RF Design of X-band TDS with variable polarization

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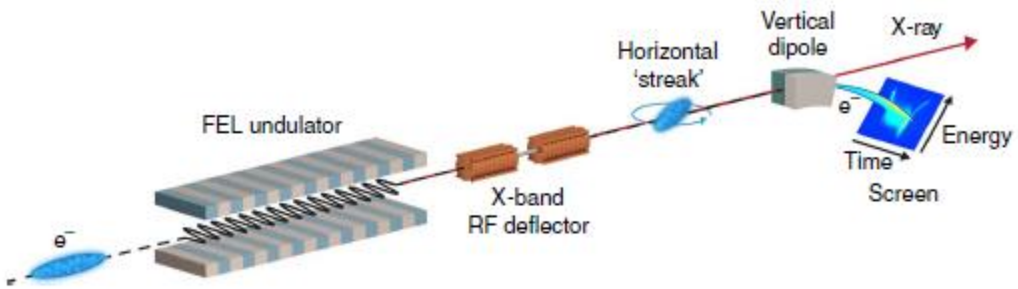
Outline

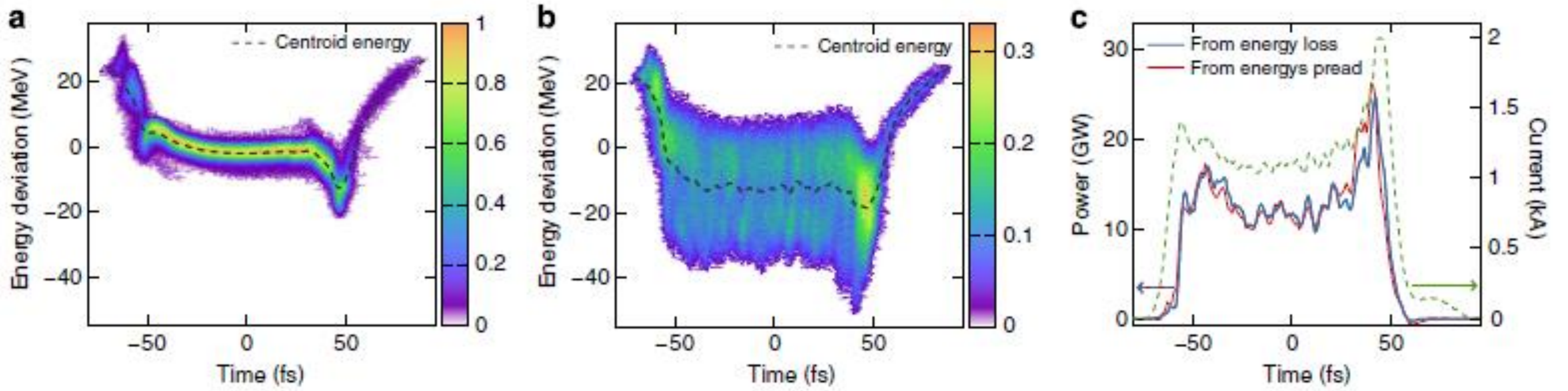
- Introduction
- Backward Travelling wave transverse deflecting structure (TDS) design
- Basic tolerances study
- Overall TDS system parameters

Introduction

Transverse Deflecting Structures for Longitudinal Diagnostics

- Measurement of the energy spread induced by the FEL process at SLAC
- Achieved **temporal Resolution < 1fs** for soft X-rays



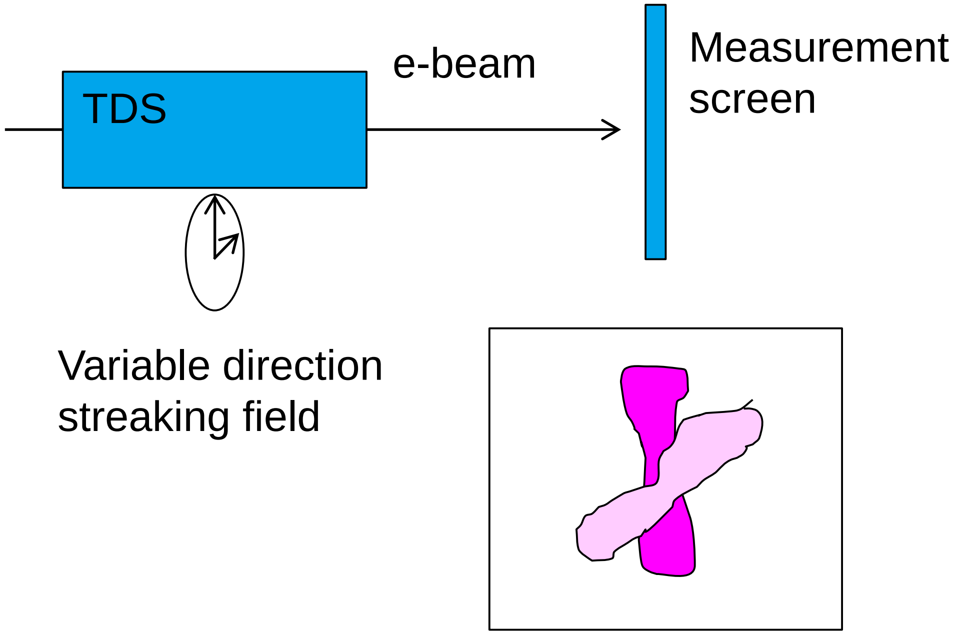


C. Behrens et al., „Few-femtosecond time-resolved measurements of X-ray free electron laser“ , Nat. Comm. 4762 (2014).

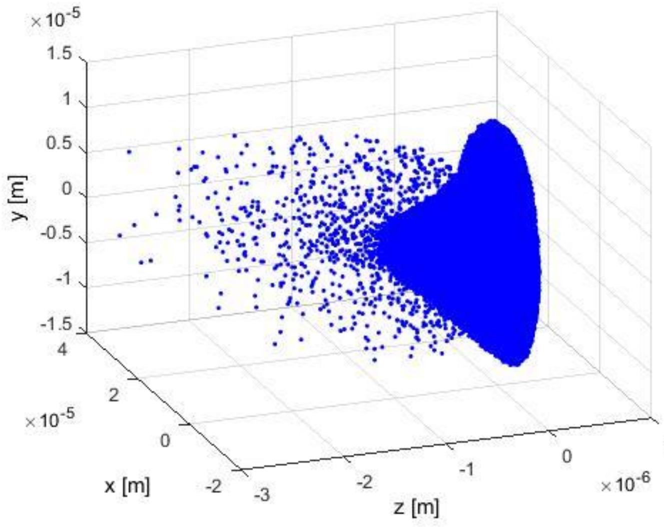
Potential applications of the variable polarization feature

> Next generation TDS

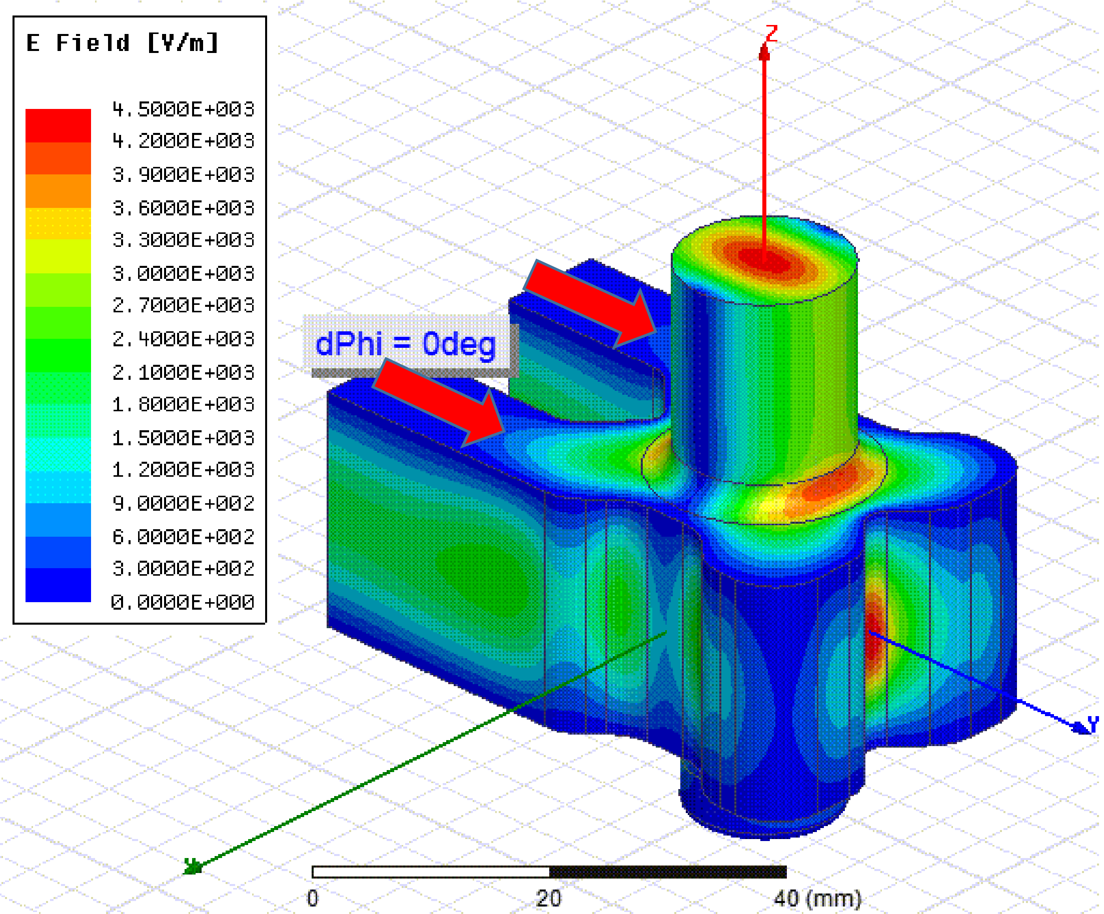
> Exciting new opportunities for e-bunch characterization (e.g. slice emittance measurement on different planes, tomography …)



- 3D reconstruction of the charge distribution
- Identify correlations, tilts of the beam distribution in 3D

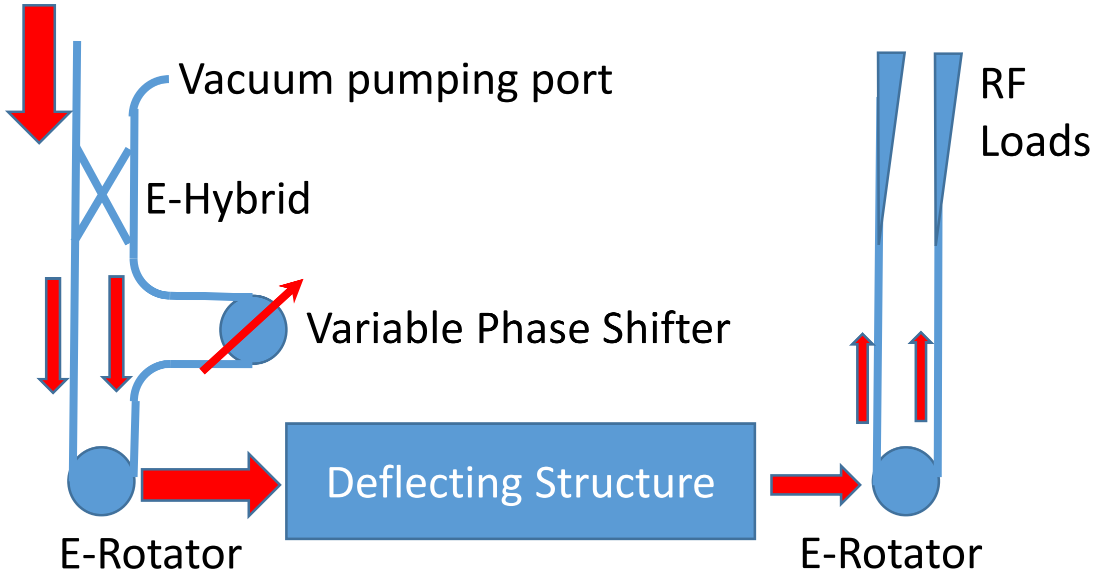


Variable polarization circular TE11 mode launcher: E-rotator



Phase difference between port 1 and port 2:

- 0 degree -> vertical polarization
- 180 degree -> horizontal polarization

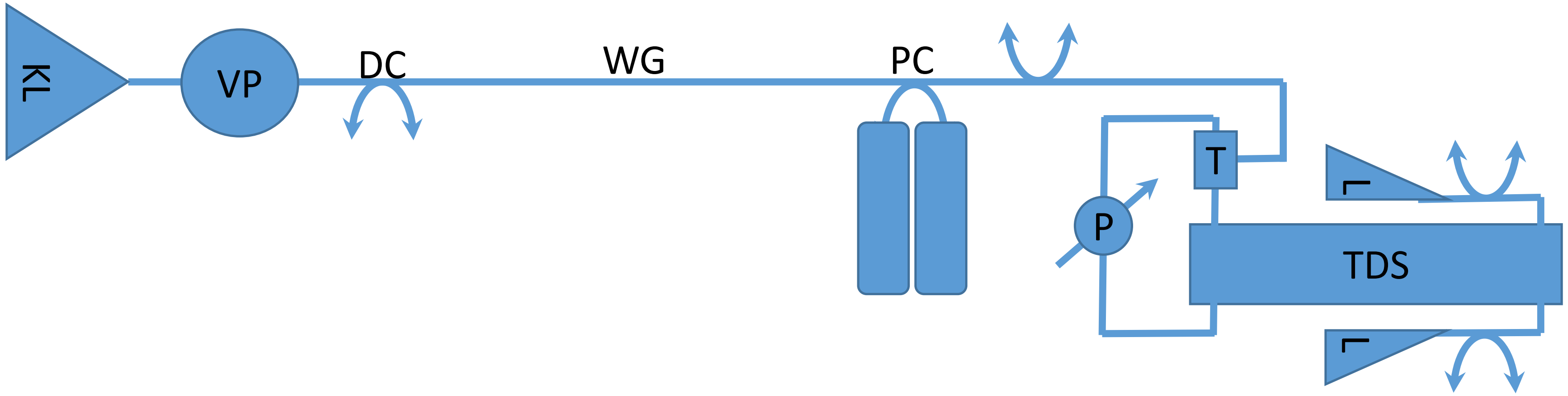


A. Grudiev, CLIC-note-1067 (2016).

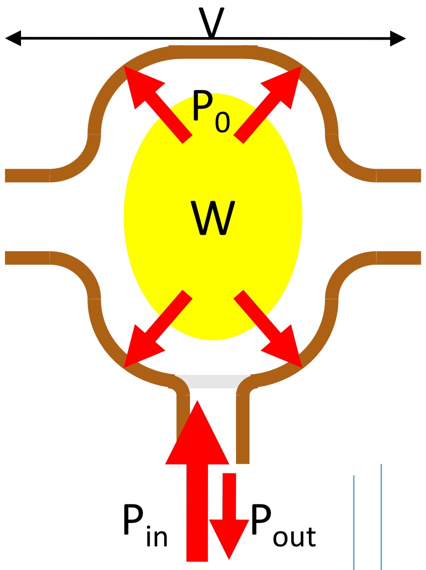
RF design

RF design of TDS taking into account RF pulse compression

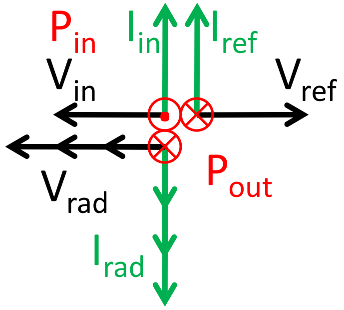
Basic layout: TDS + pulse compressor (PC)



Transient in a cavity -> pulse compression



Short-Circuit Boundary Condition:



$$P_{out} = P_{in}(t=0)\left(\frac{V_{out}}{V_{in}}\right)^2$$

$$V_{out} = V_{rad} + V_{ref} = V_{rad} - V_{in}$$

$$V_{rad} = (V_{in} * C_{resp})$$

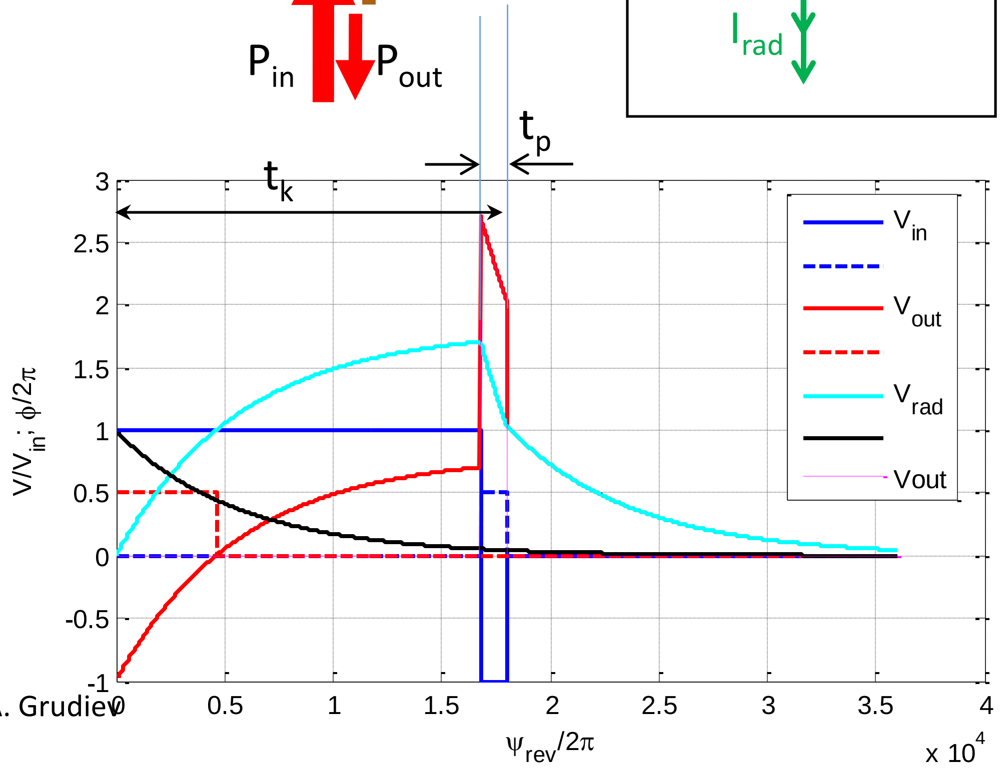
$$V_{in} = V_{in}(t=0)\exp(\omega t)$$

$$C_{resp} = \frac{1}{Q_e}\exp\left(-\frac{\omega_0 t}{2Q_l}\right)$$

$$Q_l = \frac{Q_0 Q_e}{Q_0 + Q_e}$$

Analytical expression for the pulse shape

$$\left.\frac{V_{out}}{V_{in}}(t)\right|_{t_0=t_k-t_p}^{t_k} = f(\omega=\omega_0; t_k; t_p; Q_0; Q_e)$$



Effective shunt impedance of Deflecting Structure + Pulse Compressor

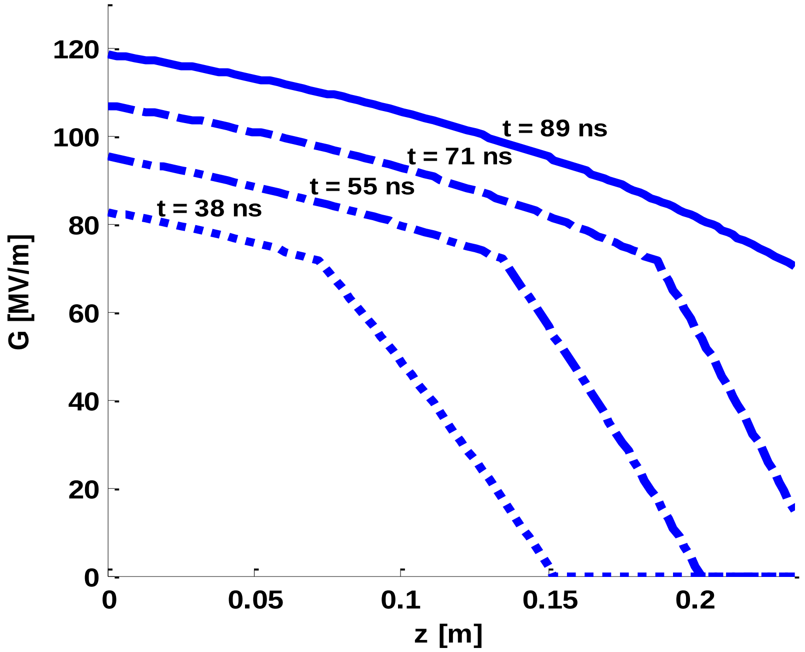
$$\text{Time-dependent gradient*: } \quad G(z,t') = G_0[t' - \tau(z)]g(z);$$

$$\tau(z) = \int_0^z \frac{dz'}{v_g(z')}; \quad t_f = \tau(L_s); \quad t' = t - t_0$$

$$G_0(t') = \sqrt{\frac{\omega}{v_{g0}} \frac{R}{Q} P_{out}(t')} = \sqrt{\frac{\omega}{v_{g0}} \frac{R}{Q} P_{in}} \frac{V_{out}}{V_{in}}(t')$$

$$V_a = \int_0^{L_s} dz' G(z', t' = t_f = t_p); \quad \tau_s = \alpha L_s = \frac{\omega}{2 v_g Q} L_s$$

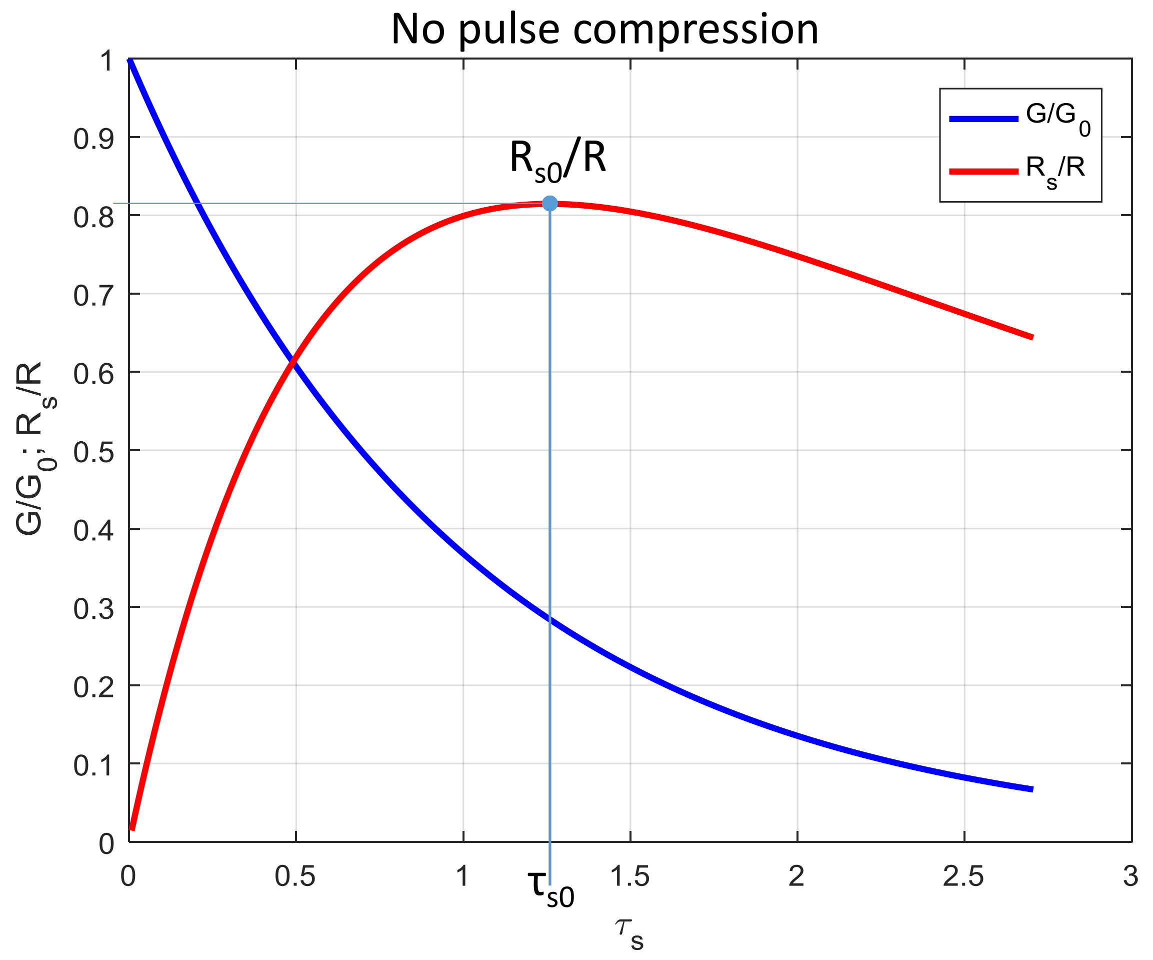
$$\text{Effective shunt impedance**: } \quad R_s = \frac{V_a^2}{P_{in} L_s} [\Omega / m]; \quad P_{tot} = \frac{V_{tot} \langle G \rangle}{R_s}$$



