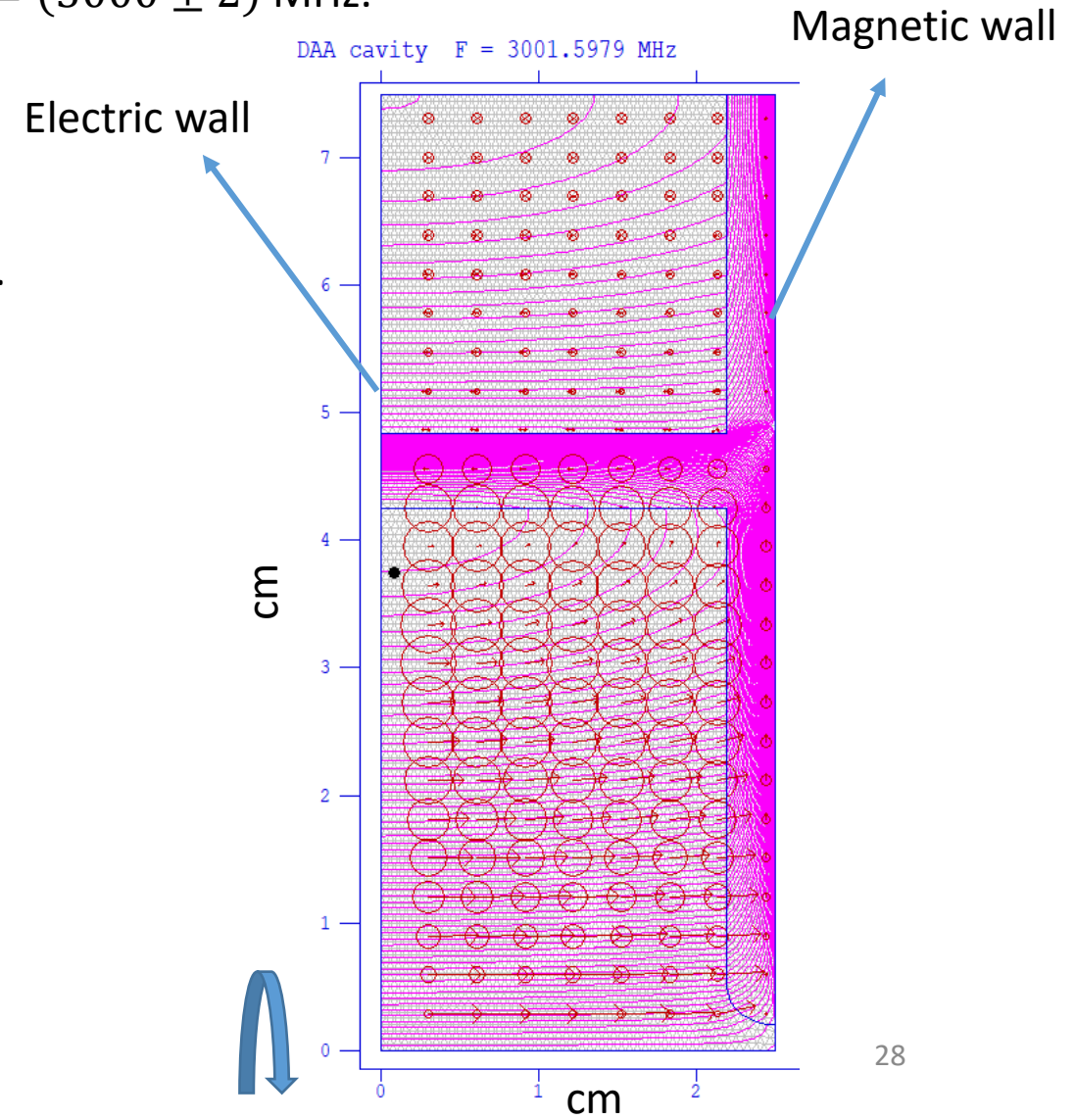
DAA cavity single cell Superfish

Resonant frequency for the mode depends on the combination of a_1, b_1, c_1 :

- ❑ Scan for a_1, c_1 and we look for the value of b_1 that makes $f = (3000 \pm 2)$ MHz.
- ❑ Look for the values of a_1, b_1, c_1 that maximizes ZTT, Q_0

Superfish: 2D electromagnetic solver for axial symmetric RF cavities.

