DAA structures for protons and dark current dynamics in High-Gradient cavities

P. Martinez-Reviriego, Alexej Grudiev, Steffen Doebert, Jordan Matias, Walter Wuensch, Nuria Catalan

31-08-2022

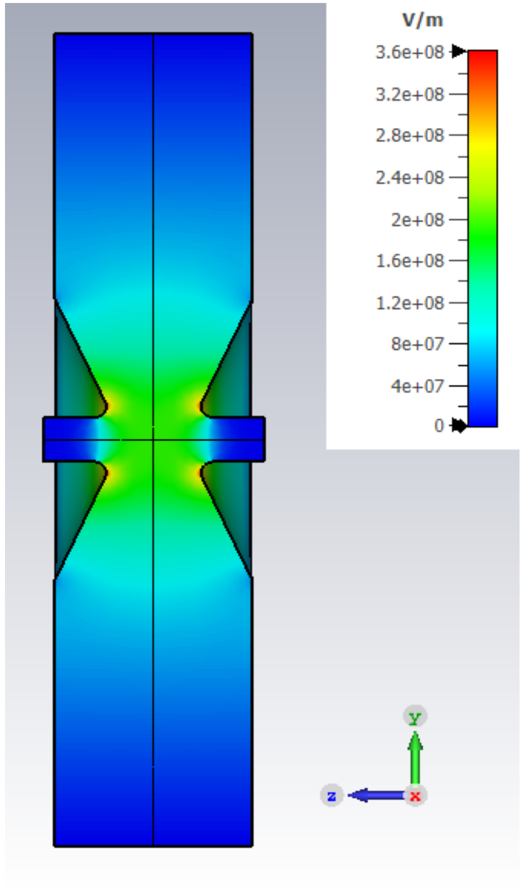
Outline

- ❑ Comparison between copper standing wave and DAA cavities
- ❑ Design procedure
- ❑ Comparison for different materials and particle velocity
- ❑ Dispersion curves
- ❑ Possible improvements for the design
- ❑ Dark current dynamics in electron line for AWAKE

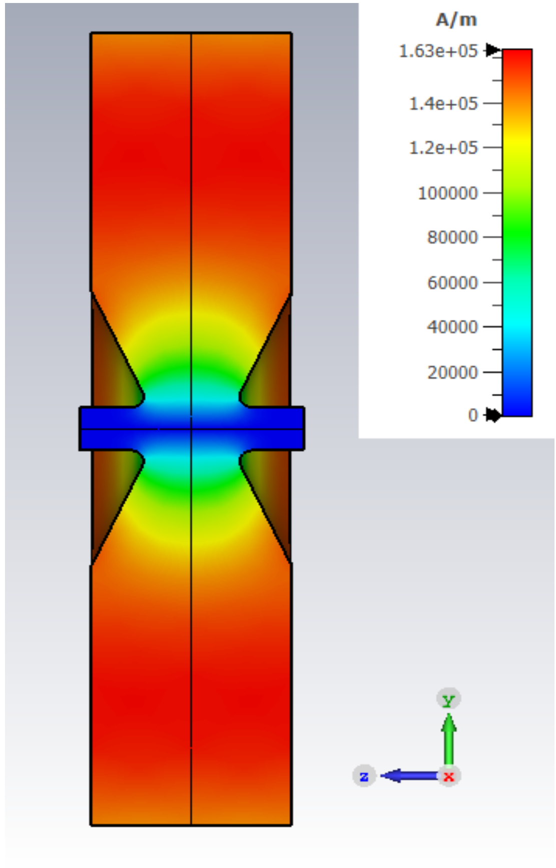
HG-CCL Copper structure single cell

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

Electric field



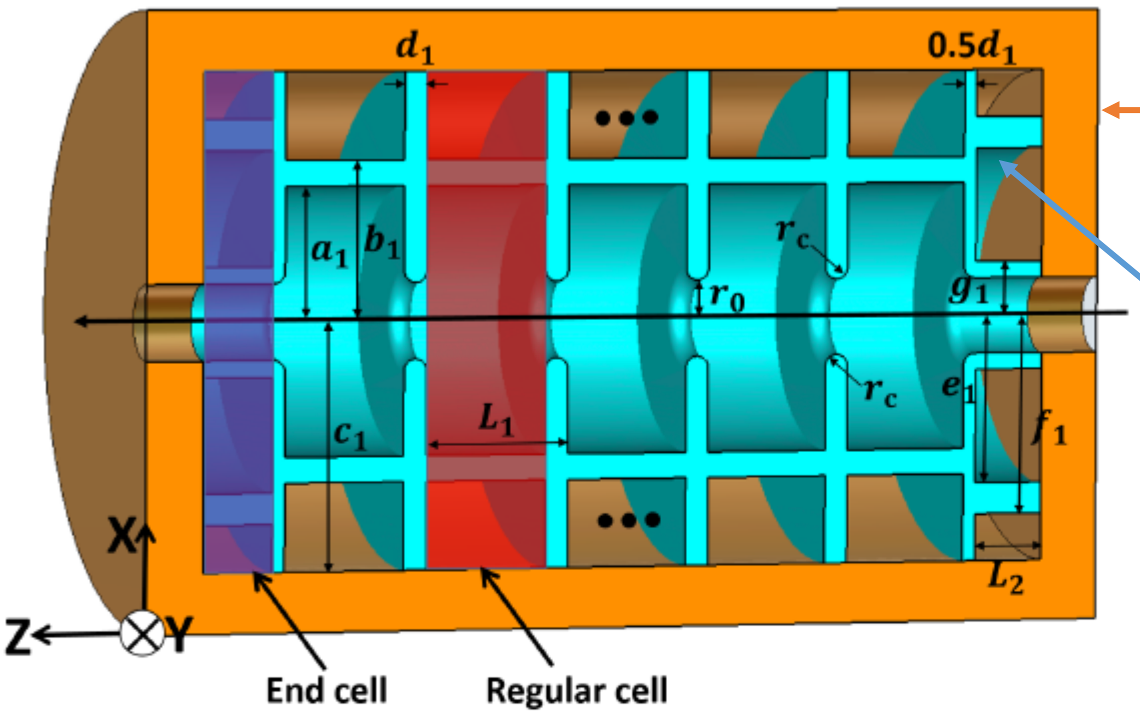
Magnetic field



We are going to use this HG standing wave cavity as reference for our studies.

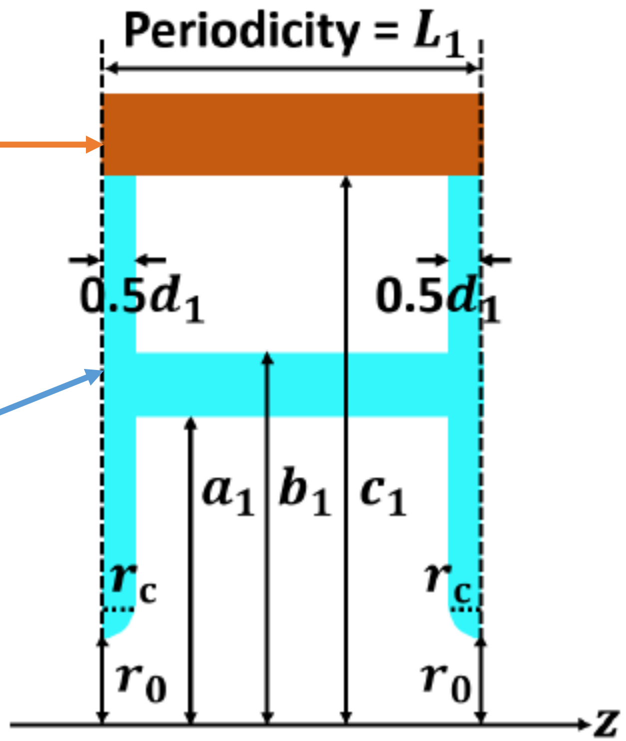
Parameter	S. Benedetti (coupled cell)	Simulation
Freq (MHz)	3000	2999.9
ZTT (MΩ/m)	60	66.3
Q	9136	9618
ZTT/Q (Ω/m)	6568	6893

DAA cavity



Copper

Dielectric:
- High ϵ_r
- Low tan δ



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

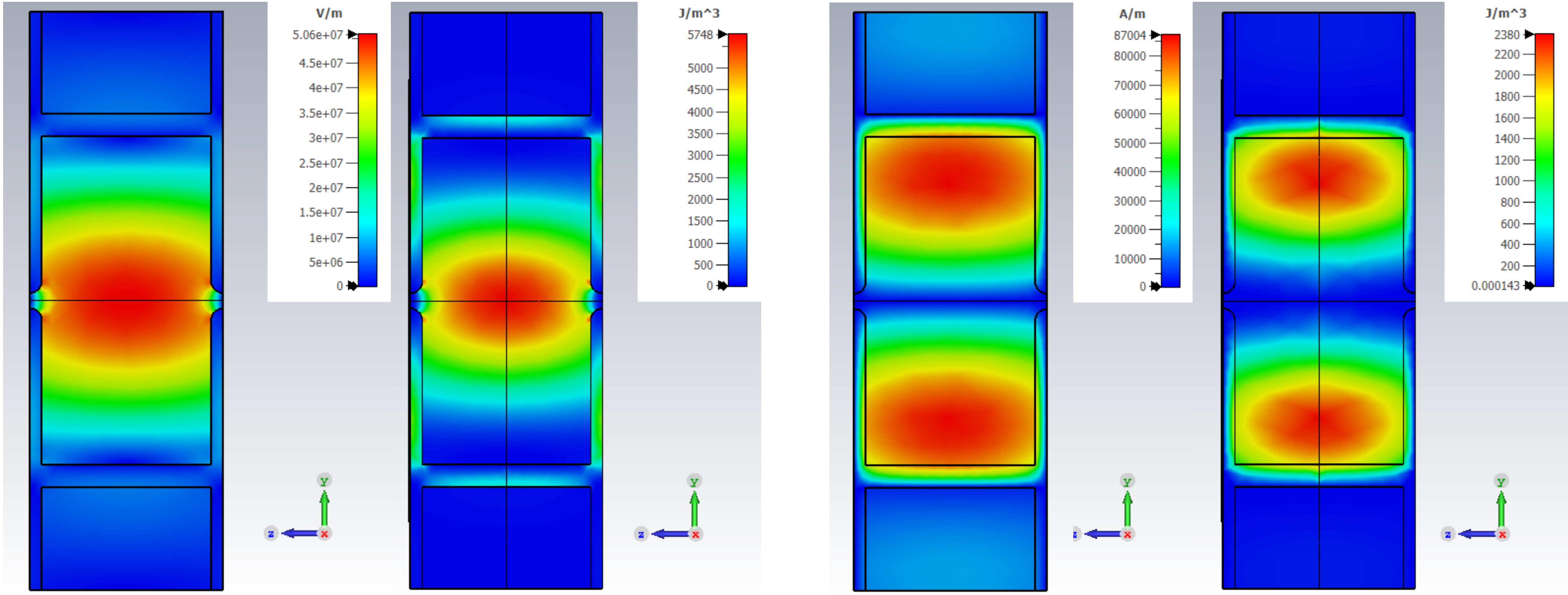
Parameter	Calculation
L_1	$\beta\lambda_0/2$
d_1	$\lambda_0/(4\sqrt{\epsilon_r})$
r_c	$d_1/2$
r_0	2 mm

Working under $TM_{02-\pi}$ mode:
- High ZTT and Q_0
- Dielectric helps to decrease cavity size.

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

DAA cavity single cell solution

Electric field | Electric Energy | Magnetic field | Magnetic Energy



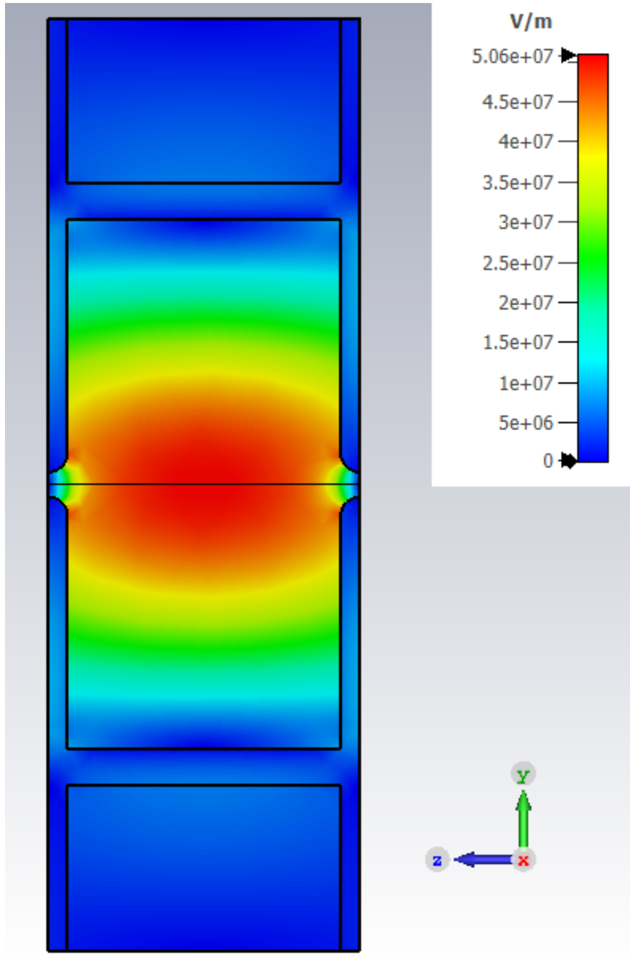
DAA cavity single cell solution

$$D = \epsilon E$$

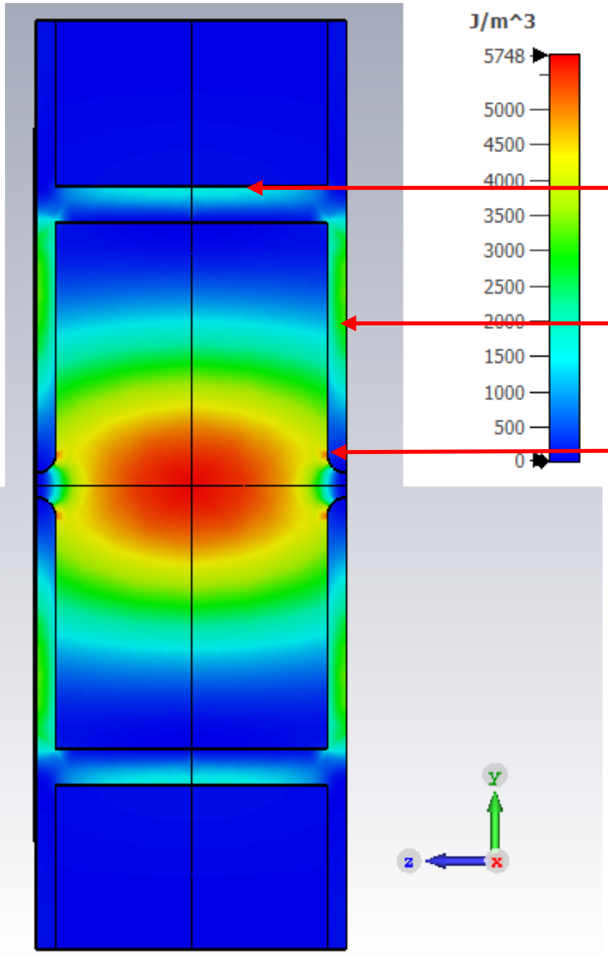
$$E_{\parallel,1} = E_{\parallel,2}$$

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

Electric field



Electric Energy



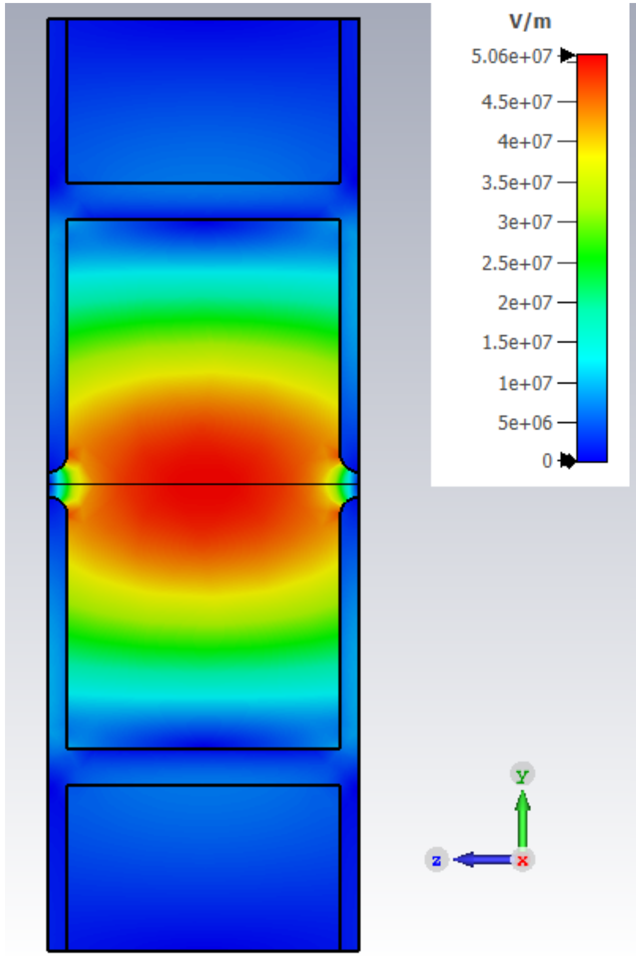
1st: Parallel boundary
- E is constant
- High D inside dielectric

2nd : D is conserved along the dielectric

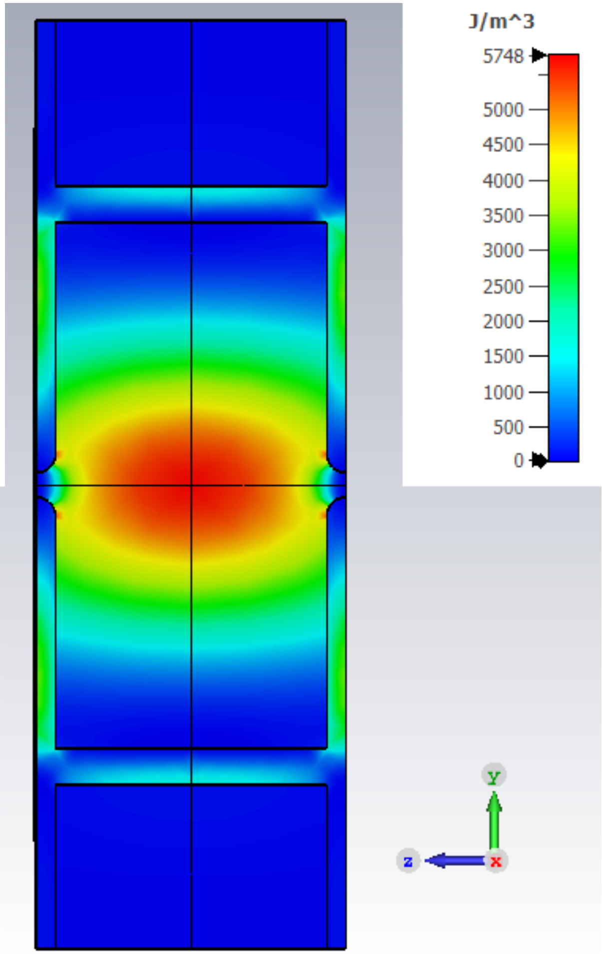
3rd : Perpendicular boundary
- D is constant
- High E in vacuum

DAA cavity single cell solution

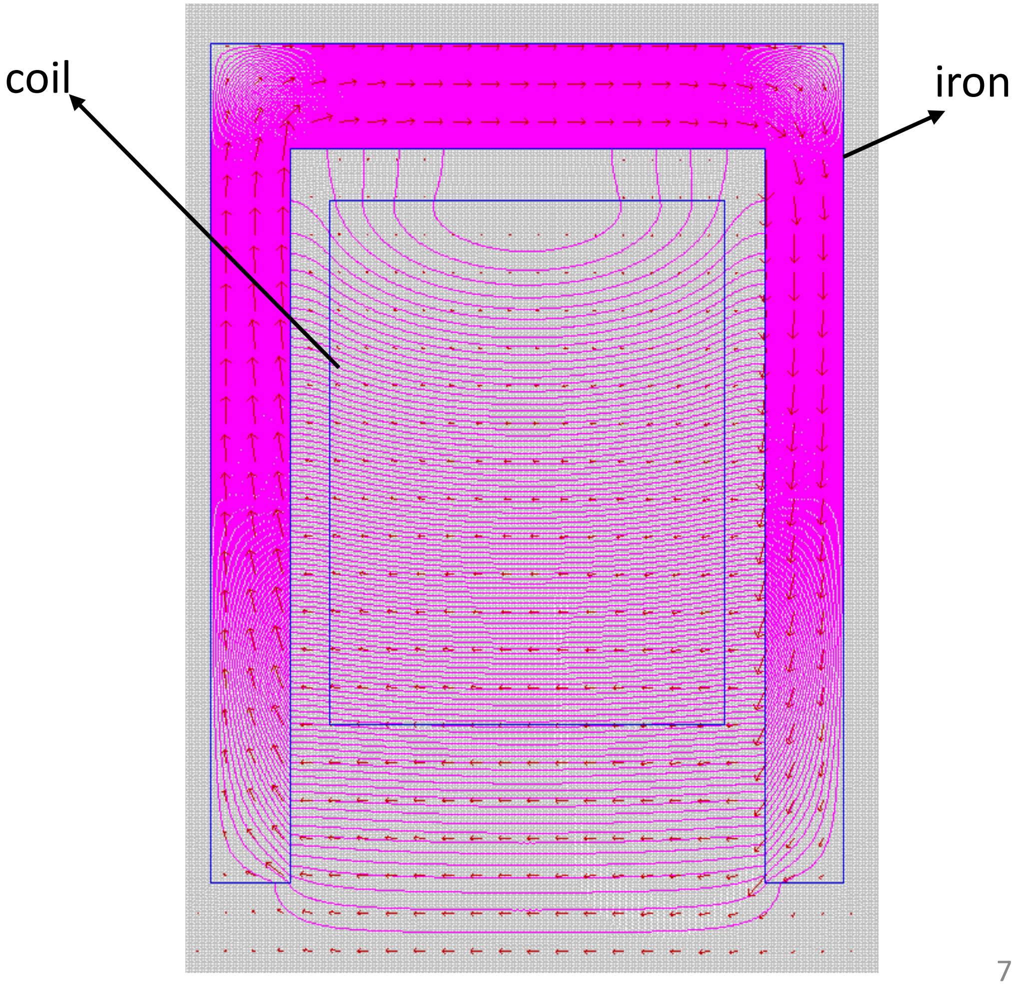
Electric field



Electric Energy



Magnetic analogy: solenoid covered with iron

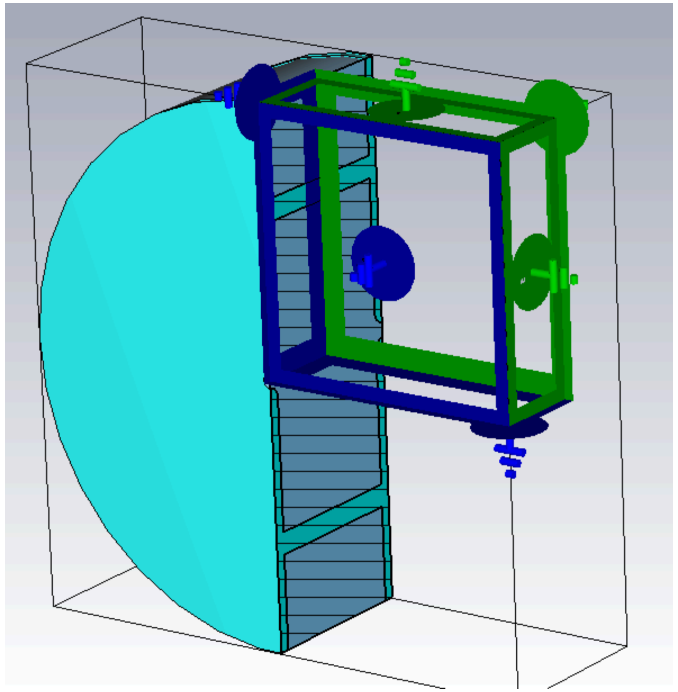


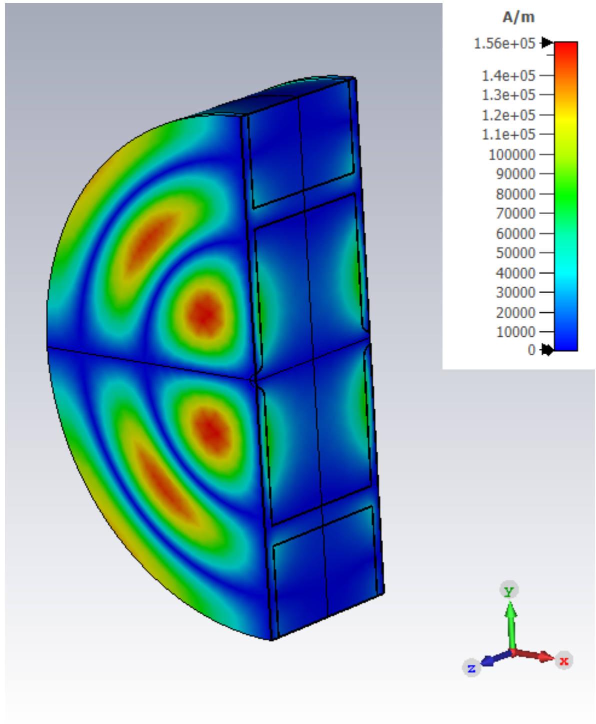
DAA cavity single cell CST

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





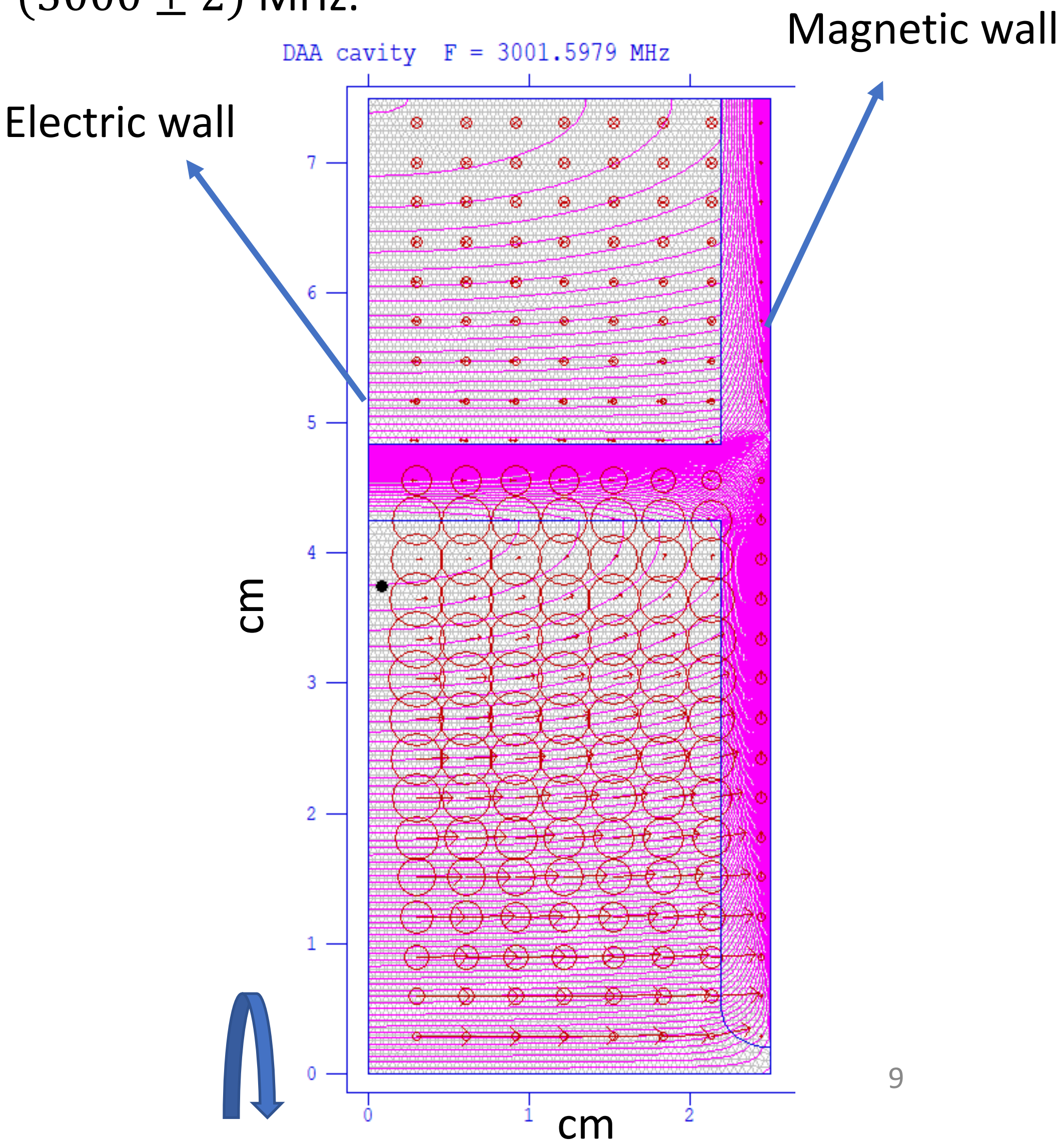
DAA cavity single cell Superfish

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**.