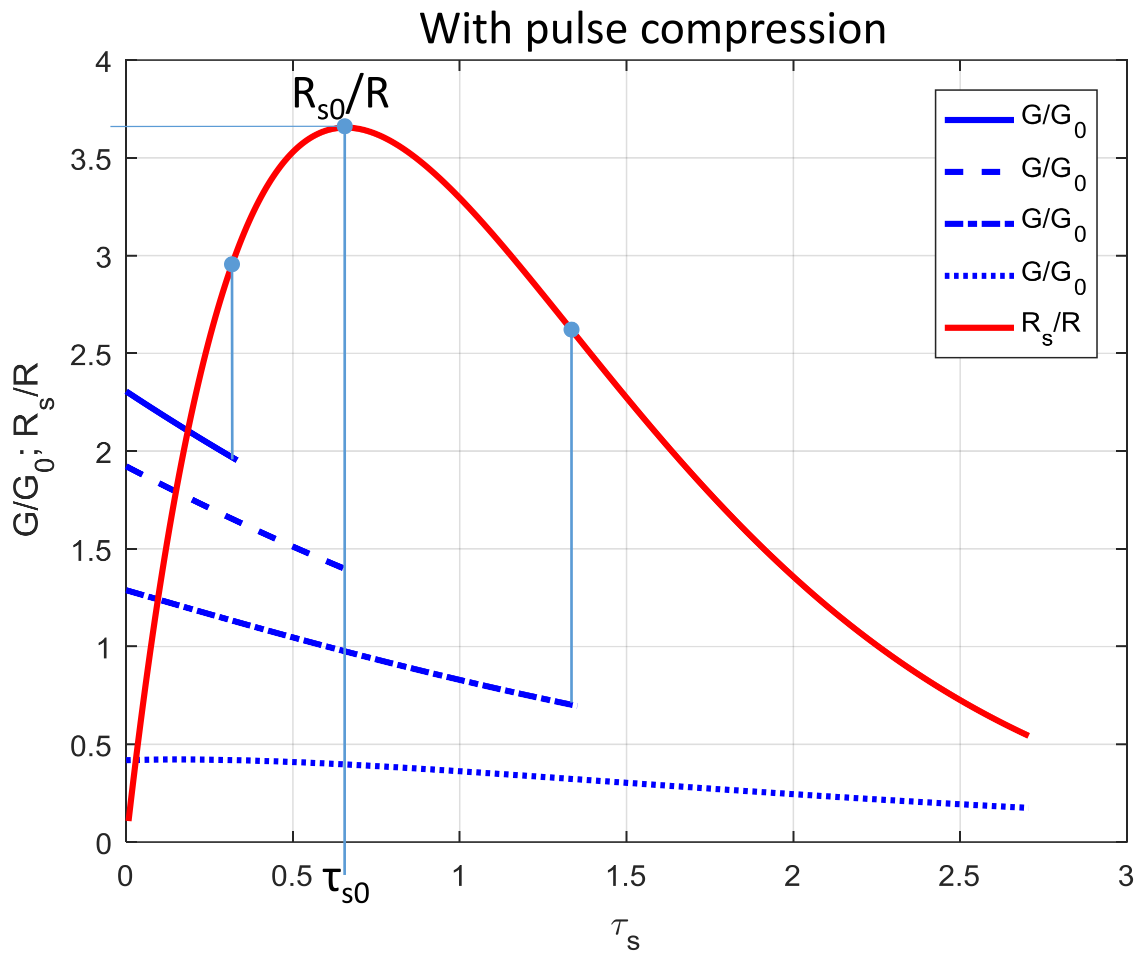
* i.e. A. Lunin, V. Yakovlev, A. Grudiev, PRST-AB 14, 052001, (2011)

** R. B. Neal, Journal of Applied Physics, V.29, pp. 1019-1024, (1958)

Effective Shunt impedance for Const Impedance (CI) TDS with and w/o RF pulse compressor

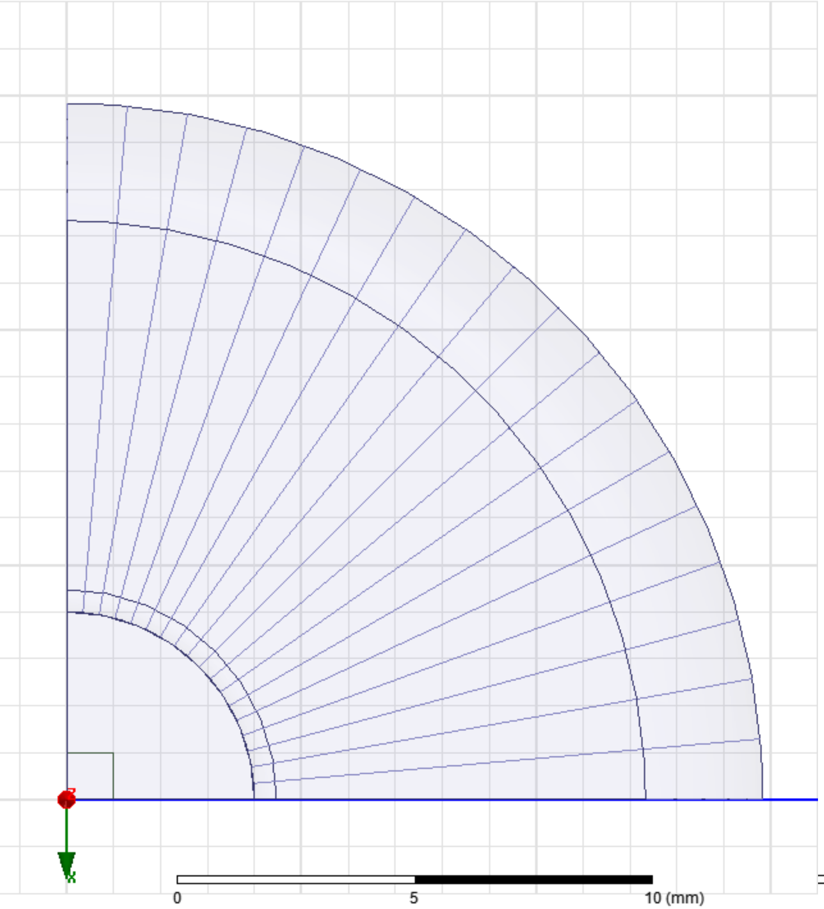


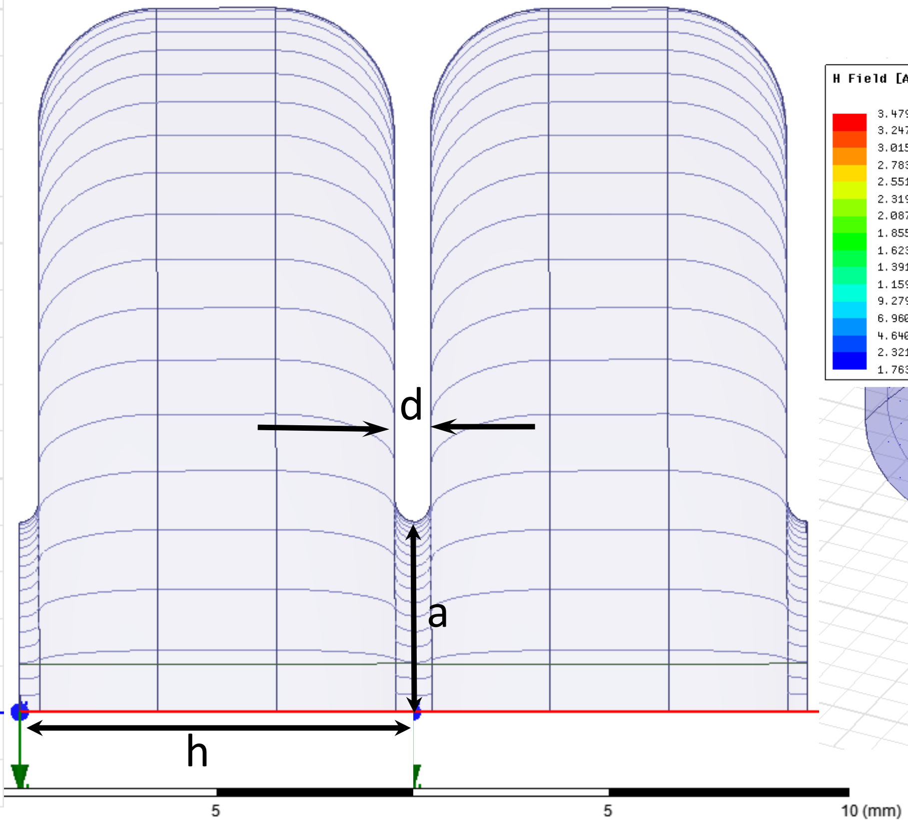
$\tau_{s0} = 1.26 \Rightarrow R_{s0}/R = 0.815$

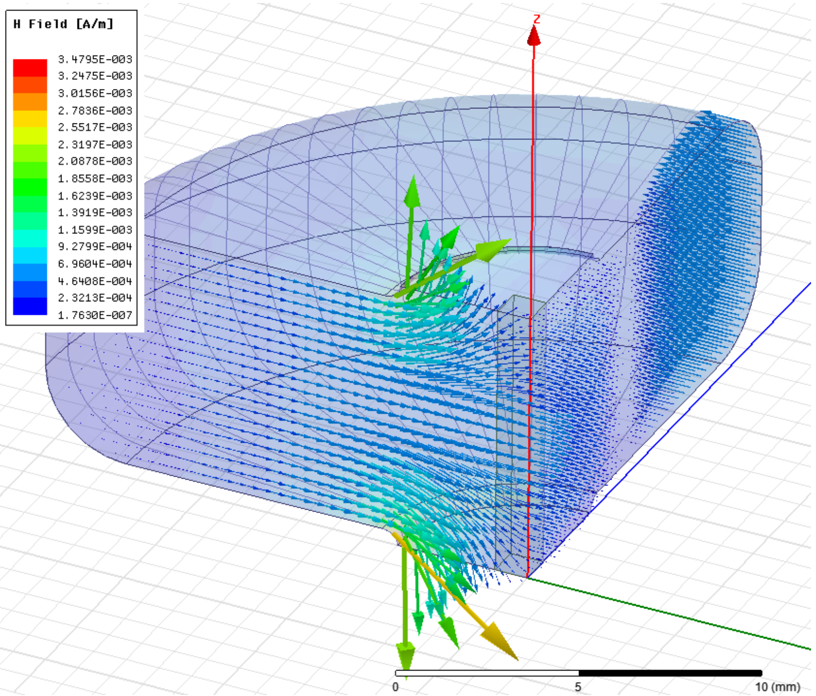


$\tau_{s0} = 0.669 \Rightarrow R_{s0}/R = 3.66$
for $Q = 6512$; $Q_0 = 180000$; $Q_e = 20000$

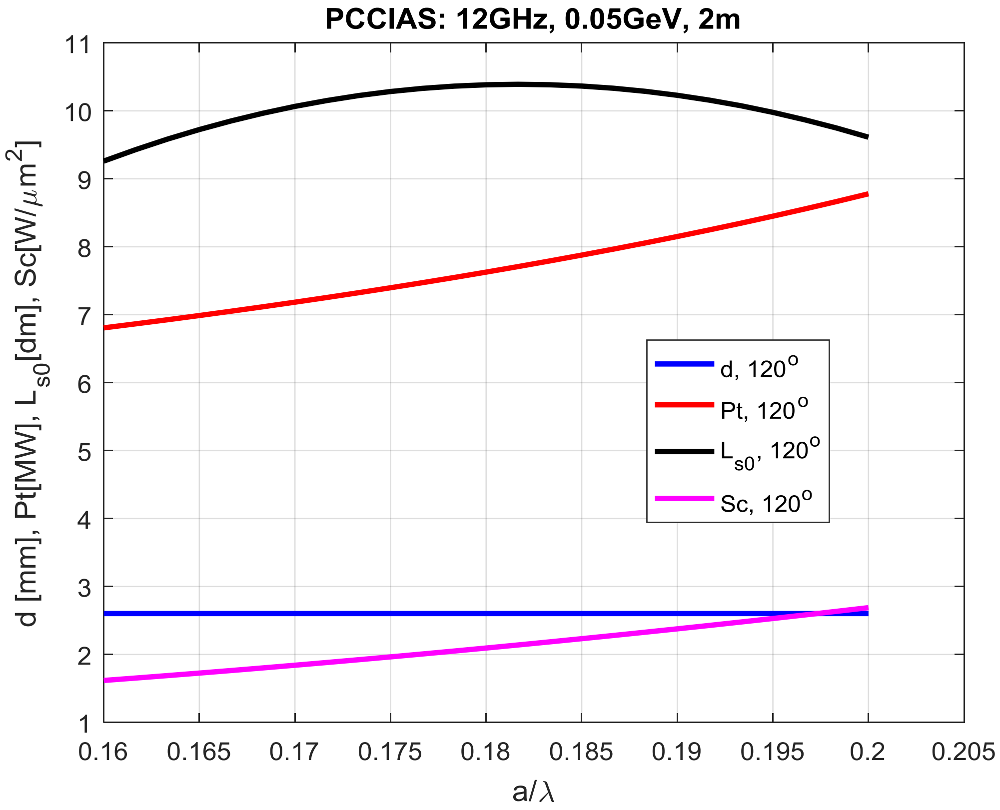
Basic cell geometry and H-field distribution