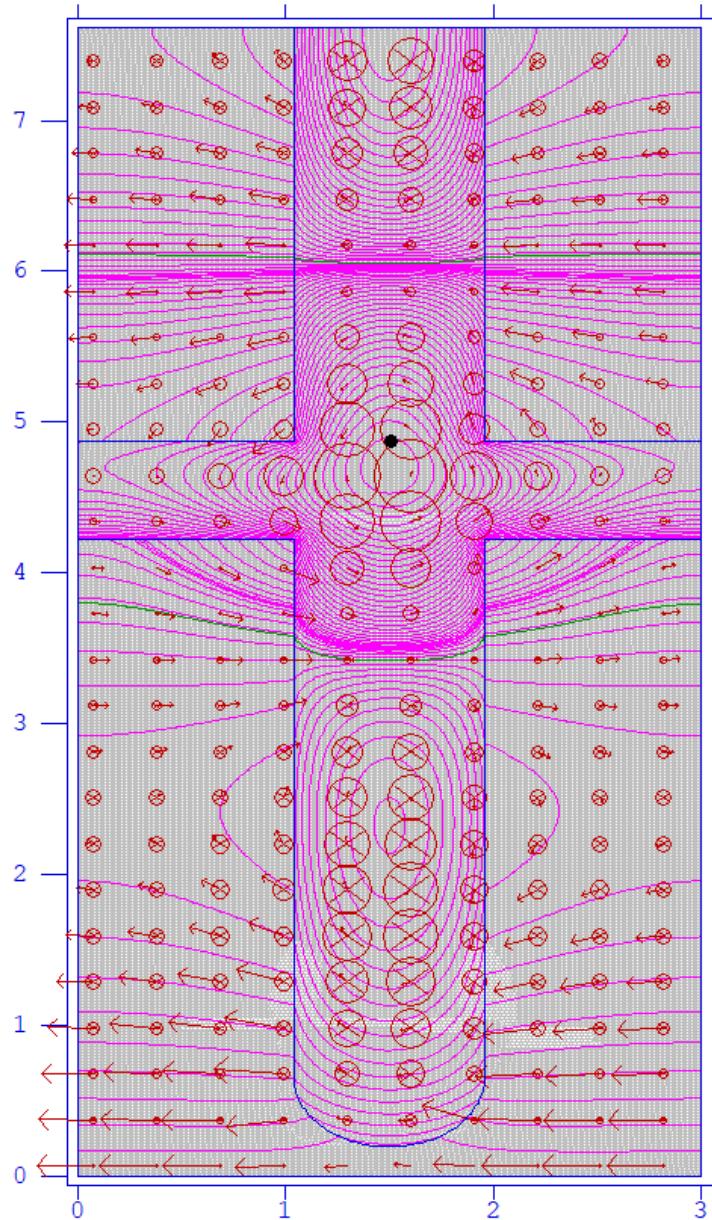
- ❑ Fast.
- ❑ Low computational cost.
- ❑ Free.
- ❑ **Reduce the number of solutions due to the symmetry.**