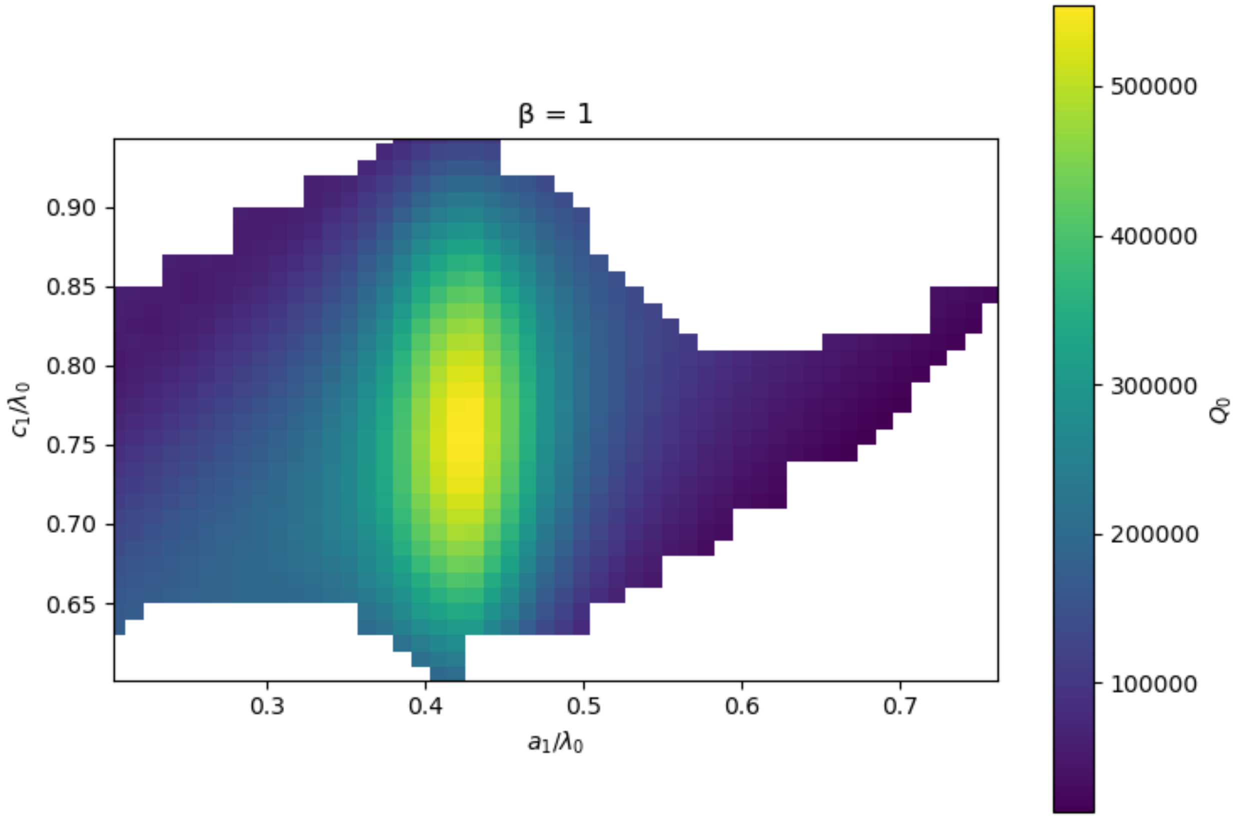
DAA cavity single cell Superfish

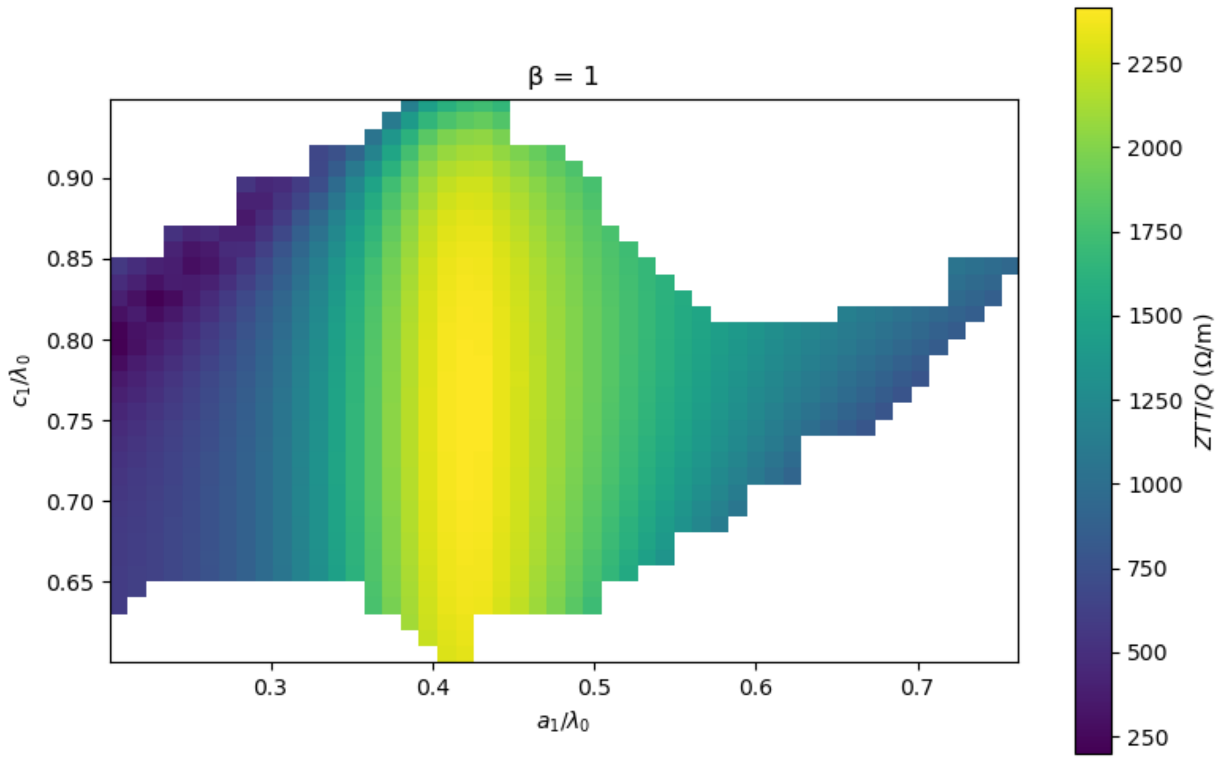
Resonant frequency for the mode depends on the combination of a_1, b_1, c_1:

- ❑ 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

Example for ideal material: $\epsilon_r = 16.66$, $\tan\delta = 0$ and $\beta = 1$

Best value for: $a_1 = 0.425\lambda_0, b1 = 0.484\lambda_0, c_1 = 0.750\lambda_0, Q_0 = 576248, ZTT/Q_0 = 2429\ \Omega/m, ZTT = 1400\ M\Omega/m$





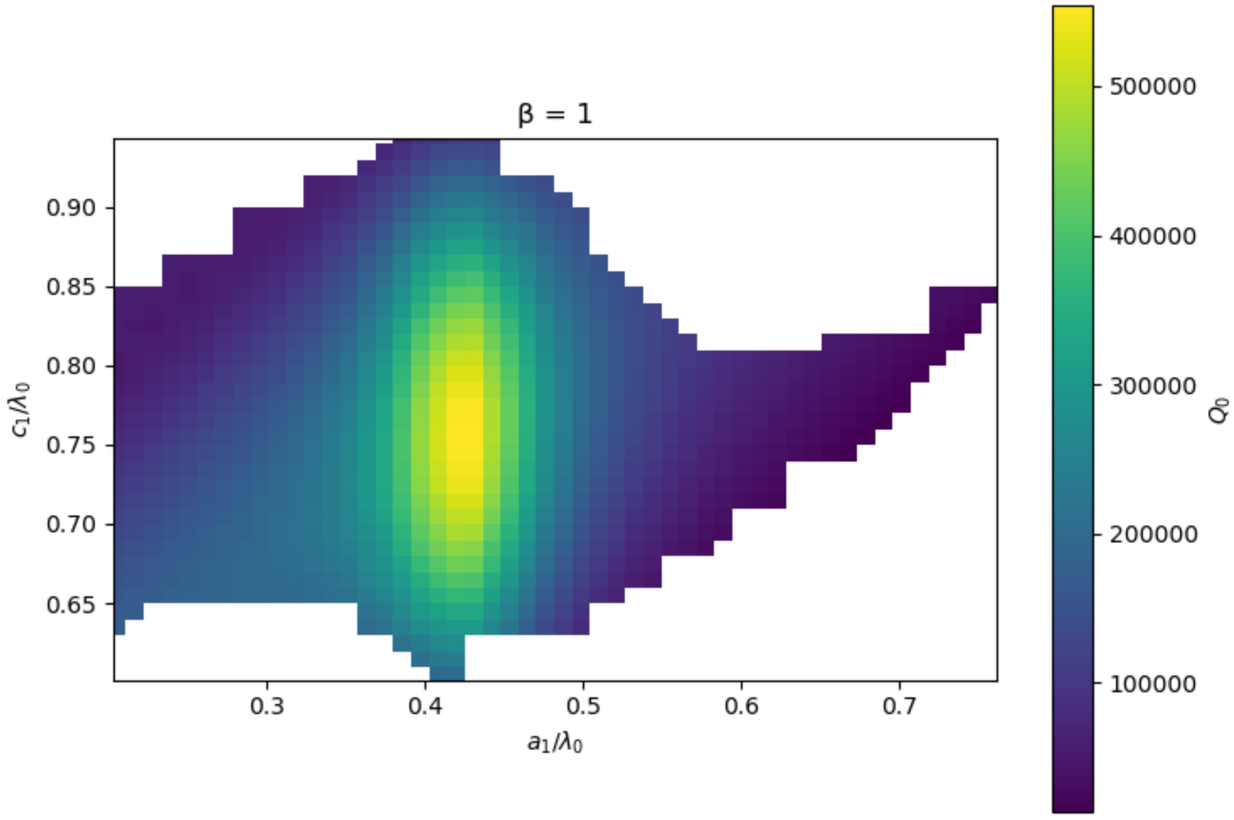
DAA cavity single cell Superfish

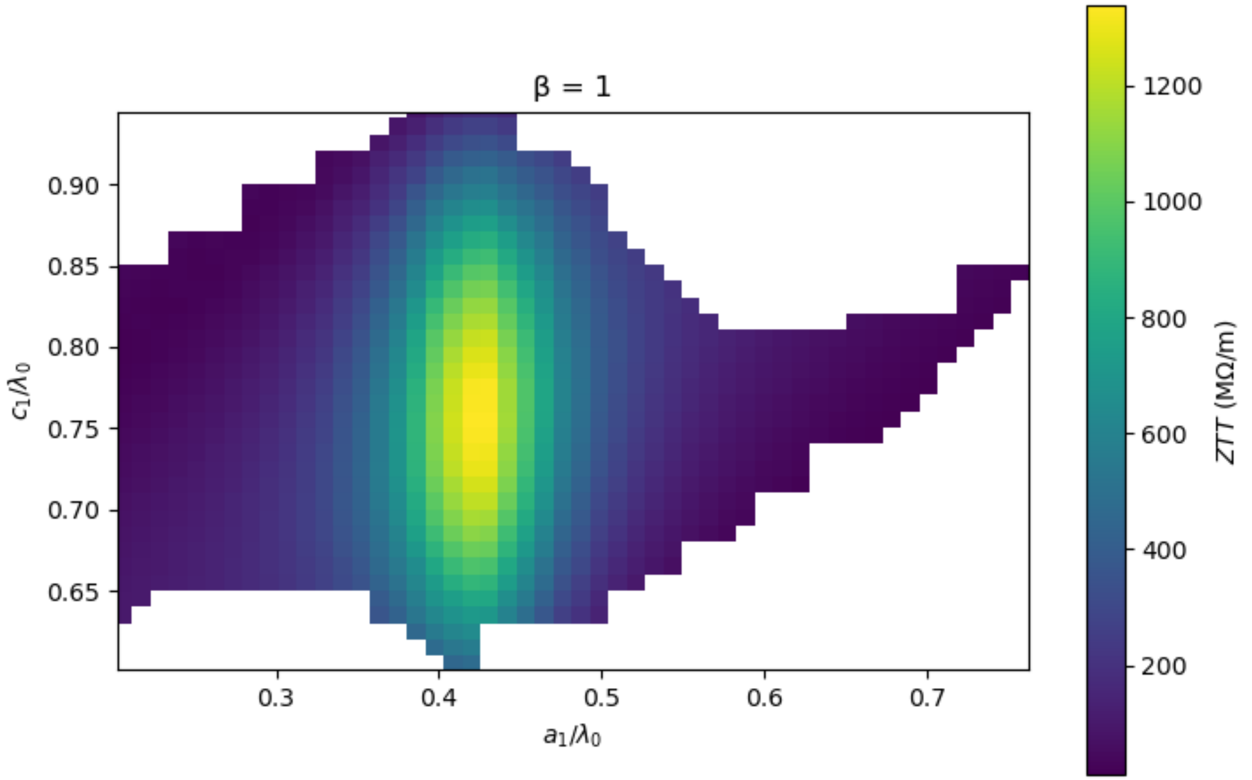
Resonant frequency for the mode depends on the combination of a_1, b_1, c_1:

- 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

Example for ideal material: $\epsilon_r = 16.66$, $\tan\delta = 0$ and $\beta = 1$

Best value for: $a_1 = 0.425\lambda_0, b1 = 0.484\lambda_0, c_1 = 0.750\lambda_0, Q_0 = 576248, ZTT/Q_0 = 2429\ \Omega/m, ZTT = 1400\ M\Omega/m$





Material and β studies with Superfish

Dielectric properties define:

Parameter	Calculation
d_1: wall thickness septum	$\lambda_0/(4\sqrt{\epsilon_r})$
a_1, b_1, c_1: Radius	Optimize to fit frequency
Q_0, ZTT	Optimize to find maximum

Particles velocity defines cell length

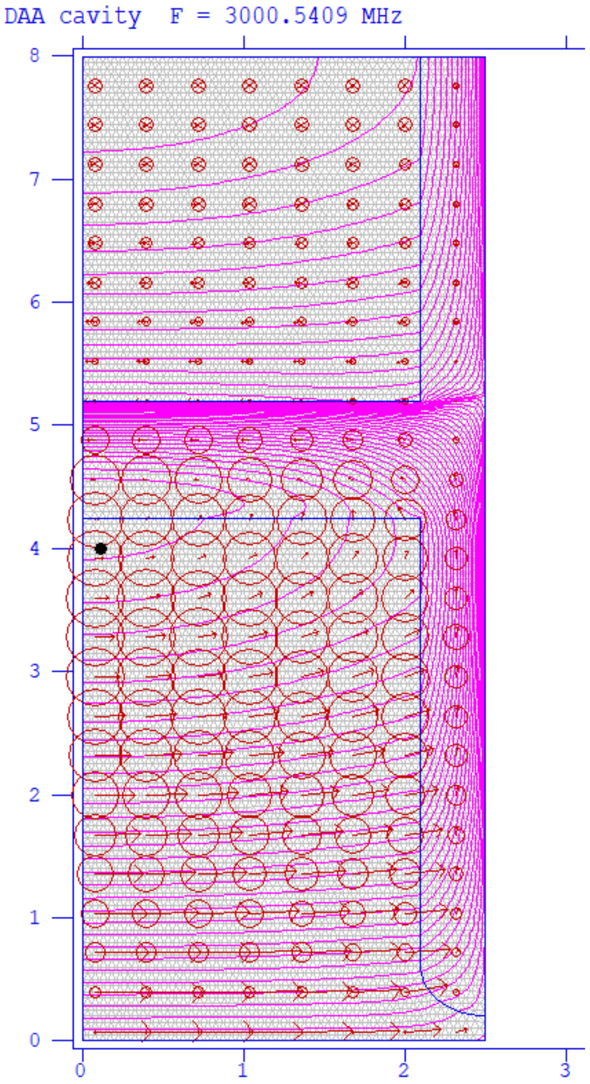
Parameter	Calculation
L_1	$\beta\lambda_0/2$
a_1, b_1, c_1: Radius	Optimize to fit frequency
Q_0, ZTT	Optimize to find maximum

Material	ϵ_r	$tan\ \delta$/ ideal
MgO: D-9	9.64	0
$MgTiO_3$: D-16	16.66	0
$BaTiO_x$: D-50	50.14	0

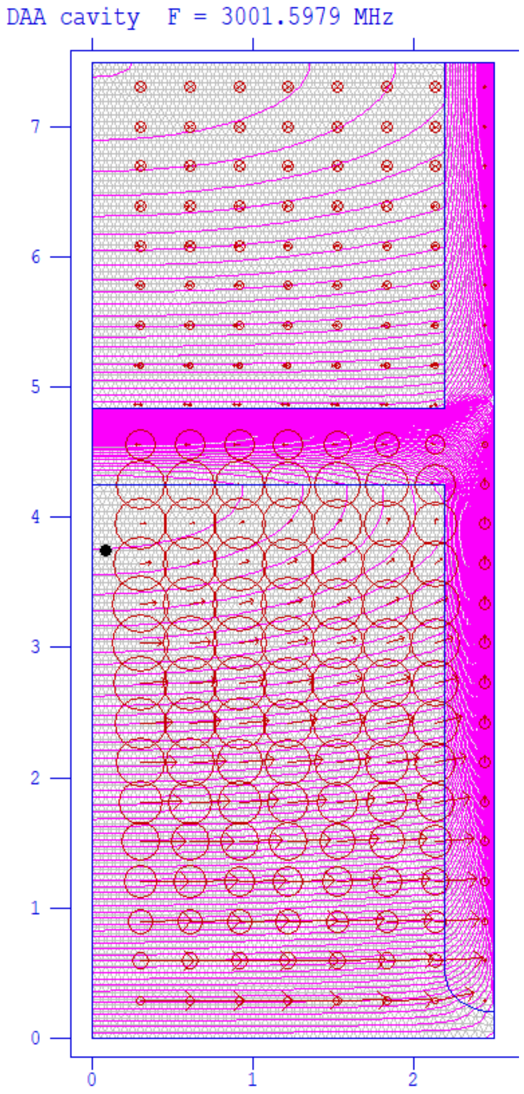
$$\beta = \{1, 0.9, 0.8, 0.7, 0.6, 0.5, 0.4\}$$