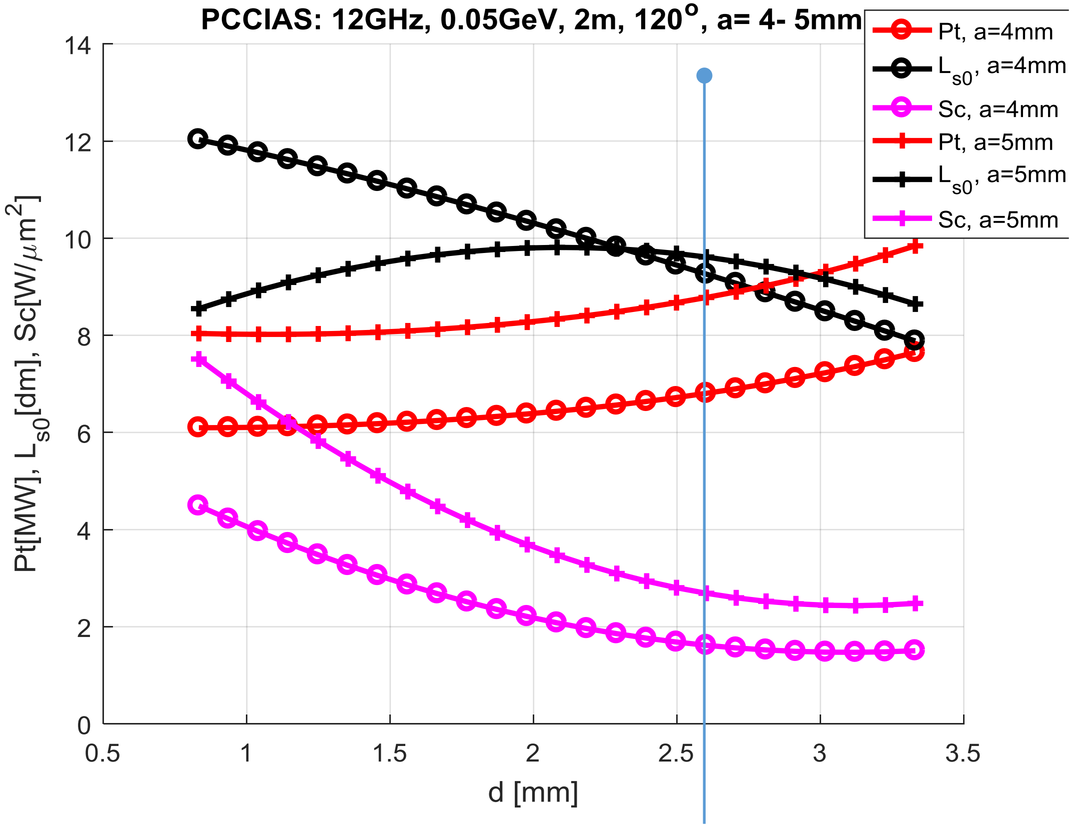






TDS+PC parameters versus cell geometry, ($\Delta\phi$ =120^o)

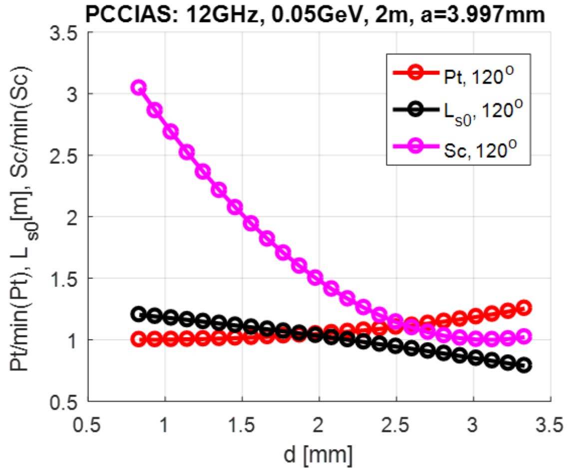




a=4mm;
d=2.6mm;
Ls = 927mm

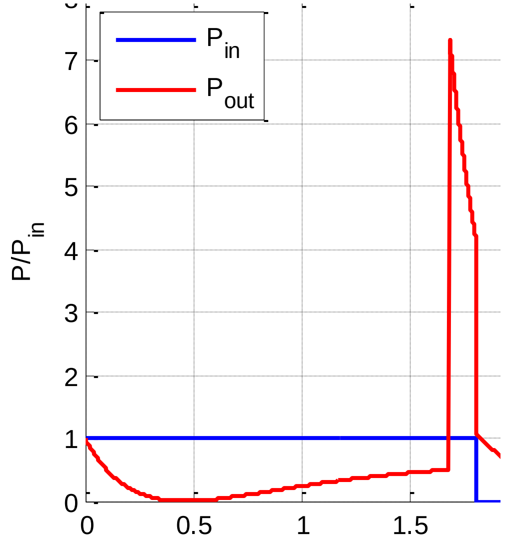
Summary table of parameters TDS + PC

Case	1	2	3	4	comments
$\Delta\phi0$ [degree]	120	120	135	150	RF phase per cell
a [mm]	5	4	4	4	Aperture radius
d [mm]	2.7	2.6	3.0	3.4	Iris thickness
Ls [mm]	952	927	747	527	Structure length
tf [ns]	112	116	121	126	Filling time
Qext	19900	20100	20420	20750	Pulse compressor
tk [ns]	1500	1500	1500	1500	50MW tube
Vd/Ls [MV/m]	25	25	25	25	Def. voltage per meter
Pk/Ls [MW/m]	4.45	3.4	3.55	3.73	Needed power per meter
Reff = Vd^2/Pk/Ls [MΩ/m]	142	184	175	167	Effective trans. Shunt impedance of TDS+PC
Max Sc [MW/mm^2]	2.6	1.6	1.48	1.3	< 6 (@ tp_eff = 50ns)
Vd [MV]	23.8	23.2	18.7	13.2	per structure
Pk [MW]	4.2	3.17	2.67	1.98	per structure.
RsPC = Vd^2/Pk [MΩ]	135	**170.5**	131	88	Reff TDS+PC per structure

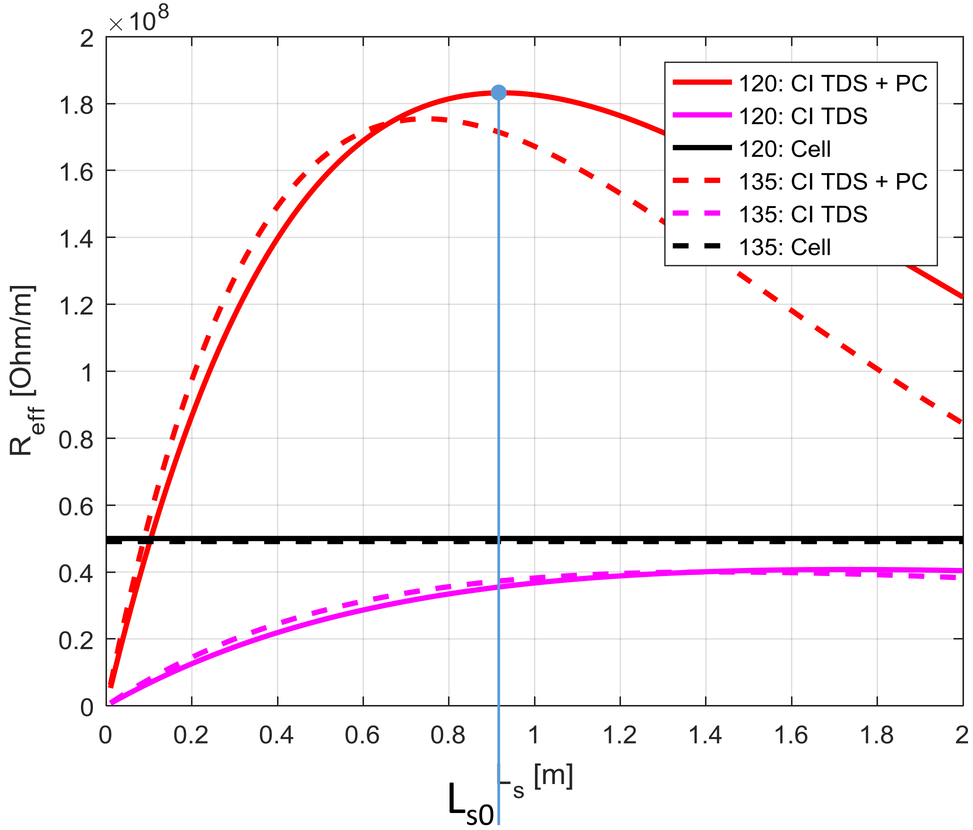


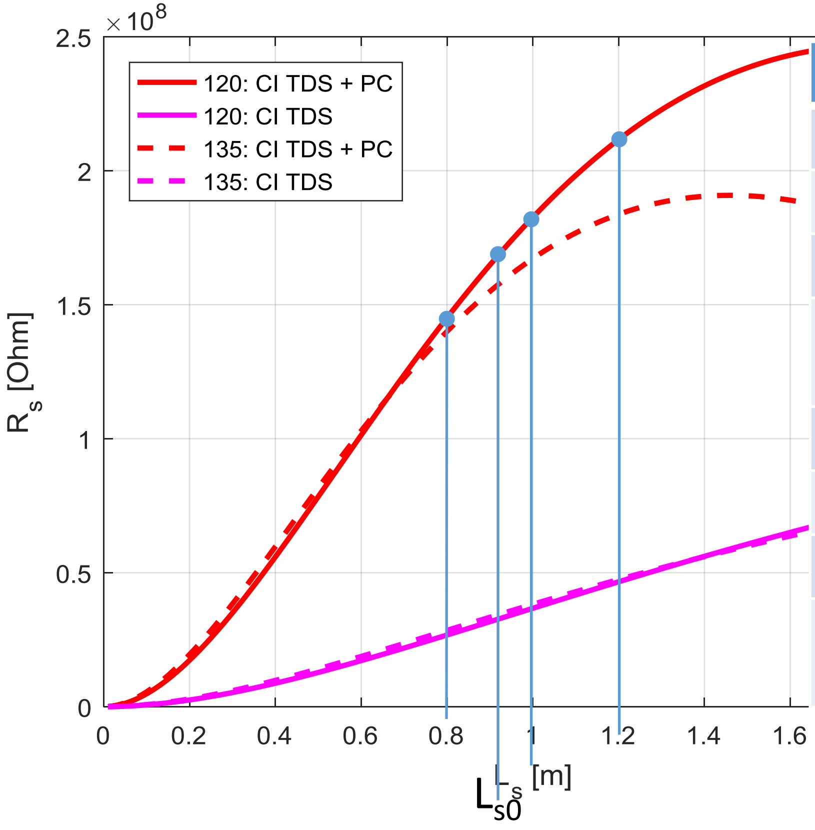
Peaked pulse: 120 ns

-> tp_eff = 60 ns



Effective shunt impedance versus structure length





L_s [m]	0.8	0.927	1	1.2
Parameters for TDS + PC				
R_{eff}[MΩ/m]	181	183	182	176
R_s [MΩ]	145	171	182	211
V_d [MV] P_k = 6 MW	29.5	32.0	33.0	35.6
Parameters for TDS along				
R_{eff}[MΩ/m]	33.4	35.7	36.7	38.8
R_s [MΩ]	26.7	33.2	36.7	46.6
V_d [MV] P_k = 6MW	12.7	14.1	14.8	16.7

Effective shunt impedance per meter length: R_{eff}.
Optimum active length: L_{s0} = 0.927 m; R_{eff} = 183 MOhm/m

- This is the optimum for a long system with many structure
- **120 deg RF phase advance (solid) is better than 135 deg one (deshed) for Ls > 0.8m**

Effective shunt impedance per structure: $R_s = R_{eff} L_s$ increasing with L_s till 1.6m

- For a single structure increasing the length results in higher effective shunt impedance per structure.
- **It is better to increase L_s if some length is available in the beam line**

Basic tolerance study

Basic tolerance study

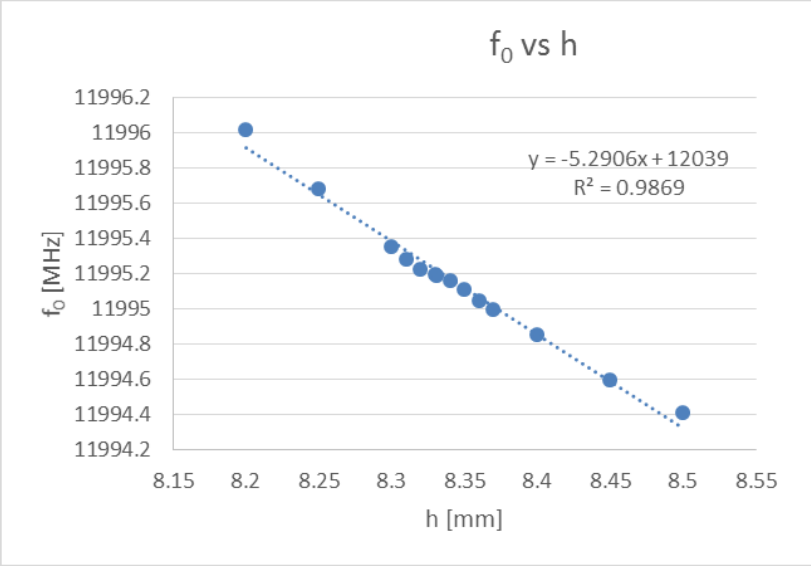
- Periodic structure support propagation of only operating modes TM11x and TM11y at operating frequency.
- No mode conversion
- The situation is very similar to the situation in typical accelerating structure operating at TM01 mode with the ONLY difference that there are two polarizations
- BOTH of these two polarizations must be in synchronism with the beam, otherwise the polarization phase will rotate and the integrated dipolar kick in the operating plane will be reduced
- In the following basic tolerance study the effect of geometrical errors on the synchronous phases of both TM11x and TM11y polarizations will be studied