DAA cavity single cell Superfish

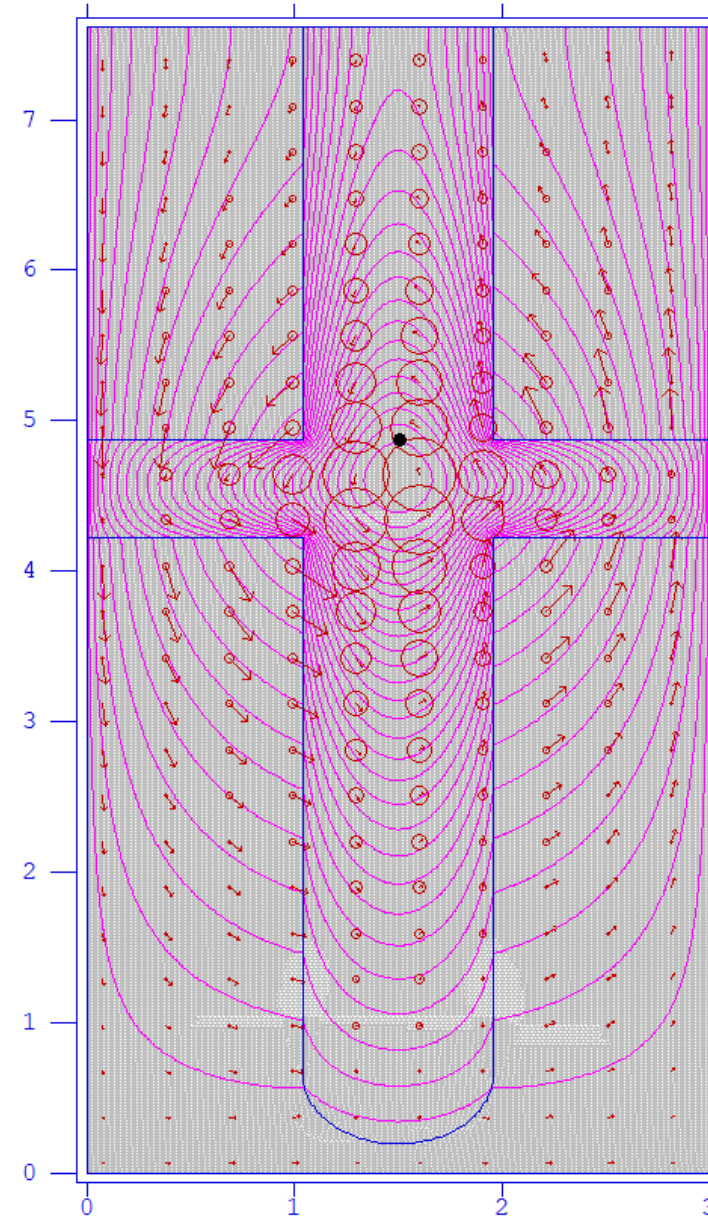
$\Delta\phi = 0^\circ$

DAA cavity F = 3353.9647 MHz

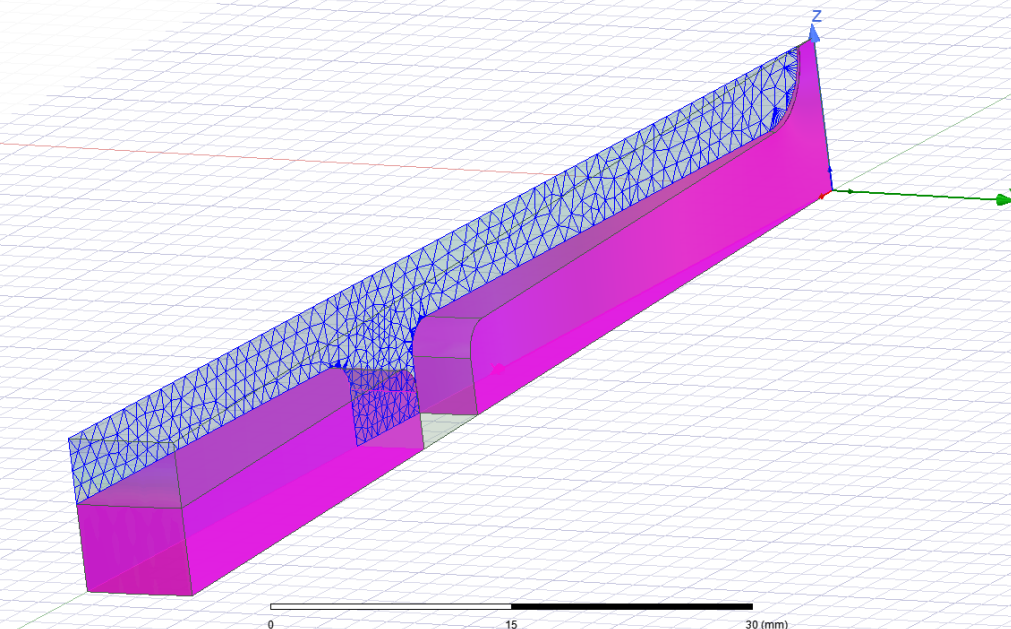
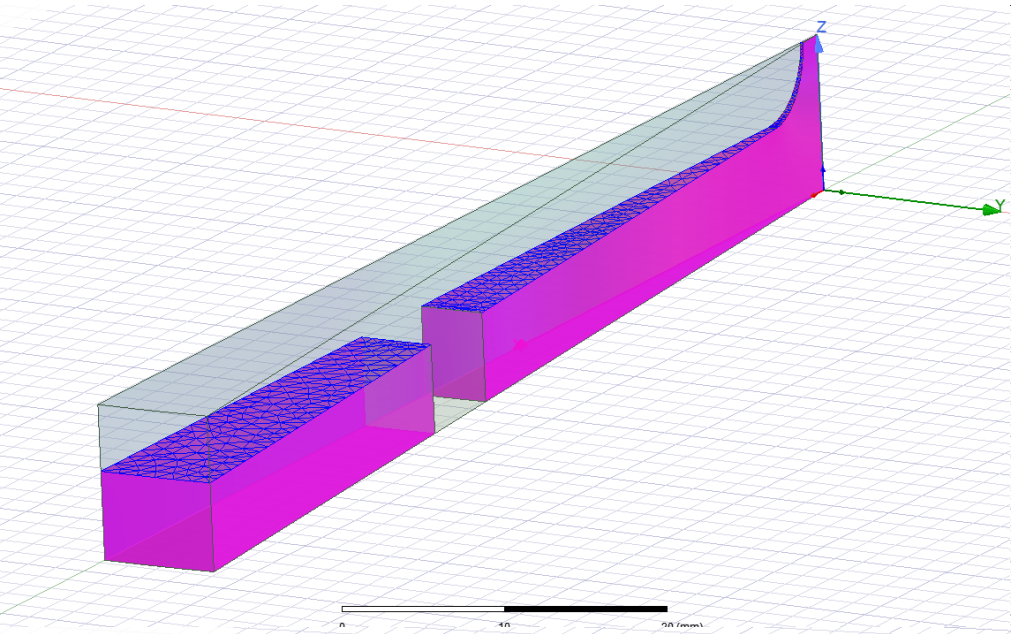


$\Delta\phi = 180^\circ$

DAA cavity F = 3183.9035 MHz



HFSS Results



D16, $\beta = 0.4$, $\epsilon_r = 16.66$, $\tan \delta = 3.43 \times 10^{-5}$

Geometry	SUPERFISH			HFSS		
	f (MHz)	Q_0	Z/Q (Ω/m)	f (MHz)	Q_0	Z/Q (Ω/m)
edge	2998.7	46949	944	2998.2	47444	949
$r = 2$ mm	2999.3	47316	959	2999.1	47755	960

$$Q_0 = \omega \frac{W}{P}$$

$$W = 2W_e = 2W_m = \frac{1}{2} \mu_0 \int |\vec{H}|^2 dV$$

$$\text{Conductor: } P_c = \frac{R_s}{2} \int |\hat{n} \times \vec{H}|^2 dS \quad R_s = \sqrt{\frac{\omega \mu_0}{2\sigma}}$$

