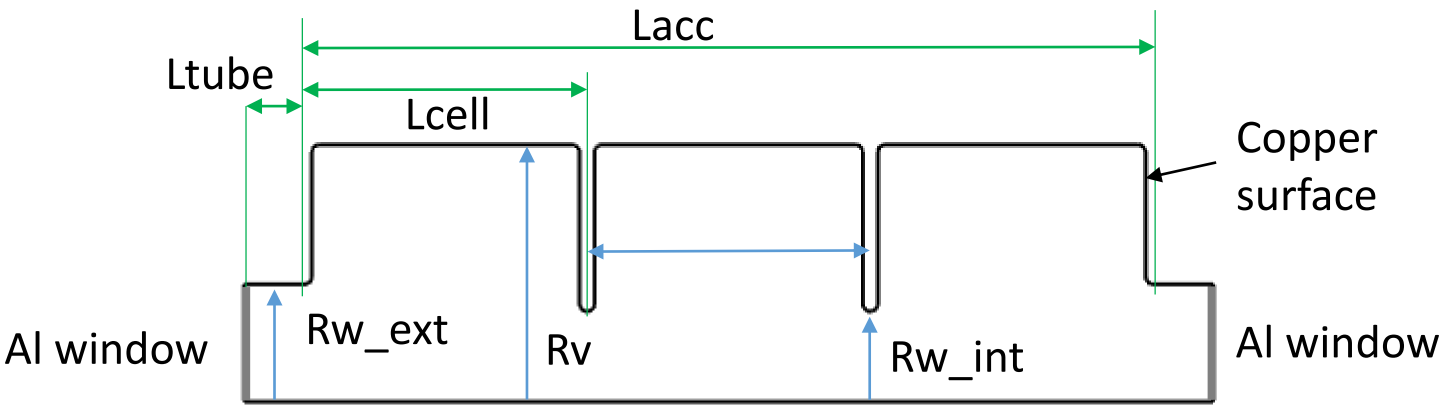
Design study of cavities for muon cooling

Juliette PLOUIN, Sophie PIERRON

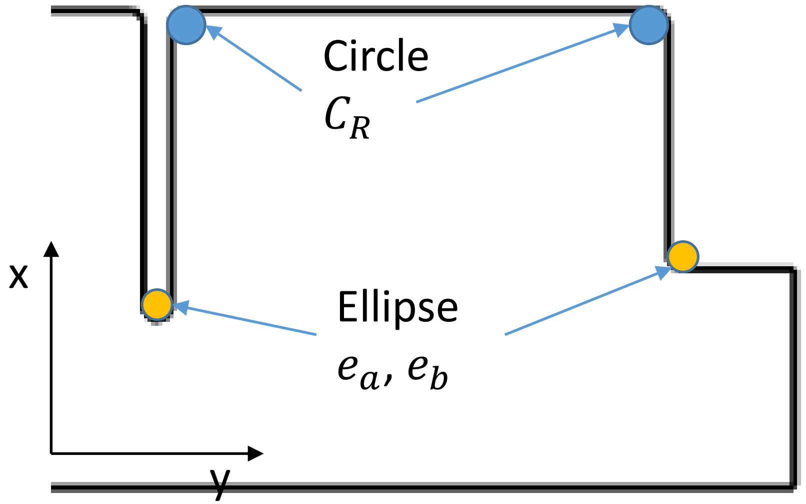
RF systems for muon cooling complex
and demonstrator (MuCol 6.2) meeting
14 oct. 2024

Cavity geometry

3-cell cavity
no windows between cells
windows at extremities
Frequency : 704 MHz
Momentum : 200 MeV/c
β=v/c : 0.884



Rw_int	Iris radius	variable
Rw_ext	Tube radius	variable
Rv	Cavity radius	variable
Lcell	*Cell length*	*$\beta\lambda/2$ = 188 mm*
Lacc	*Cavity acc. length*	*3*Lcell = 564 mm*
Ltube	*Tube length*	*40 mm*
e_a	Ellipse major axis – y axis	5 mm
e_b	Ellipse minor axis – x axis	= e_a
C_R	Top center circle radius	12 mm



Methodology

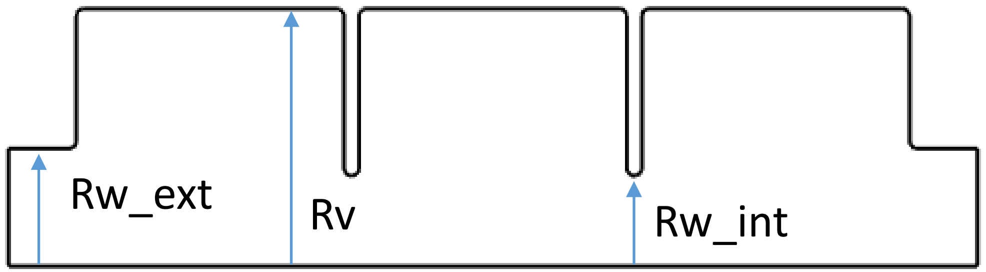
COMSOL

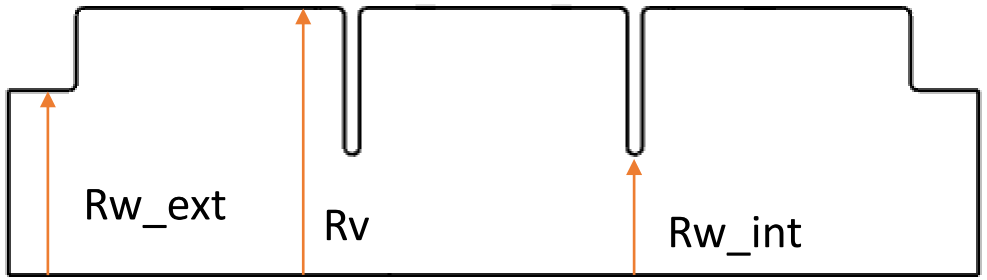
Rw_int	Iris radius	60 mm
Rw_ext	Tube radius	60 → 120 mm
Rv	Cavity radius	Adjusted to get f = 704 MHz

Rw_int	Iris radius	80 mm
Rw_ext	Tube radius	80 → 150 mm
Rv	Cavity radius	Adjusted to get f = 704 MHz

Rw_ext	Iris radius	60 mm
Rw_int	Tube radius	60 → 120 mm
Rv	Cavity radius	Adjusted to get f = 704 MHz

Rw_ext	Iris radius	60 mm
Rw_int	Tube radius	60 → 150 mm
Rv	Cavity radius	Adjusted to get f = 704 MHz





Why 60 mm and 80 mm

R = 60 mm (cf Carmelo Barbagallo, Alexej Grudiev)

15th International Particle Accelerator Conference,Nashville, TN JACoW Publishing
ISBN: 978-3-95450-247-9 ISSN: 2673-5490 doi: 10.18429/JACoW-IPAC2024-WEPR25