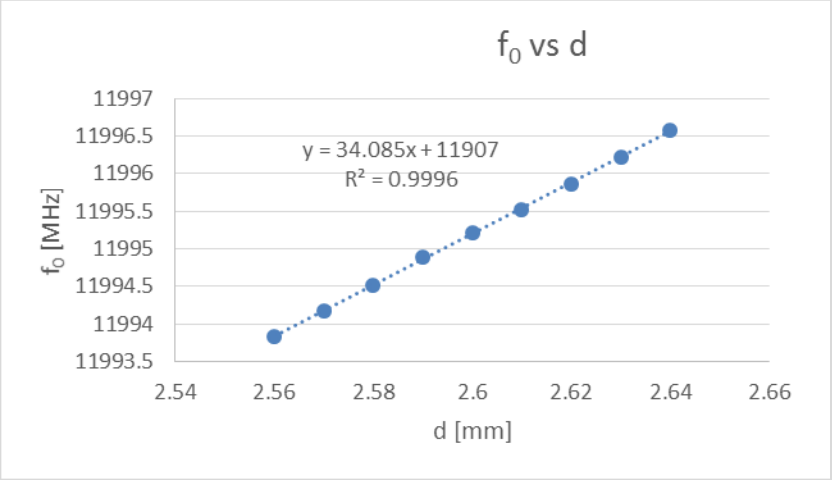
Axially symmetric errors: same for both polarizations

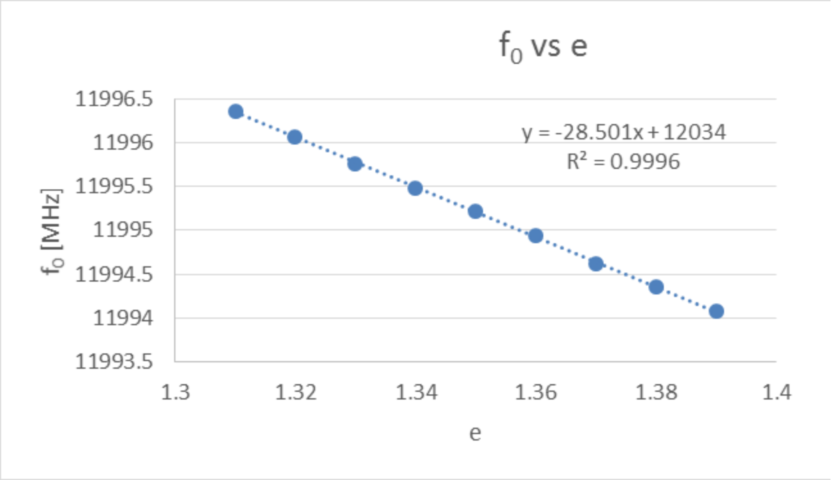
- Axially symmetric errors are shape errors in the process turning.
- They affect both polarizations in the same way.
- They result in the same RF phase advance shifts for both polarization which means:
  - No rotation of polarization (i.e. no conversion of one polarization to the other one)
  - Loss of synchronism resulting in loss of effective kick in the same way as for TM01 accelerating structure
- In summary, the error analysis is the same as for TM01 accelerating mode

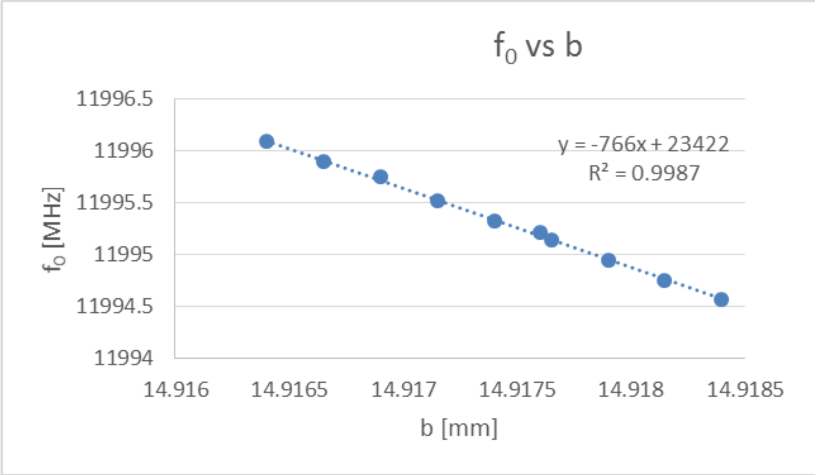
Frequency sensitivity to the axially symmetric errors.

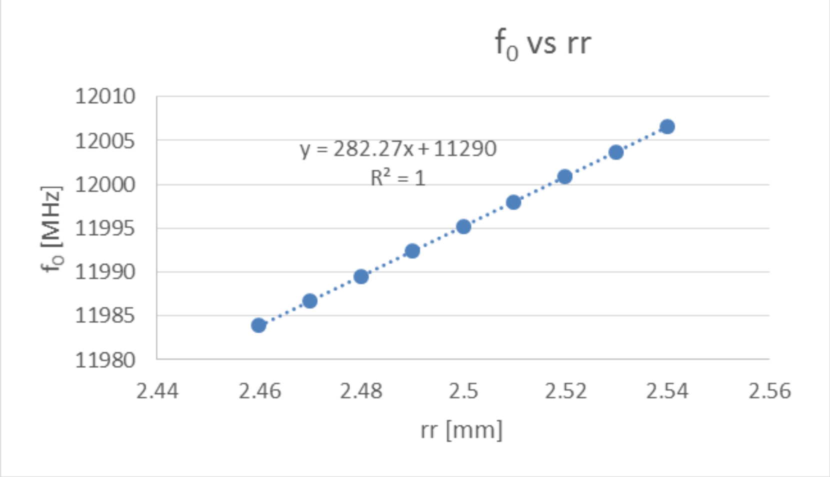
$\Delta\phi_0$ = 120 degree, dserf=1um,

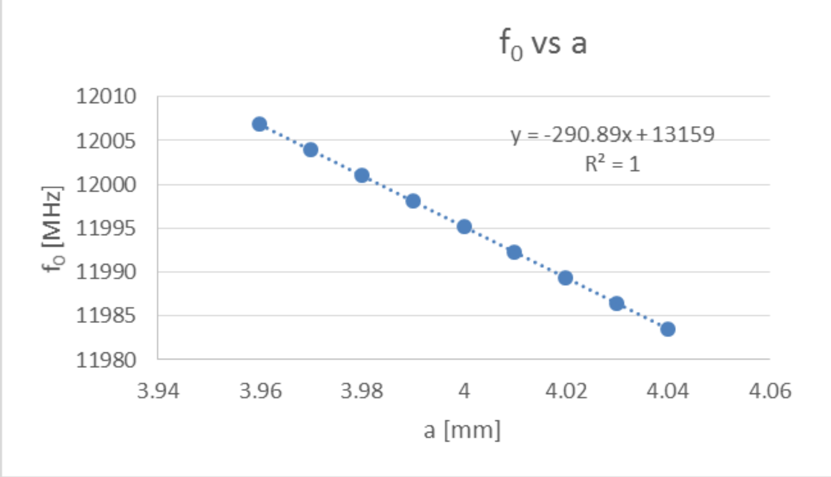












Frequency sensitivity to the axially symmetric **systematic** errors.

$df/f_0 = -v_g/c*(\Delta\phi_1-\Delta\phi_0)/\Delta\phi_0$ =>

$d(\Delta\phi_0)/dx = (\Delta\phi_1-\Delta\phi_0)/dx = \Delta\phi_0/(-v_g/c)*df_0/dx/f_0$– RF phase advance error per cell due to geometrical error **dx**

All regular disks have the same geometry => High risk of **systematic errors** (dx the same in each cell => $d(\Delta\phi_0)$ as well)
Assuming maximum acceptable loss of total kick: **dV/V_0**, over the whole structure with N_c cells,
the acceptable geometrical error **dx** in each cells can be calculated:

$dV/V_0 = (\langle V\rangle-V_0)/V_0 \sim -(d(\Delta\phi_0)*N_c/2)^2$ =>

$dx = \pm 2/Nc*(dV/V_0)^{1/2}/(d(\Delta\phi_0)/dx) = \pm 2/Nc*(-dV/V_0)^{1/2}/\Delta\phi_0*(-v_g/c)*f_0/(df/dx)$

					dV/V [%]	-1	-2	-5		-1	-2	-5
					$d(\Delta\phi_0)*N_c$ [deg]	11.46497	16.21391	25.63645		11.46497	16.21391	25.63645
					L_s=0.8m, N_c=96				L_s=1m, N_c=120			
	x [mm]	df/dx [MHz/mm]	Comments	$d(\Delta\phi_0)/dx$ [deg/mm]		dx [+-um]	dx [+-um]	dx [+-um]		dx [+-um]	dx [+-um]	dx [+-um]
1	h	-5.3	less critical	-1.98879252		-60.0499	-84.9234	-134.276		-48.0399	-67.9387	-107.42
2	b	-766	most critical	-287.436805		-0.41549	-0.58759	-0.92906		-0.33239	-0.47007	-0.74325
3	a	-291		-109.195966		-1.09369	-1.54671	-2.44557		-0.87495	-1.23737	-1.95646
4	d	34.1		12.795816		9.333266	13.19923	20.86982		7.466613	10.55938	16.69585
5	rr	282		105.818772		1.128597	1.596077	2.52362		0.902878	1.276862	2.018896
6	ae	-36.6795	ae=e*d/2*(1-s)	-13.7637576		-8.6769	-12.271	-19.4021		-6.94152	-9.81679	-15.5217

Sensitivity to single cell-to-cell frequency errors

- Single cell frequency errors on have small impact on the total kick
- How ever they can introduce reflections causing:
  - Reflection power back to klystron
  - loss of effective kick (although this is probably very small) and
  - standing wave pattern in the travelling wave structure
- This reflection has to be small: < - 35 or -40 dB

$\mathbf{R \sim \delta S_{12} \sim \delta(\exp(j\varphi_0)) \sim j\,\delta\varphi_0 \sim j\,\varphi_0 \delta f/f_0/(-v_g/c)}$ -

see more accurate derivation in [*NIM, A* 704 (2013) 14-18]

=>

$\delta f = df/dx * \delta x$ =>

max|R| = 0.01 => $\delta f = 0.01\, f_0(-v_g/c)/\varphi_0$; => $\mathbf{\delta x = 0.01\, f_0(-v_g/c)/(\varphi_0 * df/dx)}$;

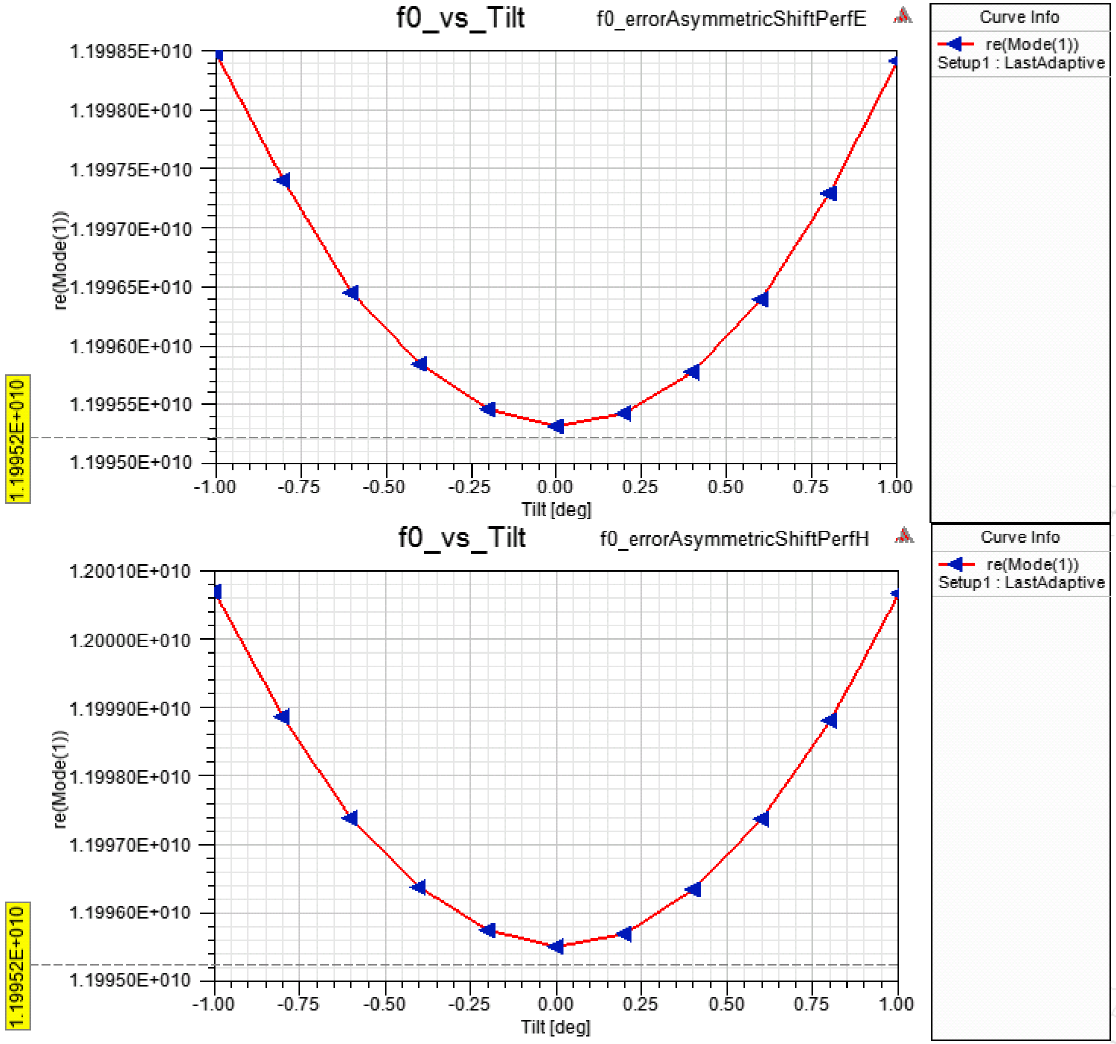
A bit less critical then systematic error