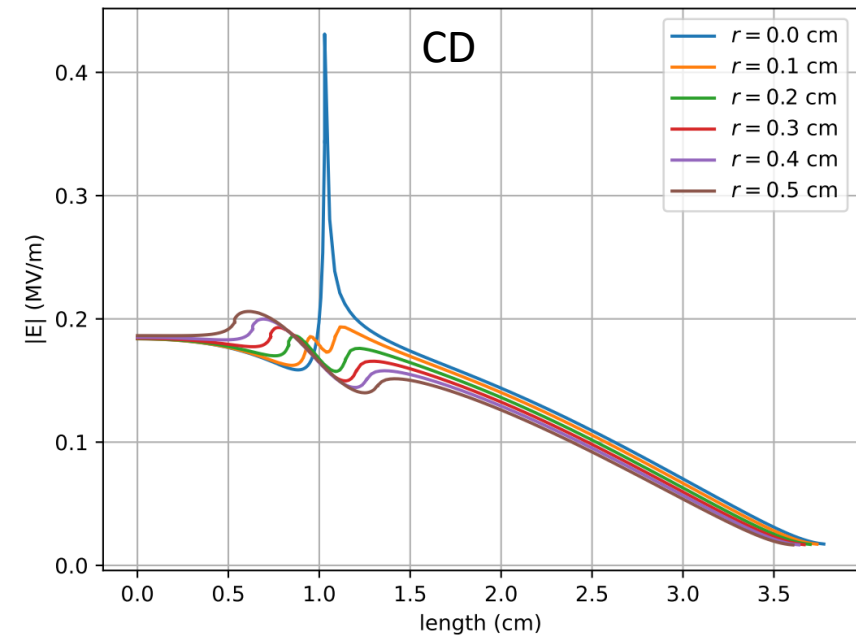
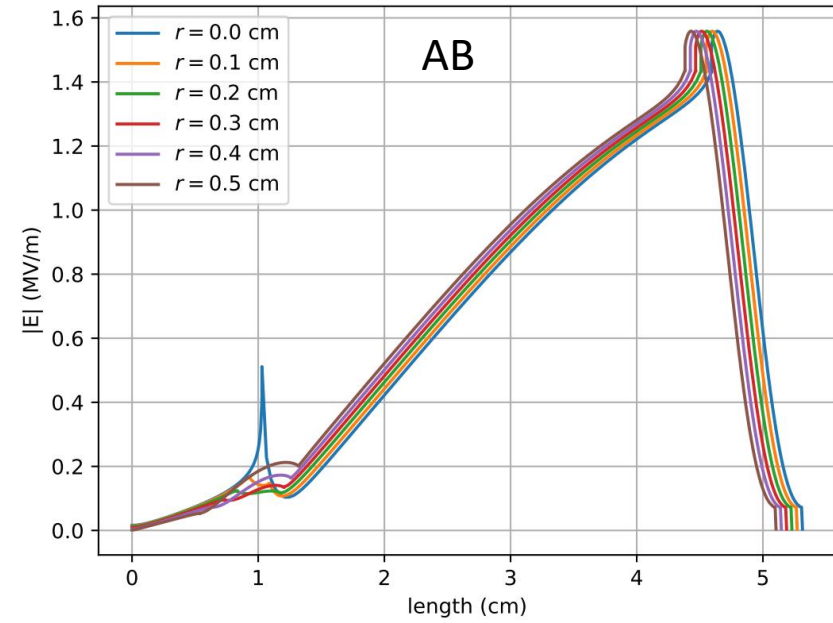
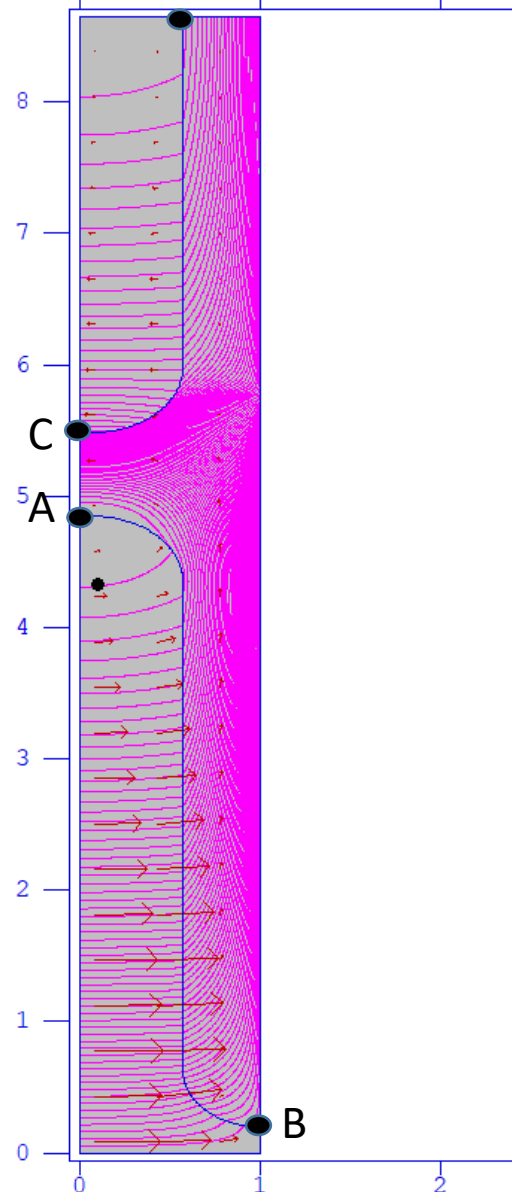
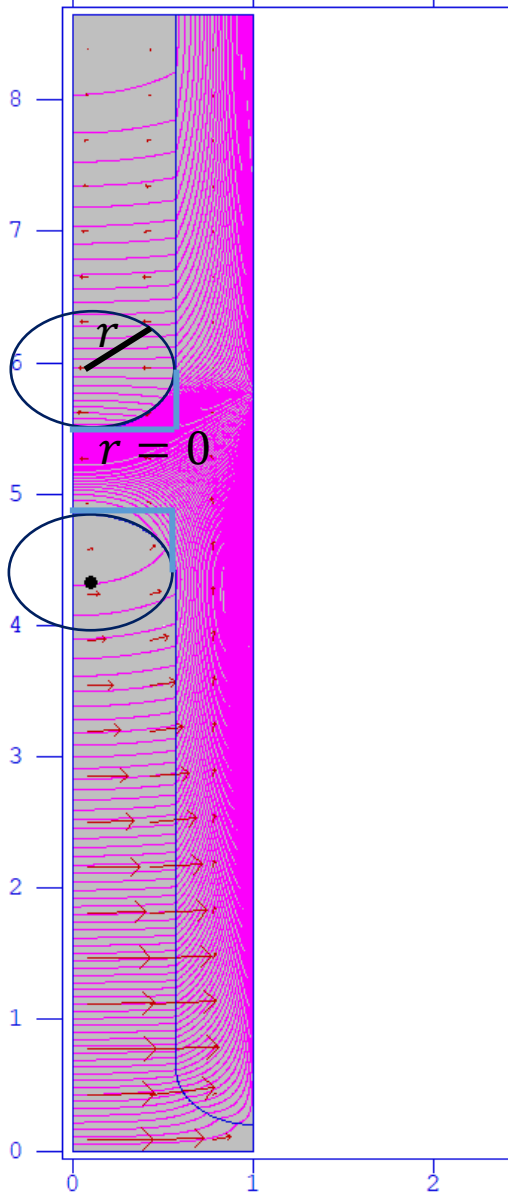
$$\text{Dielectric: } P_d = \frac{1}{2} \omega \tan \delta \epsilon_0 \epsilon_r \int |\vec{E}|^2 dV$$