CONCEPTUAL RF DESIGN AND MODELLING OF A 704 MHz CAVITY FOR THE MUON COOLING COMPLEX*

C. Barbagallo*, A. Grudiev, CERN, Geneva, Switzerland

Abstract

The Muon Cooling Complex is a crucial component of the future high-energy Muon Collider, where the ionization cooling technique is employed to reduce muon beam emittance by several orders of magnitude. This cooling technique necessitates the utilization of normal conducting, RF-accelerating cavities operating within a multi-Tesla magnetic field. This study illustrates the conceptual RF design of a 704 MHz copper cavity equipped with beryllium windows for the muon cooling demonstrator. Based on the specifications from the beam dynamics, frequency-domain eigenmode simulations have been conducted to calculate the primary RF figure of merits for the cavity. Subsequently, the cavity geometry has been optimized based on the results obtained from the eigenmode simulations. In a selected case, more advanced engineering analyses, including thermo-mechanical and Lorentz Force Detuning (LFD) simulations, have been performed to enable operation at gradients of up to 44 MV/m within

RF CAVITY DESIGN

The conceptual 704 MHz single-cell cavity for the muon cooling demonstrator was designed using the elliptical cavity parametrization detailed in [8], as depicted in Fig. 1.

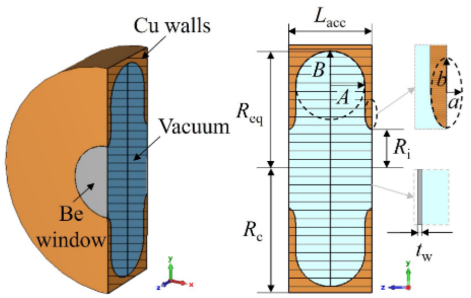


Figure 1: Design of the 704 MHz cavity for muon cooling.

R = 80 mm (cf Cooling cell conceptual design)

MuCol
Funded by the European Union

PRESENTATION OF COOLING CELL CONCEPTUAL DESIGN

Deliverable: D8.1

Date: 31/05/2024

Table 2. Reference parameter values used for the preliminary calculation of the cooling cell S5 (B5)

Cooling Cell Parameters

Beam Physics Parameters	
Momentum	200 MeV/c
Twiss beta function	107 mm
Dispersion in x	38.5 mm
Dispersion in y	20.3 mm
Beam pipe radius	81.6 mm

Design solenoid parameters*	
B0.5	0 T
B0	8.75 T
B1	1.25 T
B2	0 T
Cooling Cell length	800 mm
B0 tolerance	0.25 T
B1 tolerance	0.025 T
B0.5 tolerance	0.02 T
B2 tolerance	0.5 T

Simulated coil geometry	
Coil inner radius	250 mm
Coil length	140 mm
Coil radial thickness	169.3 mm
Coil z centre position	100.7 mm
Current Density	500 A/mm^2

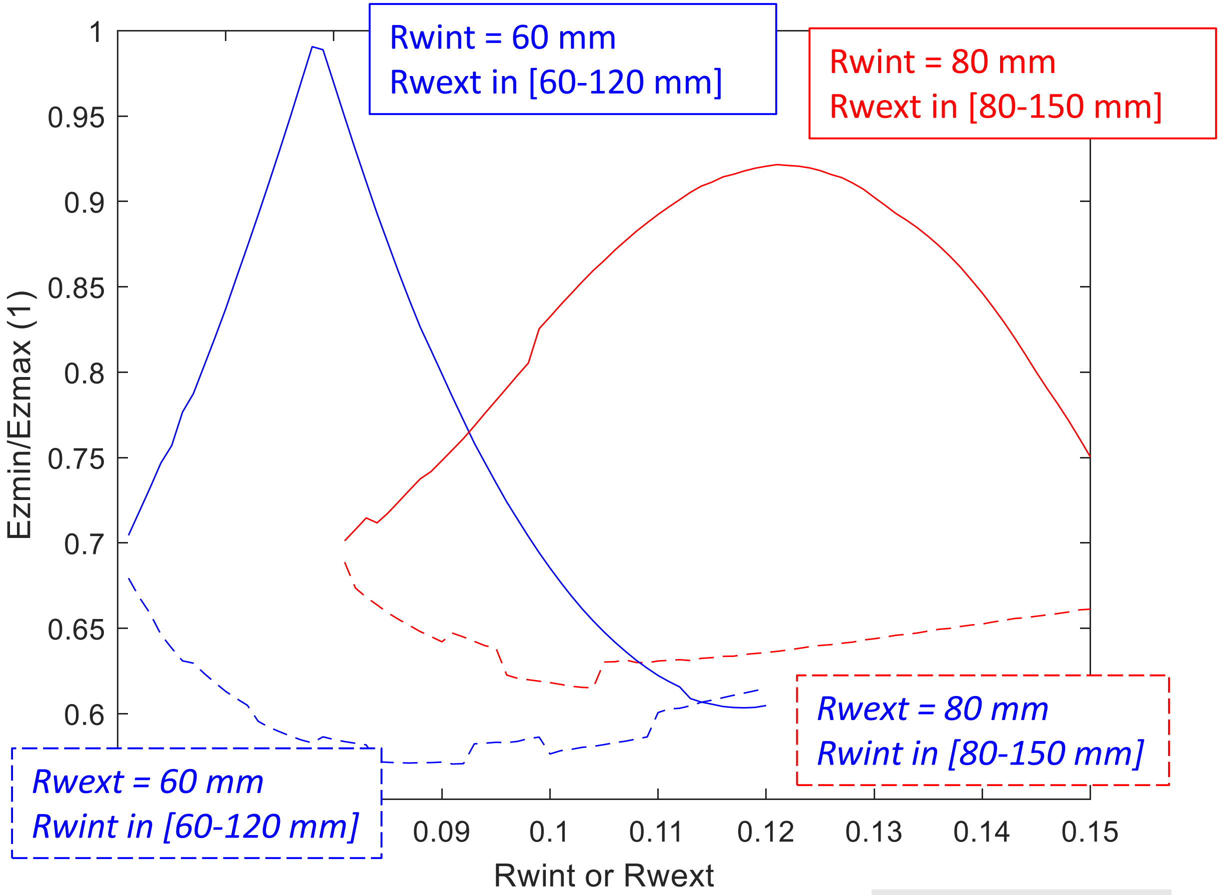
RF Cavity**	
RF cell centre-to-centre distance	188.6 mm
RF Gradient, E0	30 MV/m
Iris radius	81.6 mm
Number of RF cells	3
Frequency, f	0.704 GHz
Synchronous phase	20 degree
RF window thickness	0.1 mm