Different material with $\beta = 1$

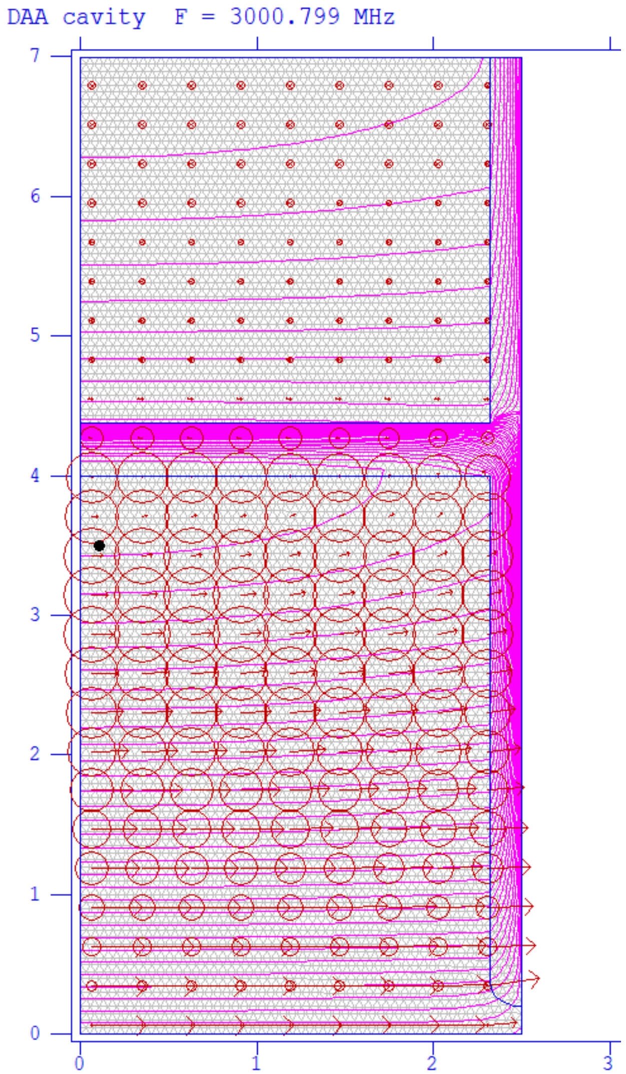
D-9



D-16

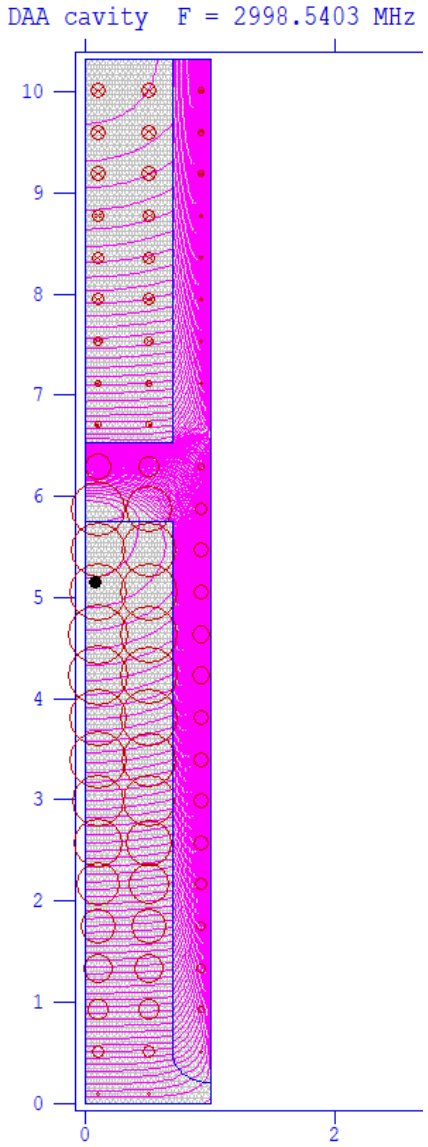


D-50

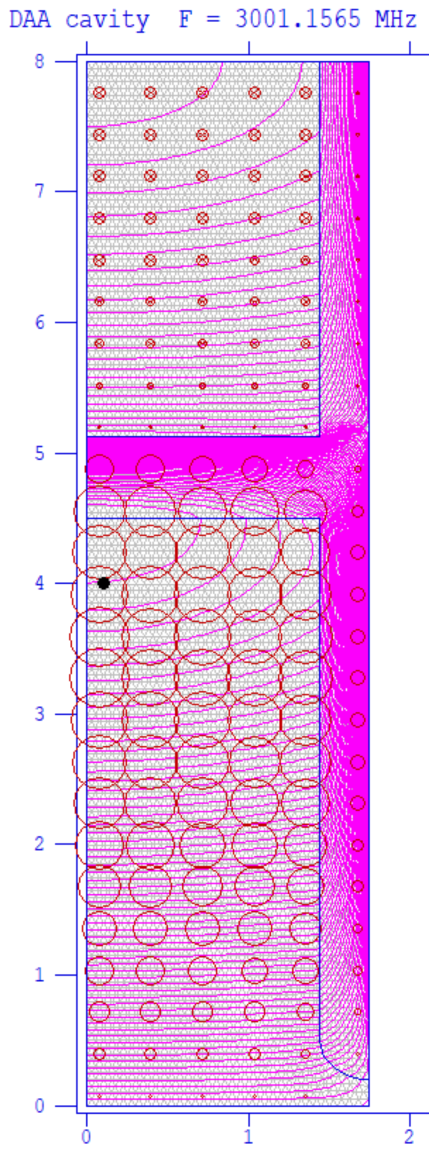


Different β for D-16

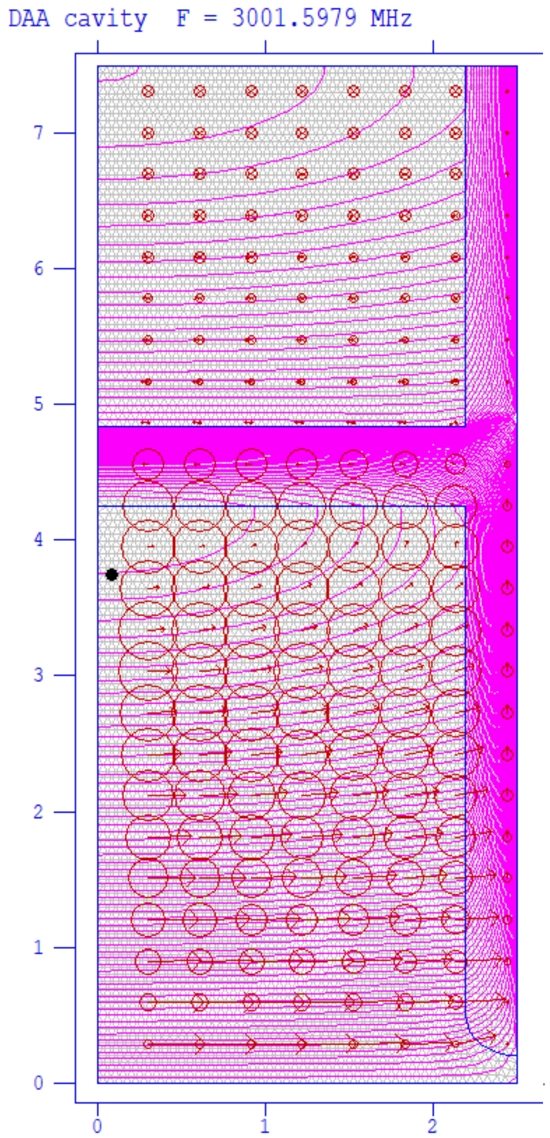
$\beta = 0.4$



$\beta = 0.7$



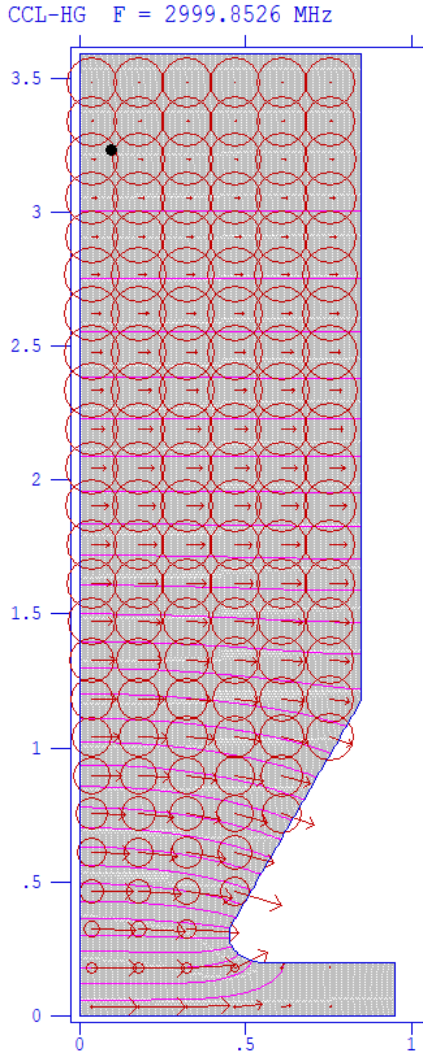
$\beta = 1$



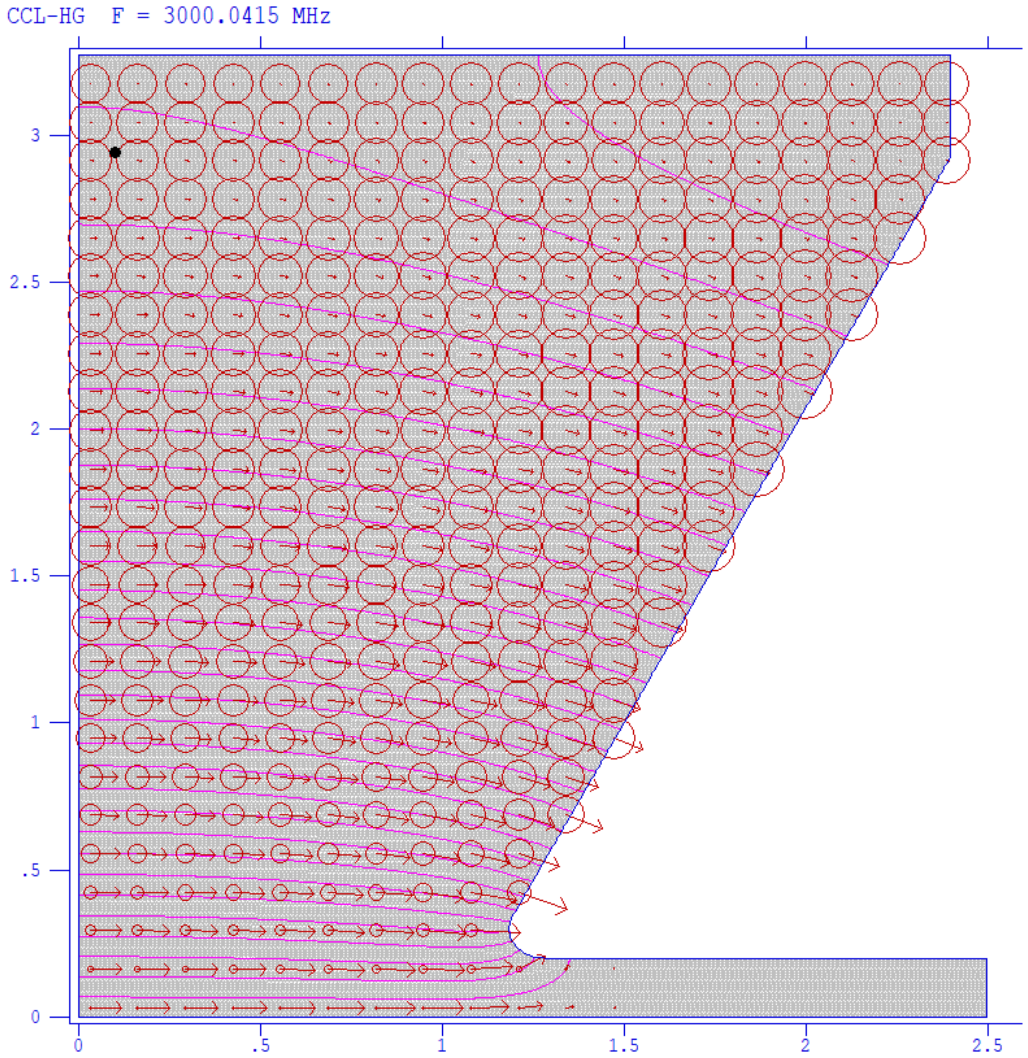
CCL-HG cavity single cell scan

Increase L with beta, keeping noses proportional

$\beta = 0.38, f = 2999.9\ MHz\ , Q_0 = 9619, ZTT = 66.3\ M\Omega/m$

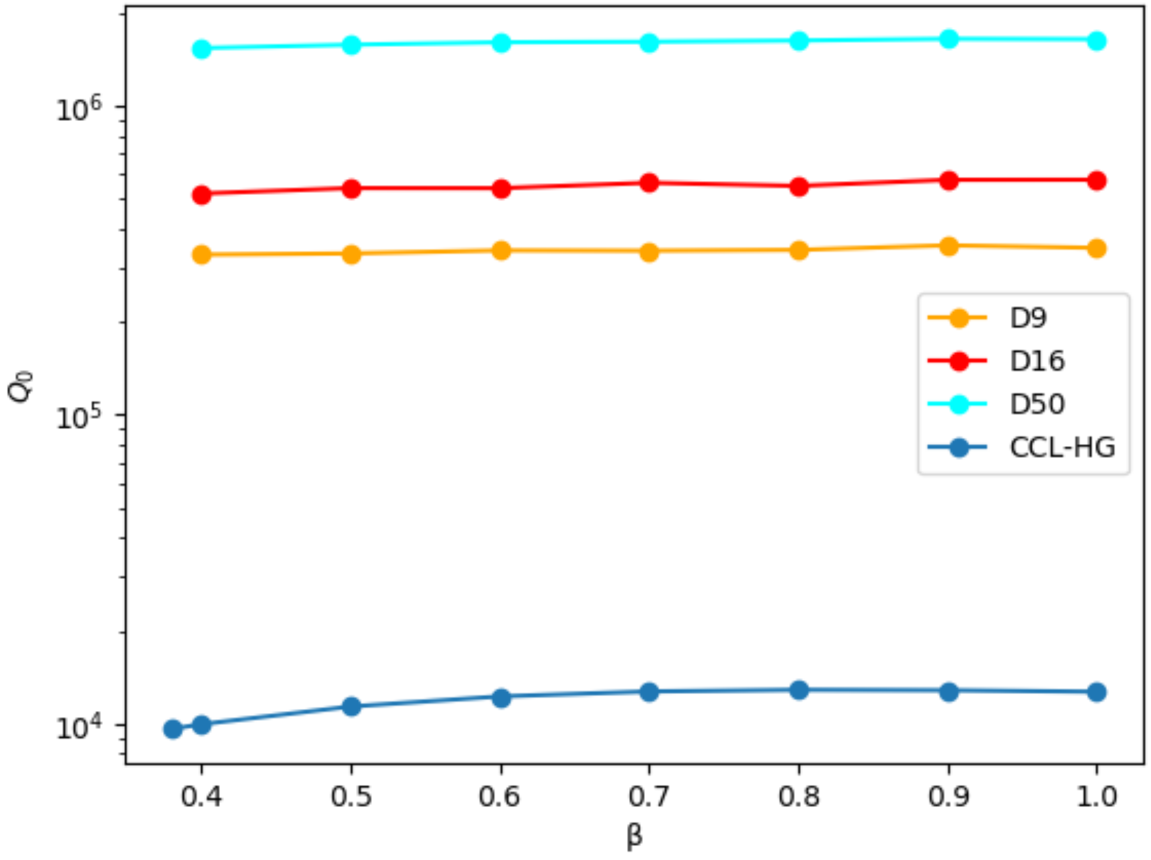


$\beta = 1, f = 3000.0\ MHz\ , Q_0 = 12703, ZTT = 74.3\ M\Omega/m$

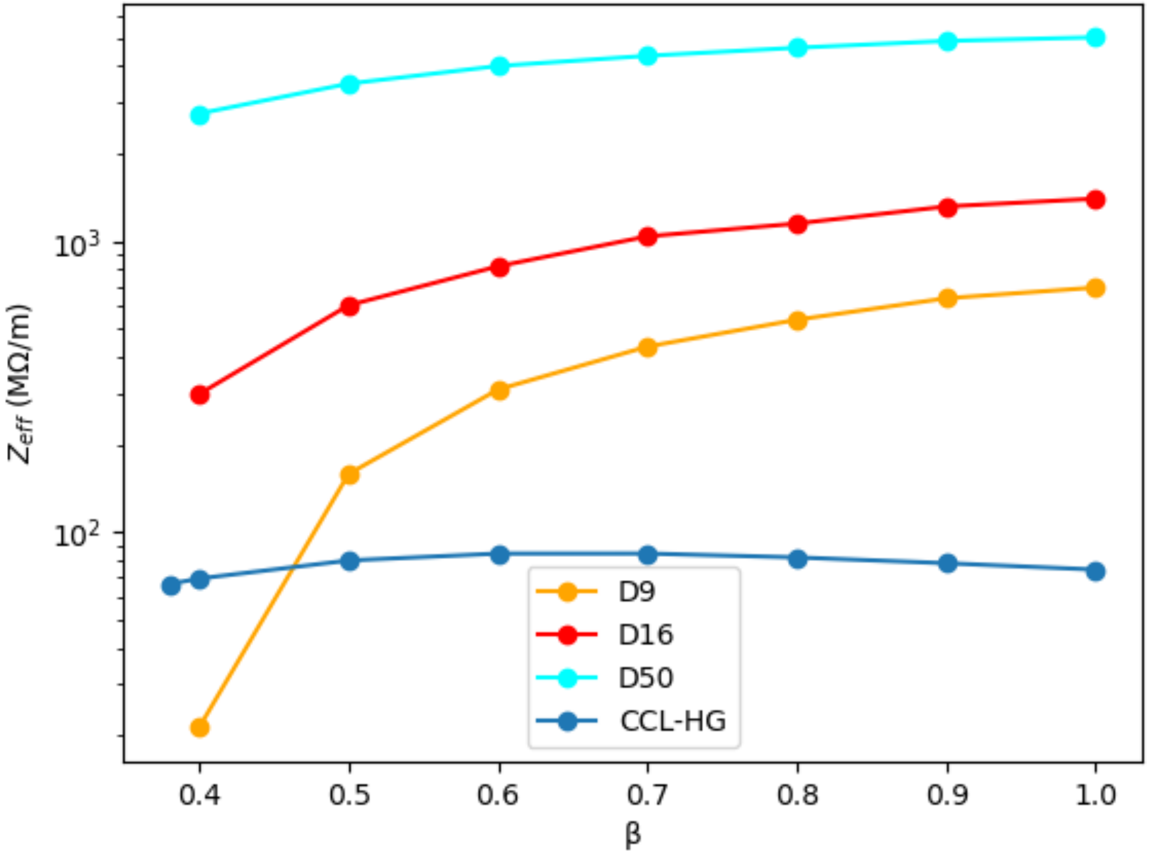


Material and β studies with Superfish

Q_0 vs β for different material

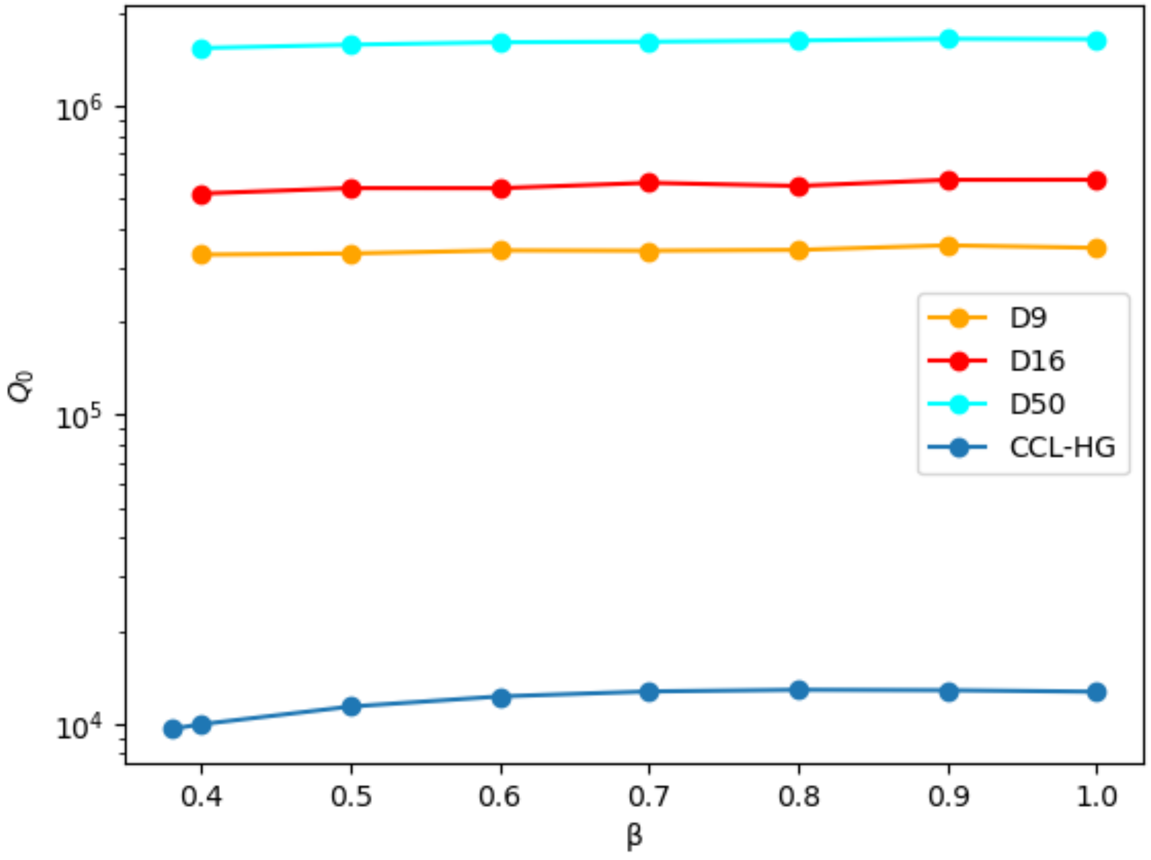


ZTT vs β for different material

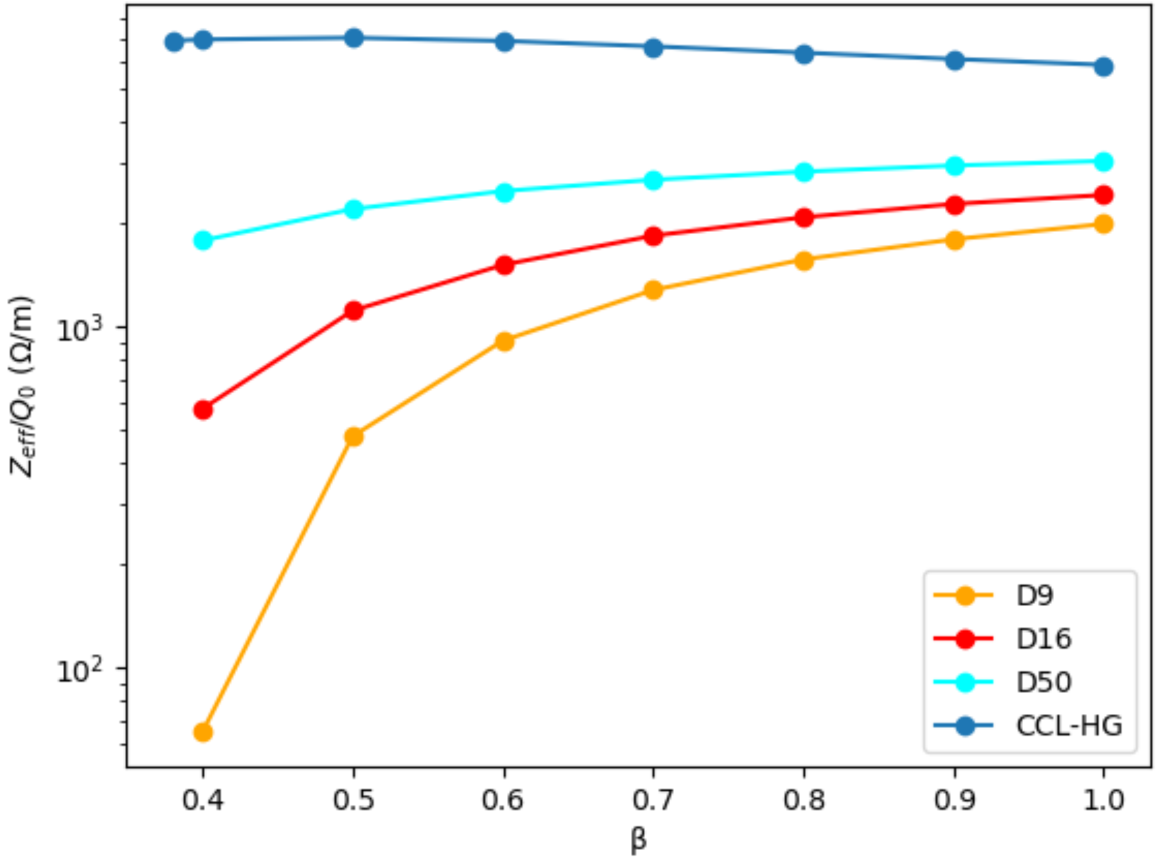


Material and β studies with Superfish

Q_0 vs β for different material

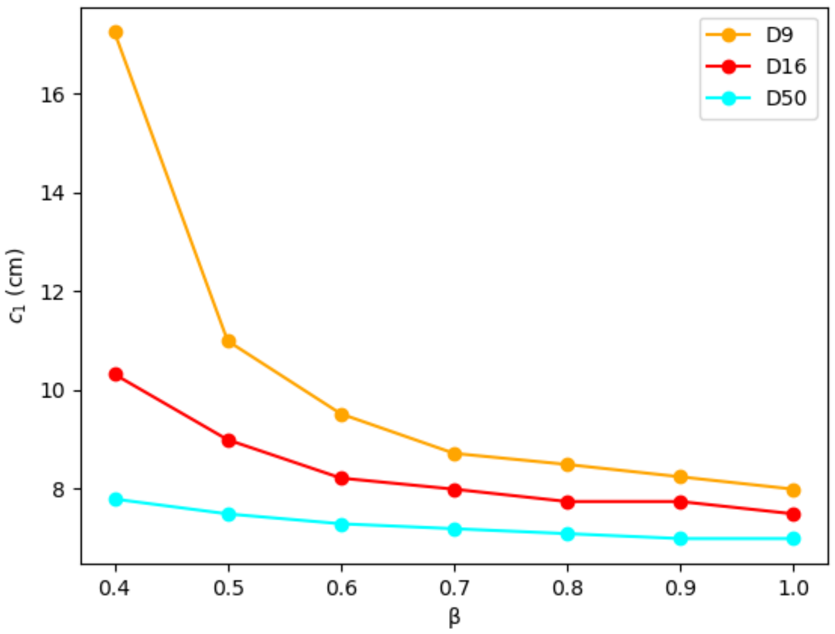


ZTT/Q_0 vs β for different material

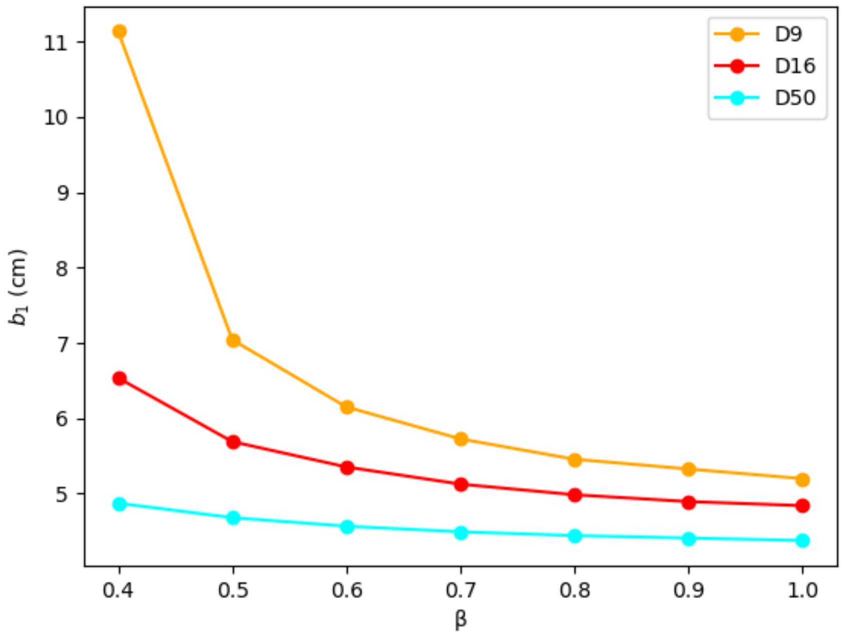


Material and β studies with Superfish

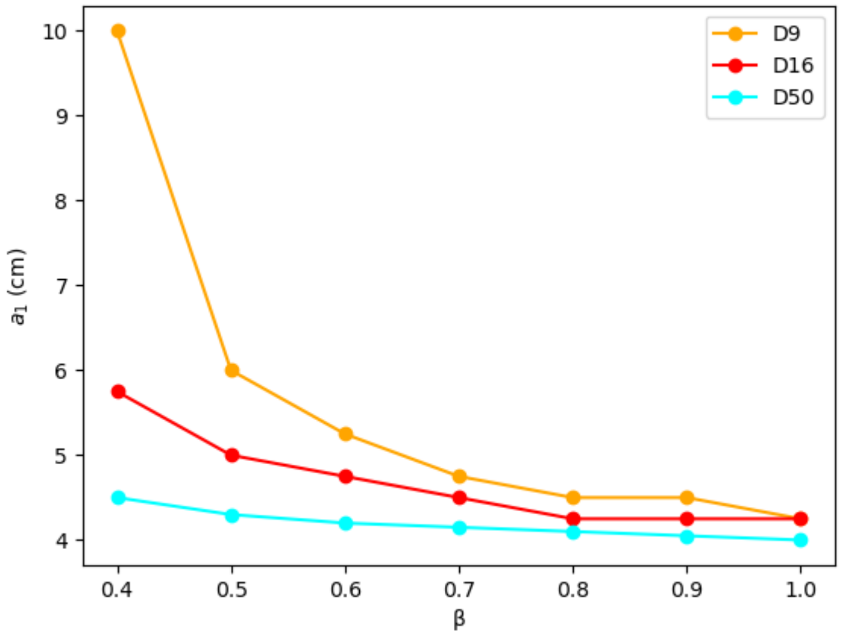
c_1 vs β for different material



b_1 vs β for different material



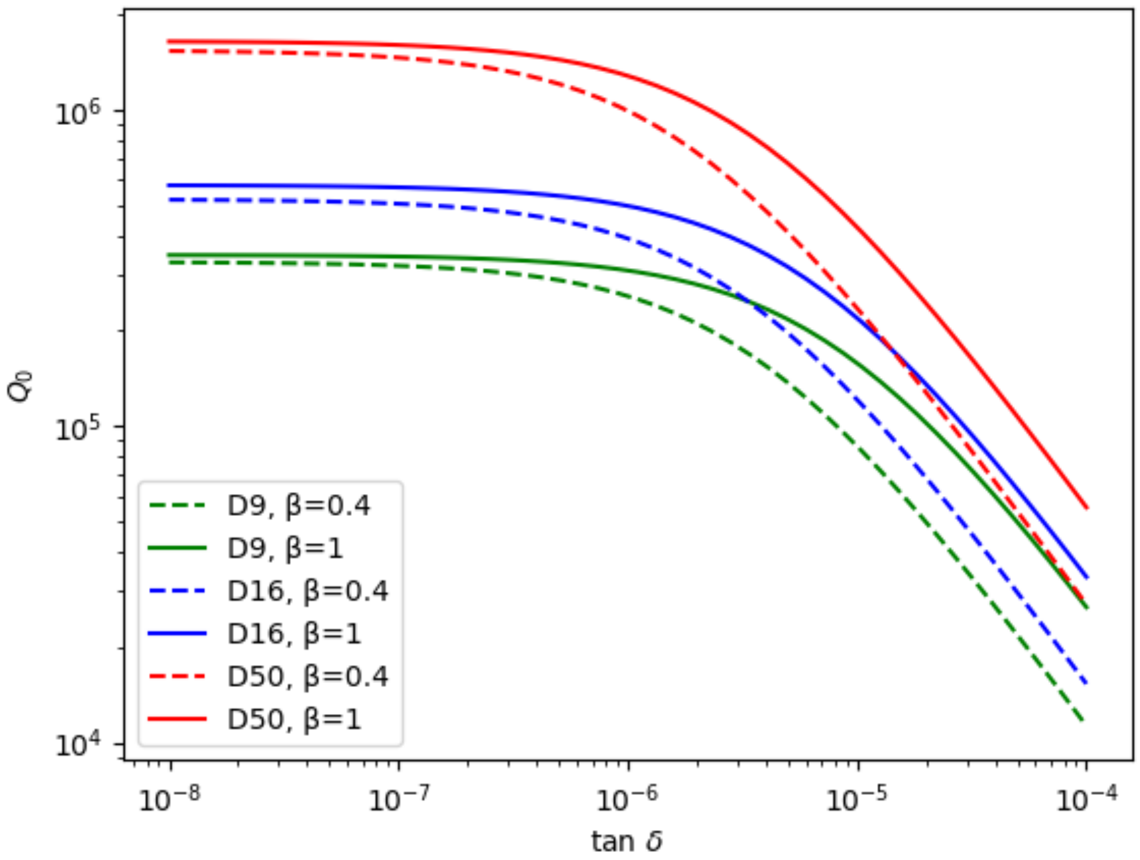
a_1 vs β for different material



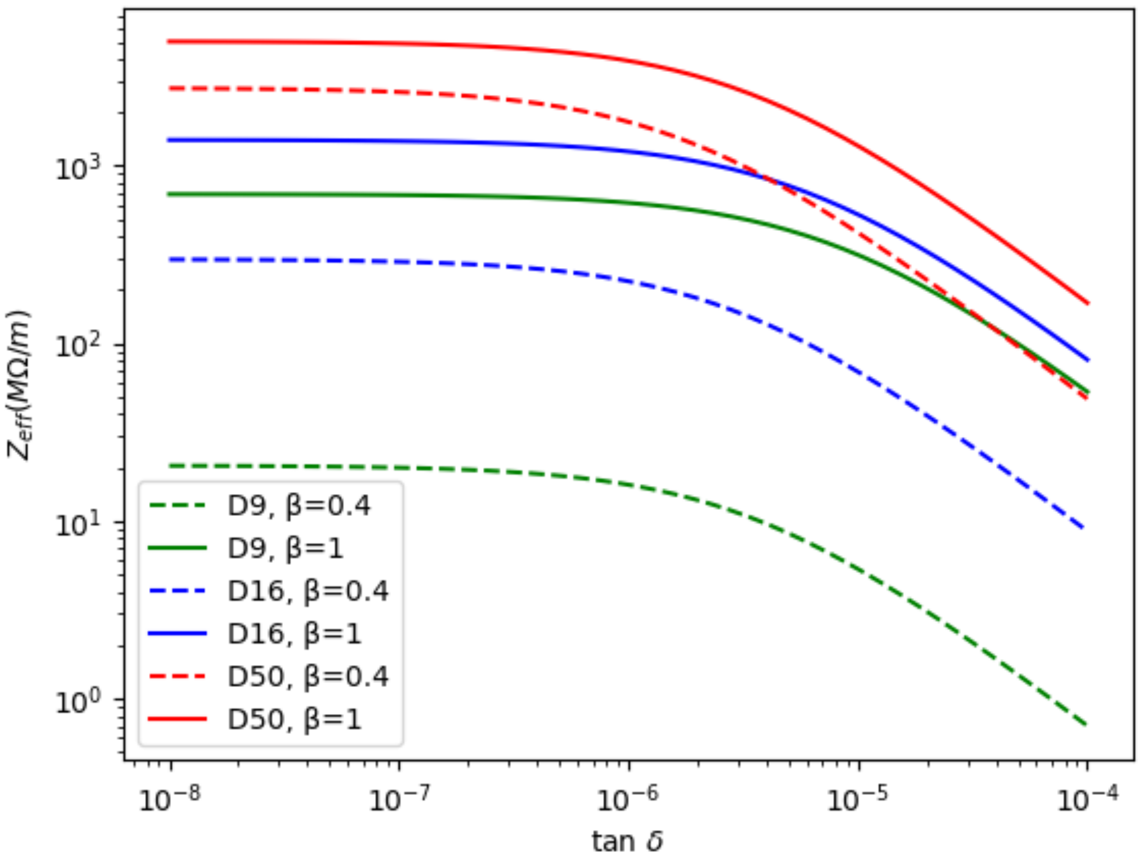
Scan in losses

Scan in losses keeping the ideal geometry.

Q_0 vs $\tan\delta$



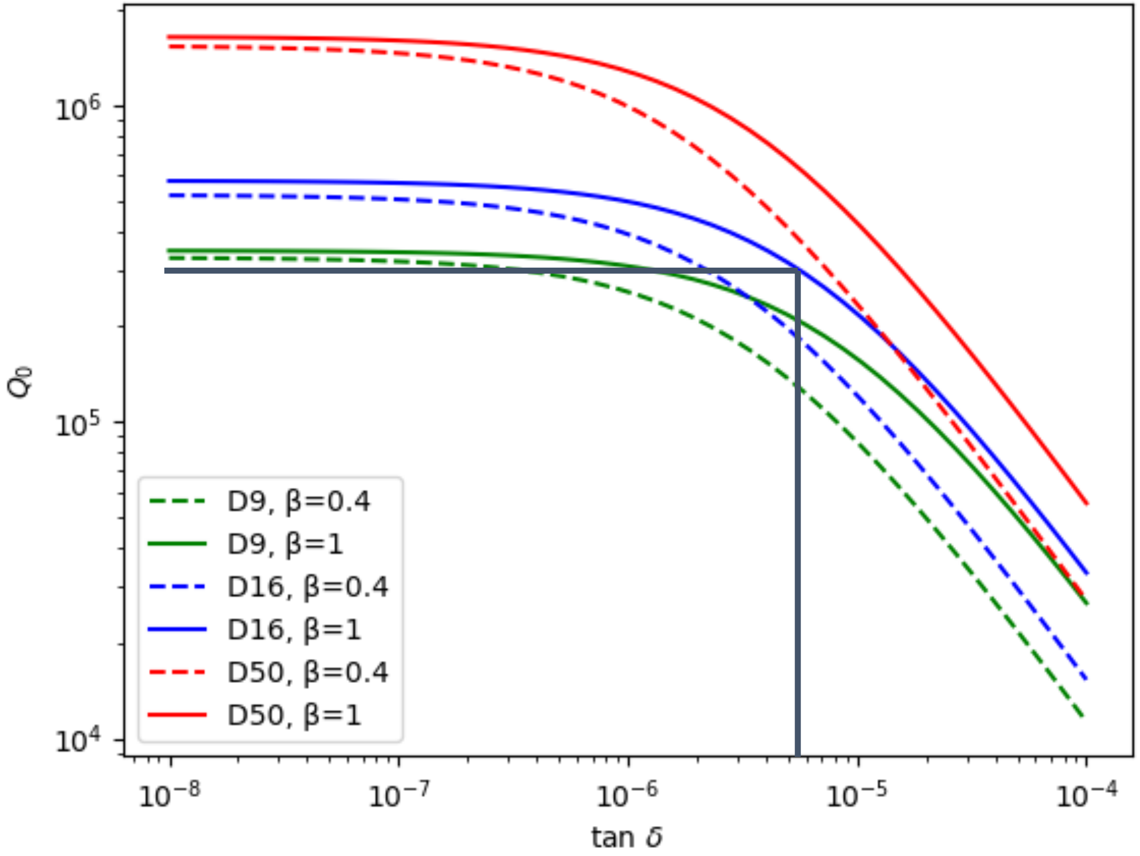
ZTT vs $\tan\delta$



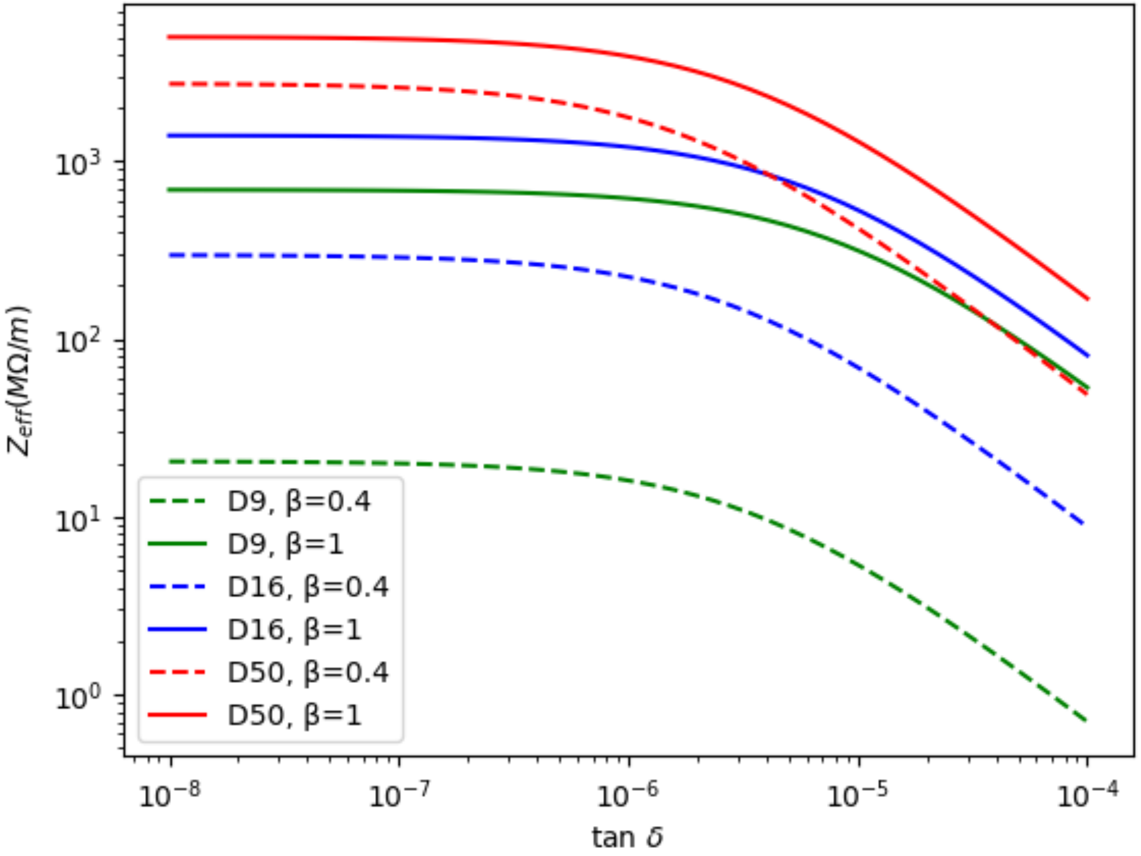
Scan in losses

Scan in losses keeping the ideal geometry.

Q_0 vs $\tan\delta$



ZTT vs $\tan\delta$

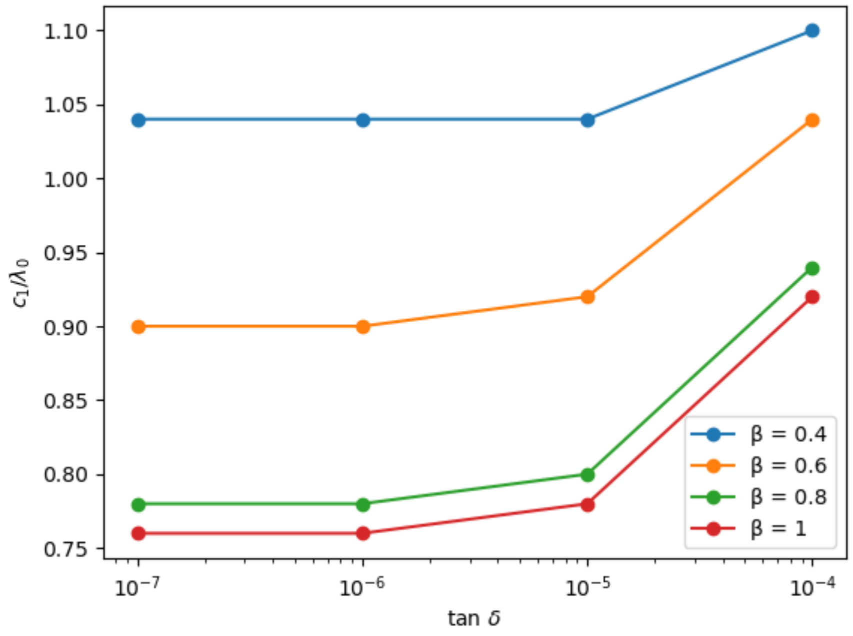


Real studies with Superfish

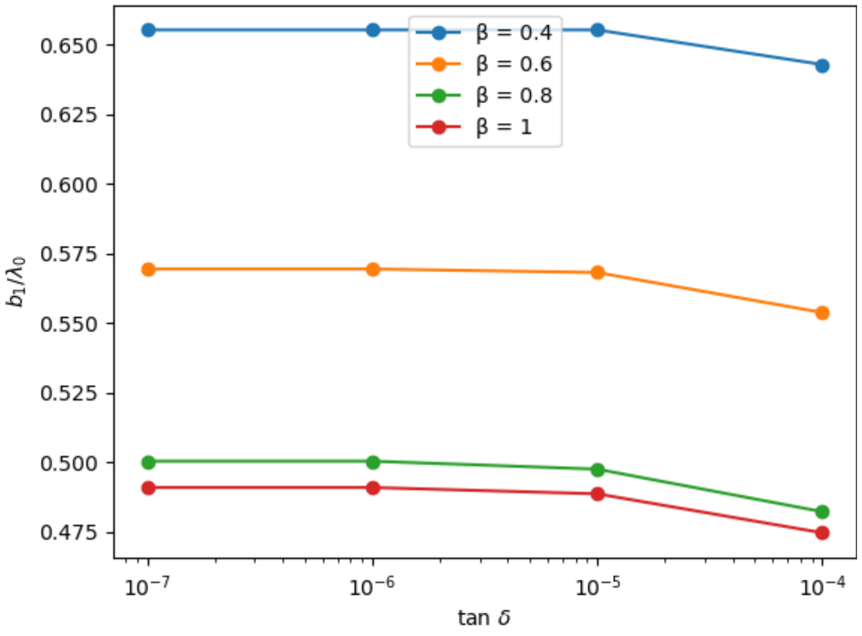
Scan in losses optimization the geometry for each value