$$\text{Coating: } P_s = \frac{1}{2R} \int |\hat{n} \times \vec{E}|^2 dS$$

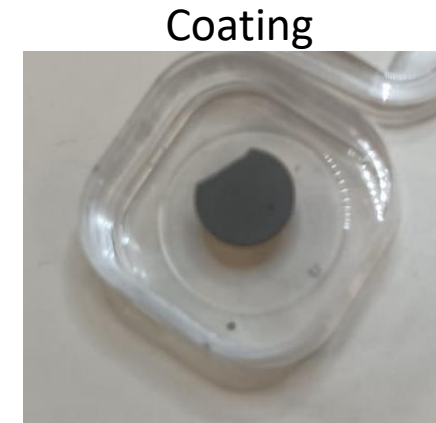
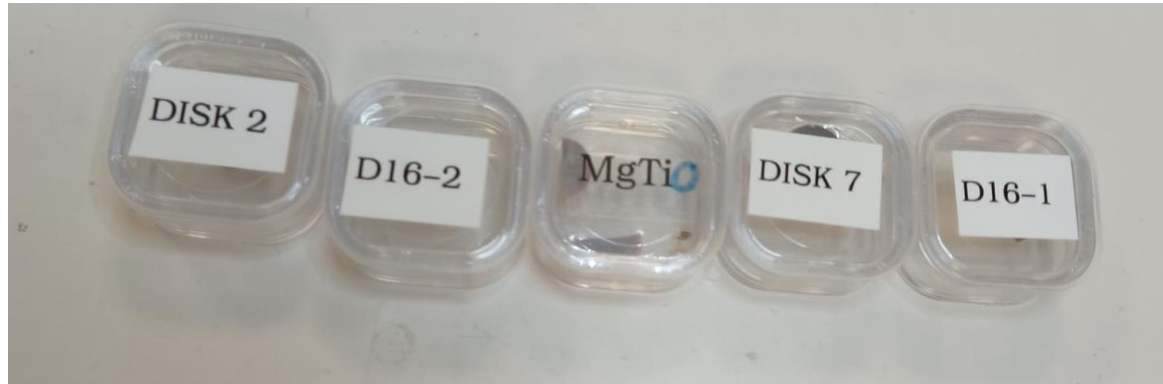
Rounded points