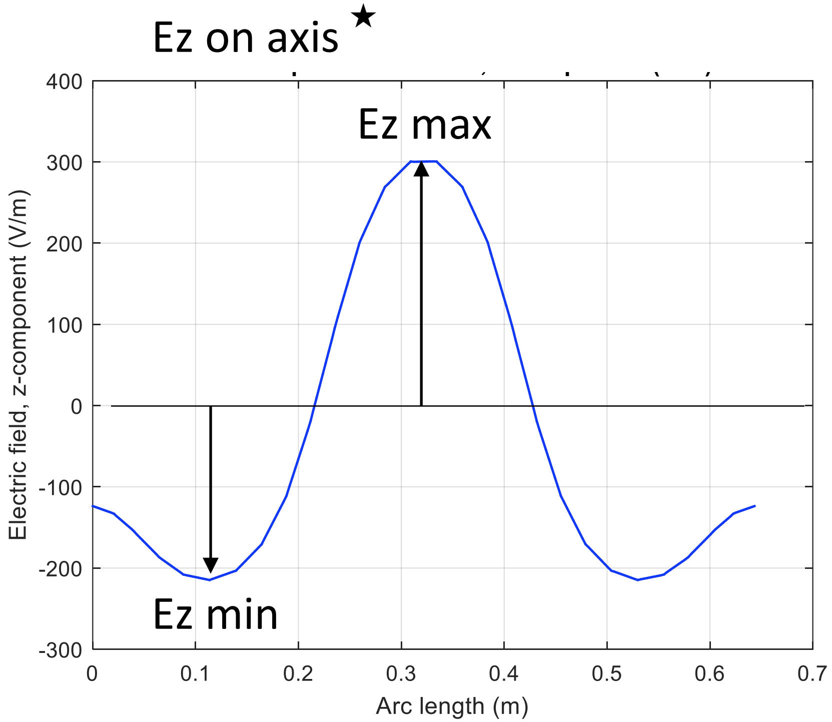
Wedge	
Material	Lithium Hydride
Wedge opening angle	10 degree
Wedge thickness	20 mm
Wedge alignment	Horizontal

Dipole	
Dipole length	100 mm
Polarity	+ - - +
Field	0.2 T
Dipole z centre position	160 mm
Dipole field direction	Vertical

Results - 1

Field flatness





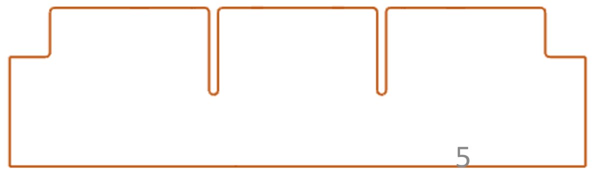
★Note: absolute field values are related to Comsol own normalization, not to our Eacc value

Correct field flatness needs $R_{wext} > R_{wint}$.

Optima are :

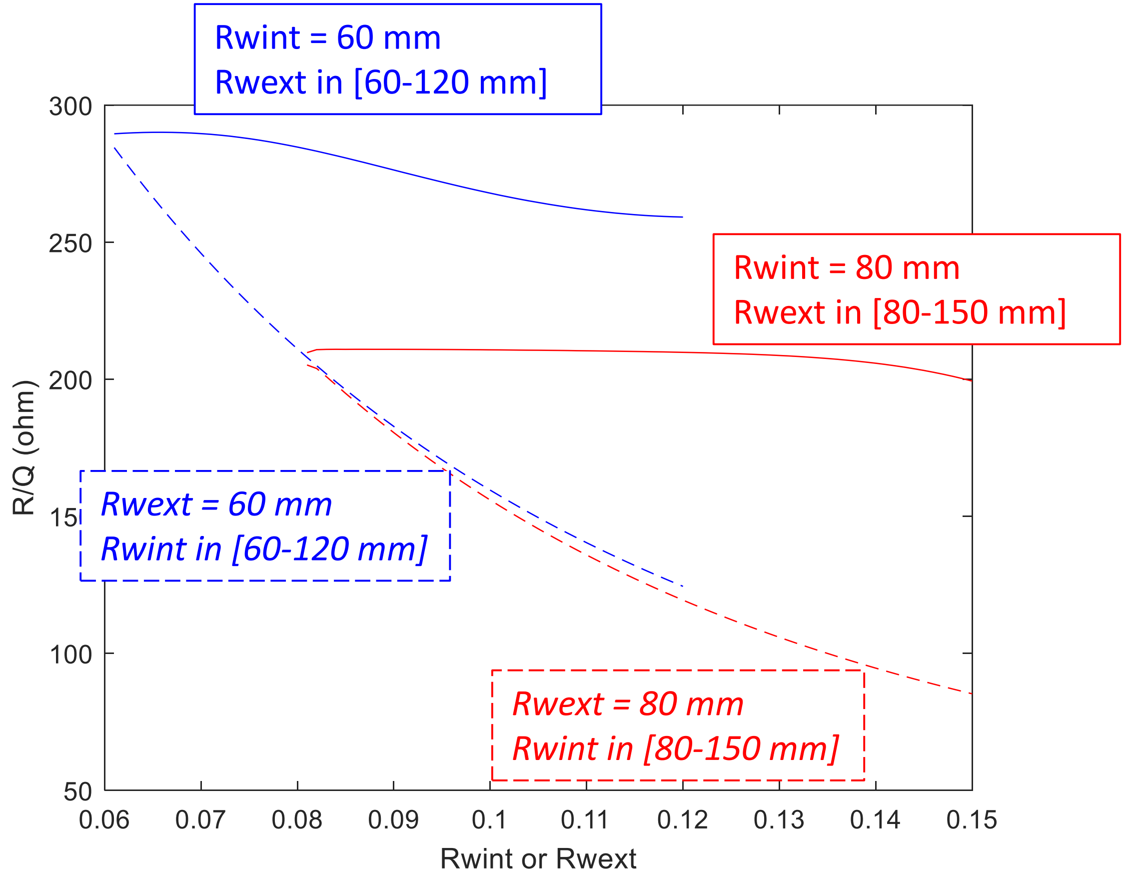
$$R_{wext} = 78\ mm$$
$$R_{wint} = 60\ mm$$
$$E_{zmin}/E_{zmin} = 0{,}99$$