Material: $\epsilon_r = 16.66$

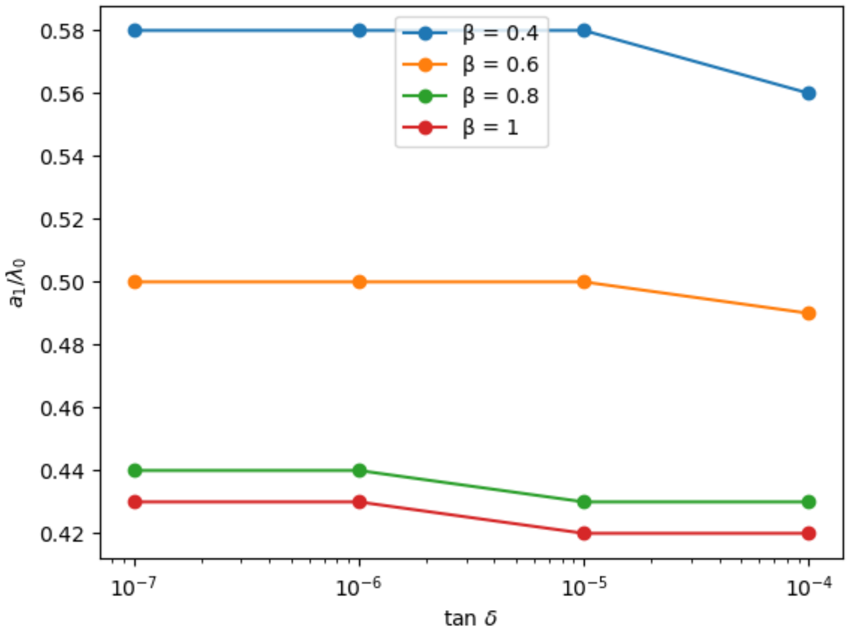
c_1 vs $\tan\delta$



b_1 vs $\tan\delta$



a_1 vs $\tan\delta$

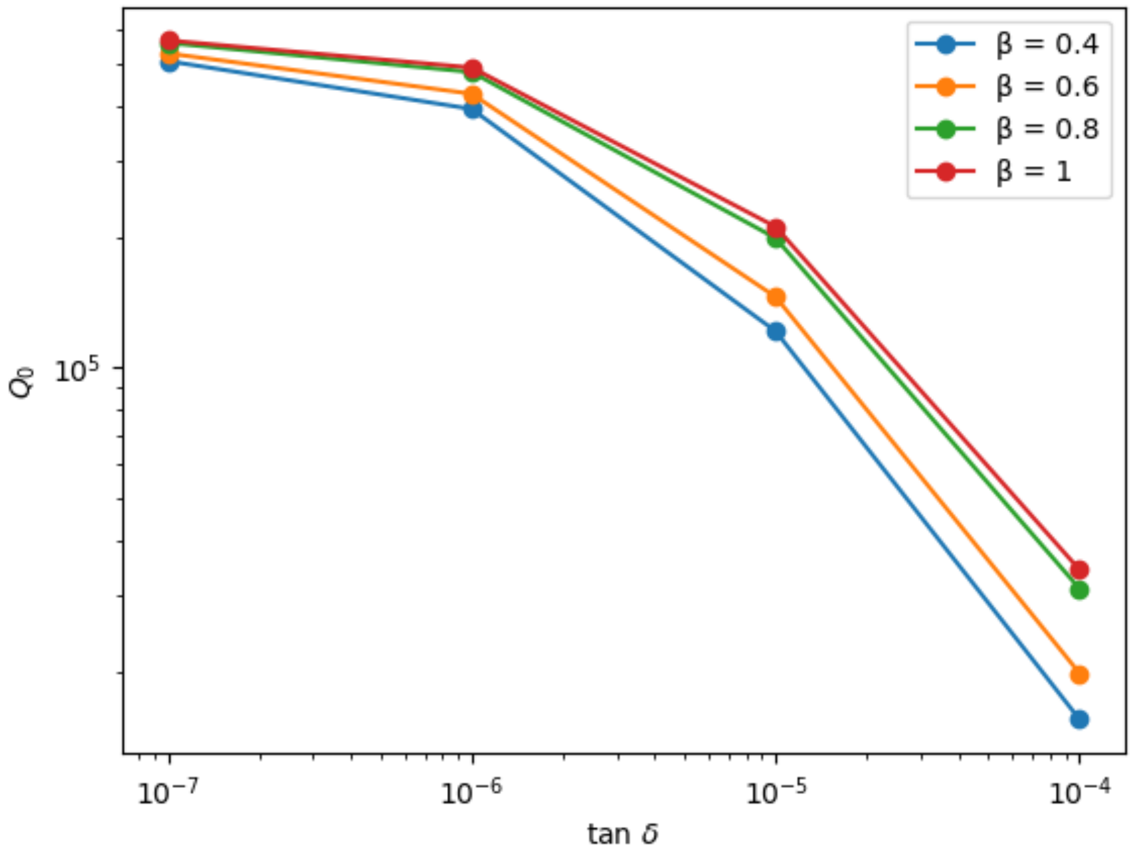


Real studies with Superfish

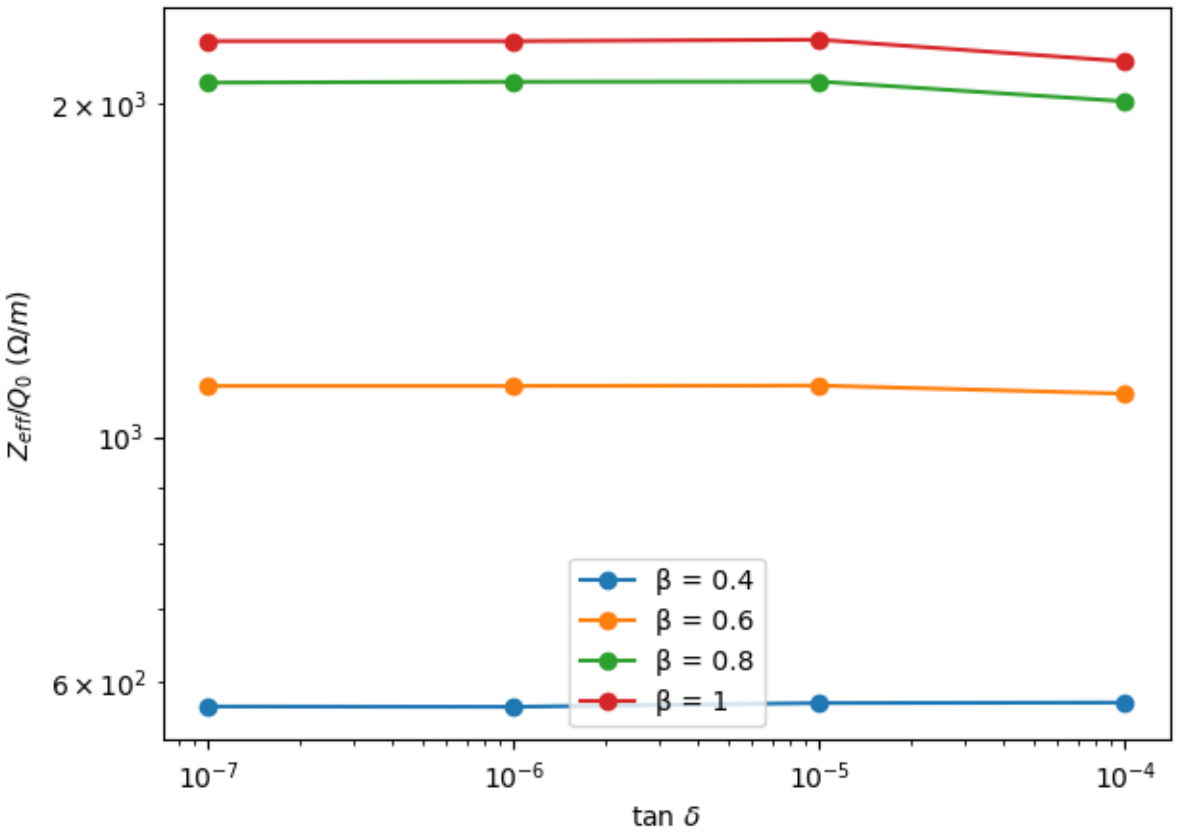
Scan in losses optimization the geometry for each value

Material: $\epsilon_r = 16.66$

Q_0 vs tan δ



ZTT/Q_0 vs tan δ

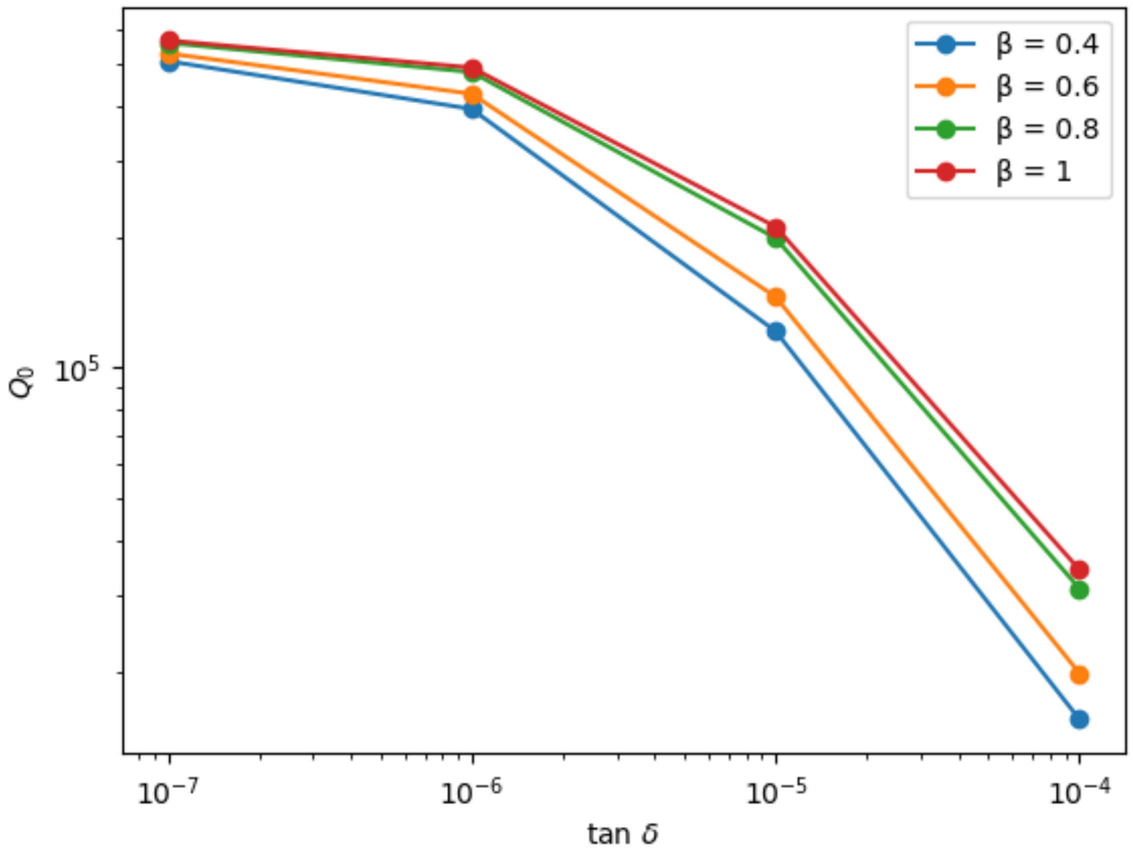


Real studies with Superfish

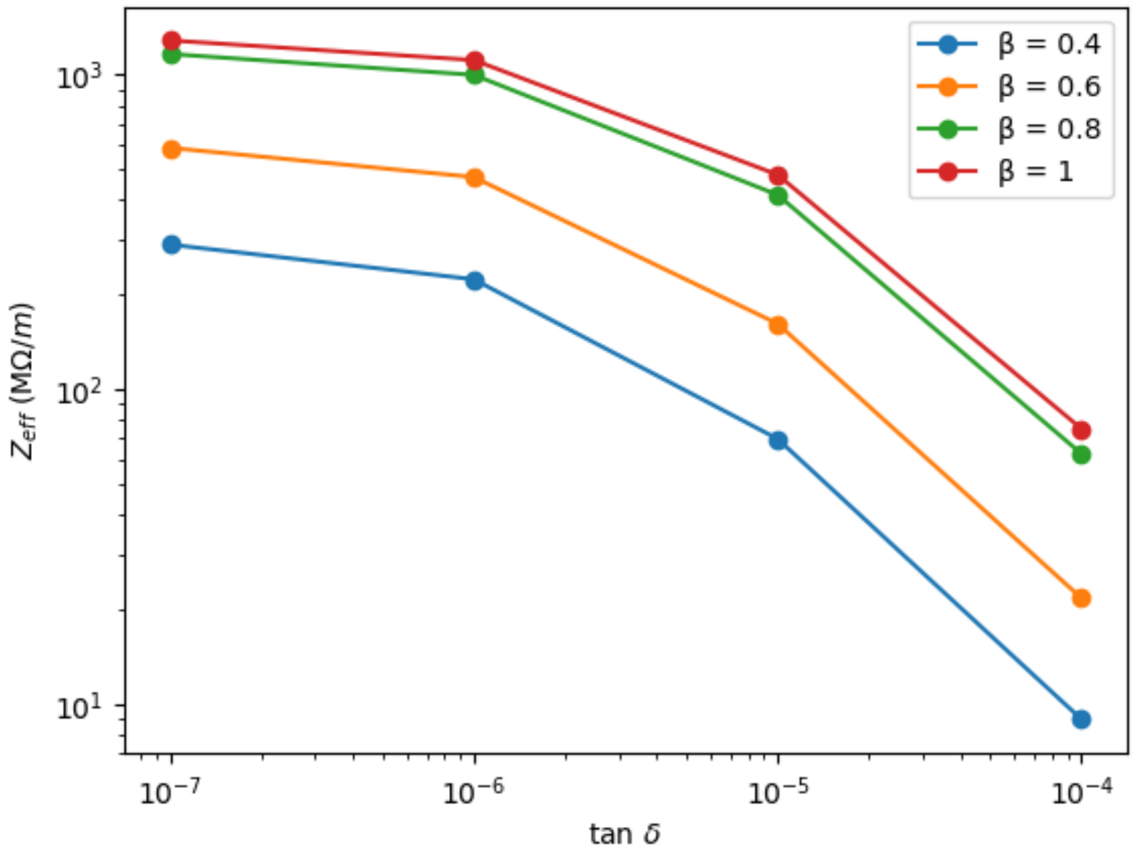
Scan in losses optimization the geometry for each value

Material: $\epsilon_r = 16.66$

Q_0 vs $\tan\delta$

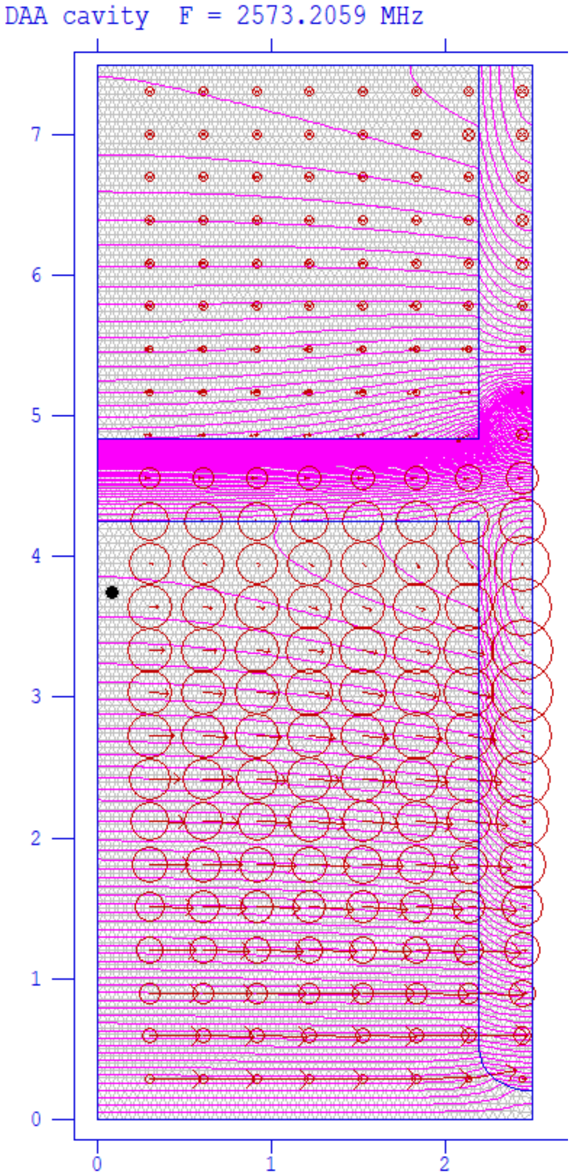


ZTT vs $\tan\delta$

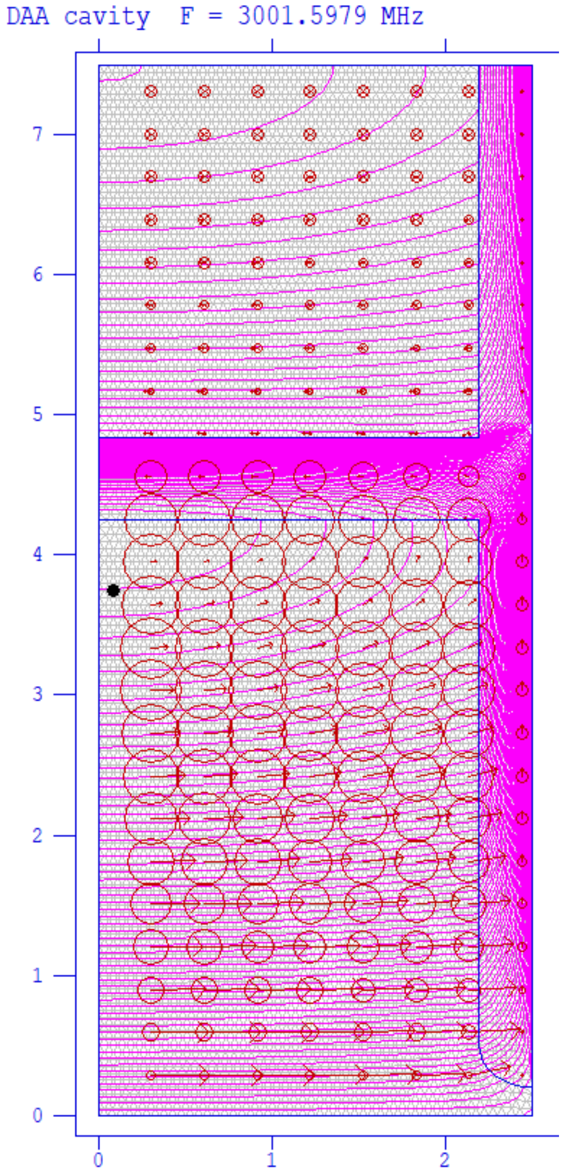


DAA cavity single cell coupling

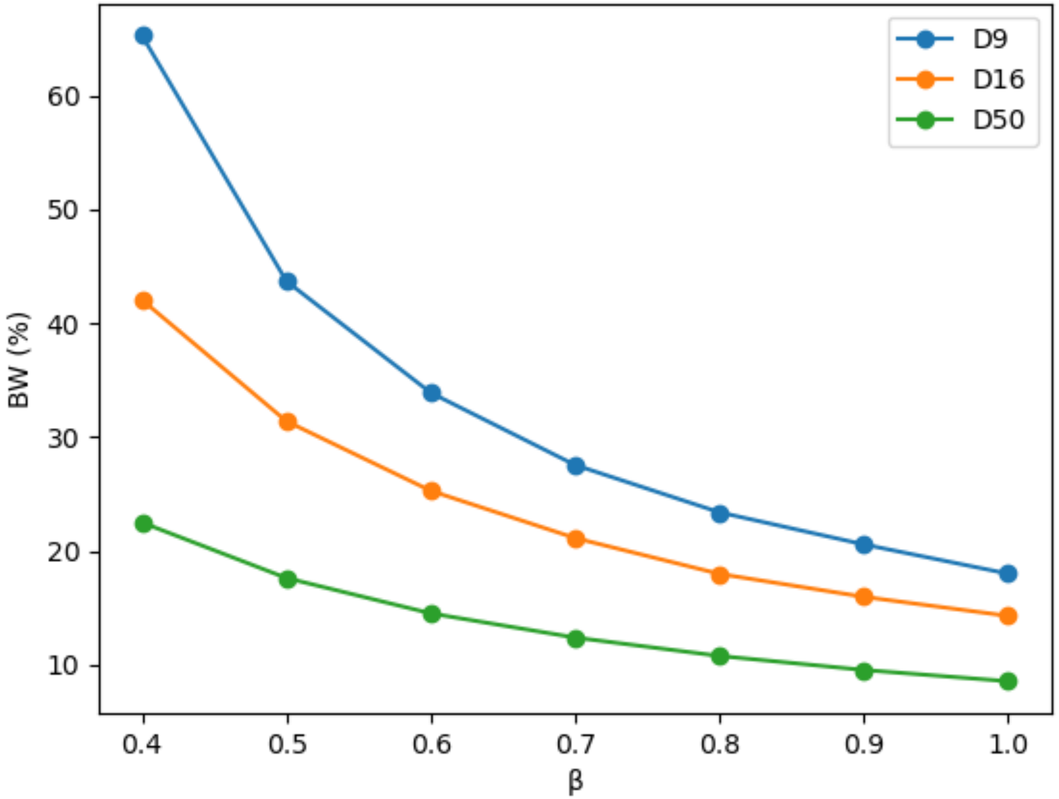
f_0



f_π

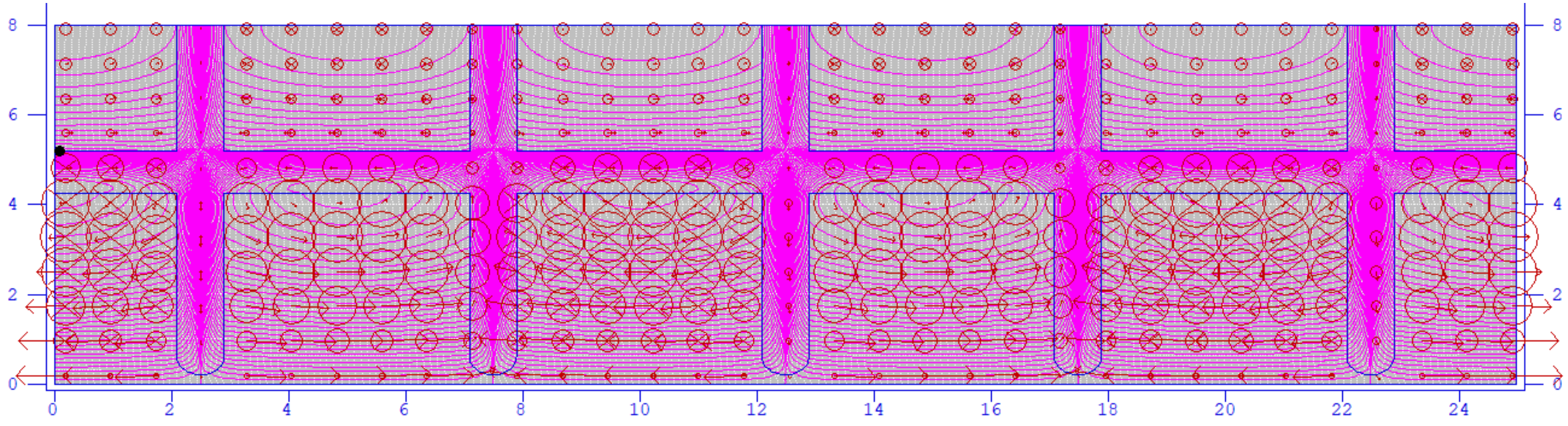


$$BW(\%) = \frac{f_\pi - f_0}{f_\pi}$$

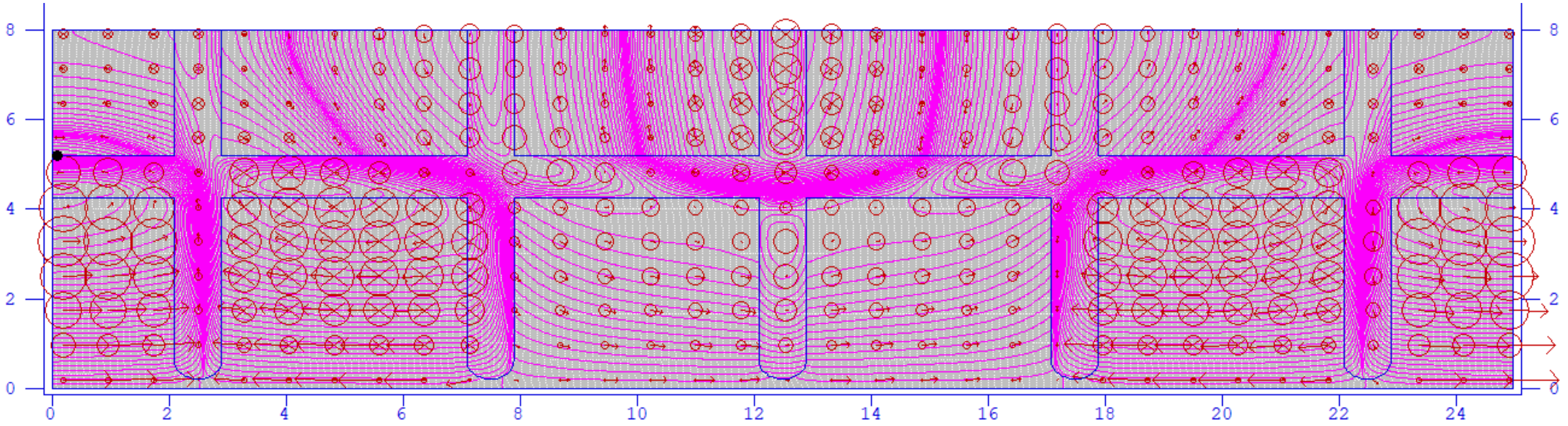


Dispersion curves

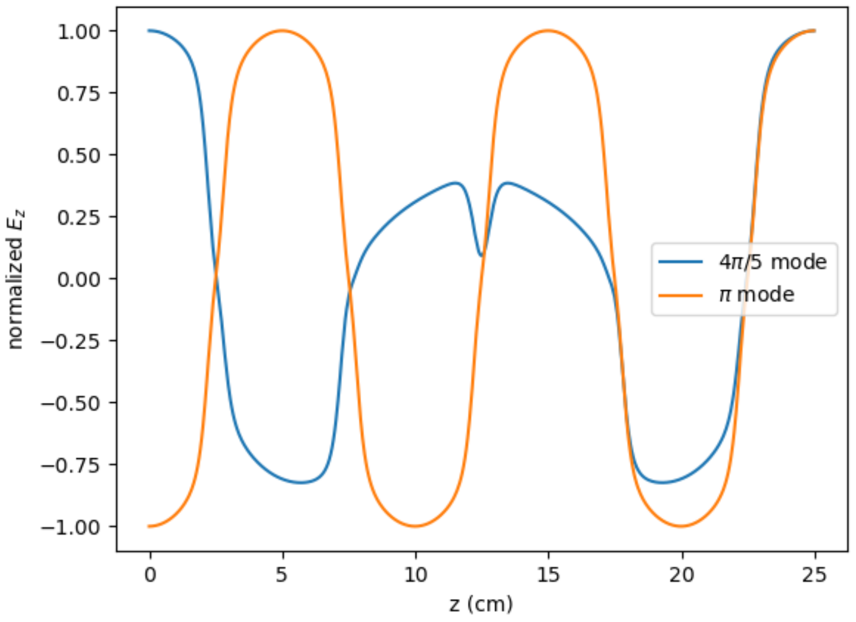
D-9: $\epsilon_r = 9.64,\ \beta = 1,\ \Delta\phi = \pi, f = 3001$ MHz



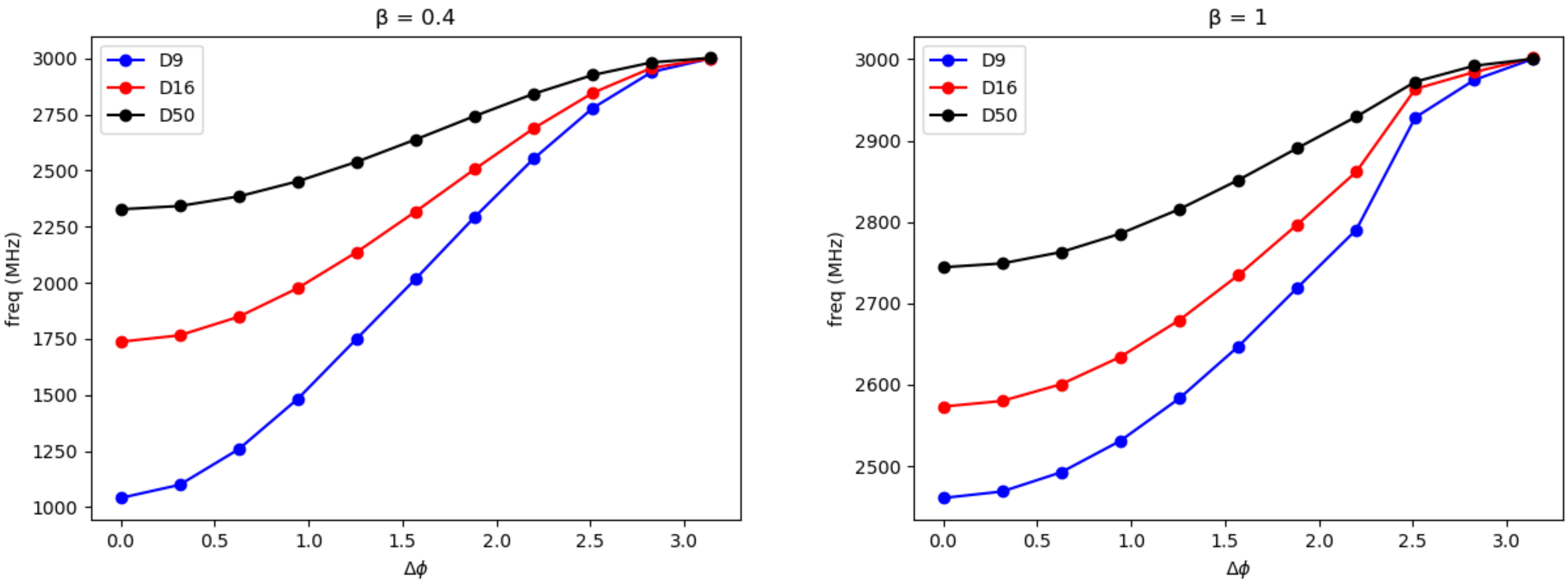
D-9: $\epsilon_r = 9.64,\ \beta = 1, \Delta\phi = 4\pi/5, f = 2929$ MHz



E_z on z-axis



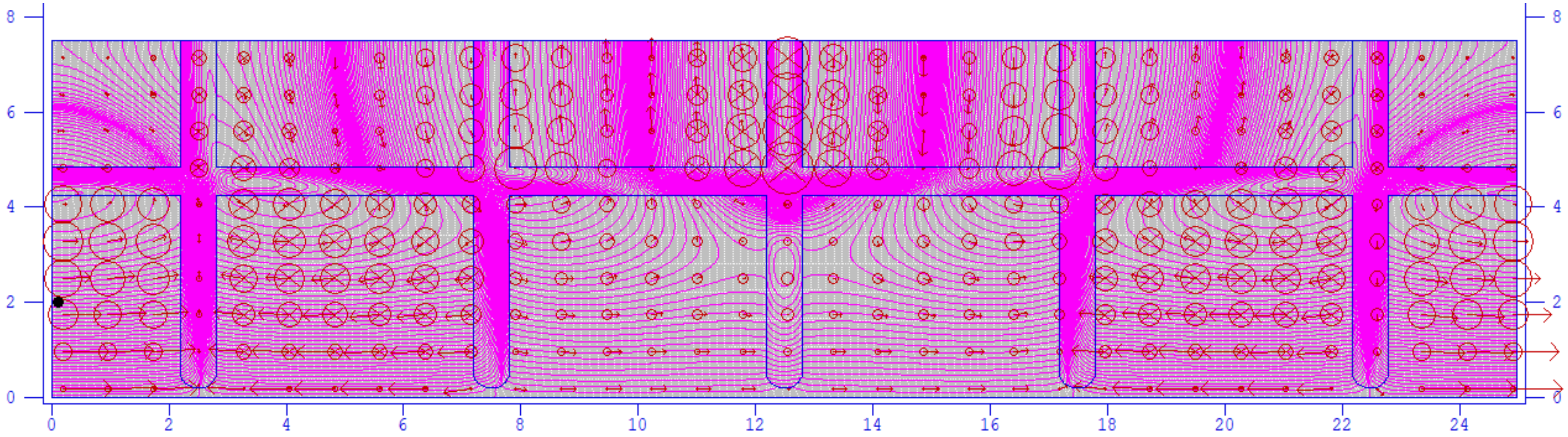
Dispersion curves



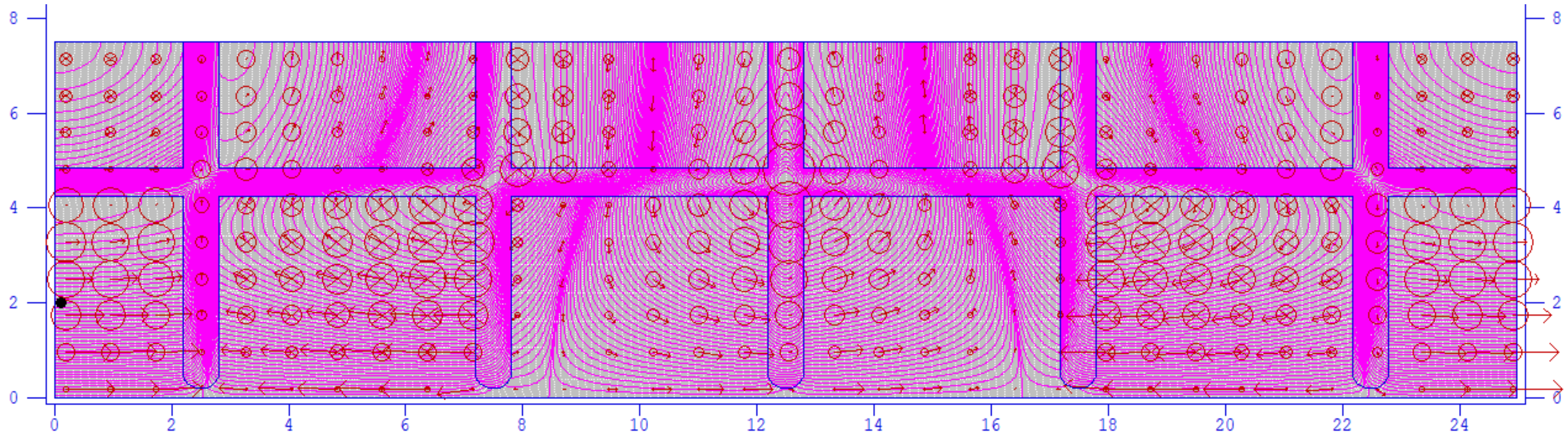
- ❑ High electrical coupling between cell.
- ❑ Coupling improves for lower ϵ_r and lower β