DAA cavity $F = 3001.8103$ MHz

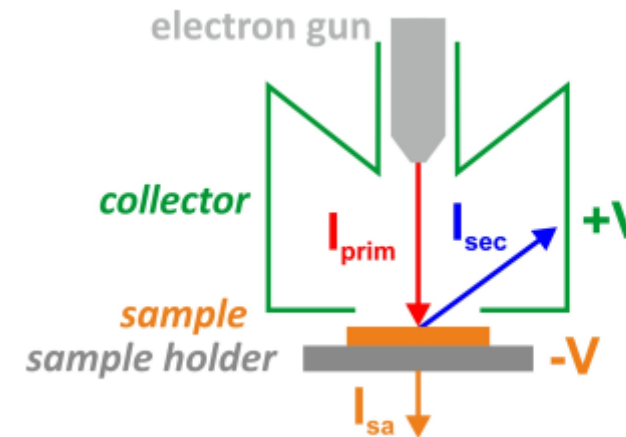
DAA cavity $DF = 3001.8103$ MHz



SEY Measurements



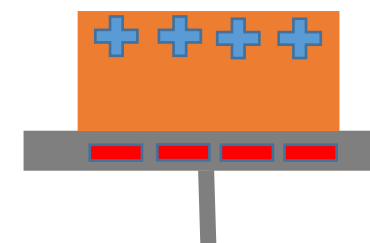
- DISK 2: Sample 5: MgTiO with one side DLC coated (US vendor).
- D16-2: Sample 9: D16 with one side DLC coated (Japan vendor).
- MgTiO: Sample 4: MgTi Oxide based Conductive Ceramic uncoated.
- DISK 7: Sample 6: MgTiO with one side DLC coated (Japan vendor).
- D16-1: Sample 8: D16 with one side DLC coated (US vendor).



Metals

$$Q = VC$$

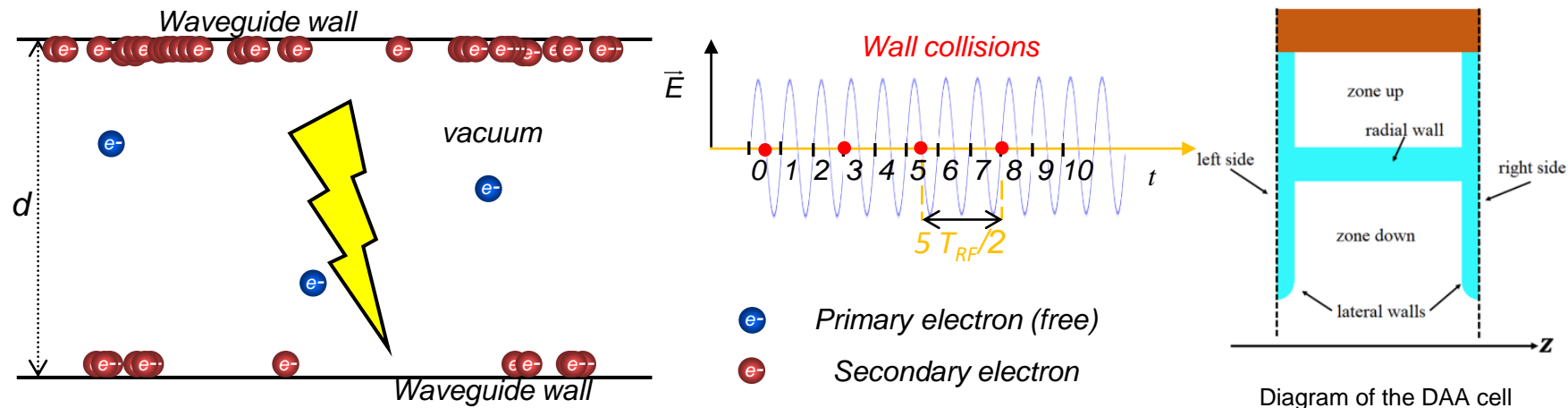
$$C = \frac{\epsilon_r \epsilon_0 S}{d}$$