$$R_{wext} = 122\ mm$$
$$R_{wint} = 80\ mm$$
$$E_{zmin}/E_{zmin} = 0{,}92$$

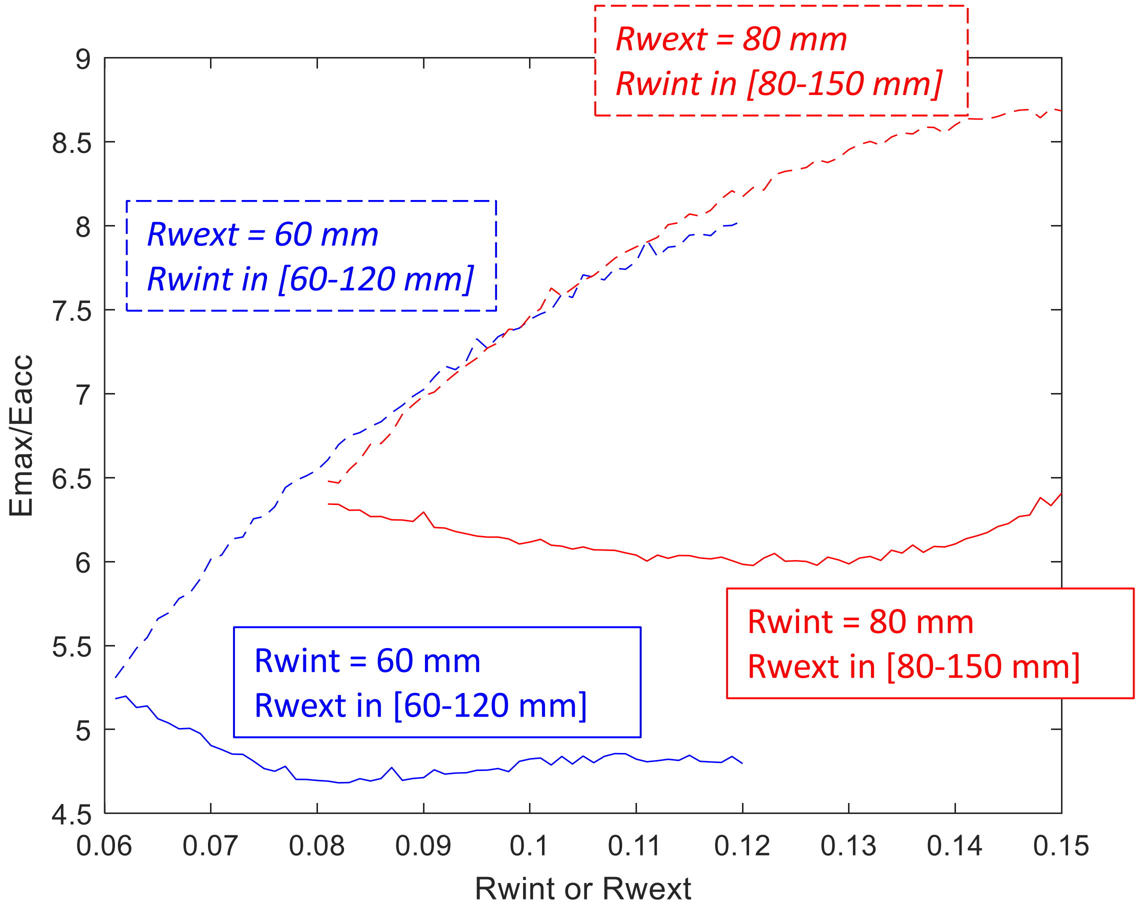


Results - 2

Shunt impedance



Max E field on surface

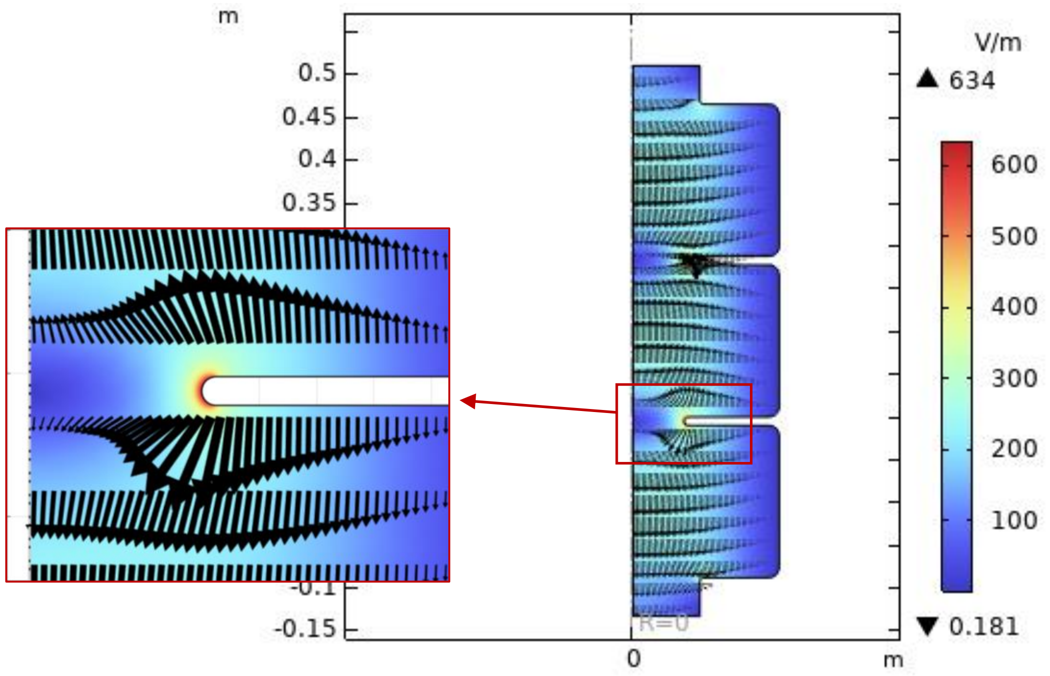


$$R_{wext} = 78\ mm$$
$$R_{wint} = 60\ mm$$
$$E_{max}/E_{acc} = 4{,}70$$
$$\mathrm{r/Q} = 286\ \Omega$$

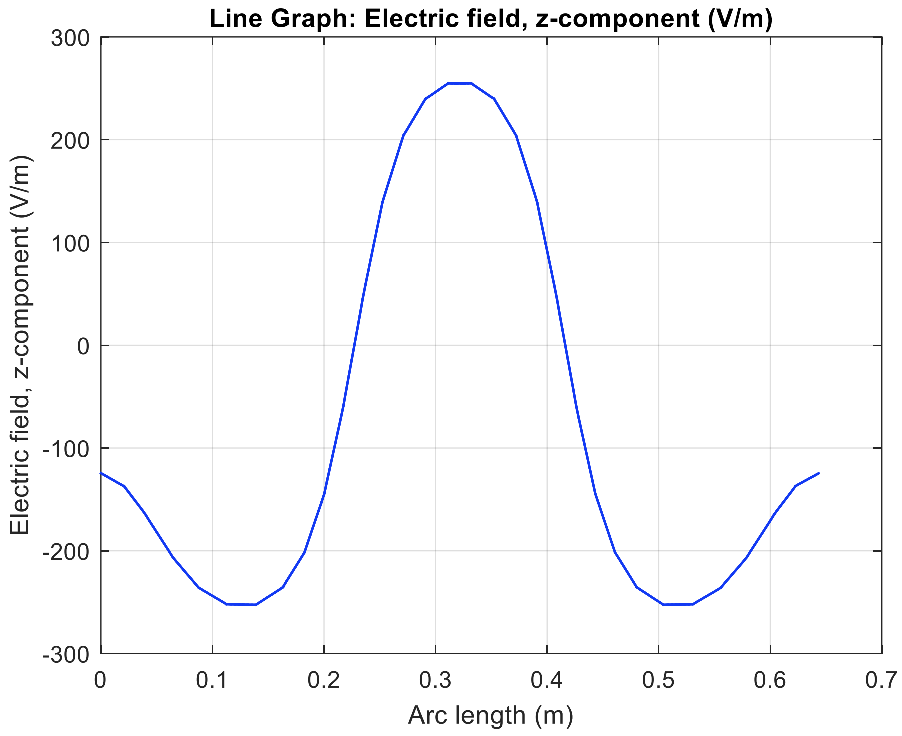
$$R_{wext} = 122\ mm$$
$$R_{wint} = 80\ mm$$
$$E_{max}/E_{acc} = 6{,}02$$
$$\mathrm{r/Q} = 210\ \Omega$$