Dispersion curves

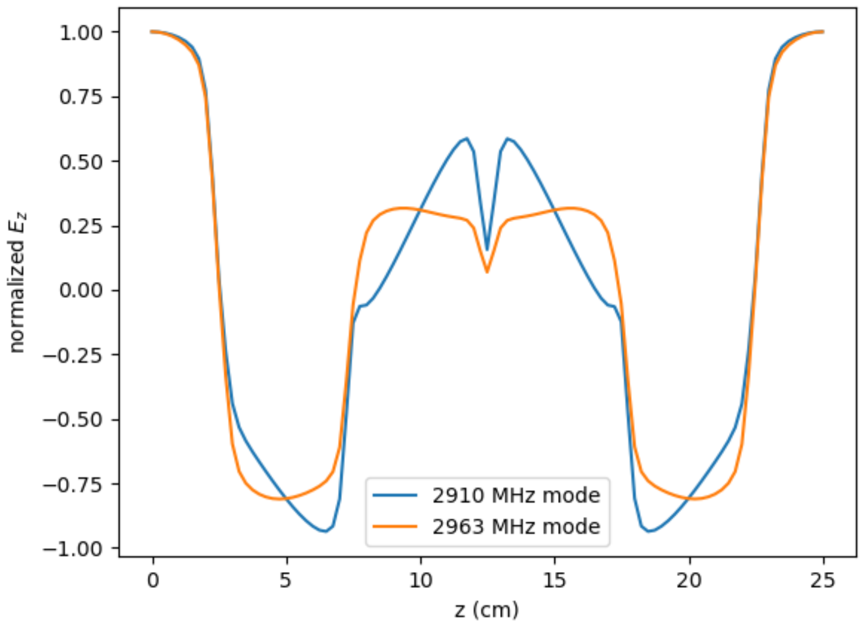
D-16: $\epsilon_r = 16.66,\ \beta = 1,\ \Delta\phi = 4\pi/5, f = 2963$ MHz



D-16: $\epsilon_r = 16.66,\ \beta = 1, \Delta\phi = 4\pi/5, f = 2910$ MHz



E_z on z-axis



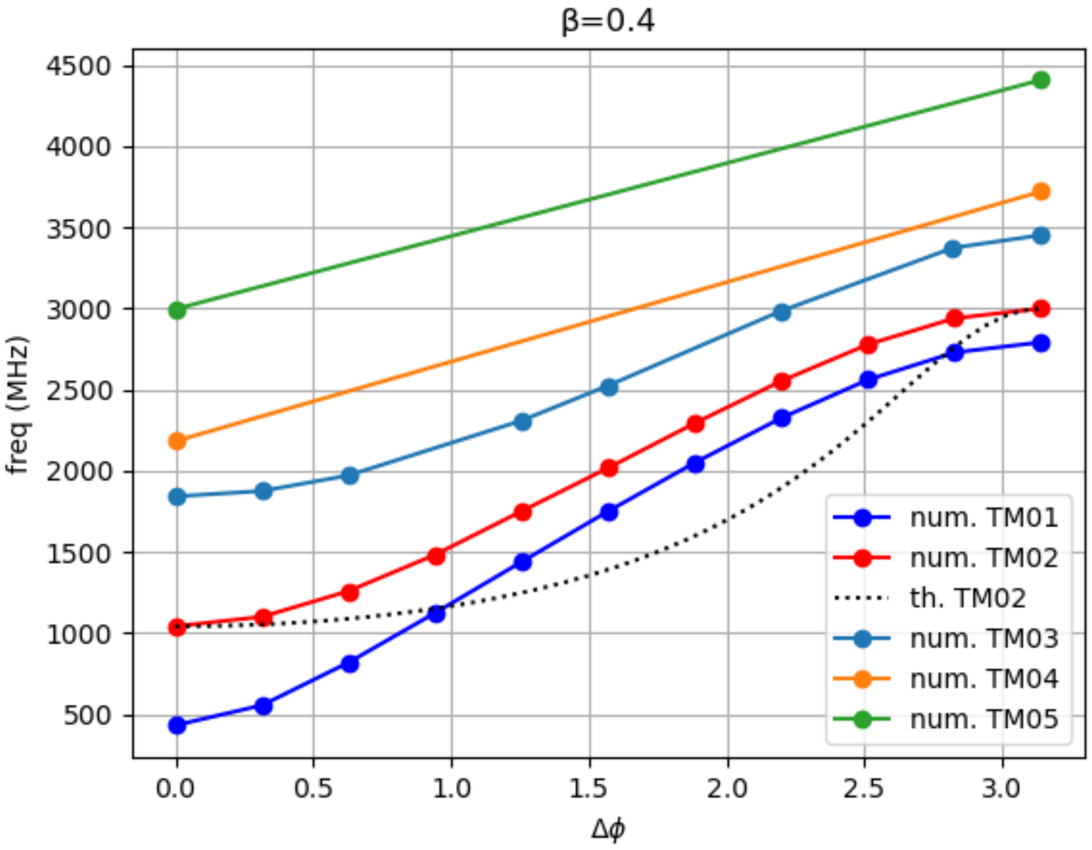
Dispersion curves

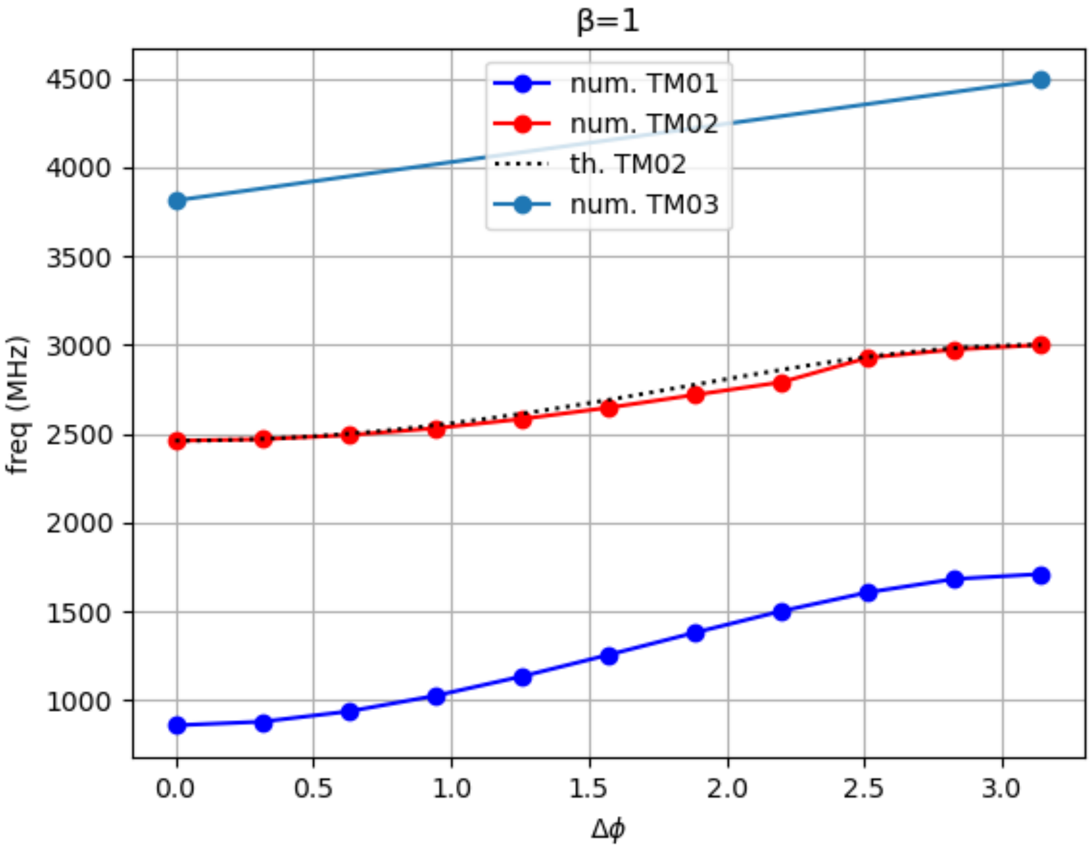
D-9: $\epsilon_r = 9.64$

$$f_{th} = \frac{f_{int}}{\sqrt{1 + k\cos\Delta\phi}}$$

Intrinsic frequency: $f_{int} = \sqrt{2}\frac{f_\pi f_0}{\sqrt{f_\pi^2 + f_0^2}}$

Coupling coefficient: $k = \frac{f_\pi^2 - f_0^2}{f_\pi^2 + f_0^2}$





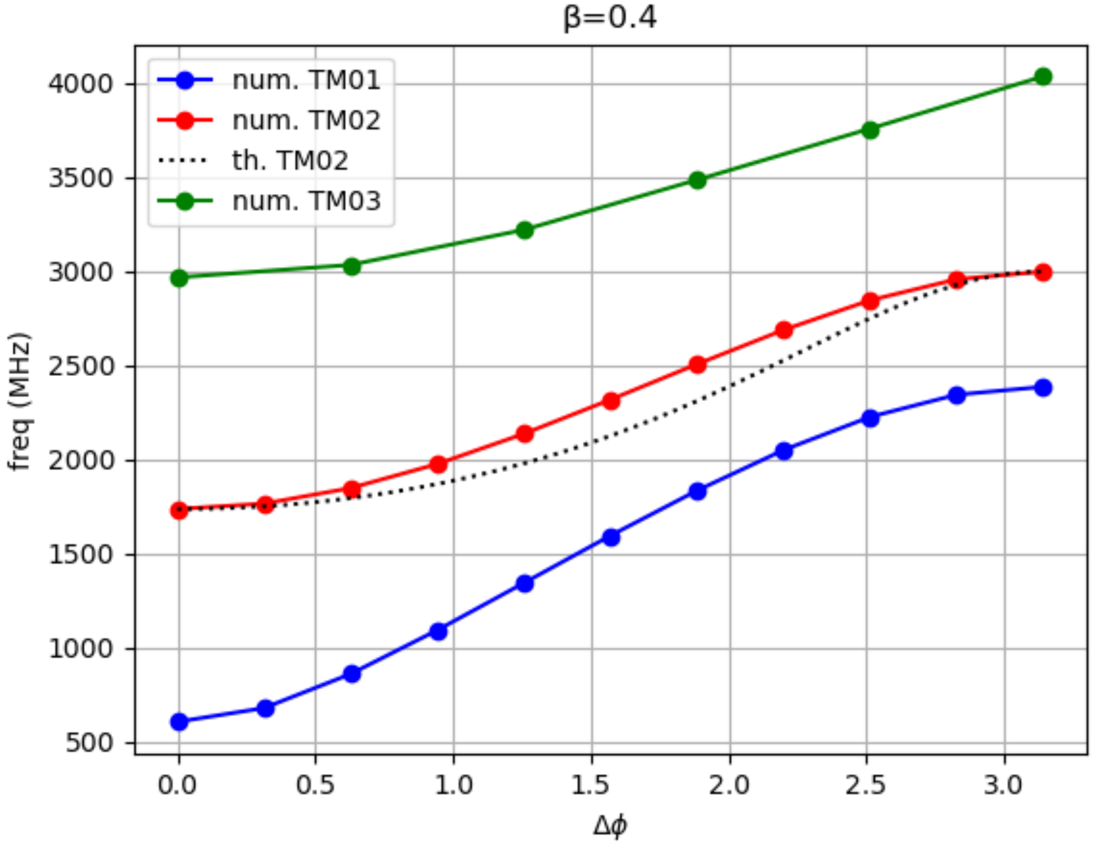
Dispersion curves

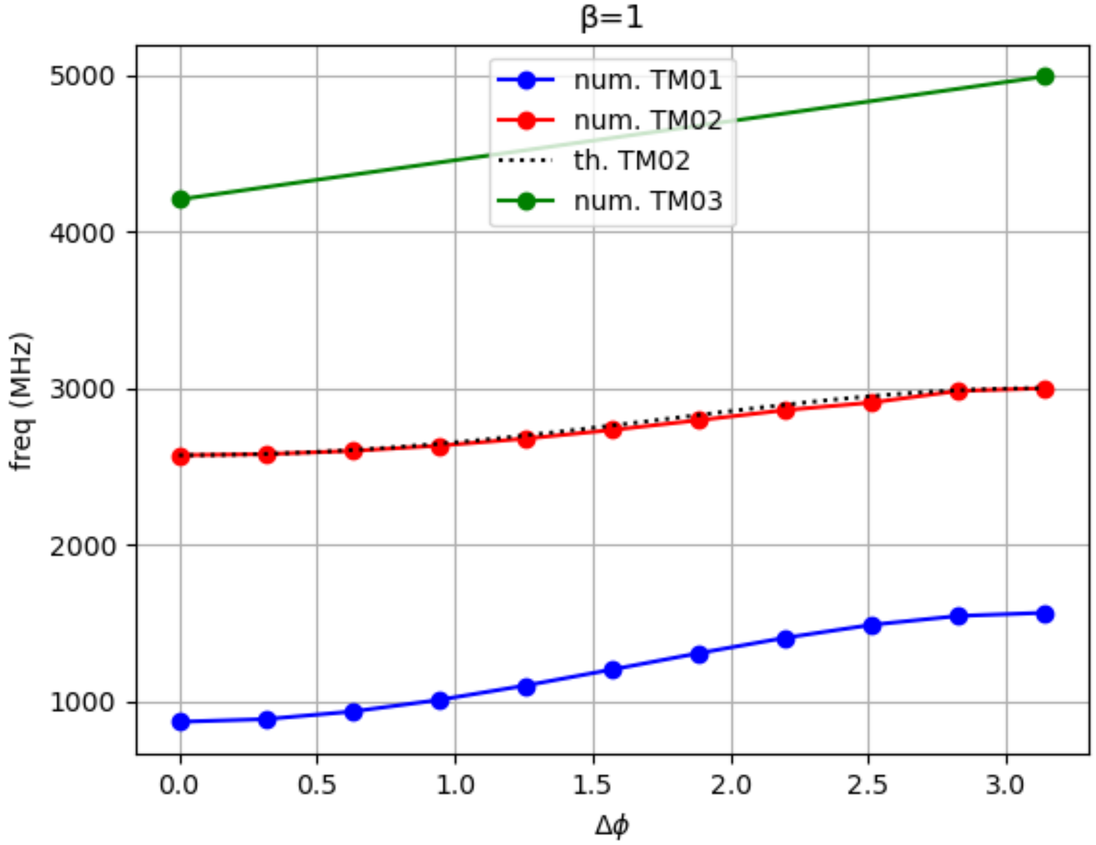
D-16: $\epsilon_r = 16.66$

Intrinsic frequency: $f_{int} = \sqrt{2}\frac{f_\pi f_0}{\sqrt{f_\pi^2+f_0^2}}$

$$f_{th} = \frac{f_{int}}{\sqrt{1 + k\cos\Delta\phi}}$$

Coupling coefficient: $k = \frac{f_\pi^2-f_0^2}{f_\pi^2+f_0^2}$





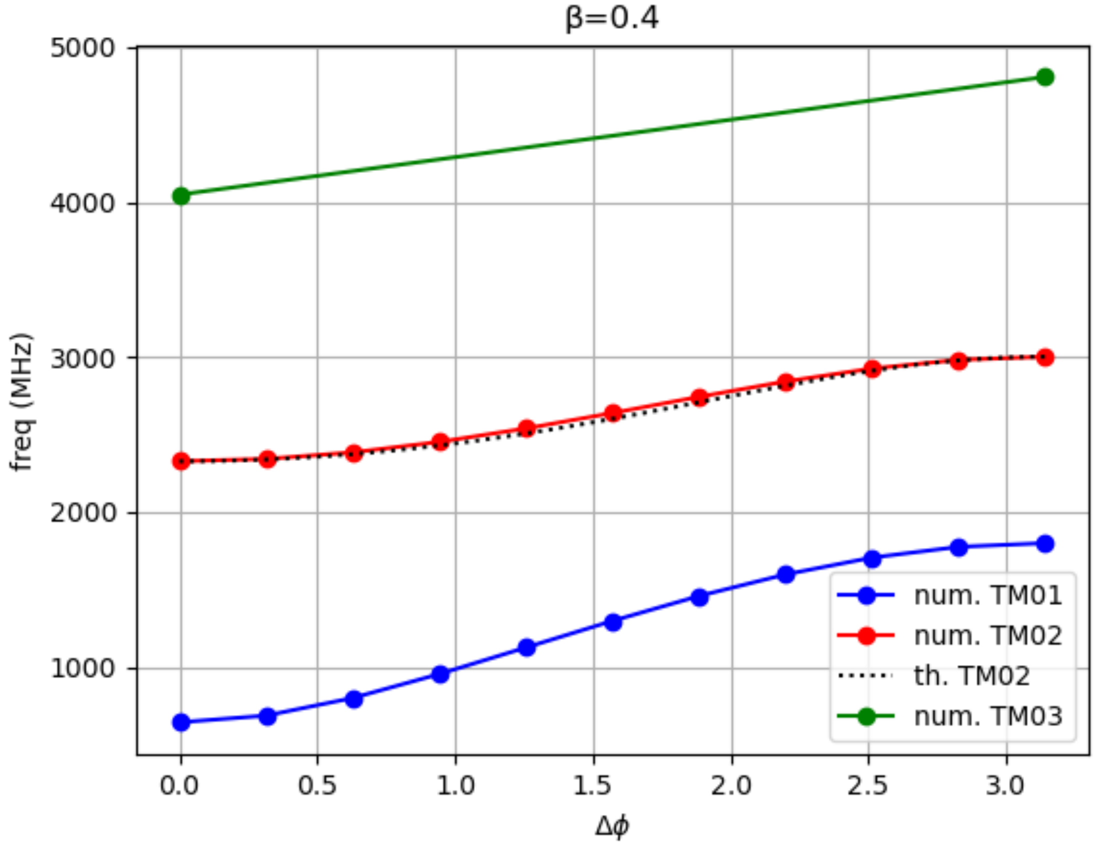
Dispersion curves

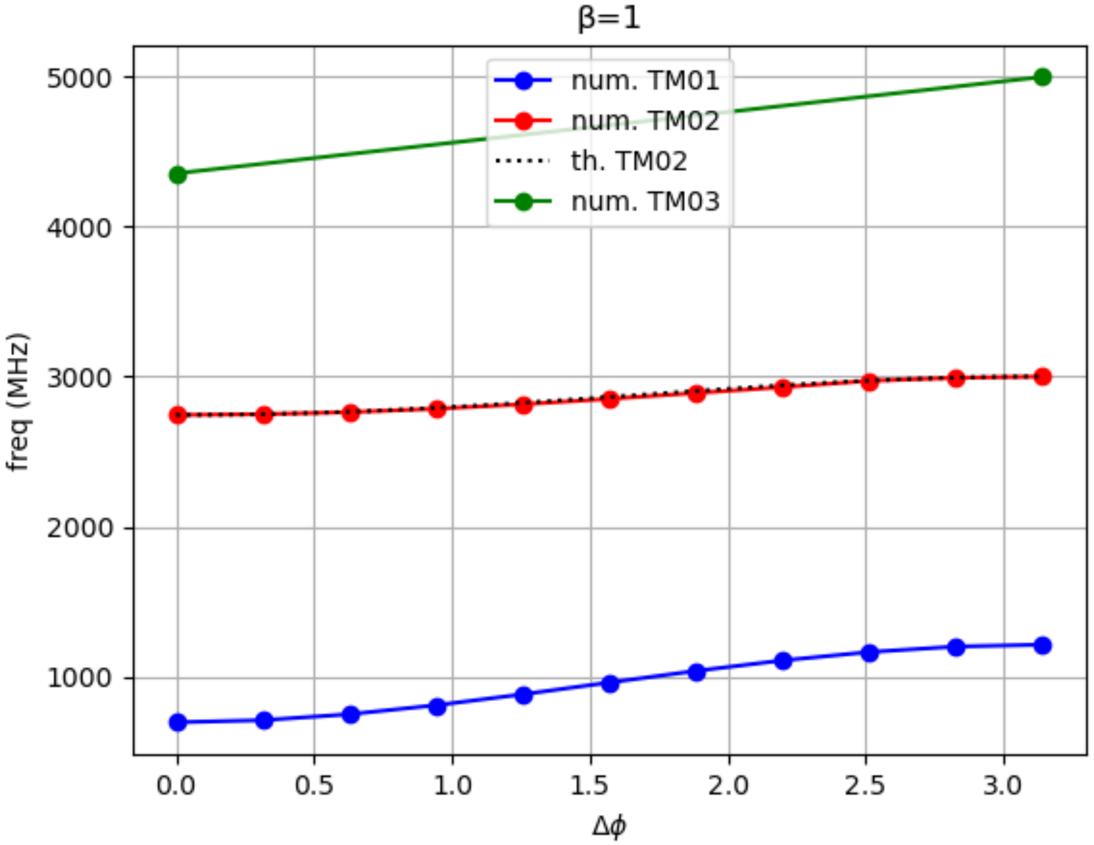
D-50: $\epsilon_r = 50.14$

$$f_{th} = \frac{f_{int}}{\sqrt{1 + k\cos\Delta\phi}}$$

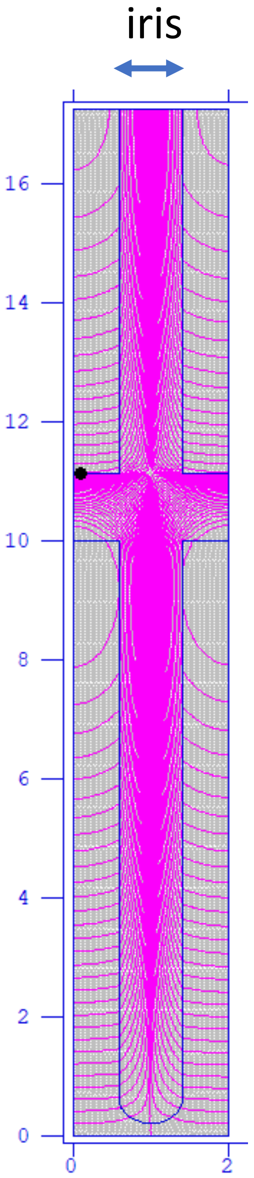
Intrinsic frequency: $f_{int} = \sqrt{2}\frac{f_\pi f_0}{\sqrt{f_\pi^2+f_0^2}}$

Coupling coefficient: $k = \frac{f_\pi^2-f_0^2}{f_\pi^2+f_0^2}$





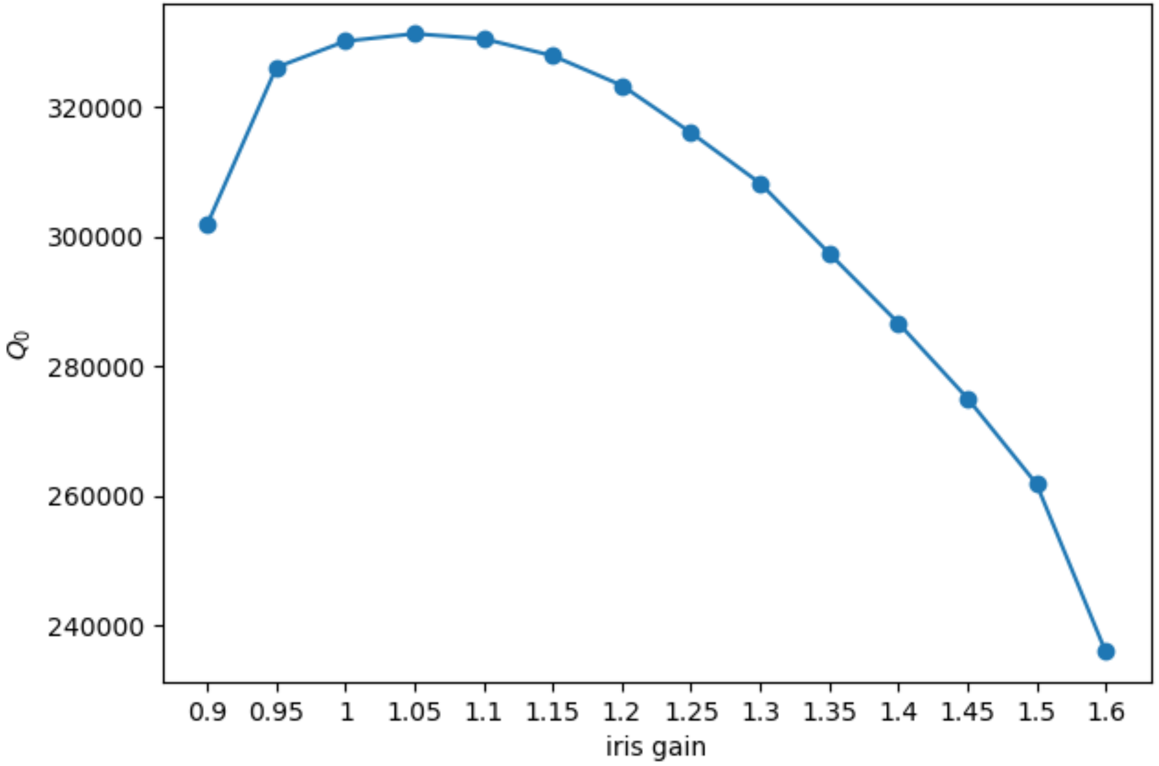
DAA cavity single cell iris optimization

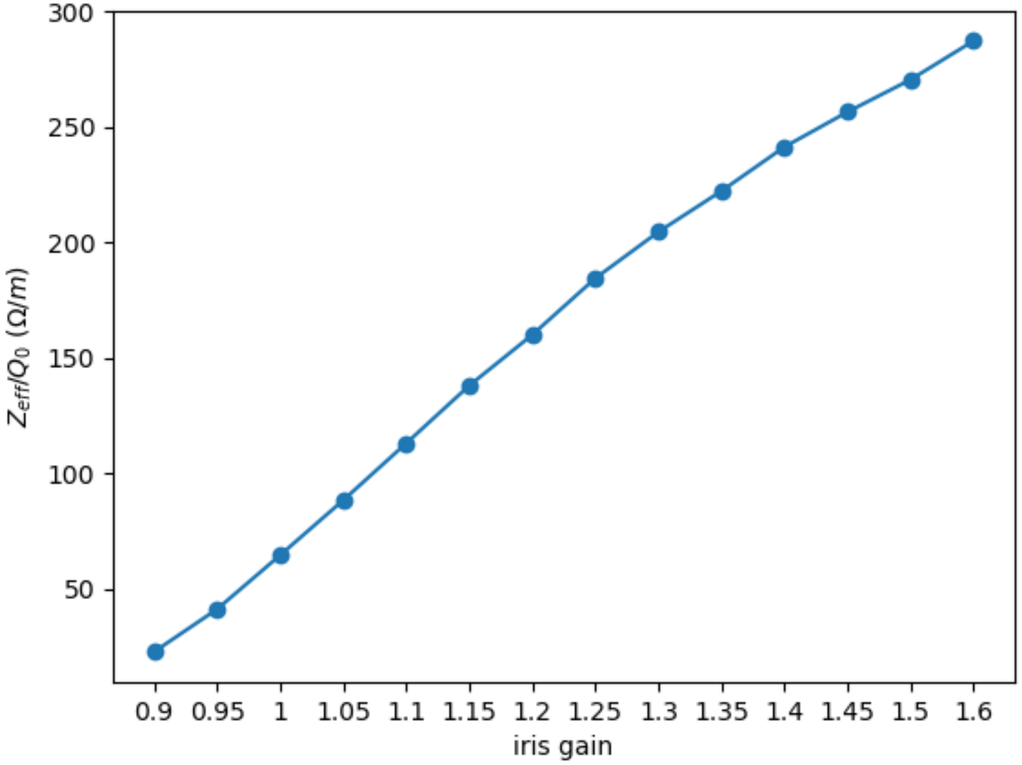


$\epsilon_r = 9.64, \beta = 0.4$

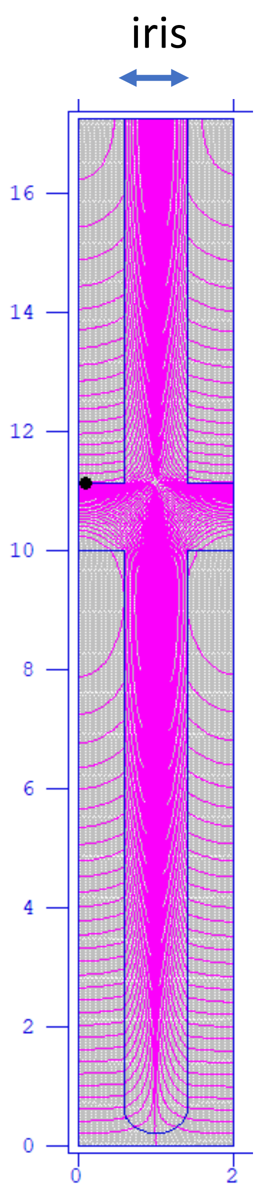
Scan in iris length: $d_0 = \lambda_0/(4\sqrt{\epsilon_r})$

Iris length $= d_0 * gain$





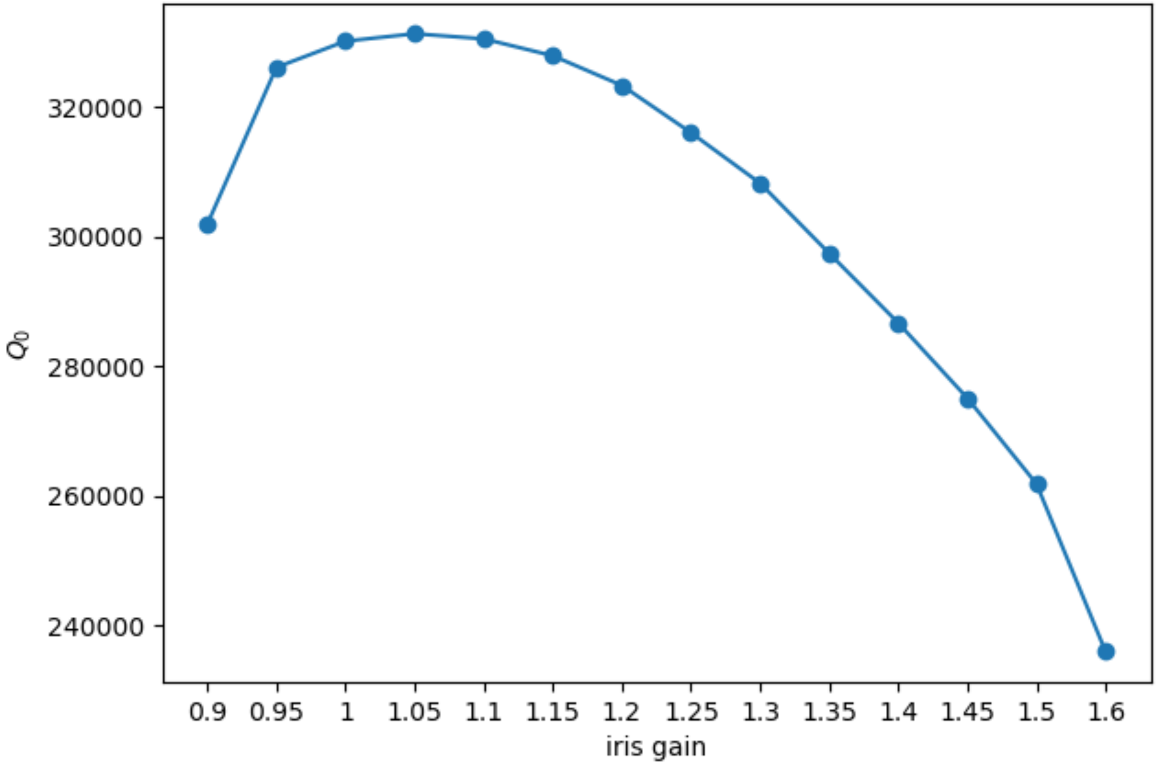
DAA cavity single cell iris optimization