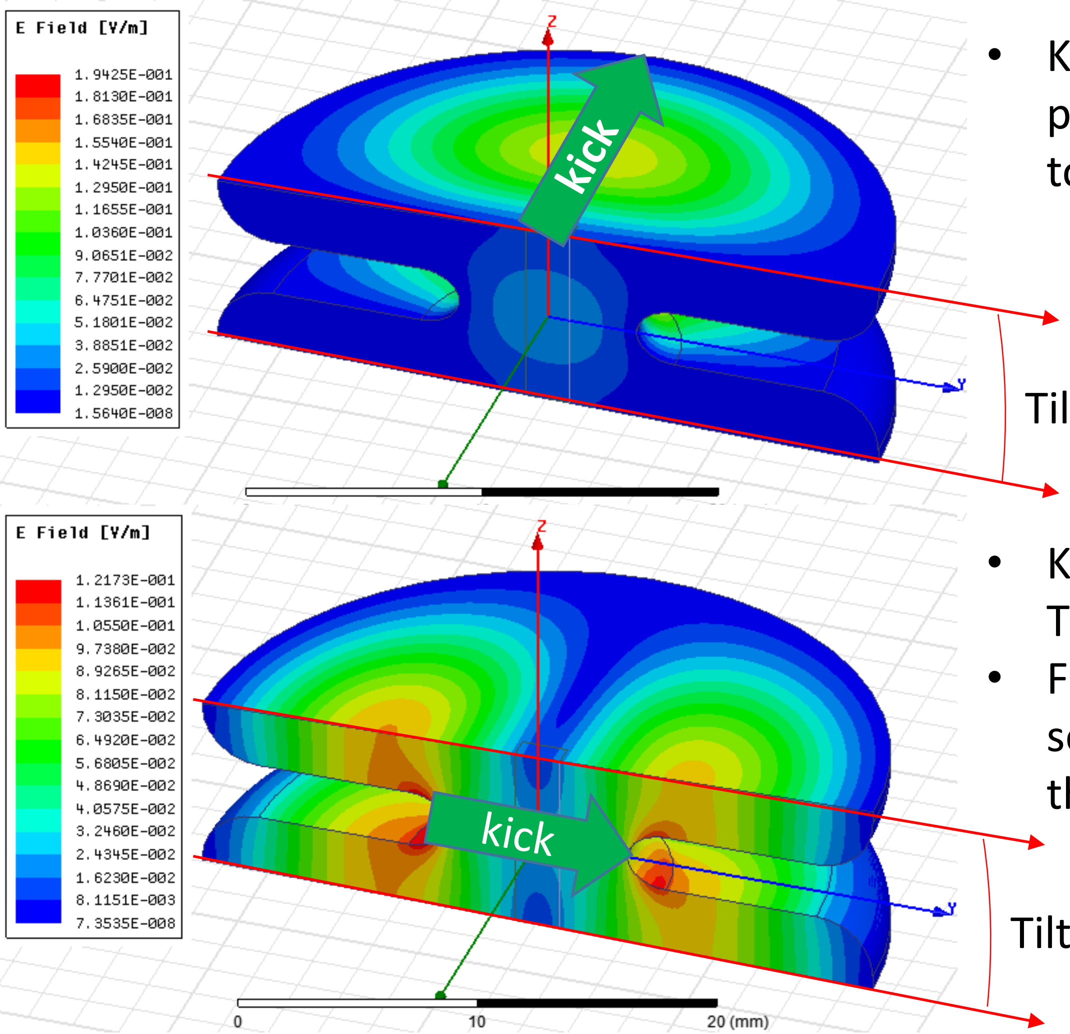
			Cell-to-cell error	
		R	0.01	
	x [mm]		δx [+-um]	
1	h		-288.088	
2	b		-1.9933	
3	a		-5.24697	
4	d		44.77622	
5	rr		5.414429	
6	ae		-41.6273	

Axially non-symmetric errors: different for two polarizations

- Axially non-symmetric errors are shape errors in the process of assembly.
- They affect two polarizations in different ways.
- They result in the different RF phase advance shifts for the two polarizations which means:
  - Rotation of polarization could take place along the structure (i.e. conversion of one polarization to the other one)
  - The average kick can be rotated to the correct plane using variable phase shifter (another reason to have it)
  - What is left is the effect similar to the loss of effective kick due to loss of synchronism but with two polarizations

Non-axially symmetric errors: different for each polarization. Tilt

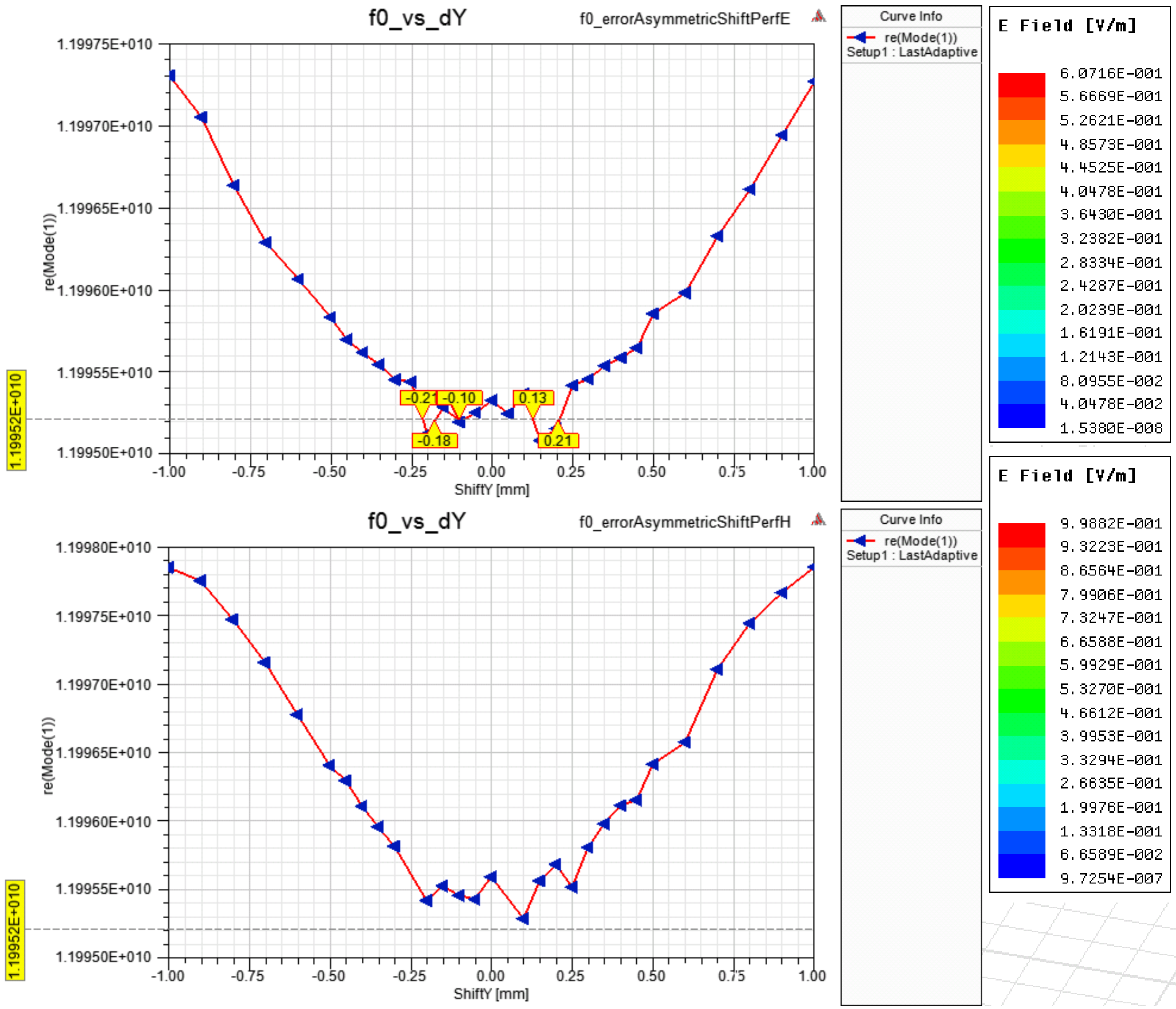


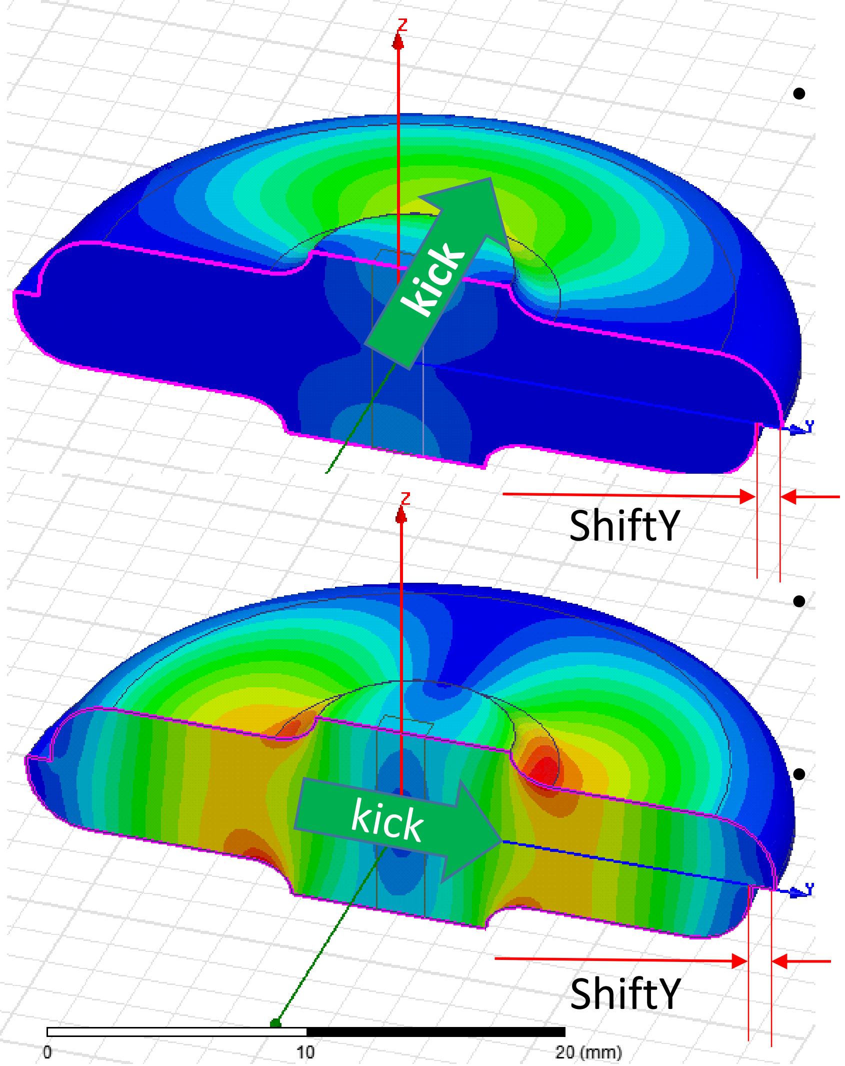


- Kick Vx is perpendicular to the Tilt plane

- Kick Vy is in the Tilt plane.
- Frequency sensitivity to the Tilt is higher

Non-axially symmetric errors: different for each polarization. Shift



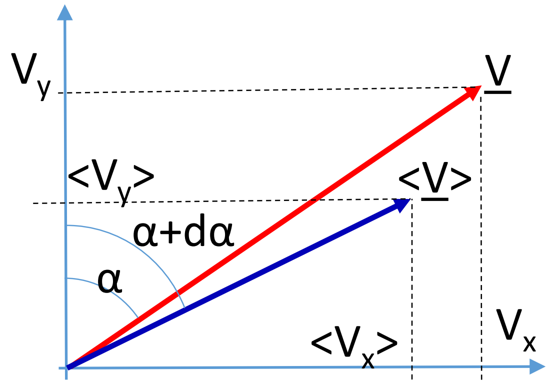


- Kick Vx is perpendicular to the ShiftY
- Kick Vy is parallel to the ShiftY.
- Frequency sensitivity is a bit higher