Results - 3

Electric field in the cavity



Ez on cavity axis ★

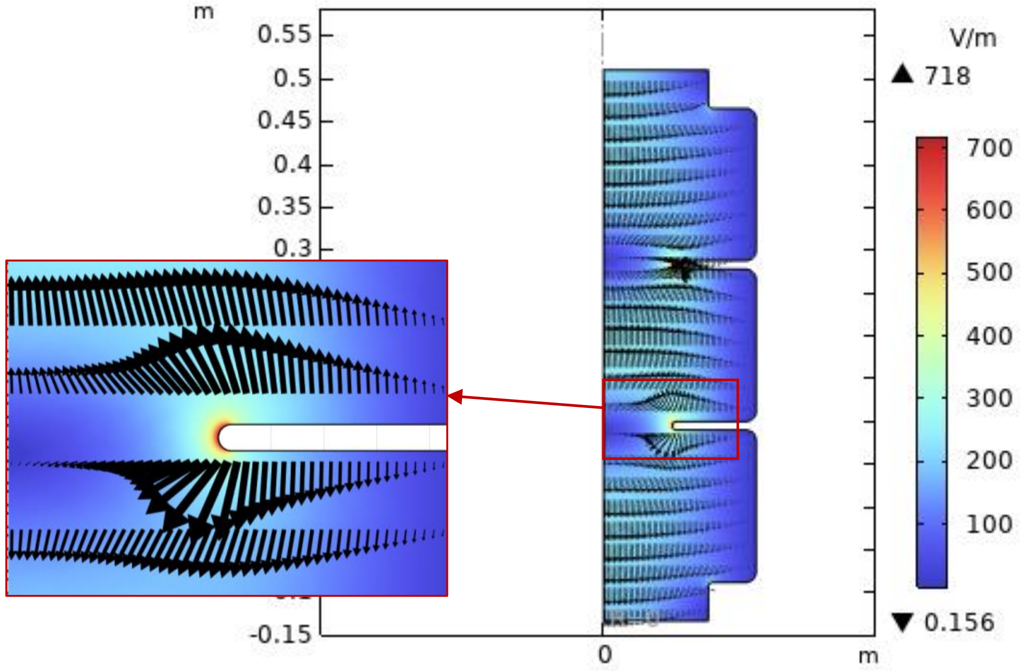


★Note: absolute field values are related to Comsol own normalization, not to our Eacc value

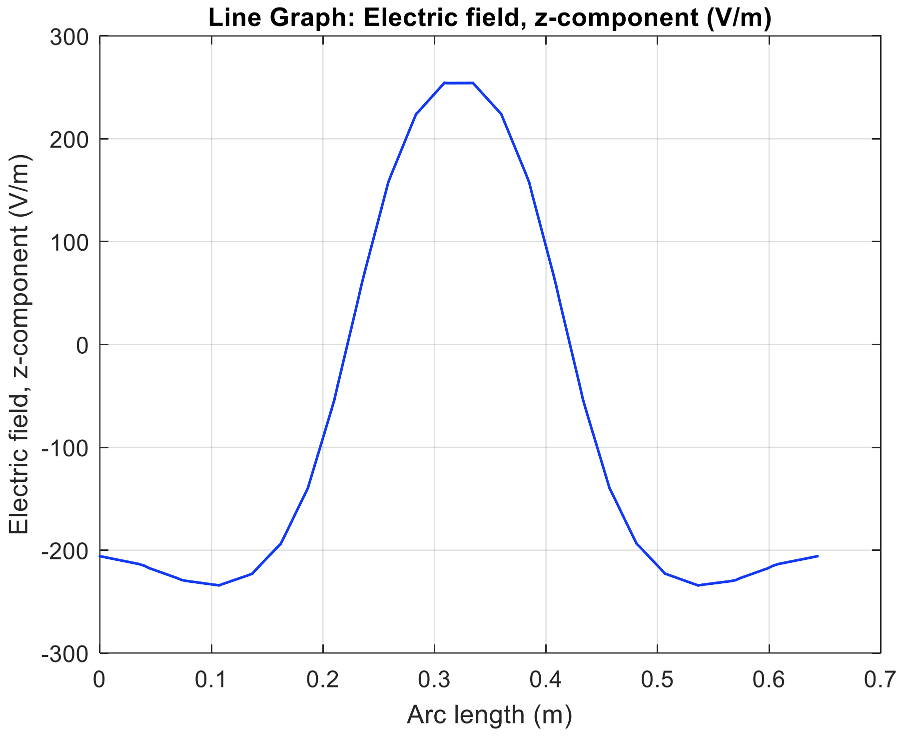
Eigenfrequency (MHz)	L_tube (m)	Cavity radius (m)	Iris radius (m)	tube radius (m)	R/Q (Ω)	Quality factor	Emax/Eacc
703.99	0.04	0.17067	**0.06**	**0.078**	286	36777	4.70

Results - 4

Electric field in the cavity



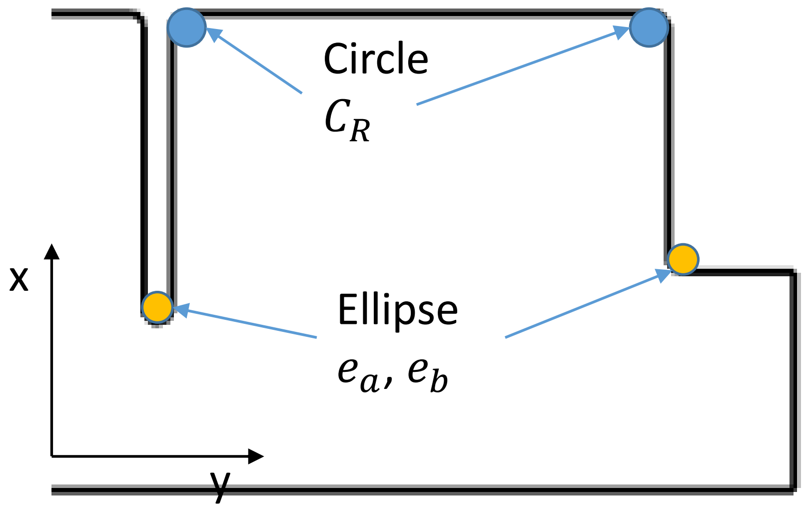
Ez on cavity axis ★



★ Note: absolute field values are related to Comsol own normalization, not to our Eacc value