Dielectric

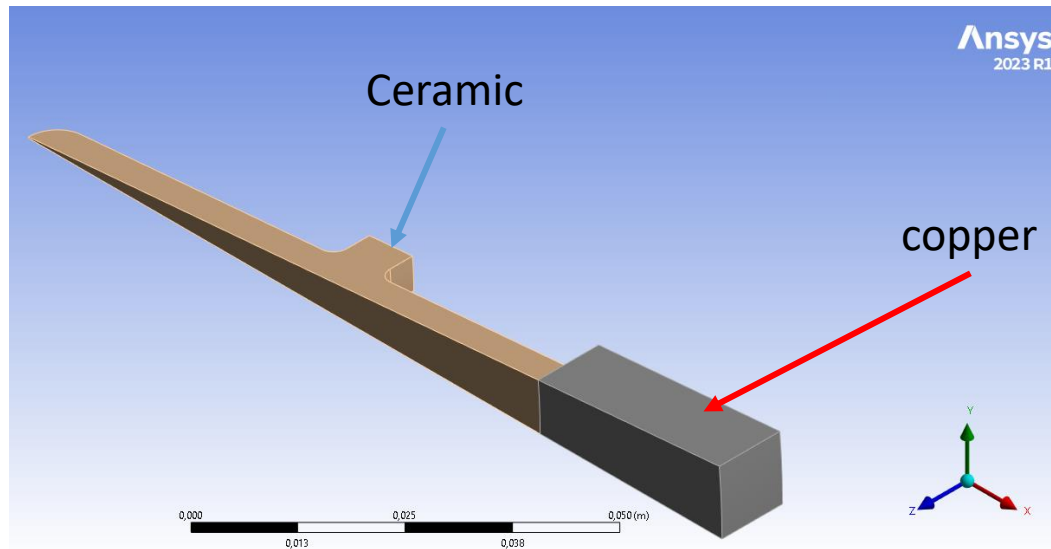
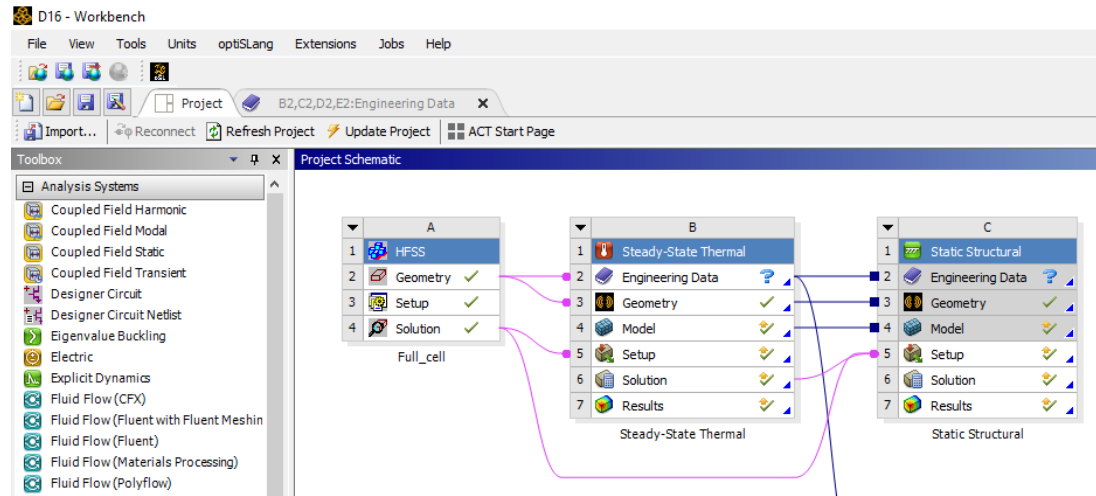
Multipactor in the DAA structure

- Multipactor breakdown is an electron avalanche-like discharge occurring in components operating under vacuum conditions and high-power RF electromagnetic fields
- The onset of multipactor discharge leads to various detrimental effects that degrade the device performance. Thus, this phenomenon poses a significant limitation on the maximum RF power handling capability of devices
- The risk of suffering a multipactor discharge in the DAA structures was analyzed by means of numerical simulations with an in-house developed code based on the Monte-Carlo method



- The simulations explore RF electric field amplitudes in the range $E_0 = [0.01, 200]$ MV/m
- The cell is divided into two zones: up and down, with separate simulations launched for each zone
- In the DAA cell multipactor appears in the range 1-200 MV/m

ANSYS Workbench



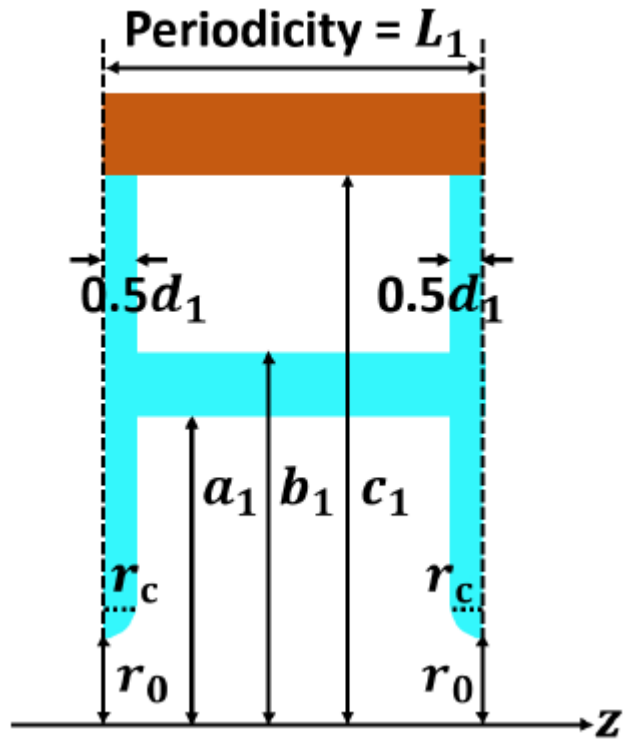
Material	MgTiO ₃	Al ₂ O ₃ 99.5%	TiO ₂ - doped Al ₂ O ₃	CVD Diamond	Copper
Density (g/cm ³)	3,6	3.89		3.52	8,933
Thermal conductivity (W/m·K)	3,8	35		2000	400
Thermal expansion (μm/m·K)	8,0	8.4		1.0	17,7
tan δ	3.43 × 10 ⁻⁵	2 × 10 ⁻⁴	1 × 10 ⁻⁵ — 6 × 10 ⁻⁶	3 × 10 ⁻⁶	
ε _r	16.66	9.8	9.64	5.7	

<https://www.americanelements.com/magnesium-titanate-12032-30-3>

<https://www.makeitfrom.com/material-properties/Magnesium-Titanate-IEC-60672-Type-C-320>