Frequency sensitivity to the non-axially symmetric **systematic** errors

$df/f_0 = -v_g/c*(\Delta\phi_1-\Delta\phi_0)/\Delta\phi_0$ =>
$d^2(\Delta\phi_{0\,x,y})/dz^2 = \Delta\phi_0/(-v_g/c)*d^2f_{0\,x,y}/dz^2/f_0$ – RF phase advance per cell shows second order error due to geometrical error **dz** (Tilt or Shift)

- There is reduction of both polarizations but by different amount: $dV_x/V_x < dV_y/V_y$
- This can be expressed as reduction of kick amplitude dV AND rotation of the kick dα
- In the system with variable polarization dα is compensated



Two polarization: $V = V_x + V_y = V_0*\sin\alpha + V_0*\cos\alpha$
$dV/V_0 = -[\sin^2\alpha*(d^2(\Delta\phi_{0x})/dz^2)^2 + \cos^2\alpha*(d^2(\Delta\phi_{0y})/dz^2)^2] * (N_c/2*dz^2)^2$=>
$dz^2 = 2/N_c*(-dV/V_0/[\sin^2\alpha*(d^2(\Delta\phi_{0x})/dz^2)^2 + \cos^2\alpha*(d^2(\Delta\phi_{0y})/dz^2)^2])^{1/2}$

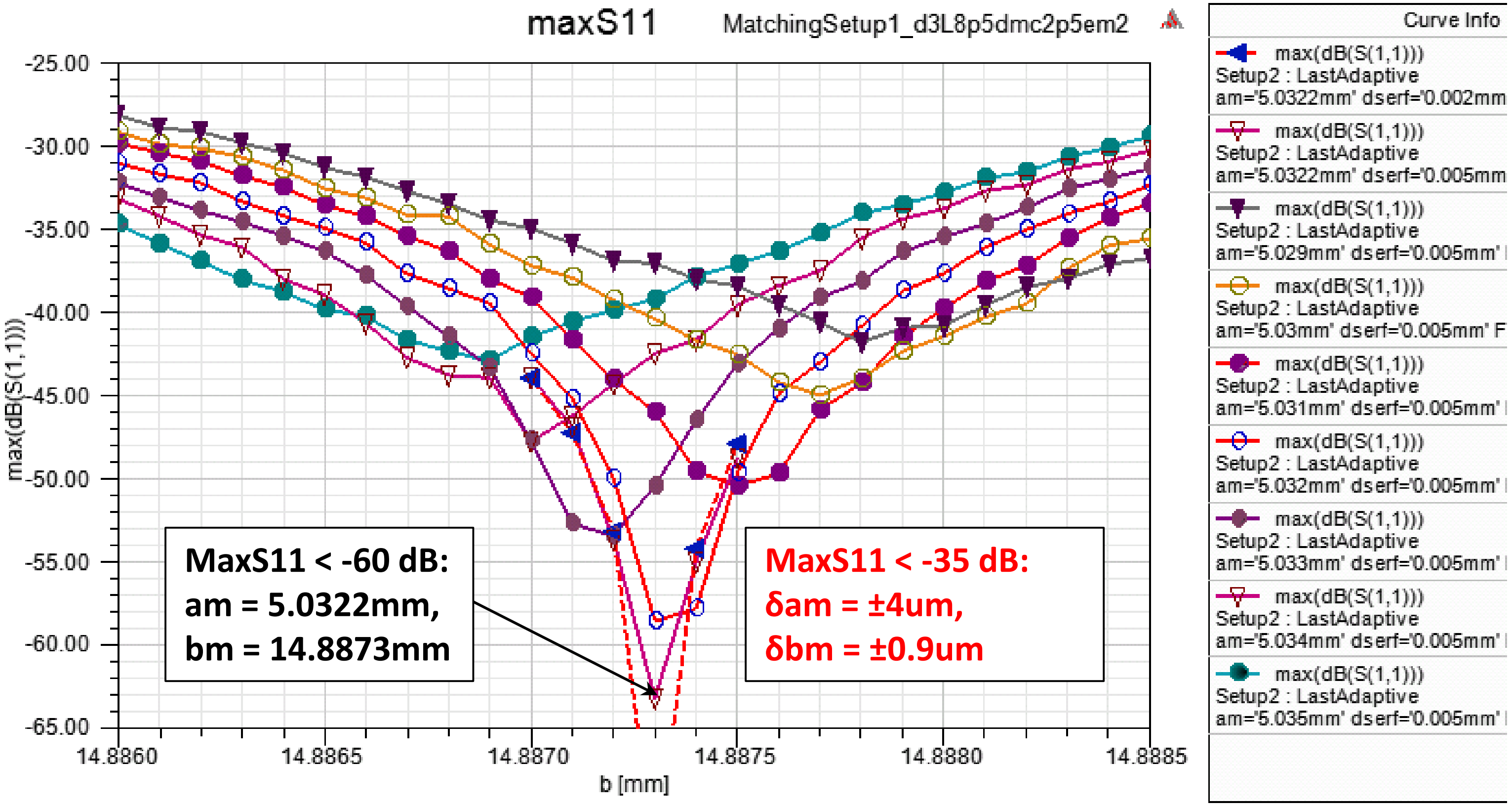
						dV/V [%]	-1	-2	-5		-1	-2	-5
						$d(\Delta\phi_0)*N_c$	11.46497	16.21391	25.63645		11.46497	16.21391	25.63645
						L_s=0.8m, N_c=96				L_s=1m, N_c=120			
	z	α [deg]	d^2f/dz^2 [MHz/deg^2]	Comments	$d^2(\Delta\phi_0)/dz^2$ [deg/deg^2]		dz [±deg]	dz [±deg]	dz [±deg]		dz [±deg]	dz [±deg]	dz [±deg]
1	Tilt Vx	90	3.13		1.174513316		0.318876	0.37921	0.476831		0.285211	0.339175	0.42649
2	Tilt Vy	0	5.15	more critical	1.932505936		0.248594	0.29563	0.371735		0.222349	0.264419	0.332489
3		45	4.261419951		1.599071718		0.273286	0.324993	0.408657		0.244434	0.290683	0.365514
			d^2f/dz^2 [MHz/mm^2]		$d^2(\Delta\phi_0)/dz^2$ [deg/mm^2]		dz [±mm]	dz [±mm]	dz [±mm]		dz [±mm]	dz [±mm]	dz [±mm]
4	Shift Vx	90	2.45		0.919347484		0.360422	0.428616	0.538956		0.322371	0.383366	0.482057
5	Shift Vy	0	4.44	more critical	1.666082787		0.267733	0.31839	0.400355		0.239468	0.284777	0.358088
6		45	3.585812321		1.345554096		0.29792	0.354289	0.445495		0.266468	0.316886	0.398463

The same tilt in each cell -> “banana”

The same shift in each cell -> “book shelfing”

Matching Disk-loaded waveguide to a Circular waveguide: dsurf = 2um and 5um

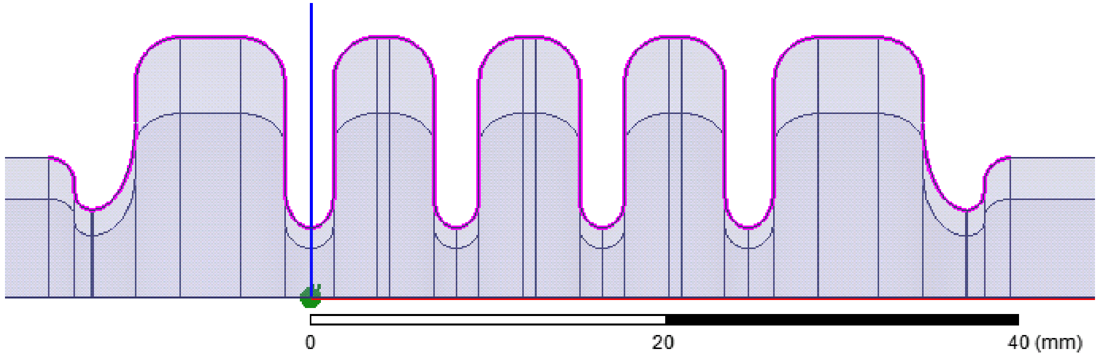
Matching using PEC



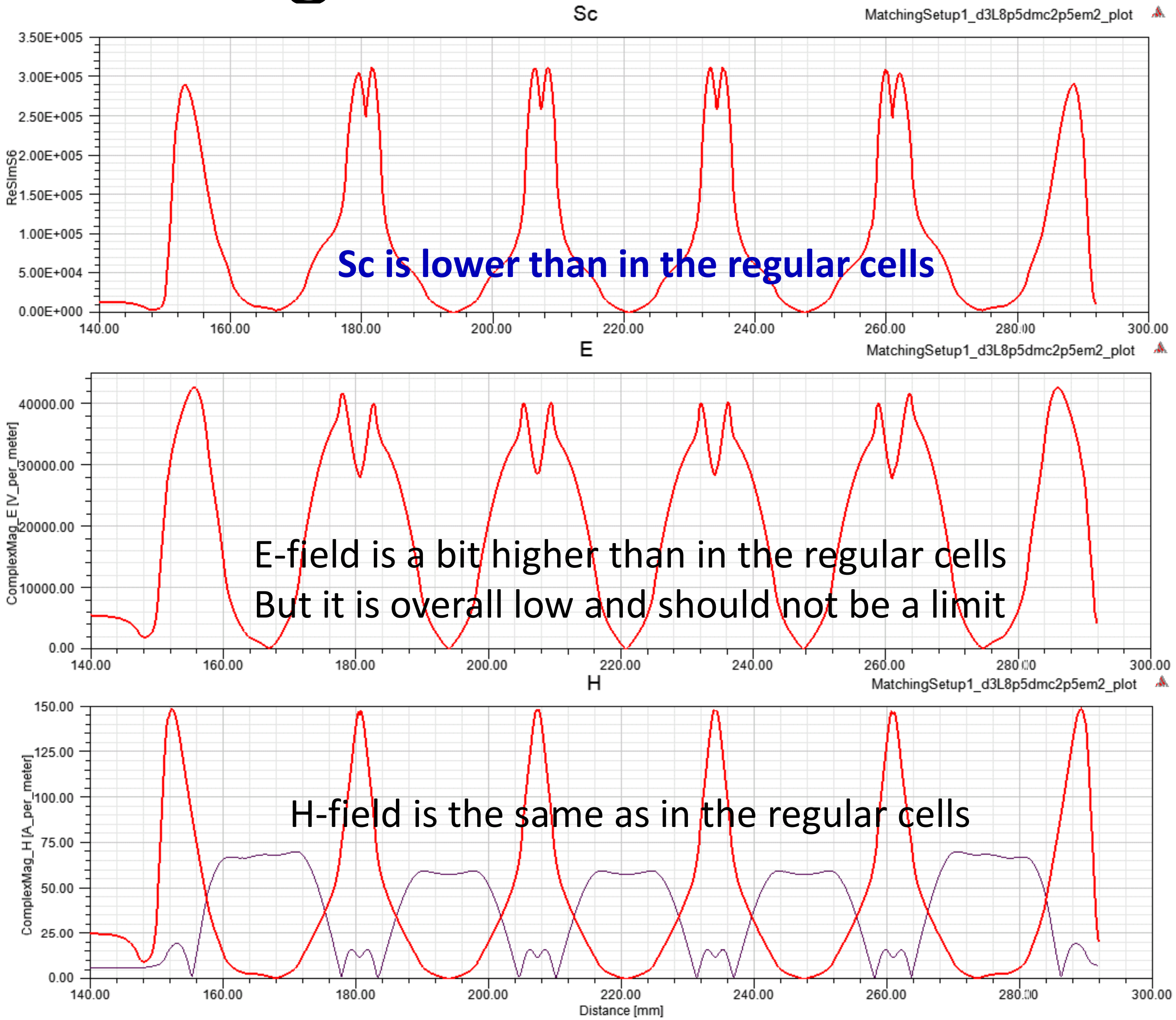
Similar to systematic error

Surface fields in the matching cell for Pin=4W

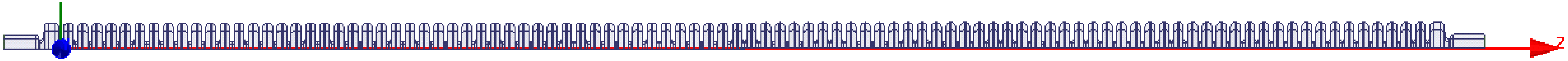
Distribution of the Sc, E and H fields along the polyline shown below for Pin = 4W