Eigenfrequency (MHz)	L_tube (m)	Cavity radius (m)	Iris radius (m)	tube radius (m)	R/Q (Ω)	Quality factor	Emax/Eacc
703.99	0.04	0.17779	**0.08**	**0.122**	209.69	38081	6.02

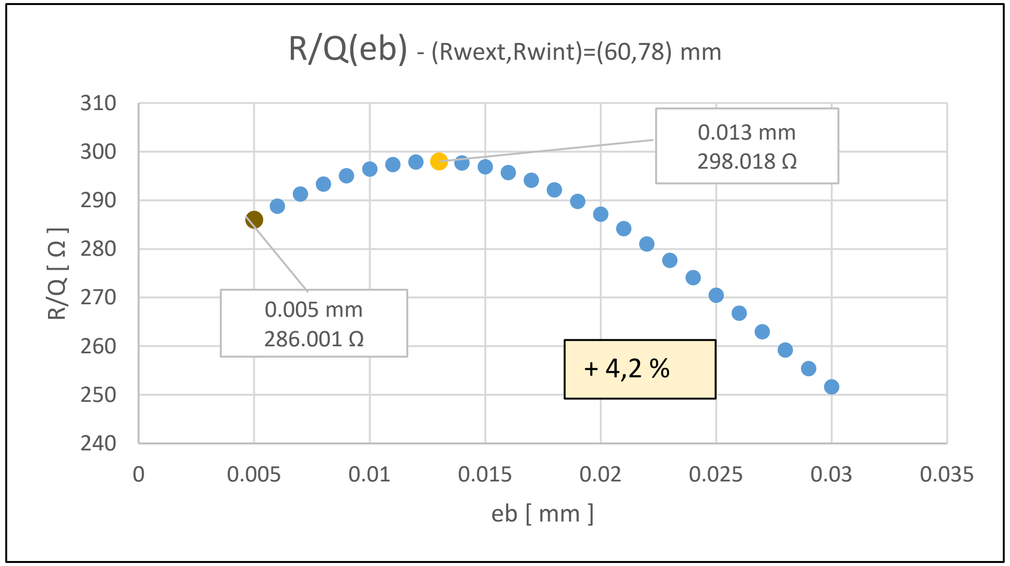
Adjusting iris geometry

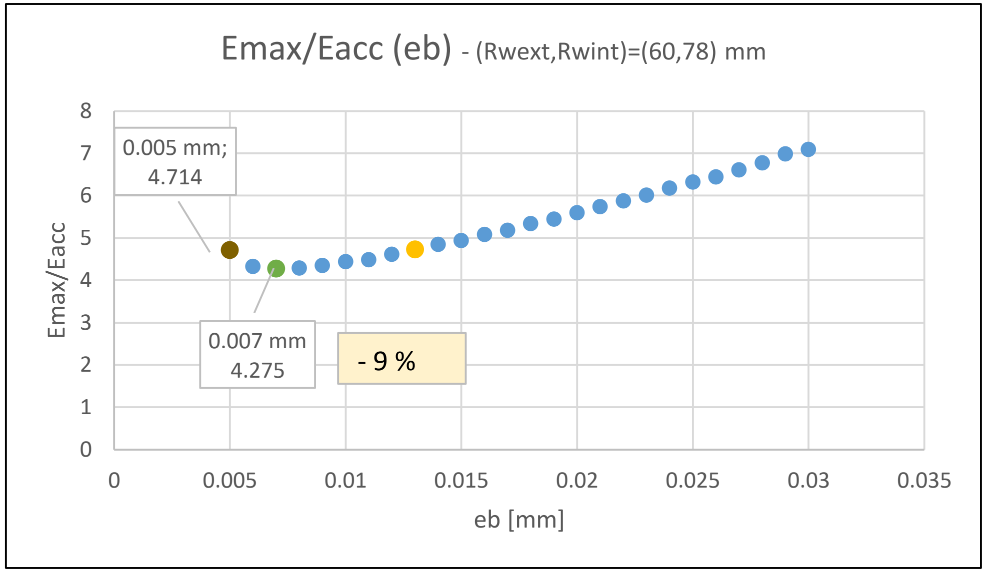


e_a	**varied**	Ellipse major axis – y axis
e_b	$= e_a$	Ellipse minor axis – x axis
C_R	12 mm	Top center circle radius