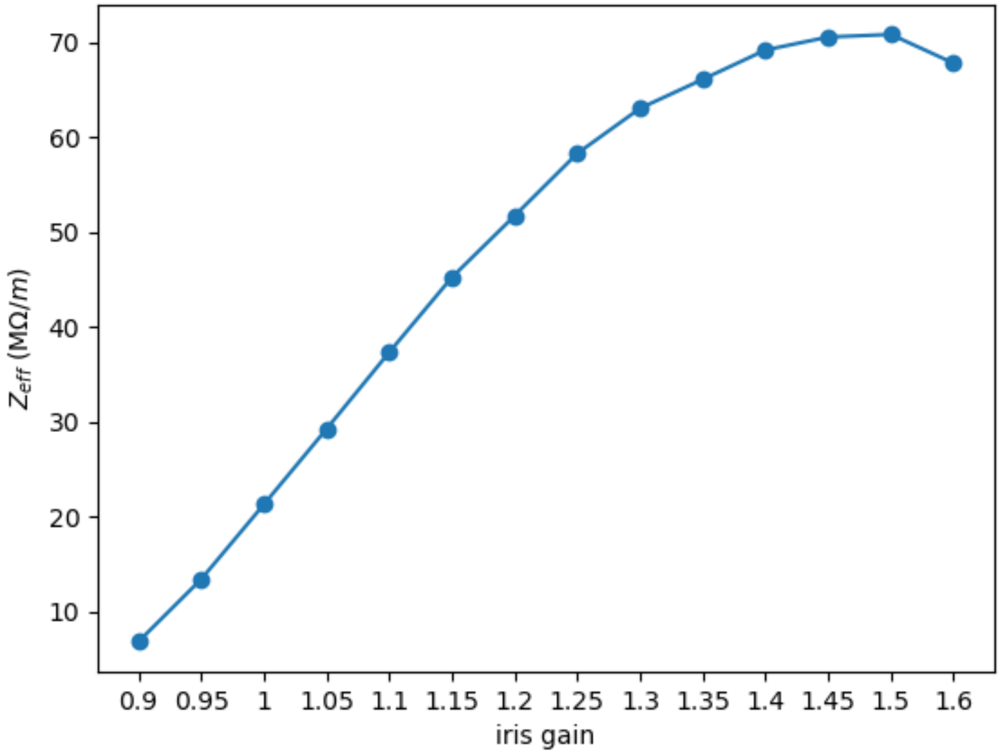


$\epsilon_r = 9.64, \beta = 0.4$

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

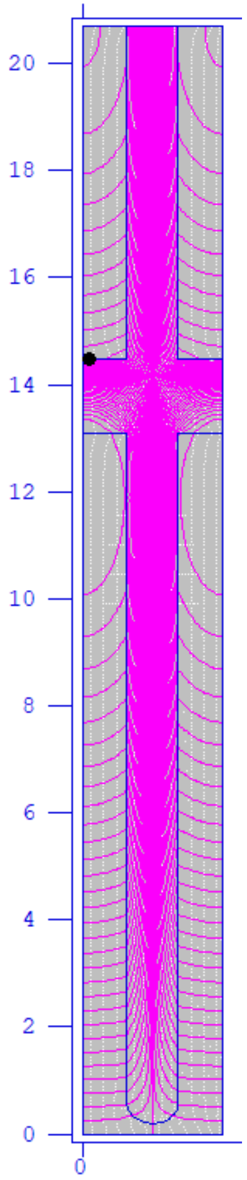
Iris length $= d_0 * gain$



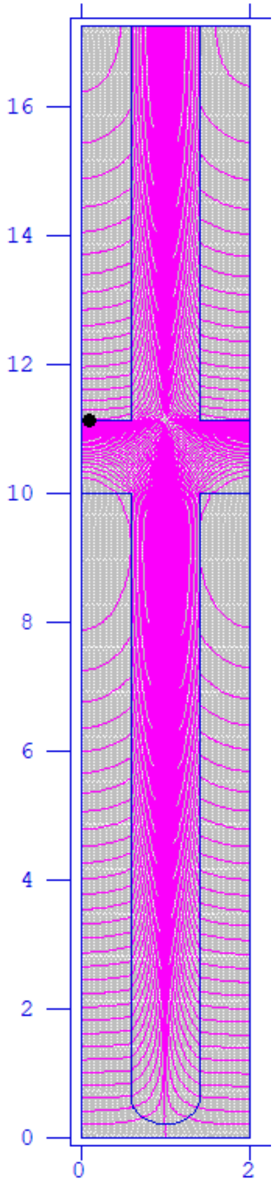


Iris scan for D-9 with $\beta = 0.4$ and $G = 1$ MV/m

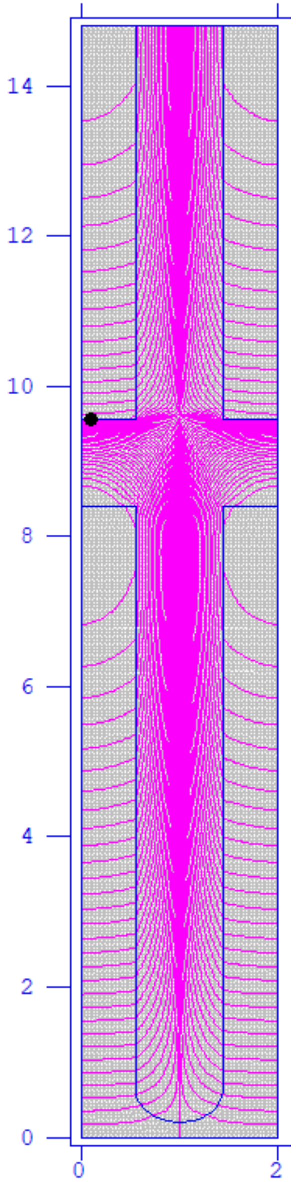
0.9: W = 29.4467 mJ



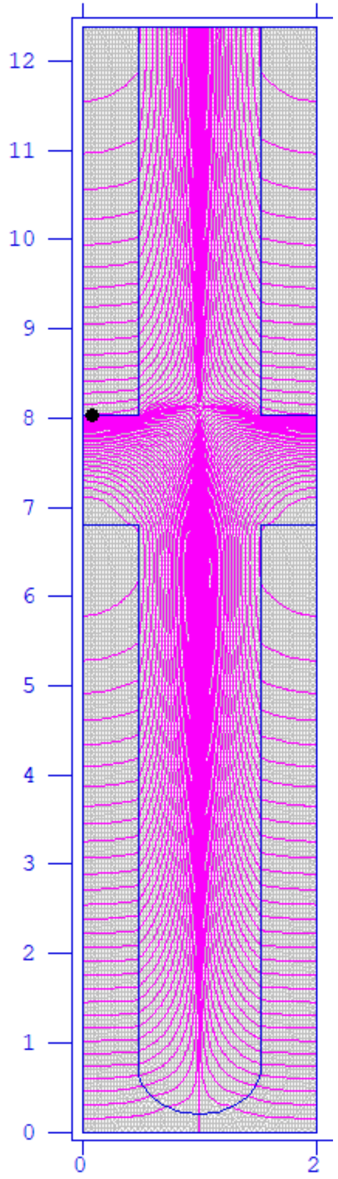
1: W = 10.6929 mJ



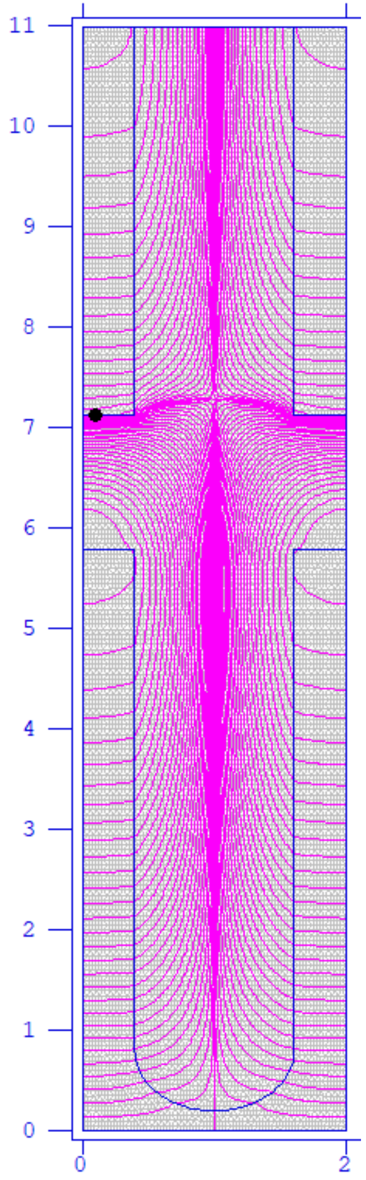
1.1: W = 6.0718 mJ



1.3: W = 3.4882 mJ



1.5: W = 2.6951 mJ



DAA cavity single cell iris optimization

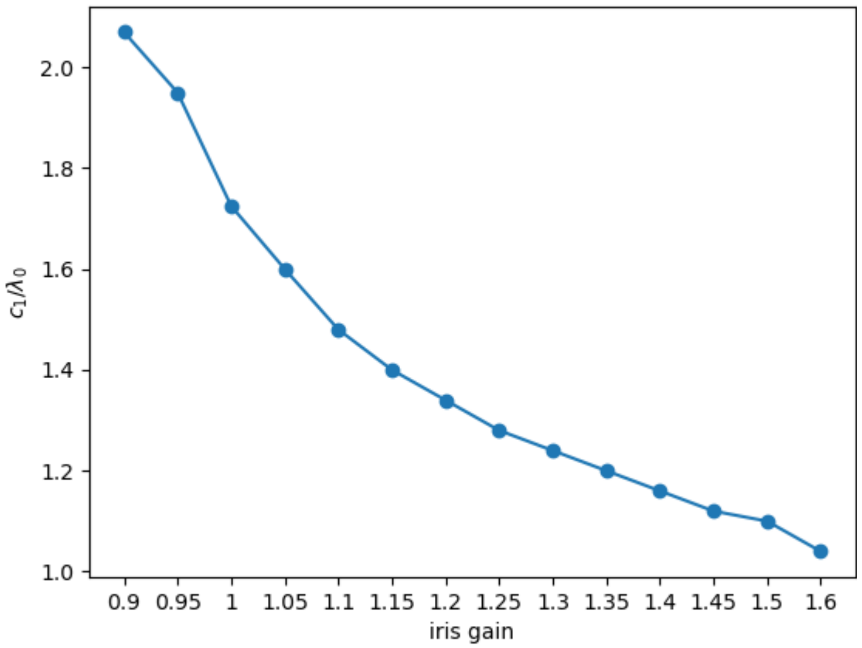
Scan in iris length optimization the geometry for each value

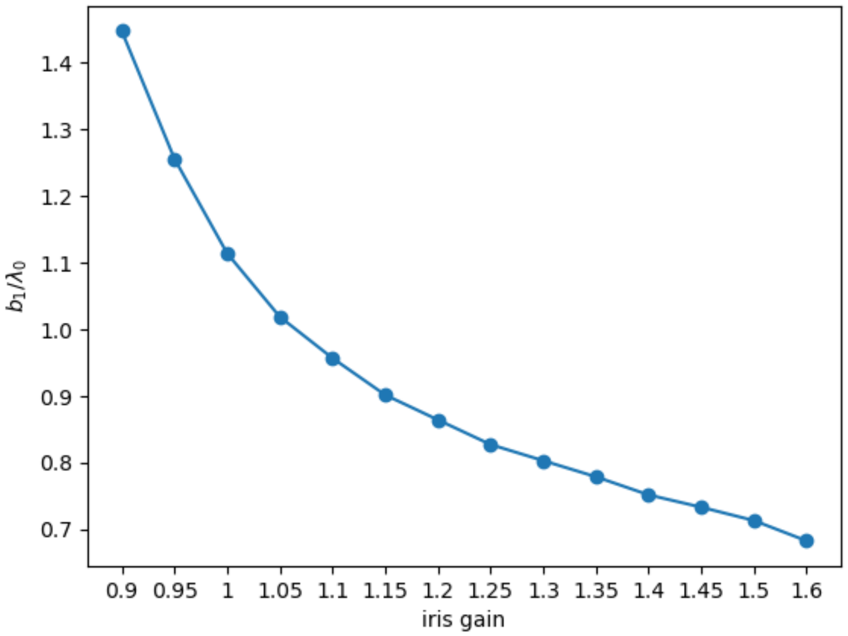
Material: $\epsilon_r = 9.64, \ \beta = 0.4$

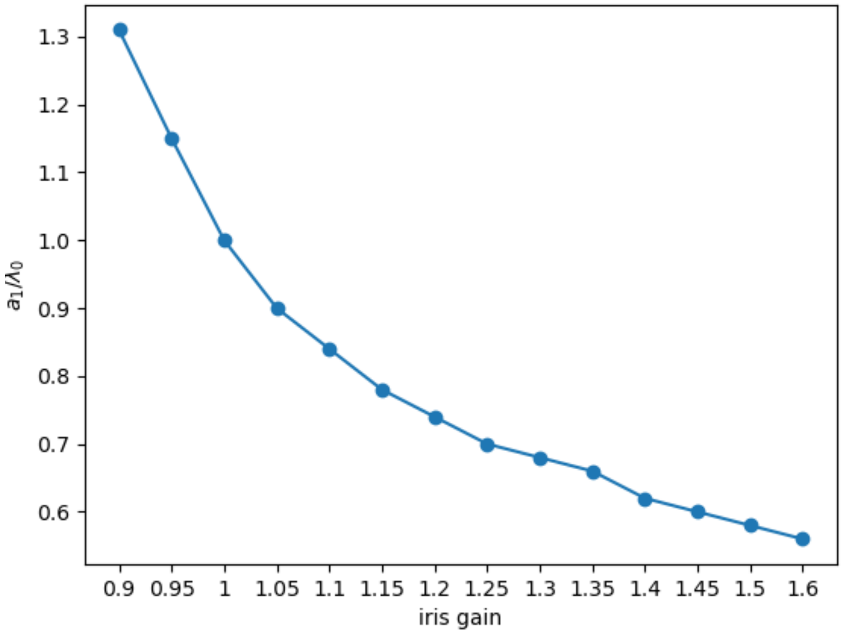
c_1 vs iris gain

b_1 vs iris gain

a_1 vs iris gain



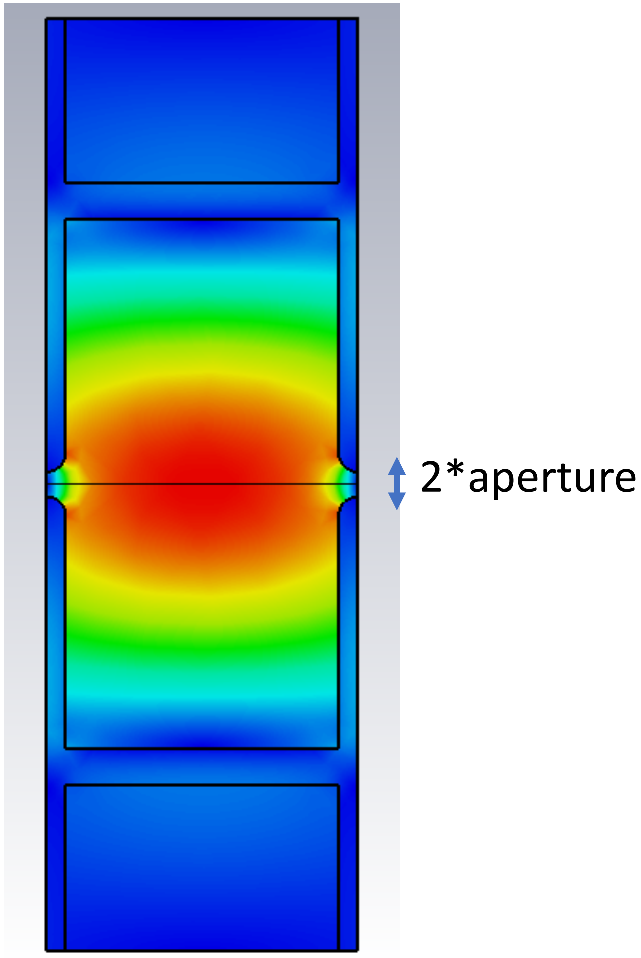


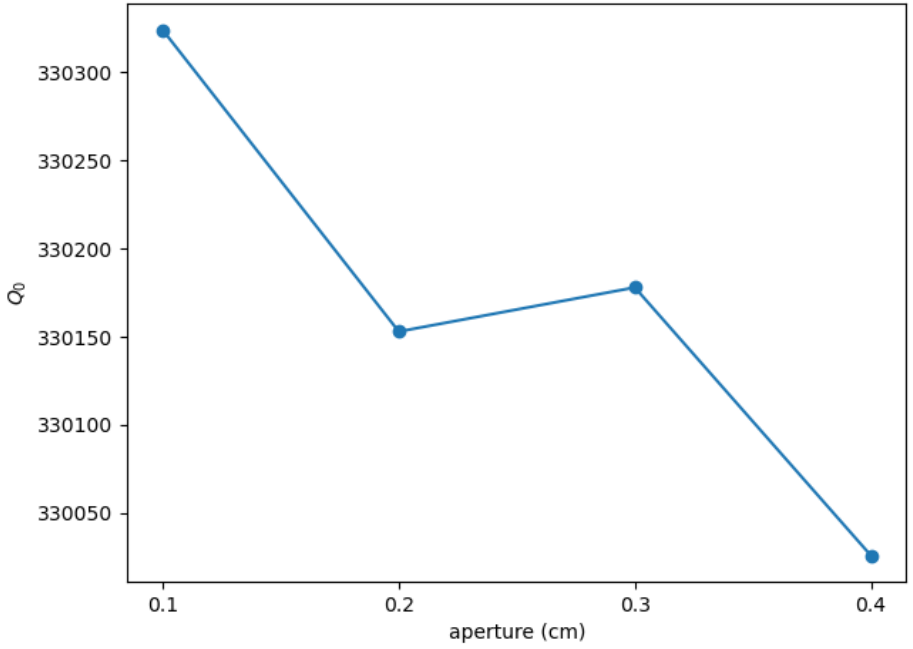


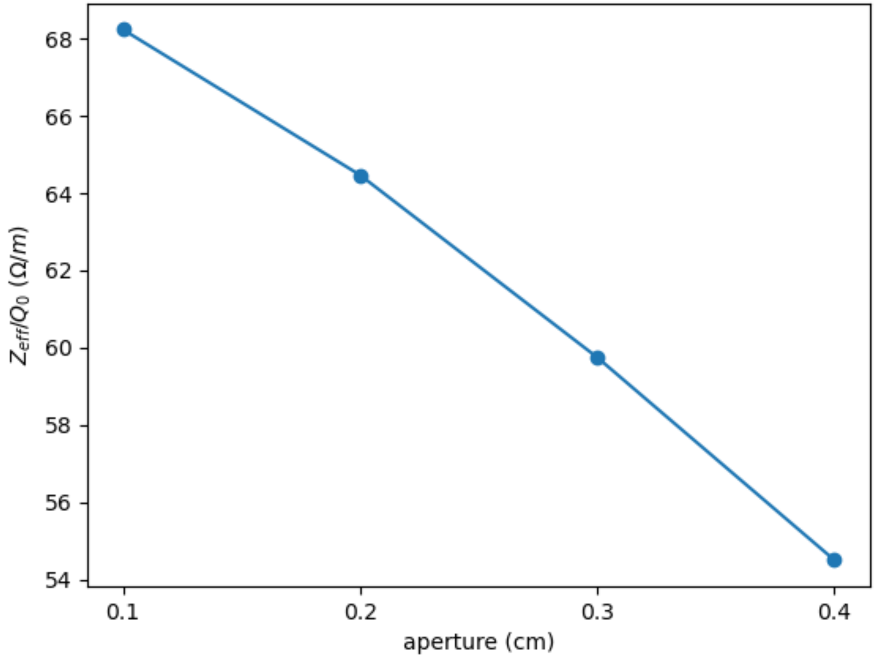
DAA cavity single cell aperture optimization

$\epsilon_r = 9.64, \beta = 0.4$

Scan in aperture: $d_0 = 2$ mm







Conclusions and next steps

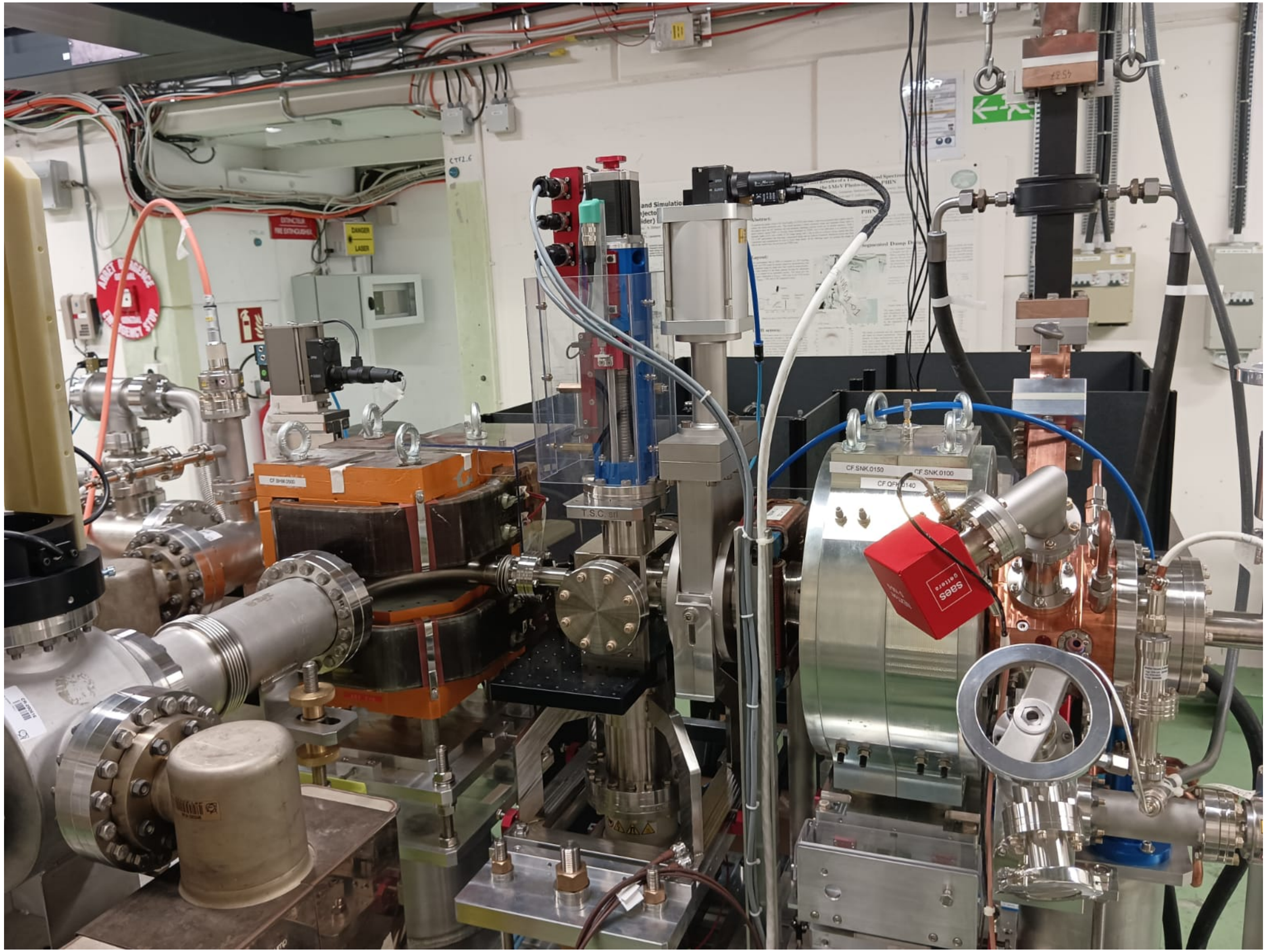
Conclusions:

- DAA have extremely high Q_0 and ZTT:
  - Results are better for high ϵ_r and β
  - Lower input power needed.
- ZTT/Q worse than Copper structures
  - Higher total energy needed.
- Very high coupling between cells
  - Modes overlapping can be a problem for low ϵ_r and β
- Iris length is an important parameter to add in the optimization process.

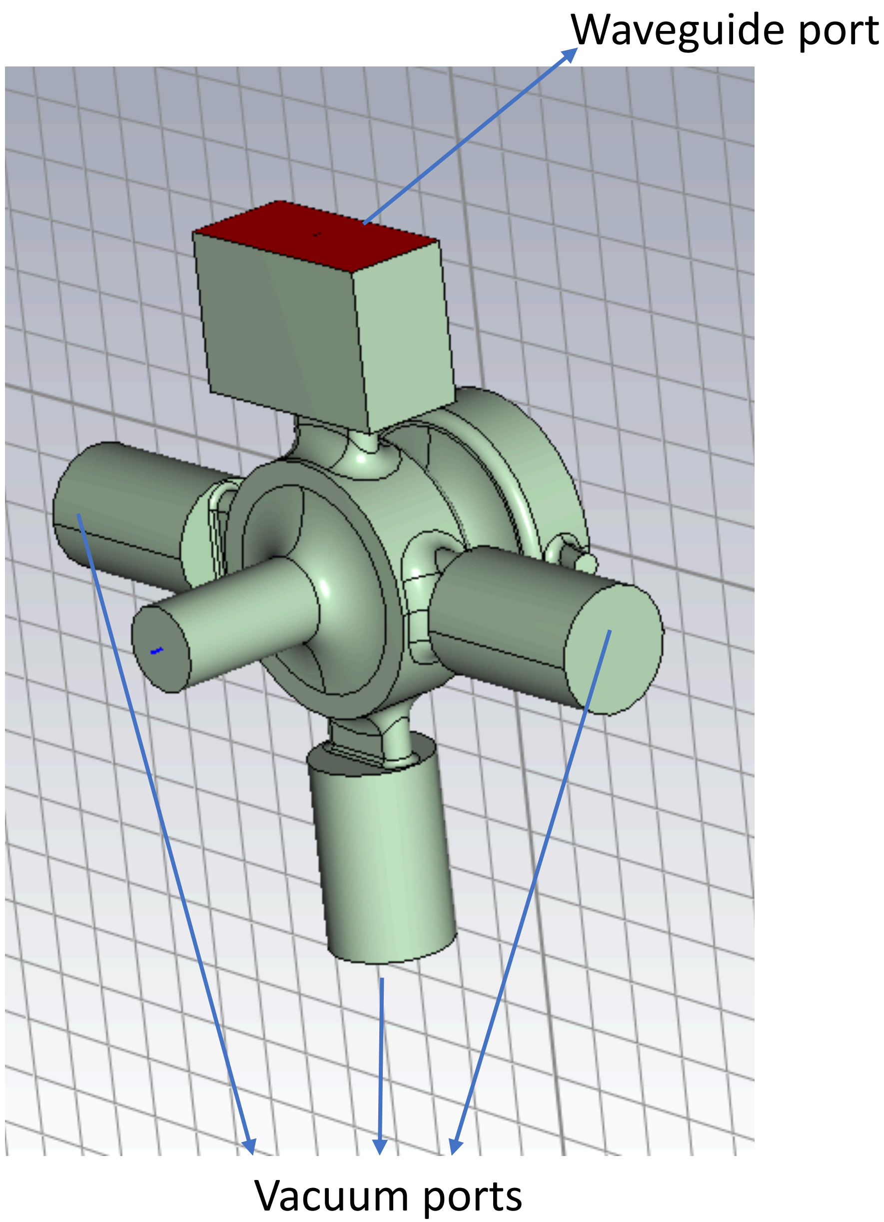
Next steps:

- Redo optimization including the iris length.
- End cells.
- Bi-periodic structure.
- Triple point (singularities).
- Look for a real material.
- Multipactor studies.

Work at AWAKE electron injector



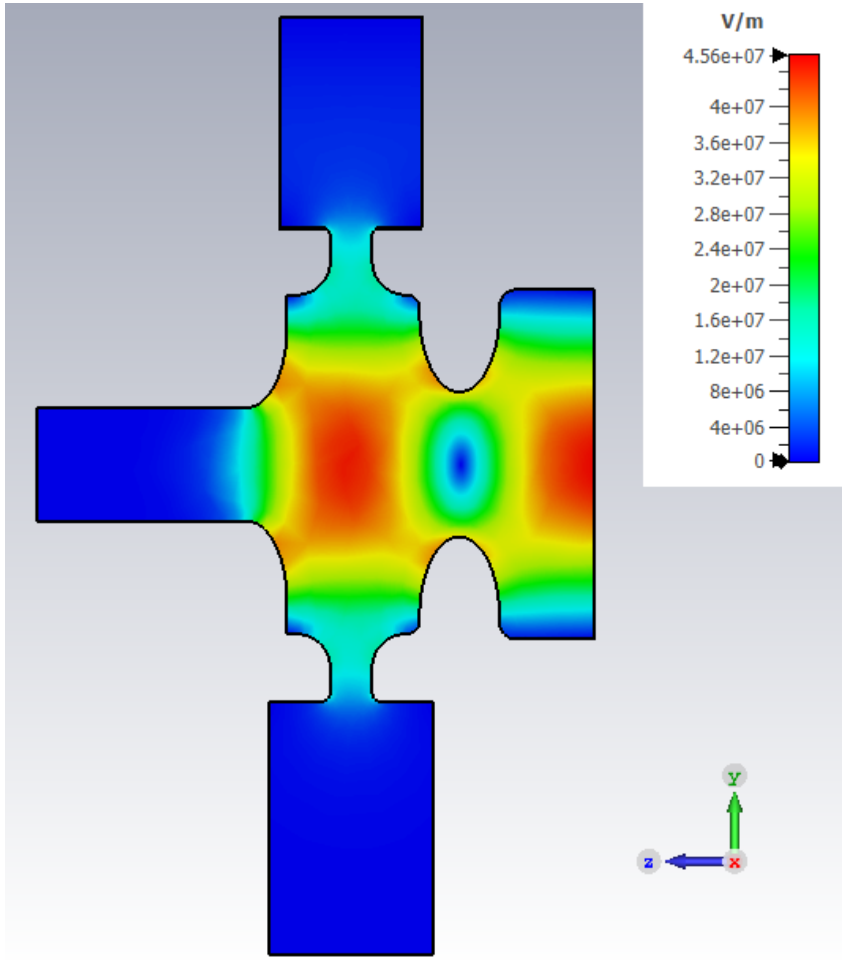
RF GUN



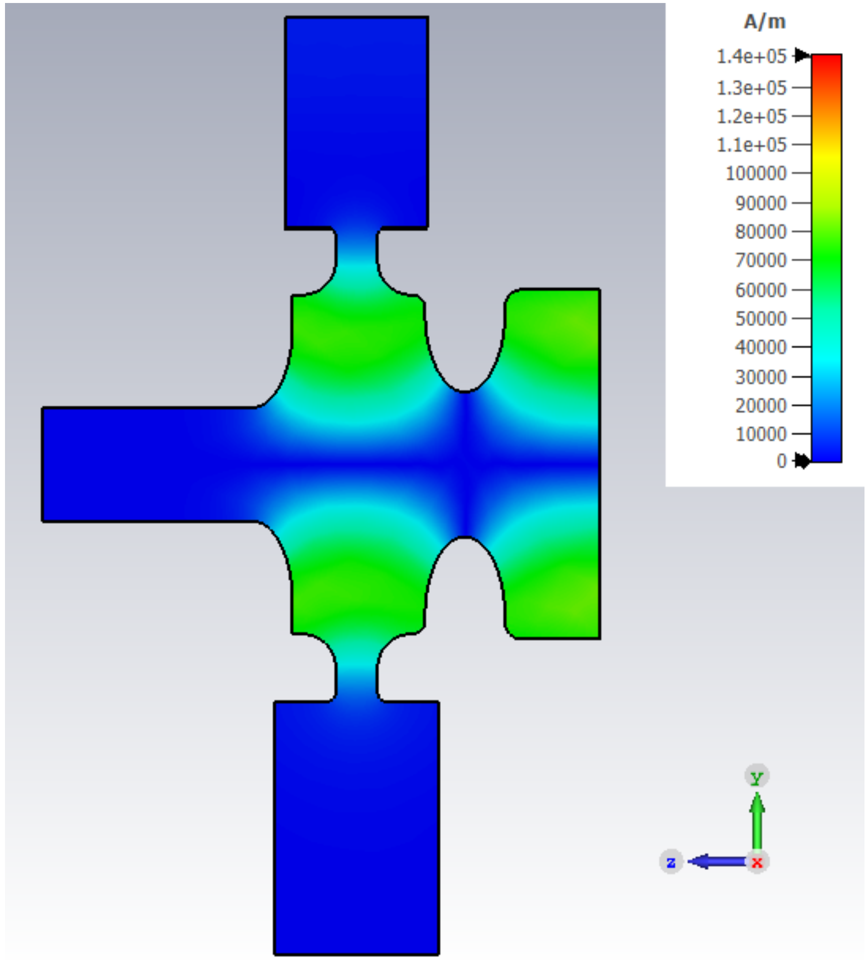
Parameter	Superfish
Mode freq (MHz)	2998.5
Mode	π-mode
Cathode E (MV/m)	120
Q	13995