<https://accuratus.com/alumox.html>

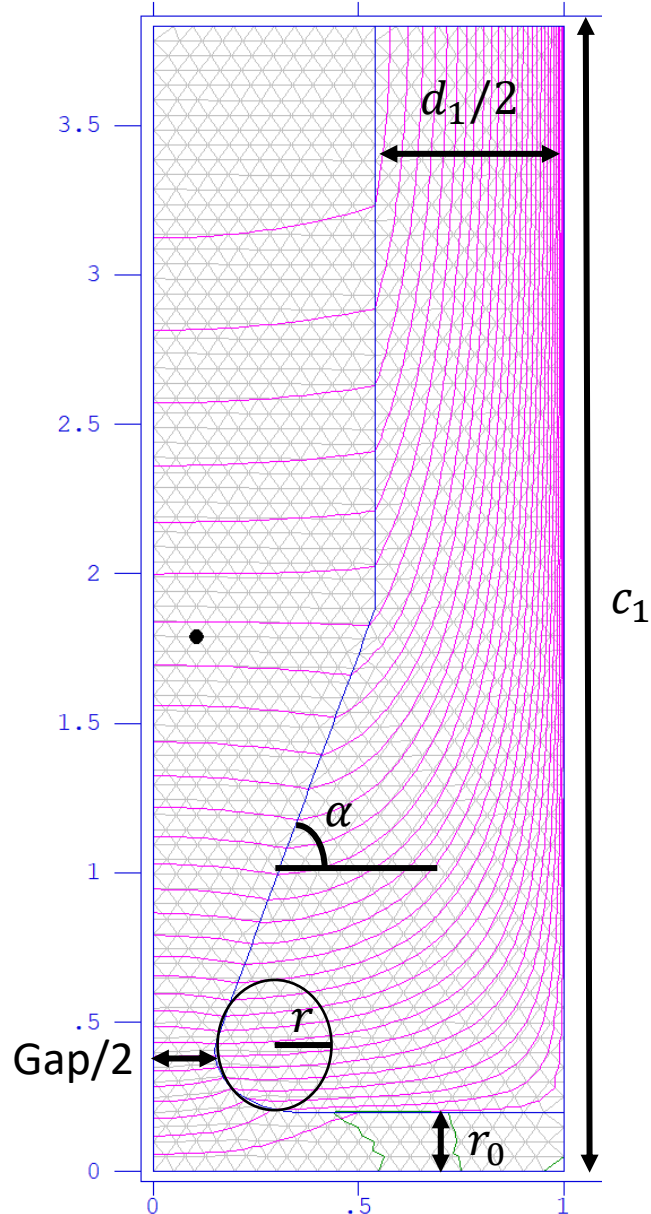
Tolerance studies



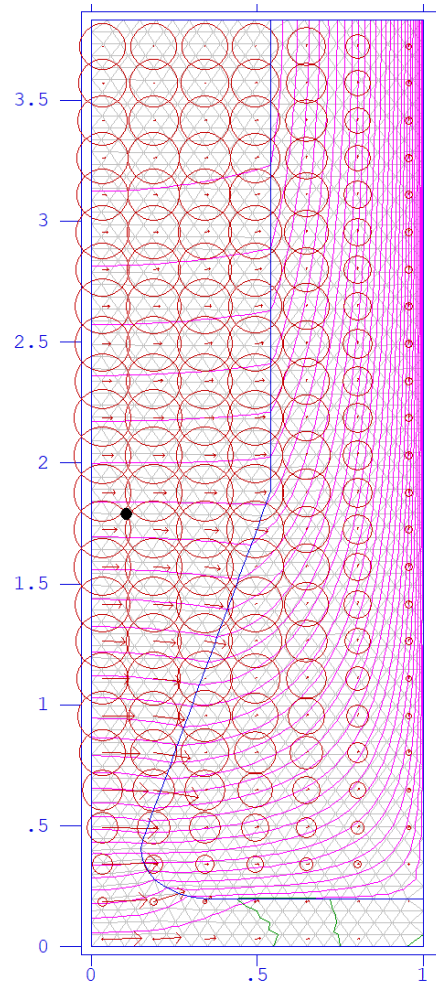
Parameter	$\frac{df}{dl}$ (kHz/ μm)					
	D9		D16		D50	
material						
β	0.4	1	0.4	1	0.4	1
a_1	1.7	2.3	4.0	2.1	2.7	1.1
b_1	-11.0	-42.8	-28.0	-51.8	-53.1	-63.9
c_1	-2.0	-5.5	-2.2	-3.6	-1.3	-1.4
d_1	-29.5	-12.1	-39.1	-12.8	-34.5	-12.6
r_0	1.1	1.4	1.6	1.1	2.0	0.8
L_1	-71.3	-4.8	-38.8	-3.1	-10.3	-1.2

Dielectric Disk Loaded Accelerating (DDA) Cavity

DDA cavity $F = 2998.1333$ MHz



$$d_1 = \frac{\lambda_0}{4\sqrt{\epsilon_r}} \xi$$



$D16, \beta = 0.4, \epsilon_r = 16.66, \tan \delta = 3.43 \times 10^{-5}$
 $gain = 1.5, gap = 0.3$ cm, $\alpha = 75^\circ, r = 0.2$ cm

Parameter	With nose	Without nose
Q_0	21180	20299
Z/Q (Ω/m)	2154	1234
Z ($M\Omega/m$)	45.6	25.0
T	0.9076	0.8055
E_p/E_a	6.27	2.38

Same W