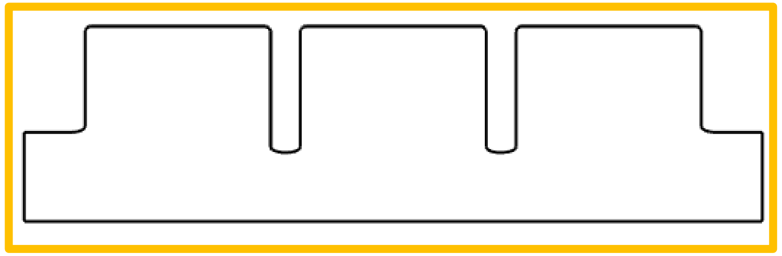
Results - 1

Iris radius (m)	tube radius (m)
0.06	0.078

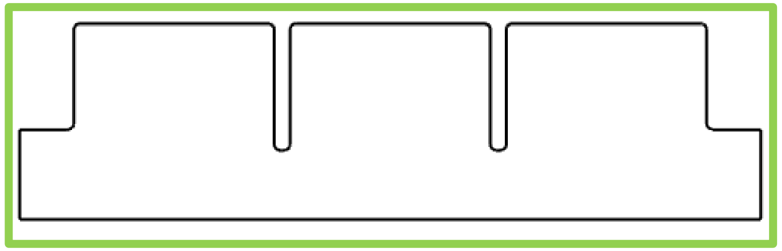




r/Q optimized

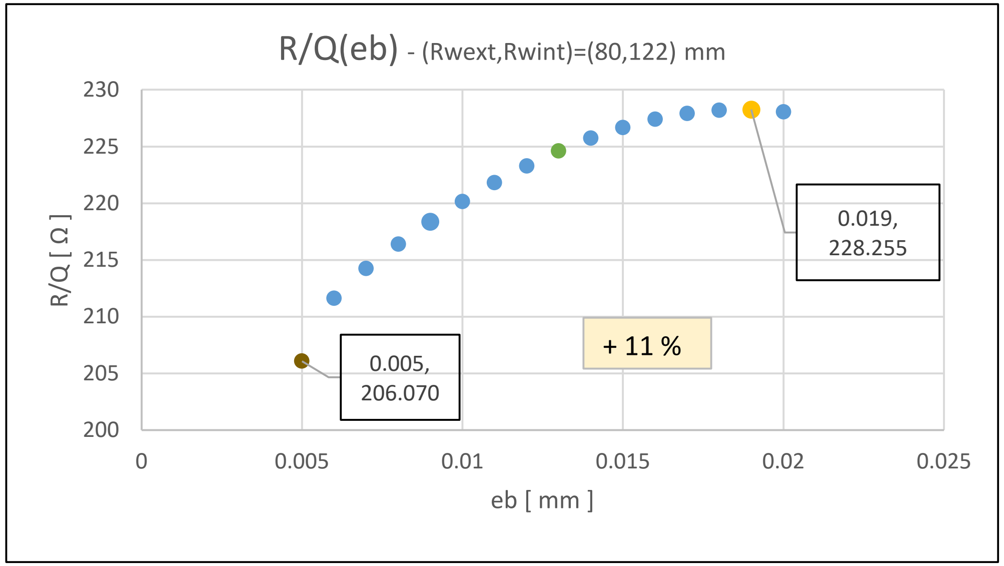


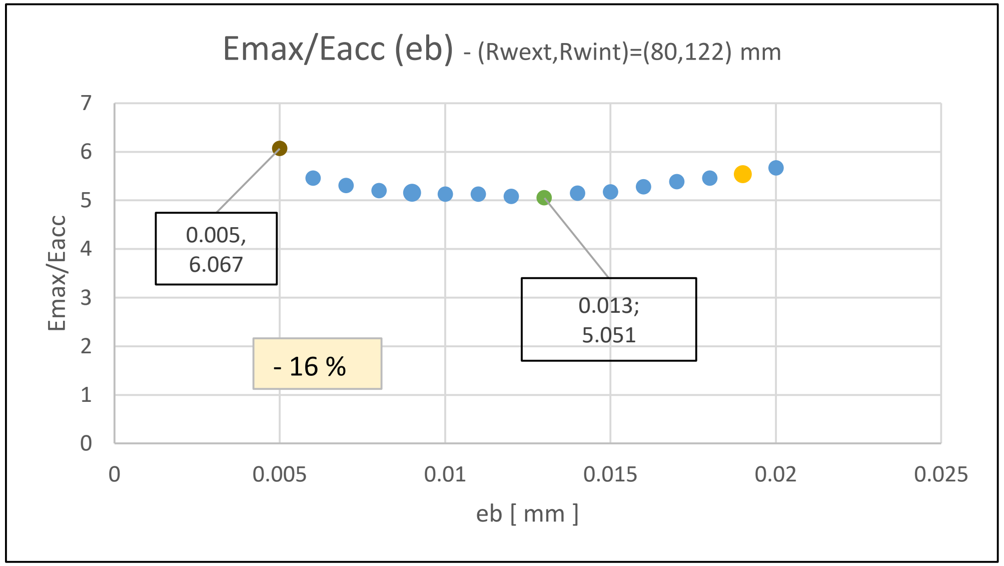
Emax/Eacc optimized



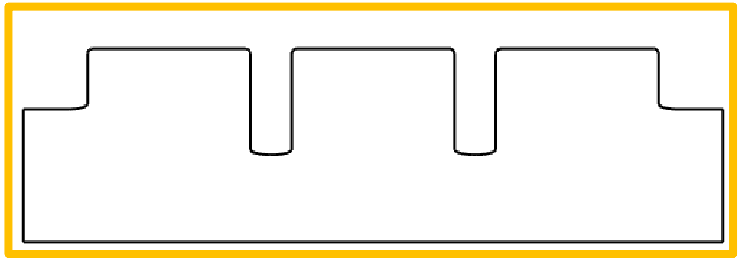
Results - 2

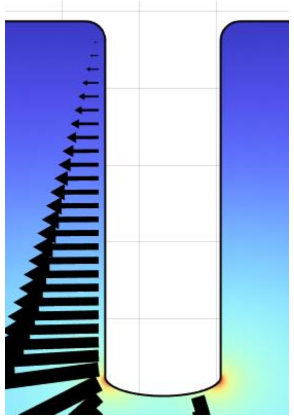
Iris radius (m)	tube radius (m)
0.08	0.122