CST eigenmode solution

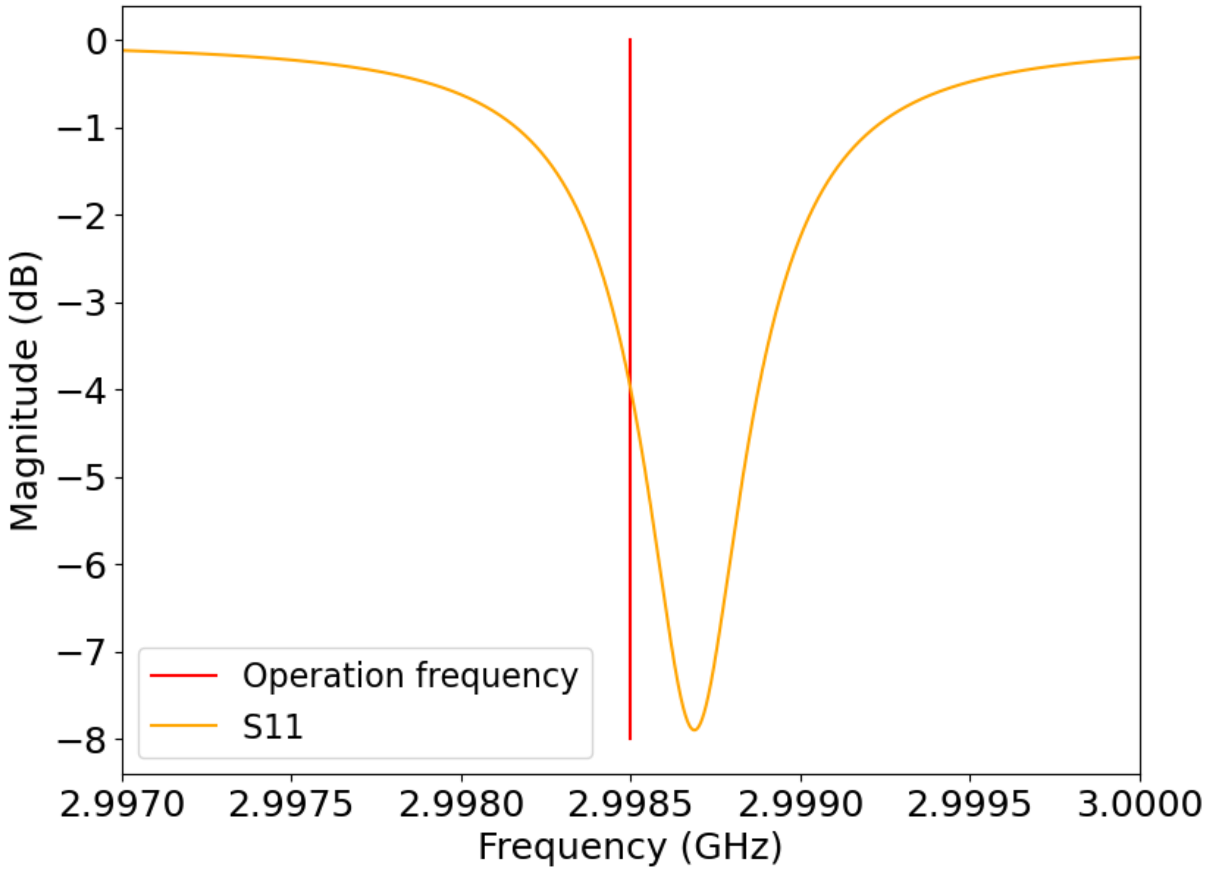
Electric field

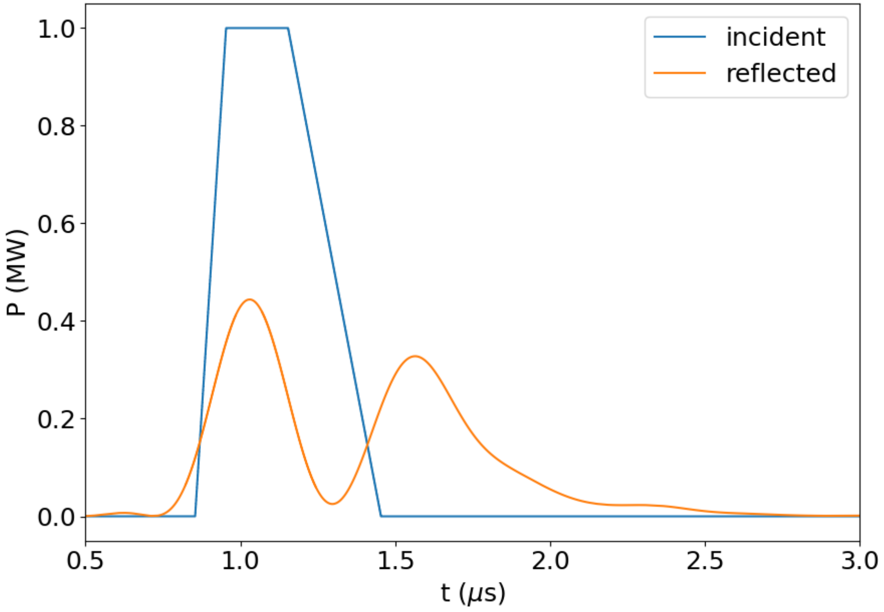


Magnetic field

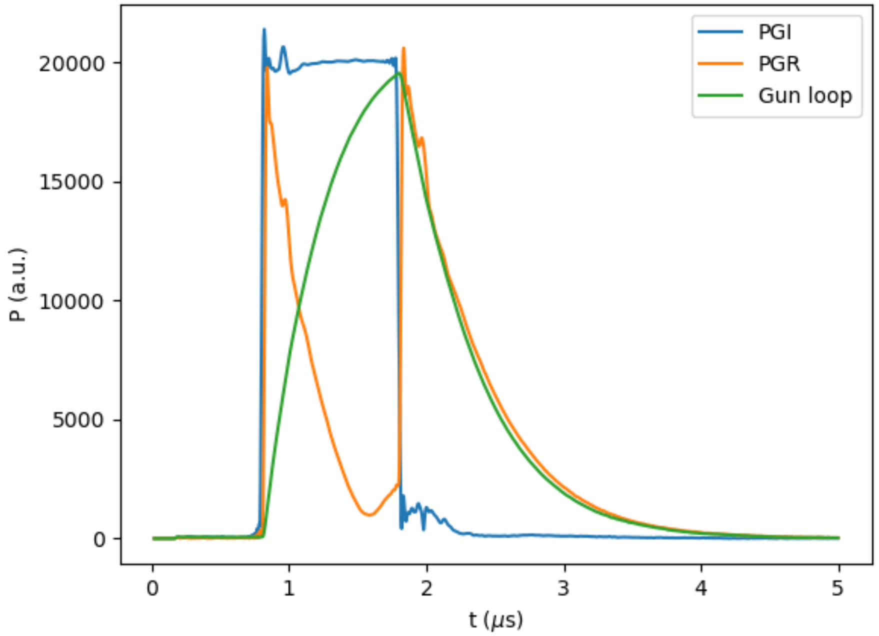


CST S-parameters



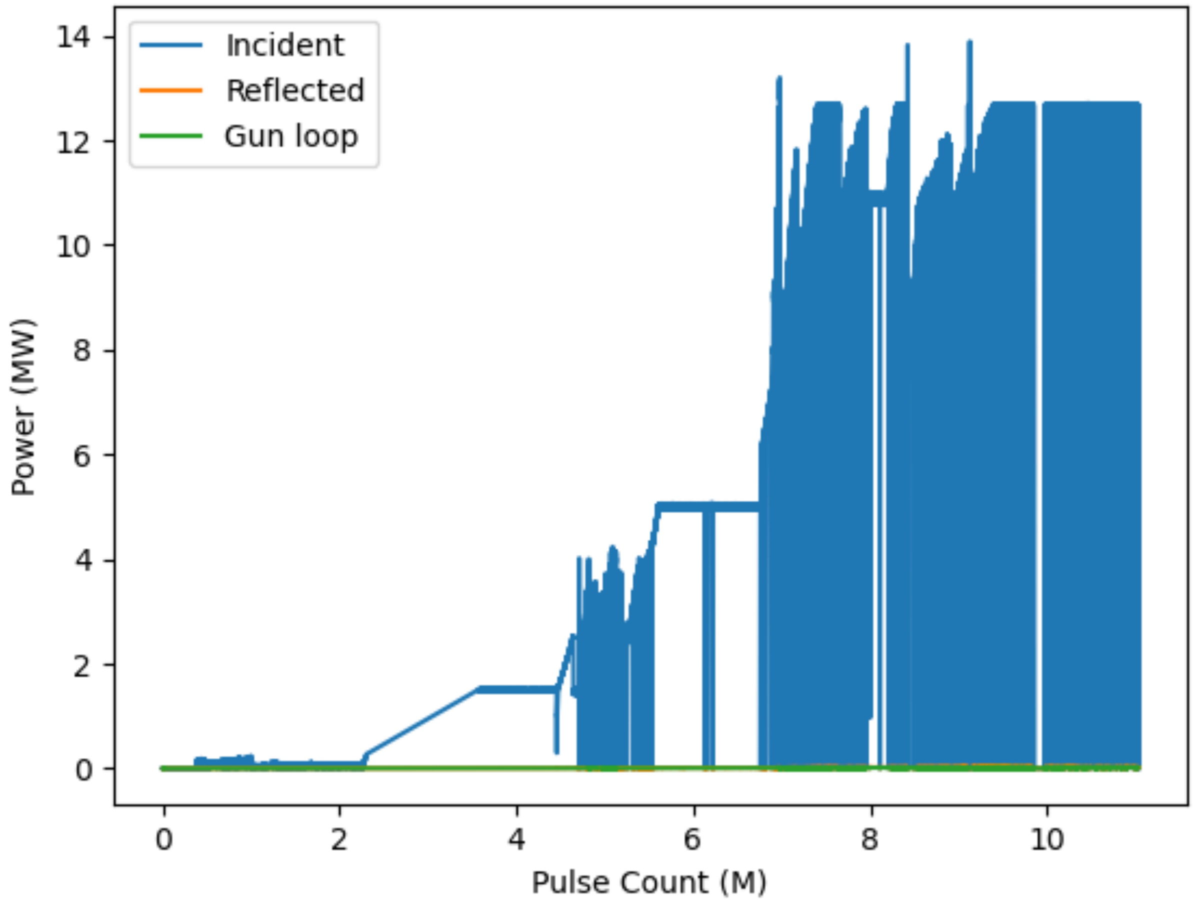


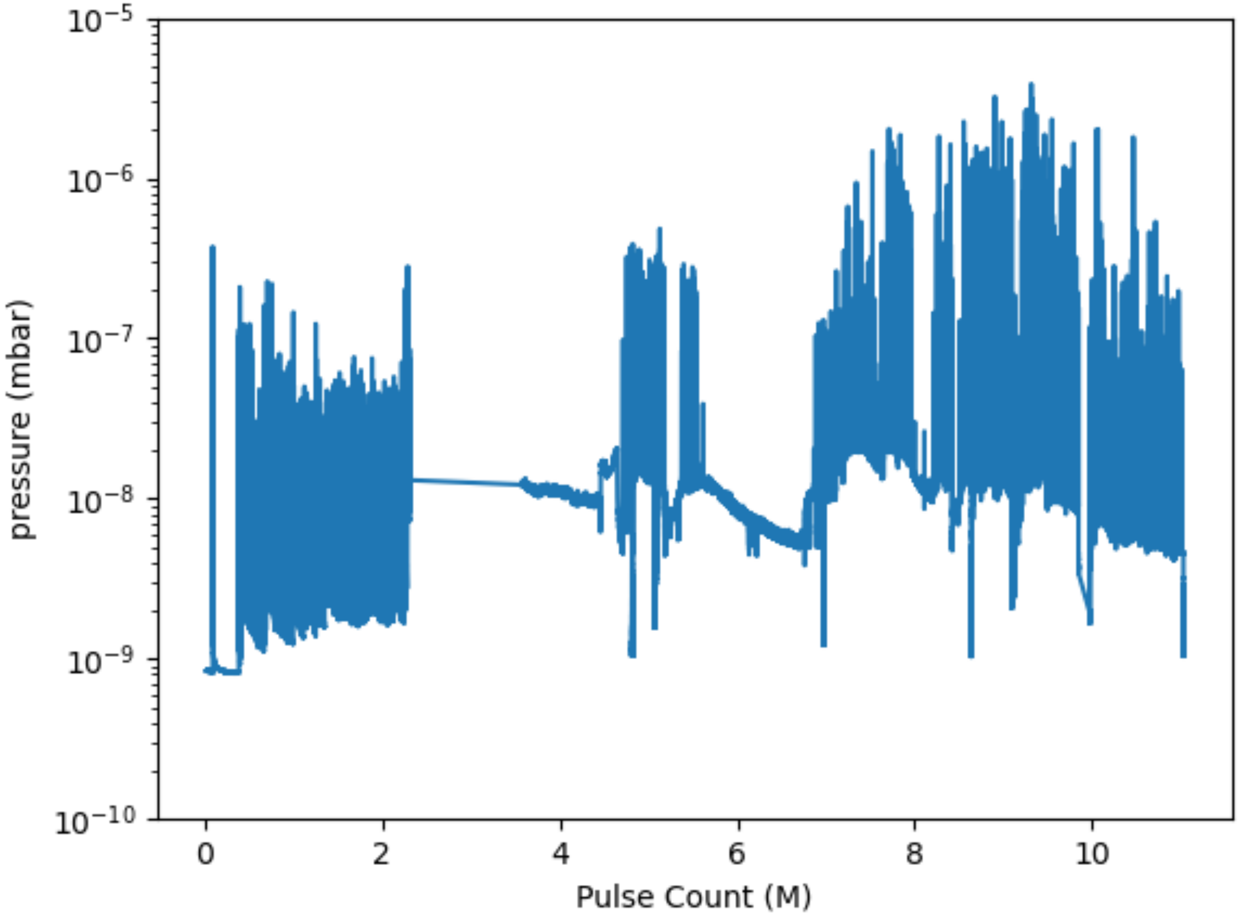
simulation



measurement

Conditioning process

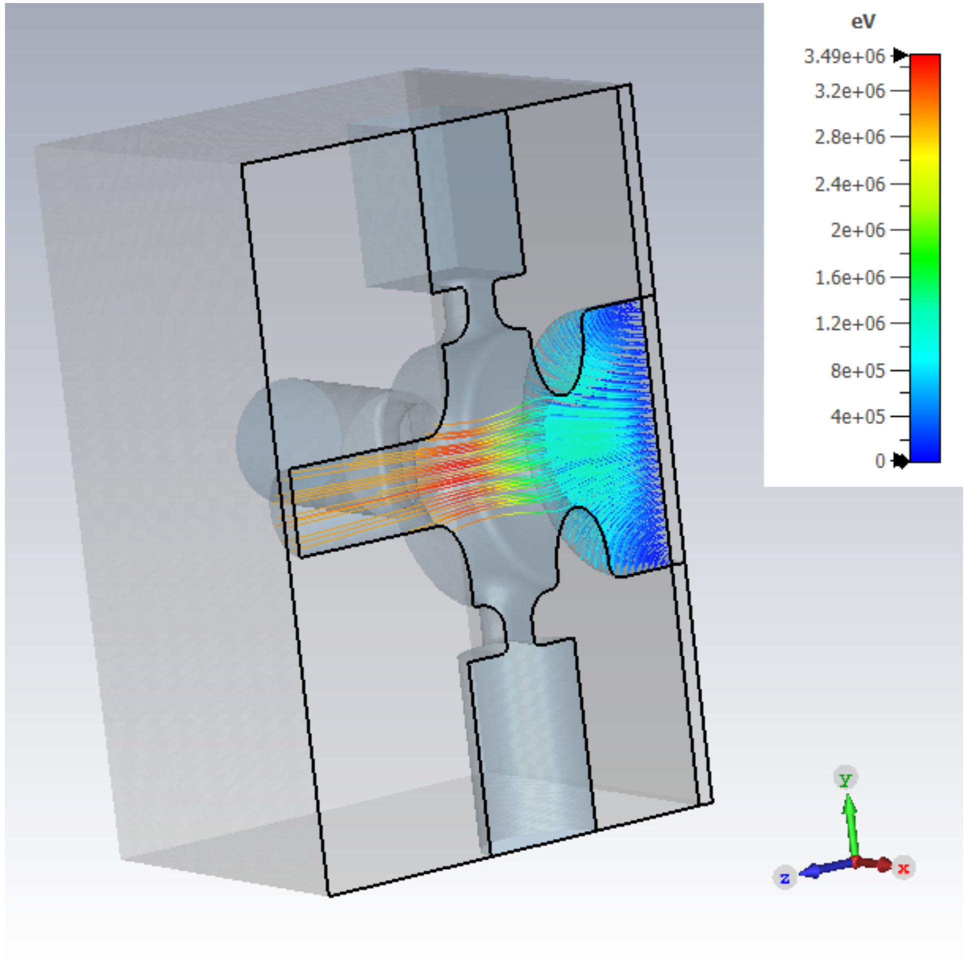




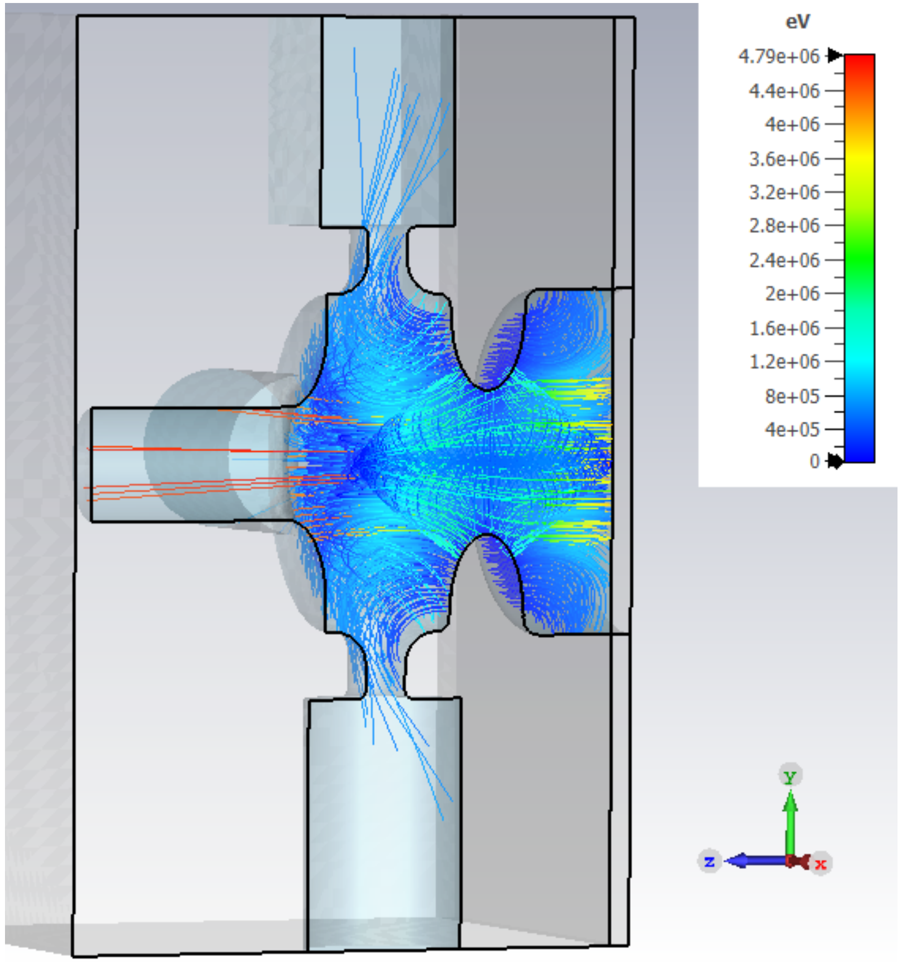
- ❑ High reflected signal does not allow to detect BD in the power pulse.
- ❑ Sudden high vacuum levels allow to detect BD but not the RF pulse.
- ❑ Dark current signals would allow to synchronize BD and RF pulse detection.

CST dark currents tracking

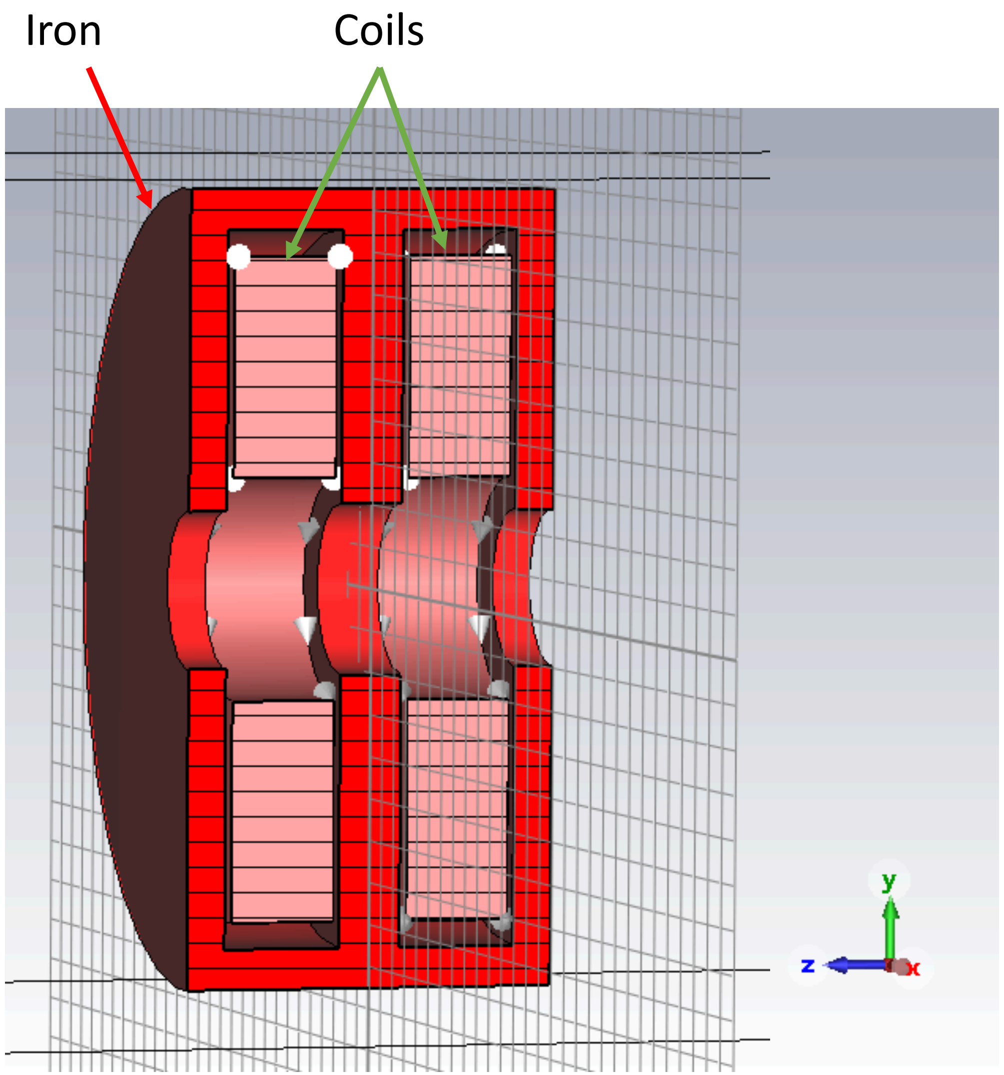
Emission from cathode



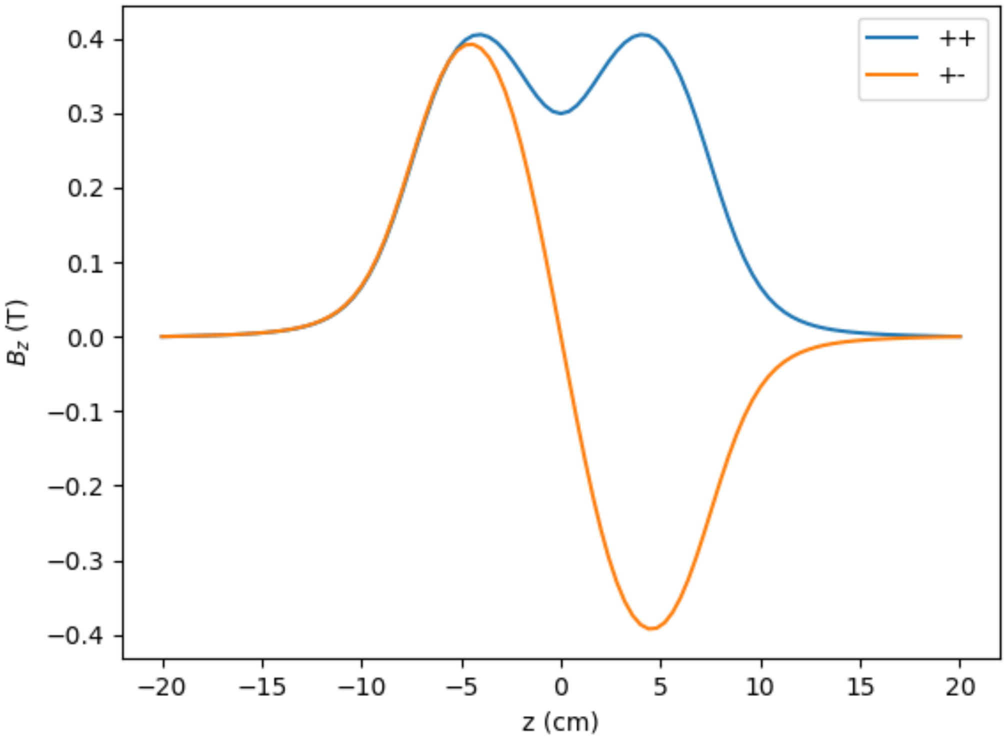
Emission from iris



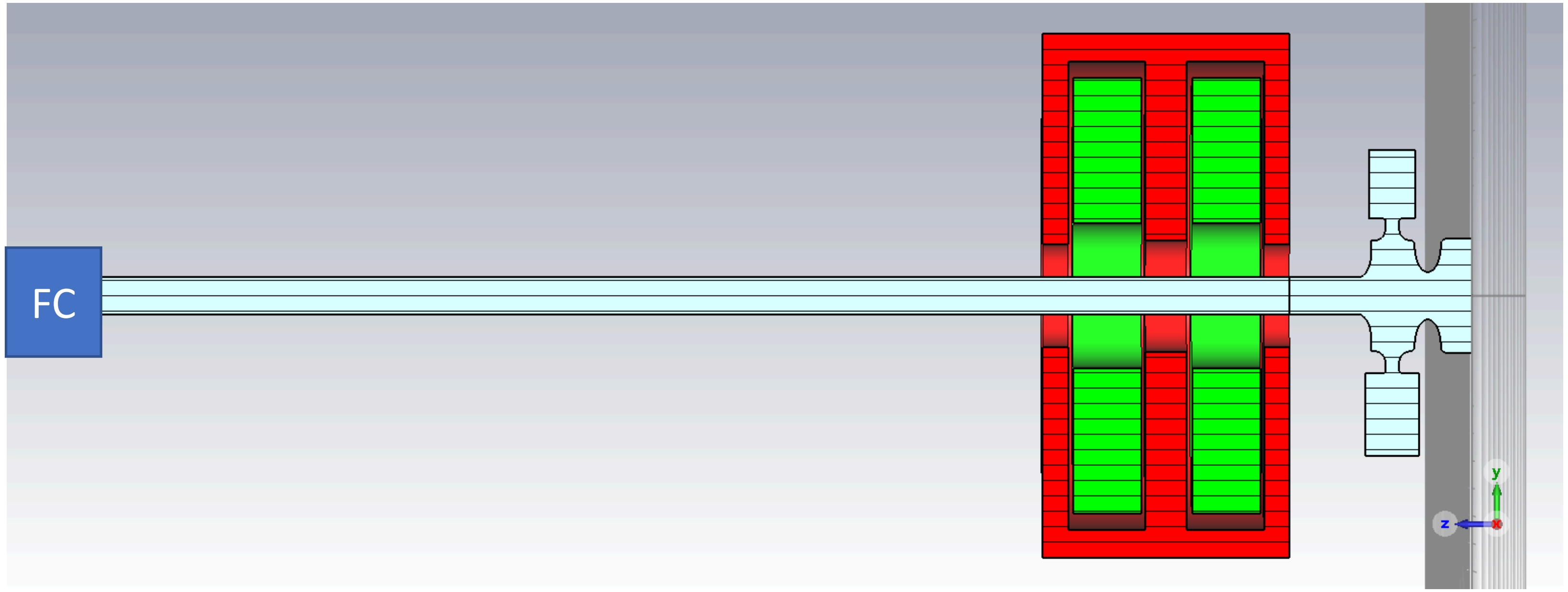
Solenoid



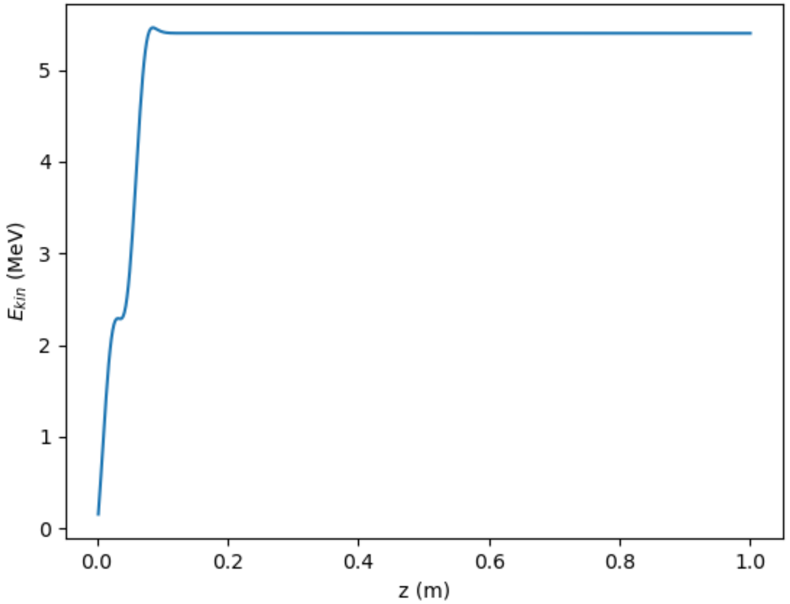
Configuration	++	+-
Current (A)	182	192
Maximum B_z (T)	0.405	0.392



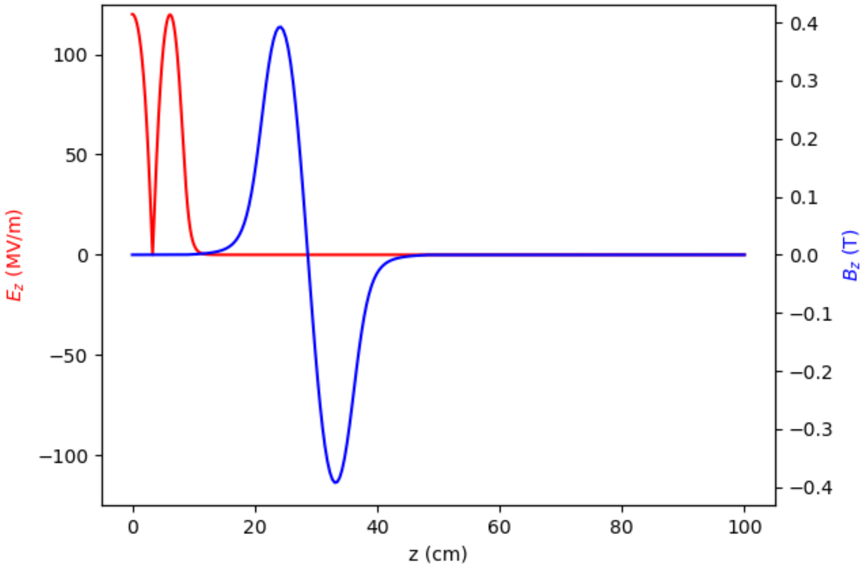
PIC simulations



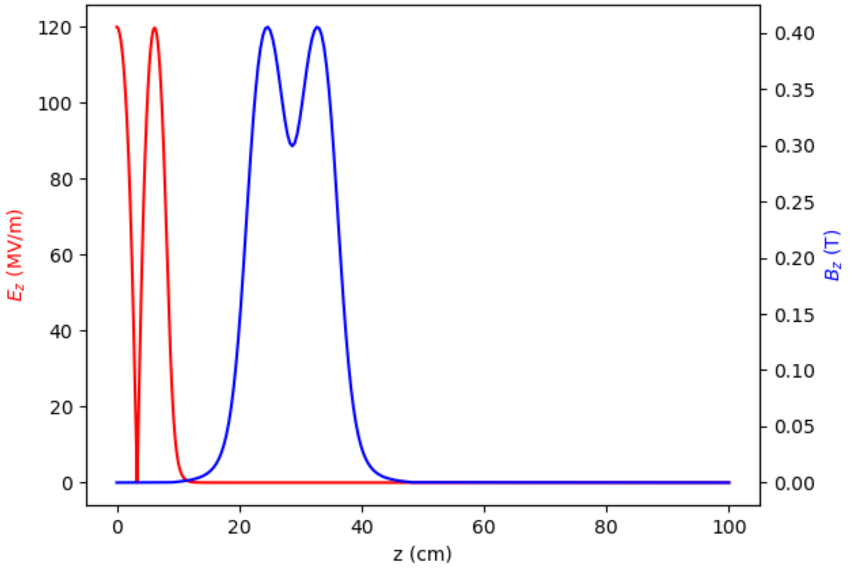
Electron beam kinetic energy



+ −

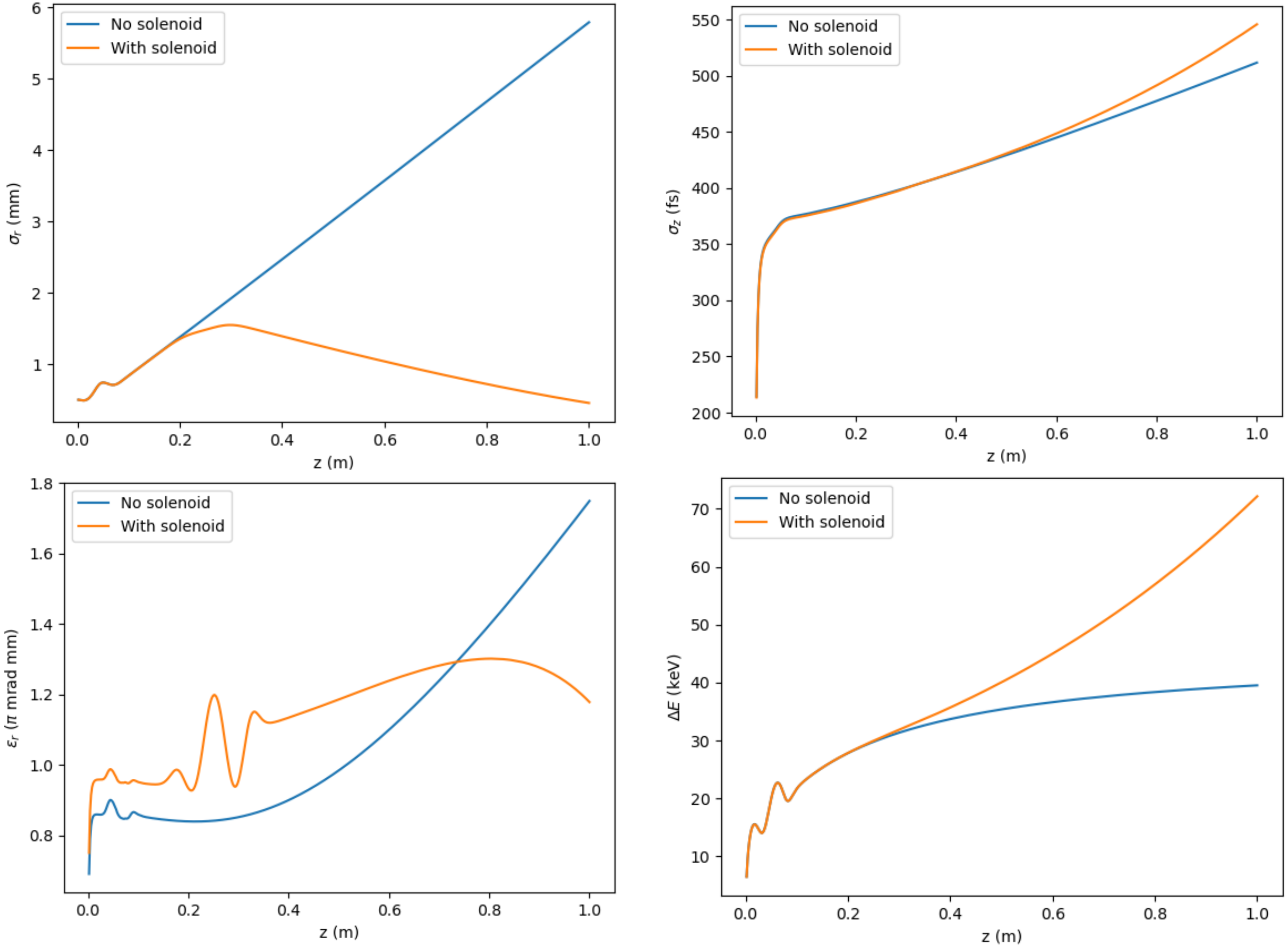


+ +



ASTRA beam dynamic simulations

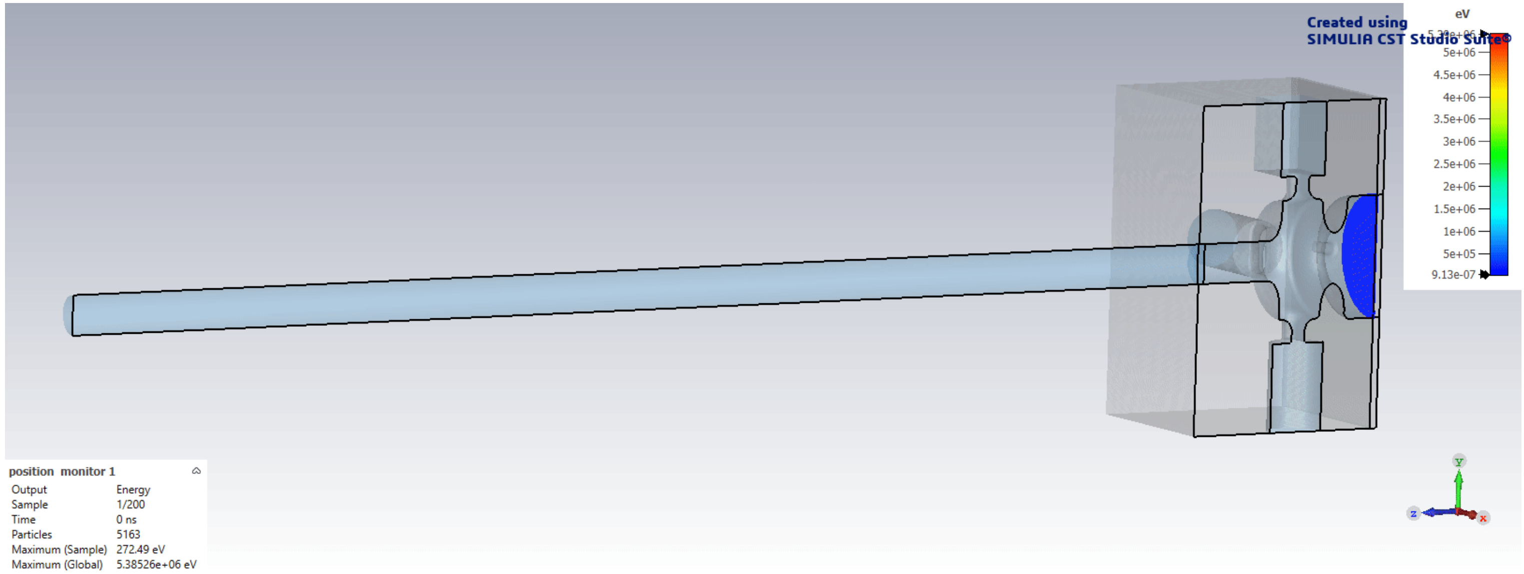
Parameter	Value
Bunch charge	100 pC
Bunch length	1 ps
Maximum B_z	0.28 T
Maximum E_z	120 MV/m



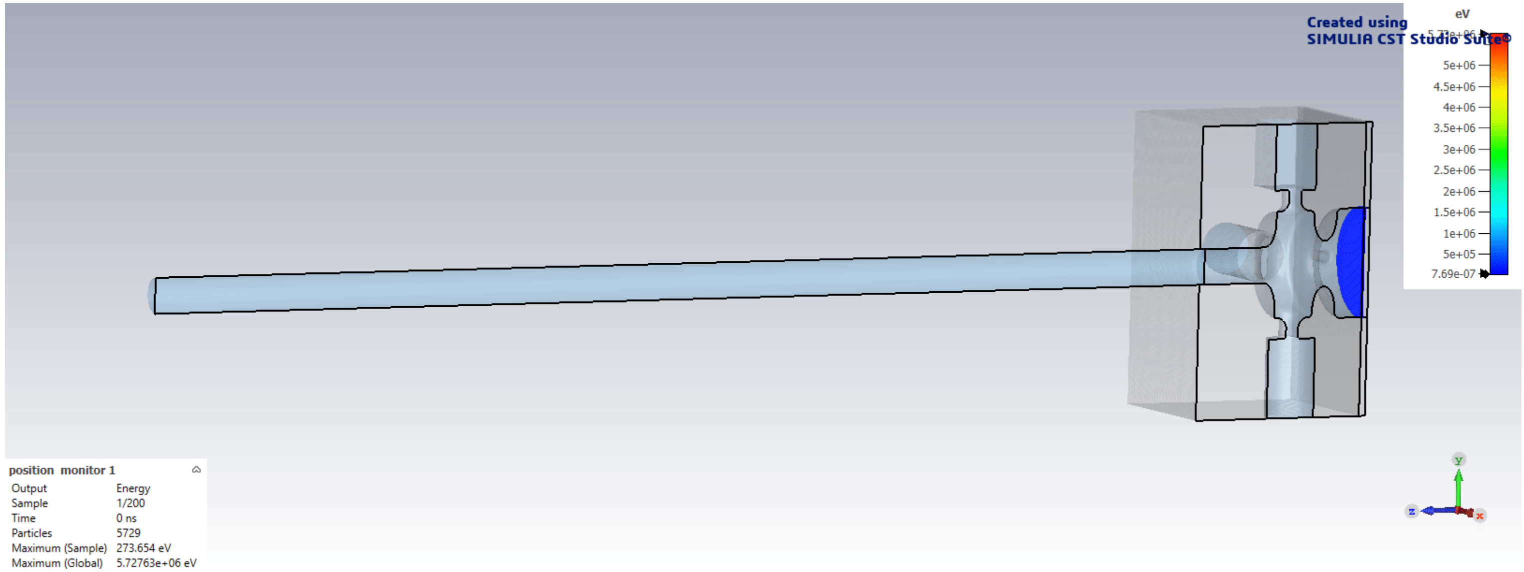
- Radial size and emittance improve with the solenoid
- Longitudinal size and energy dispersion get worse: Bunch compressor needed.

PIC Dark current simulations

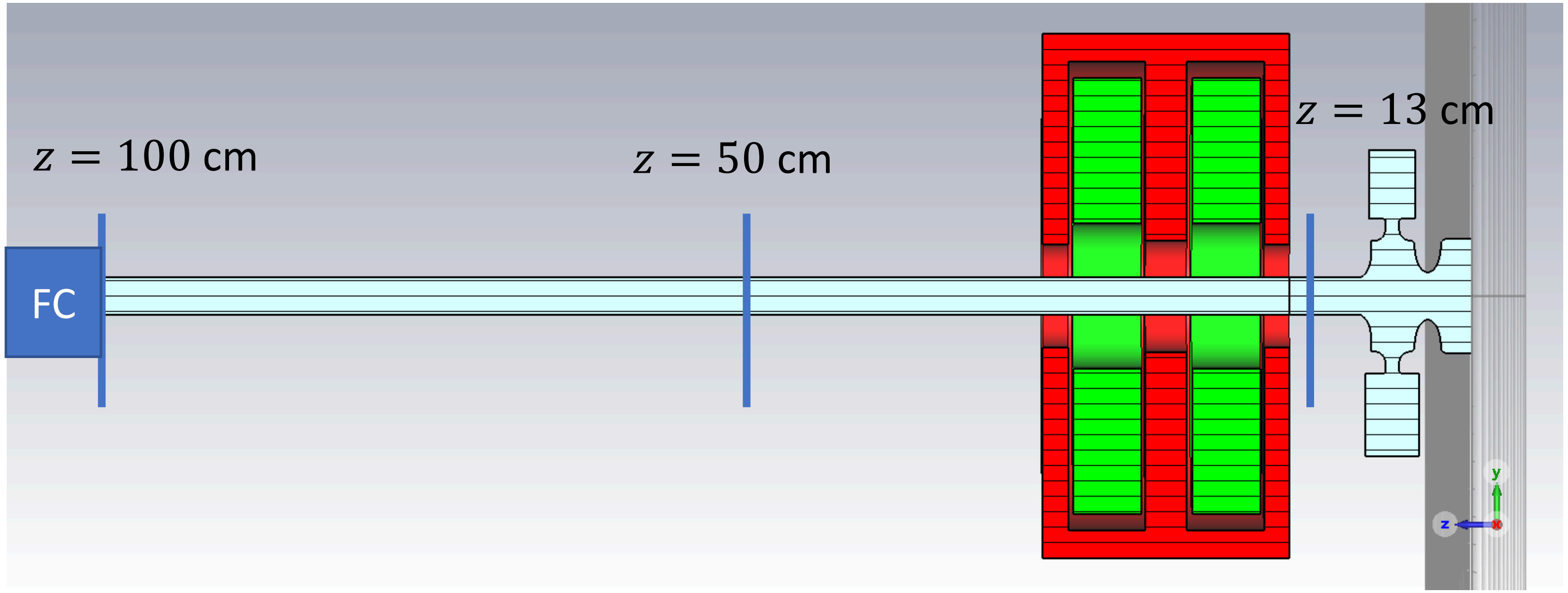
No Solenoid

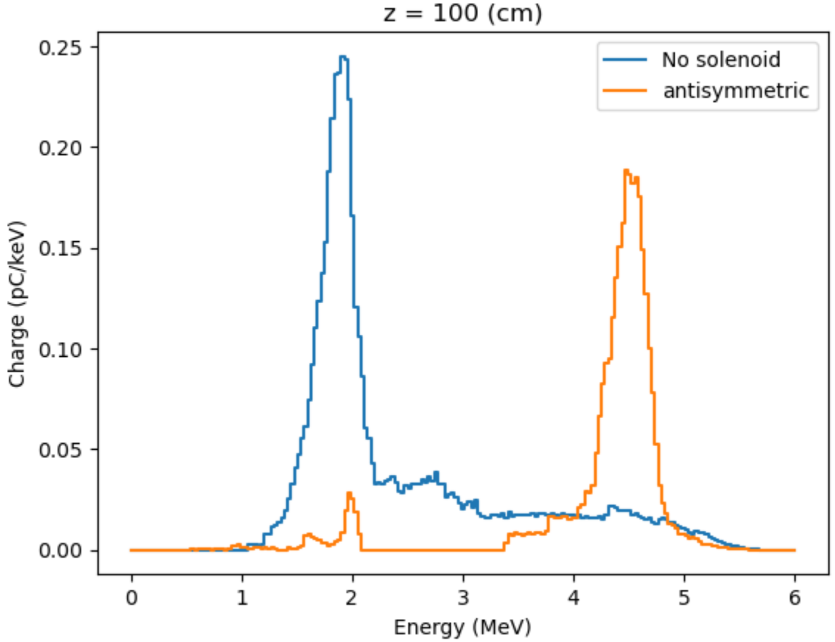


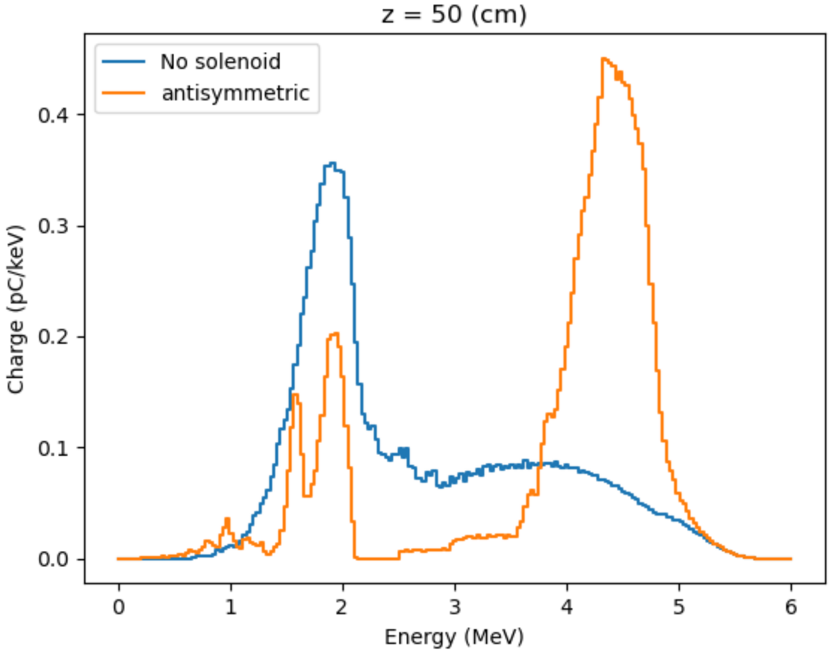
Solenoid: Antisymmetric mode

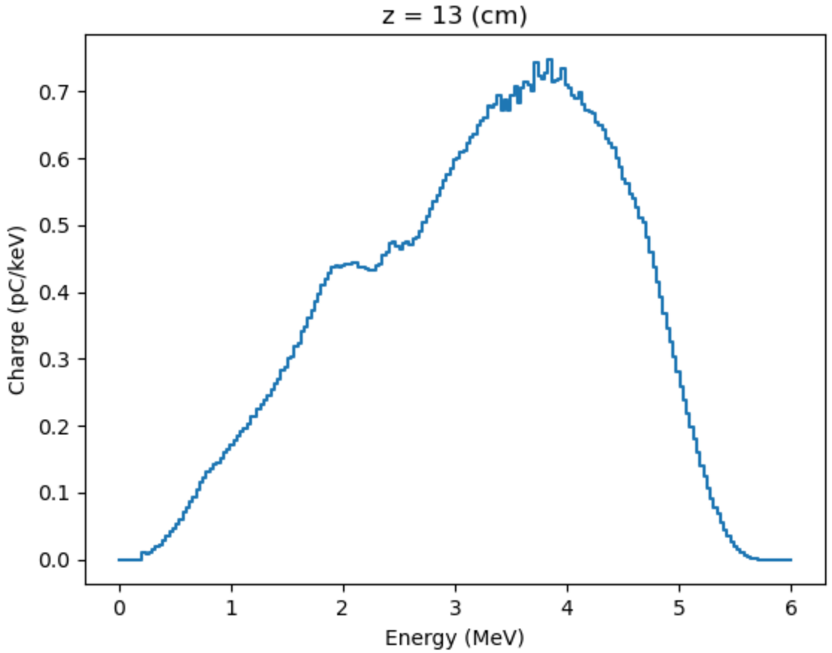


PIC simulations

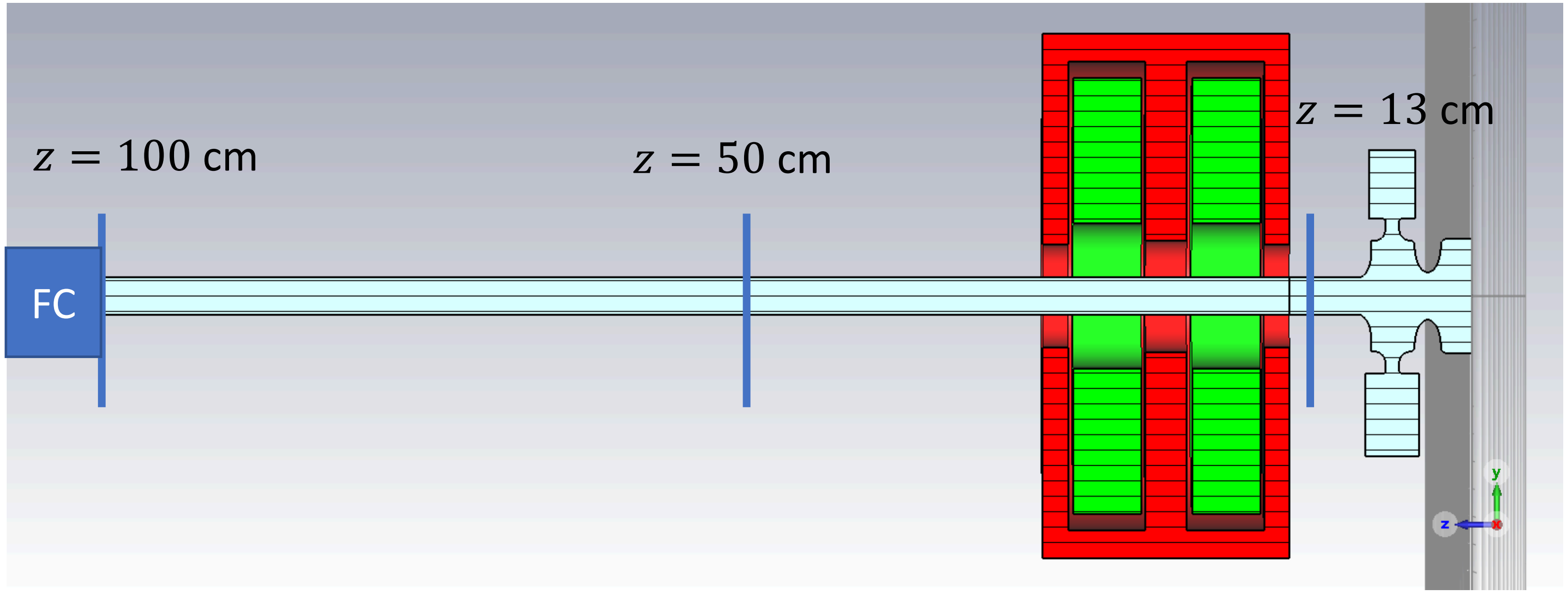


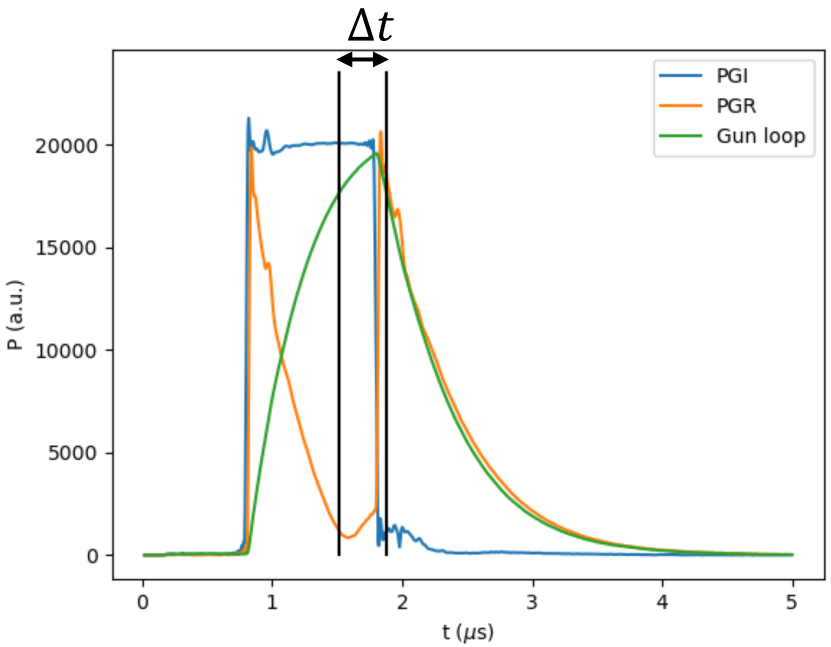






PIC simulations

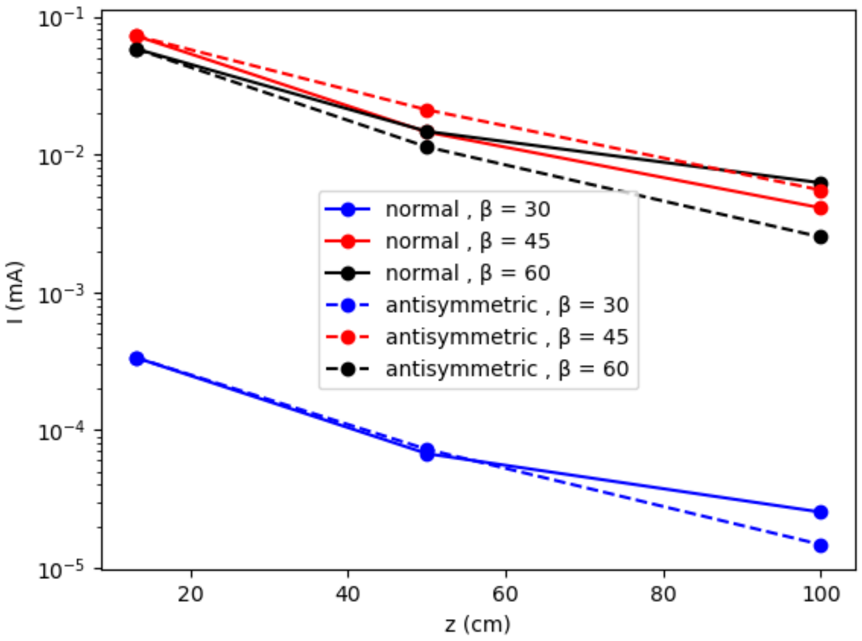




$$\Delta t = 368 \text{ ns}$$

$$F = \Delta t * \frac{f_{RF}}{N_{cycles}}$$

$$I = F \sum Charge_i$$



Thank you very much!

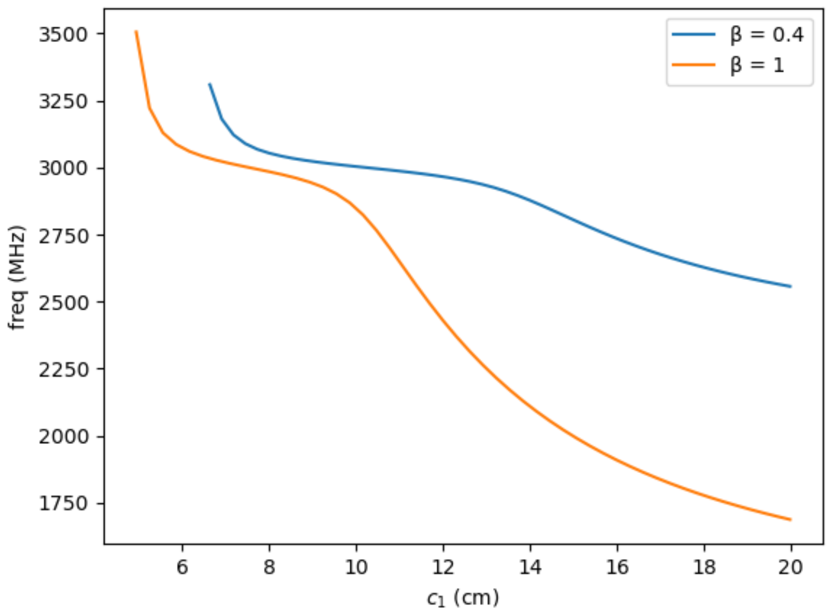
Back-up

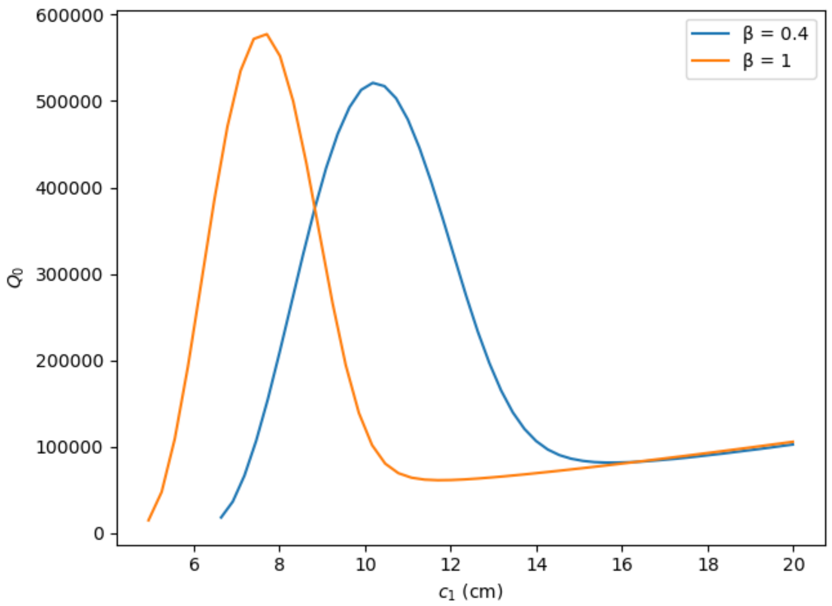
Behaviour fixing a_1, b_1

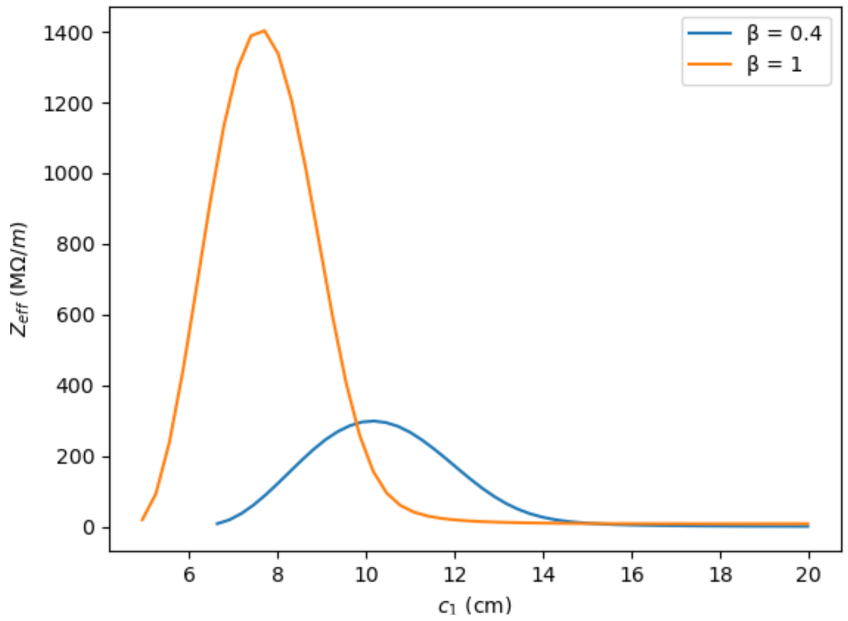
Study of the frequency behaviour of $TM_{02} - \pi$ scanning in Copper radius.

- We fixed a_1, b_1 and we do a scan in c_1 looking for the values of $freq, Q_0, ZTT$.

Ideal material: $\epsilon_r = 16.66, \tan\delta = 0$





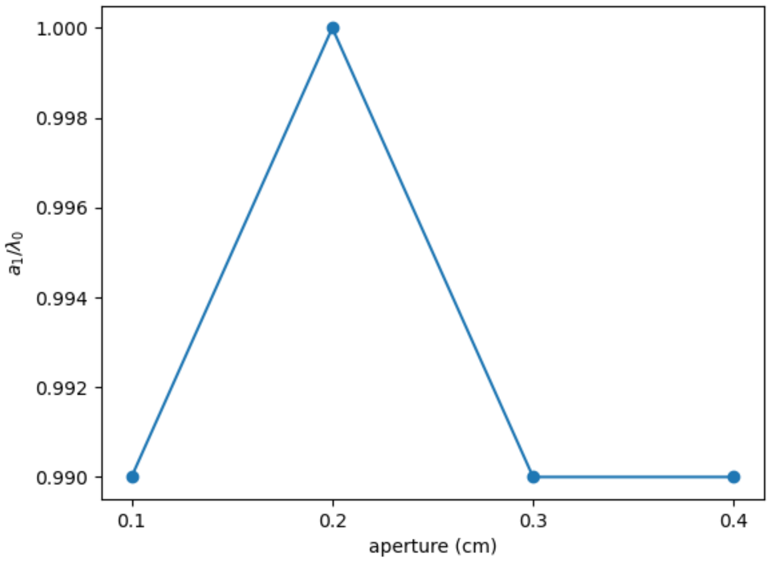


Ideal studies with Superfish

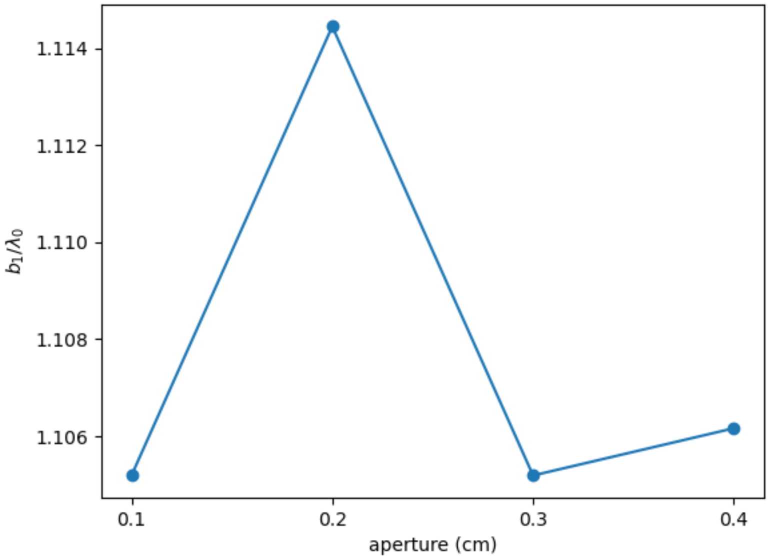
Scan in iris length optimization the geometry for each value

Material: $\epsilon_r = 9.64,\ \beta = 0.4$

a_1 vs aperture



b_1 vs aperture



c_1 vs aperture