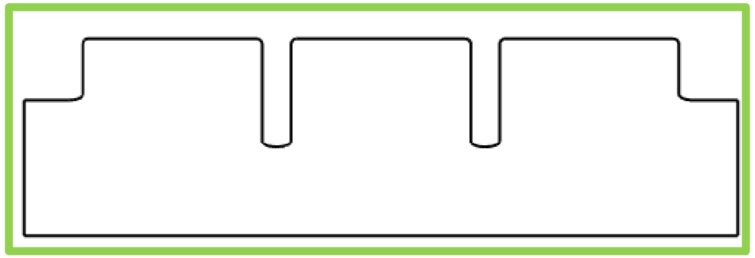


r/Q optimized





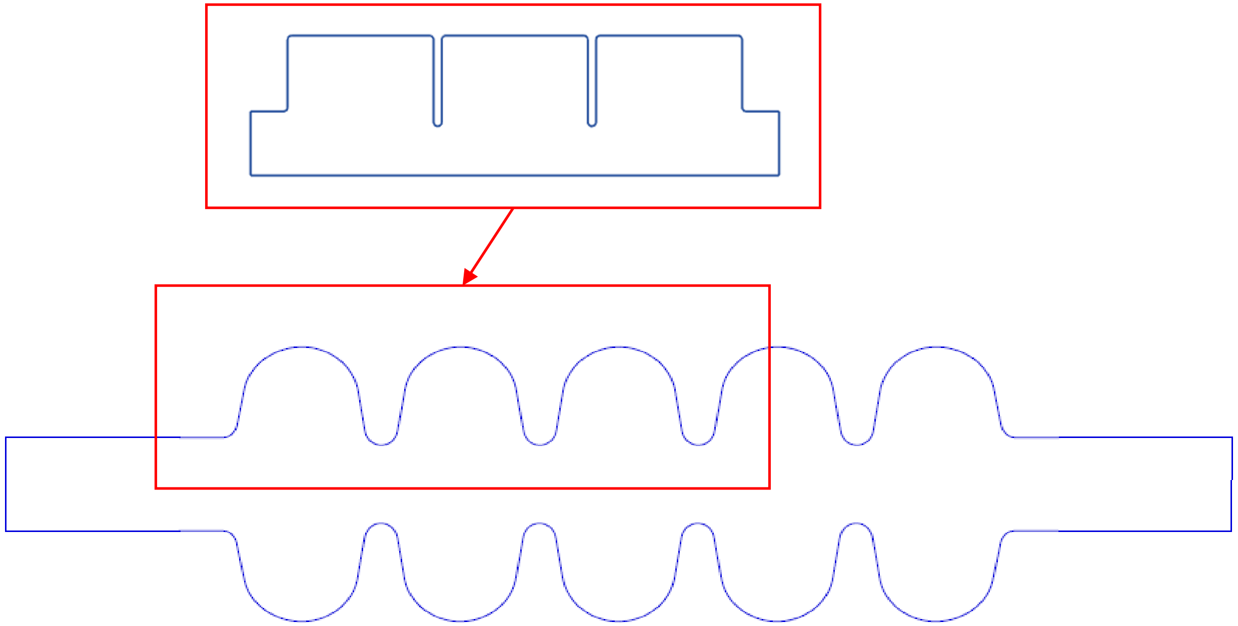
Emax/Eacc optimized



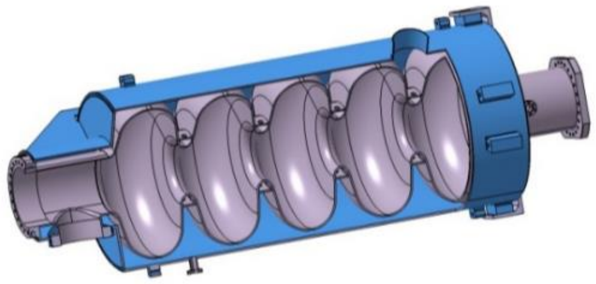
Lowering Emax/Eacc

With this design, it seems difficult to have a Emax/Eacc lower than 4

Elliptical cavities = design optimized for low peak fields…



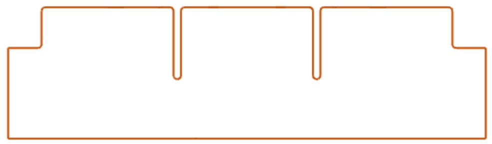
ESS high beta cavity

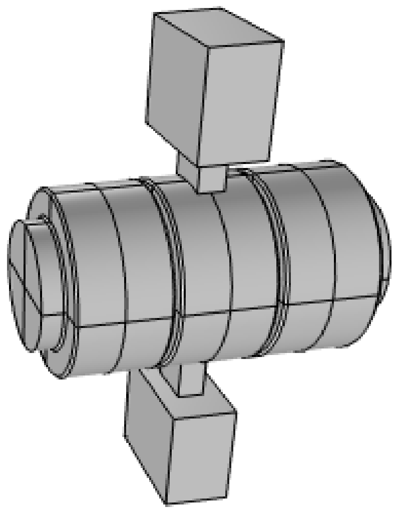


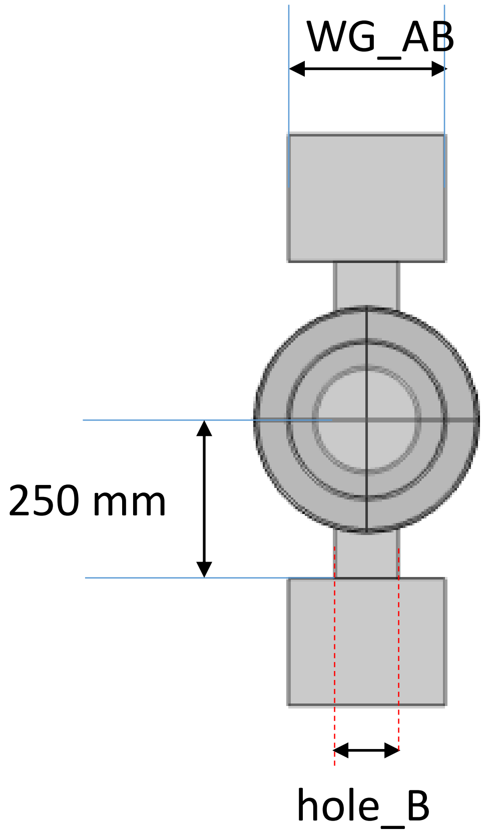
Iris radius	m	0,06	0,08	0,06
Tube radius	m	0,078	0,122	0,07
beta		0,884	0,884	0,86
Frequency	Hz	7,04E+08	7,04E+08	7,04E+08
Lacc	m	0,564	0,564	
Enom	**MV/m**	**30**	**30**	
TTF		0,73	0,72	
Eacc	MV/m	21,9	21,6	
Vcav	MV	12,4	12,2	
R/Q	(Ω)	286,0	209,7	
Emax/Eacc		4,7	6,02	2,2
Emax	**MV/m**	**102,9**	**130,0**	
Quality factor		36777	38081	
Shunt impedance	MOhms	10,52	7,99	
Pdiss	**MW**	**14,50**	**18,59**	

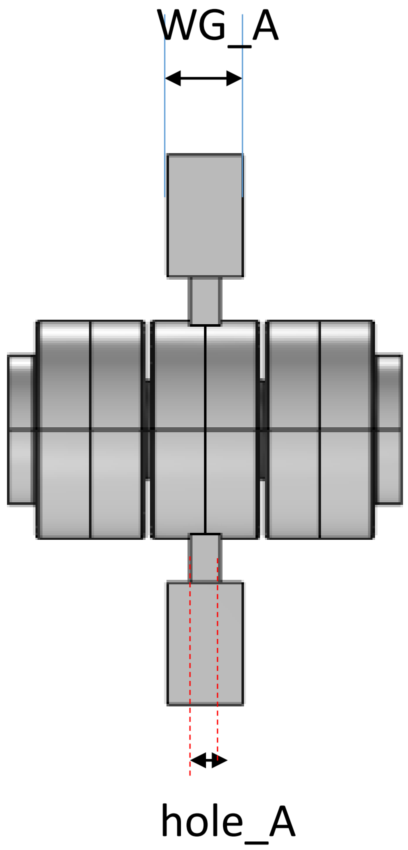
Coupler

$$R_{wext} = 122\ mm$$
$$R_{wint} = 80\ mm$$
$$E_{max}/E_{acc} = 6{,}02$$
$$r/Q = 210\ \Omega$$



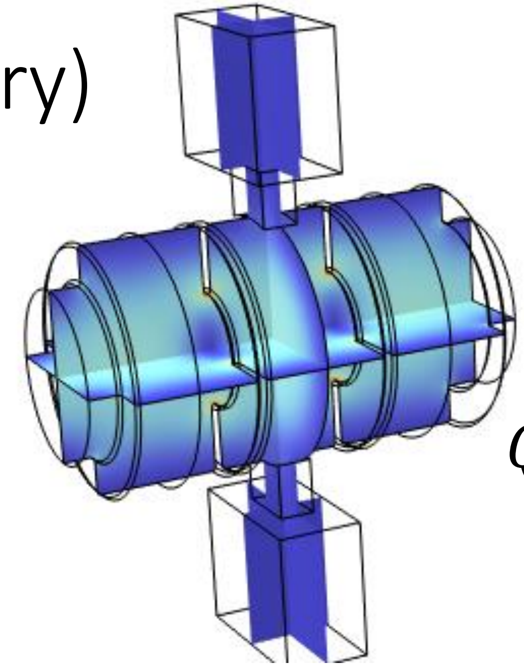






hole_A	50[mm]	
hole_B	hole_A*2	
WG_A	123.825[mm]	WG975 'A'
WG_B	WG_A*2	WG975 'B'

Coupling (very preliminary)



$$Q_{ext} = \frac{f}{\Delta f} = \begin{cases} 1{,}73 \times 10^5 & \text{for 2 ports} \\ 3{,}47 \times 10^5 & \text{for 1 ports} \end{cases}$$