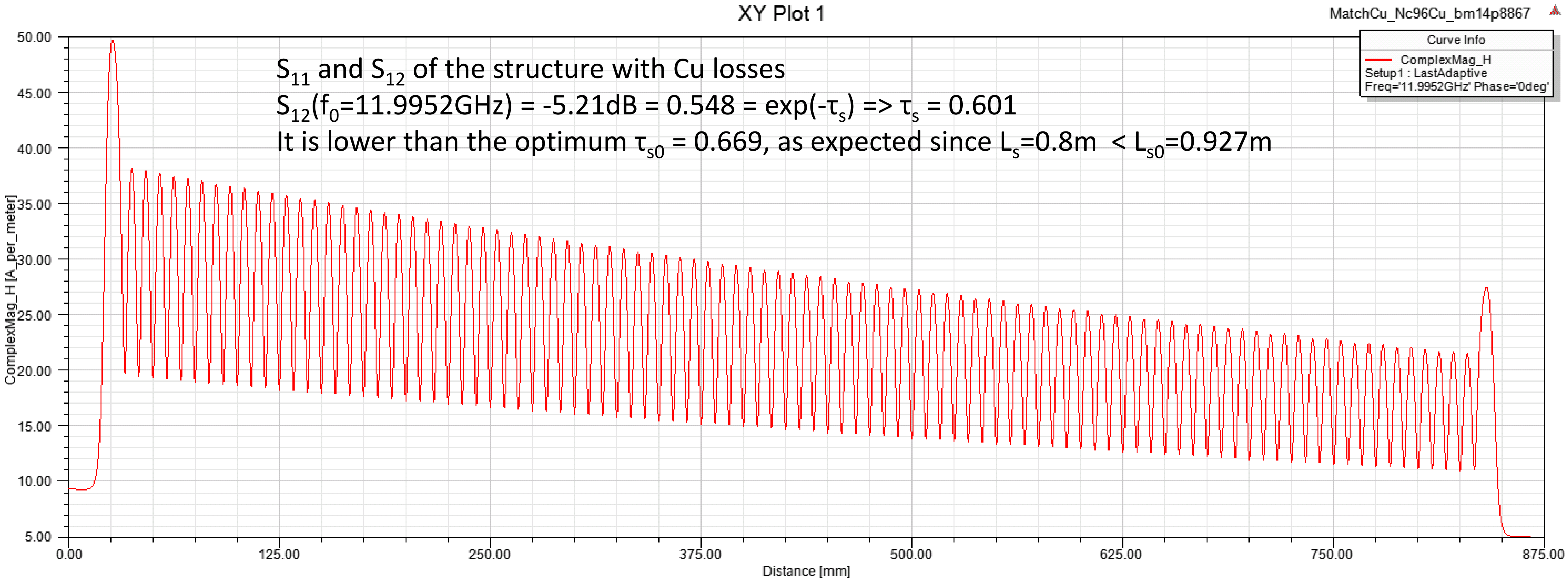


Max Surface Fields	at Pin=1W	at Pin=50MW
E [MV/m]	0.021	150
H [kA/m]	0.075	530
S [MW/mm^2]	8e-8	4



Field distribution in full length Cu structure: bm=14.8867mm, Nc=96, dsurf=5um





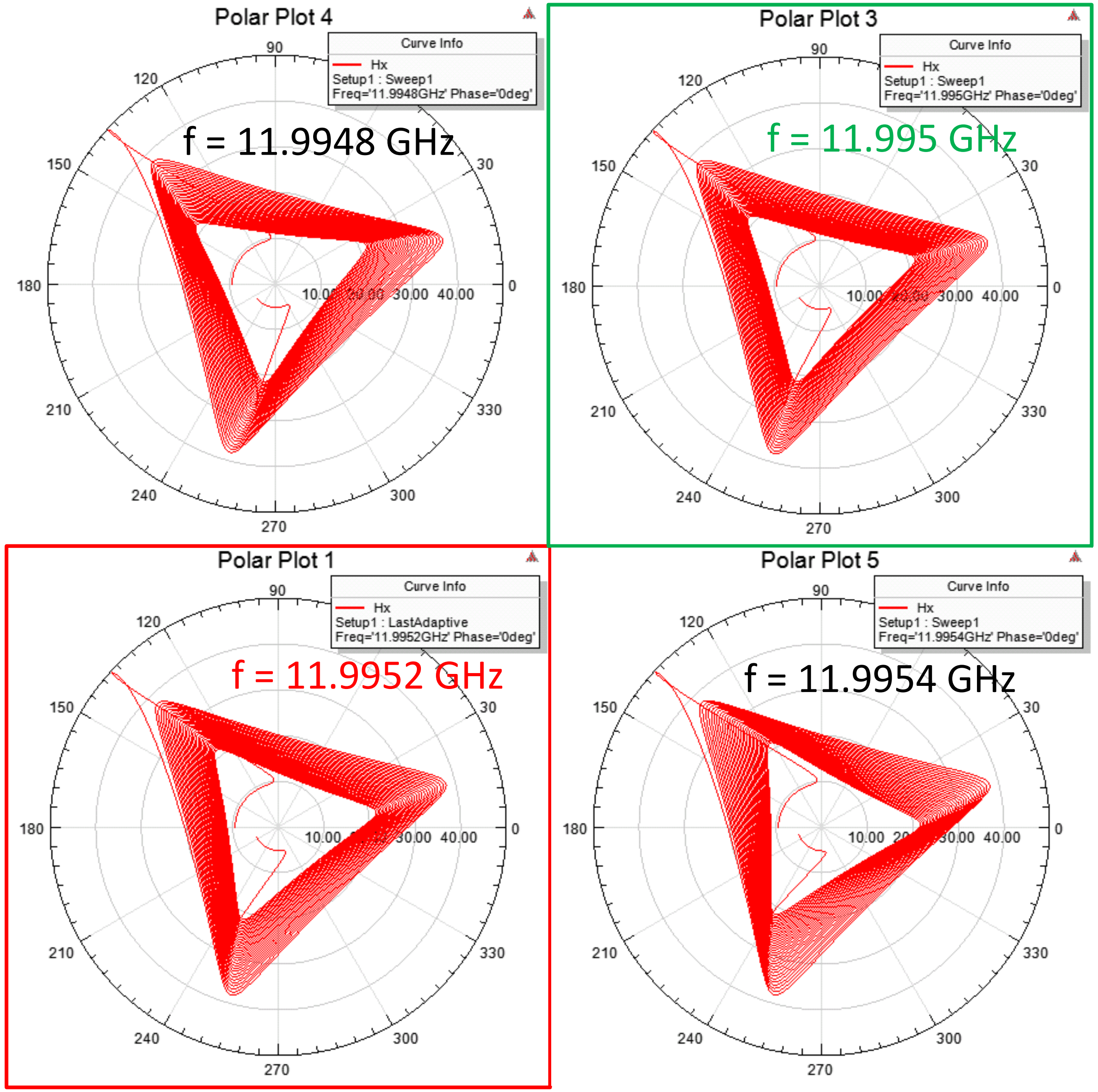
S_{11} and S_{12} of the structure with Cu losses

$S_{12}(f_0\text{=11.9952GHz}) = -5.21\text{dB} = 0.548 = \exp(-\tau_s) \Rightarrow \tau_s = 0.601$

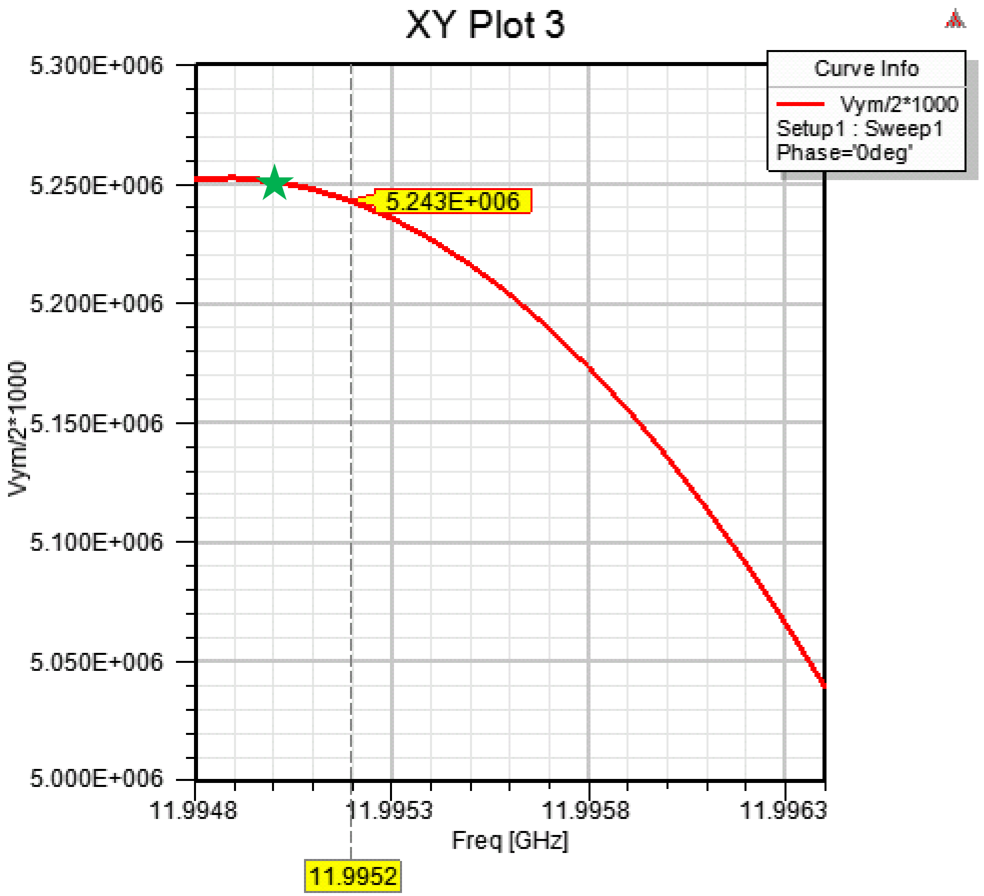
It is lower than the optimum $\tau_{s0} = 0.669$, as expected since $L_s\text{=0.8m} < L_{s0}\text{=0.927m}$

7/3/2017, A. Grudiev

Field distribution in full length Cu structure: bm=14.8867mm, Nc=96, dsurf=5um

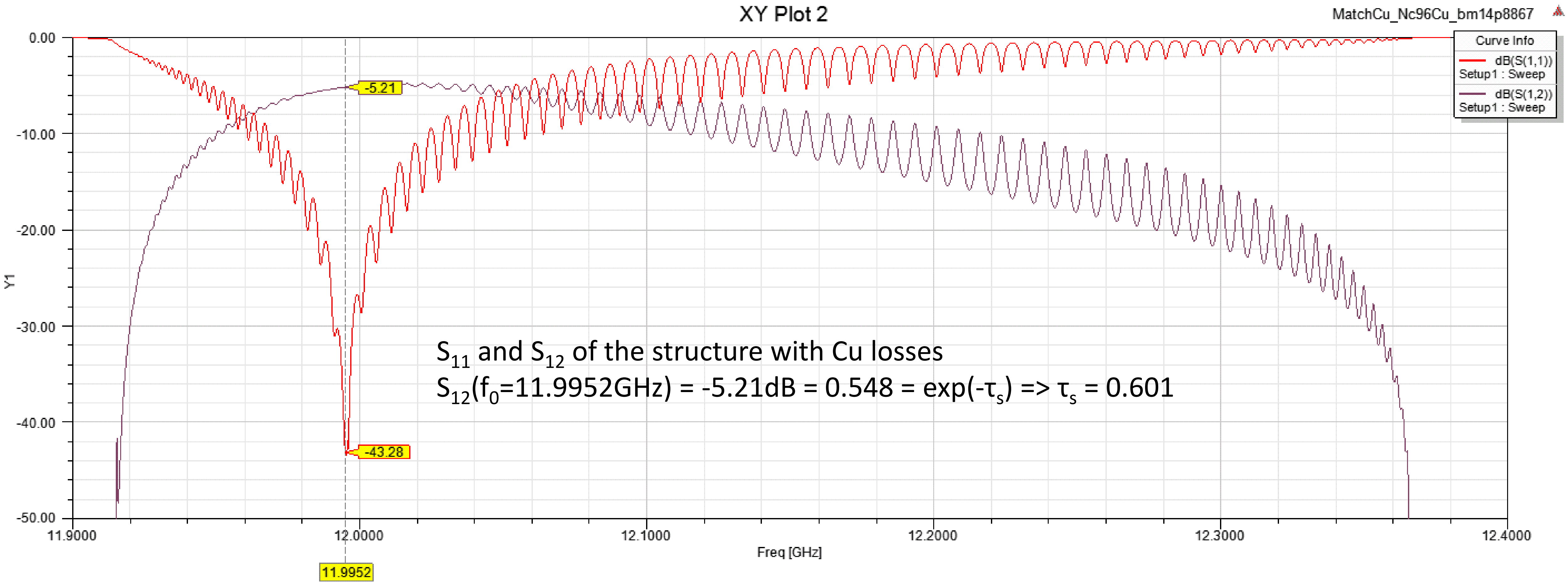


Deflecting voltage for 1 MW input power into the structure (no pulse compression)

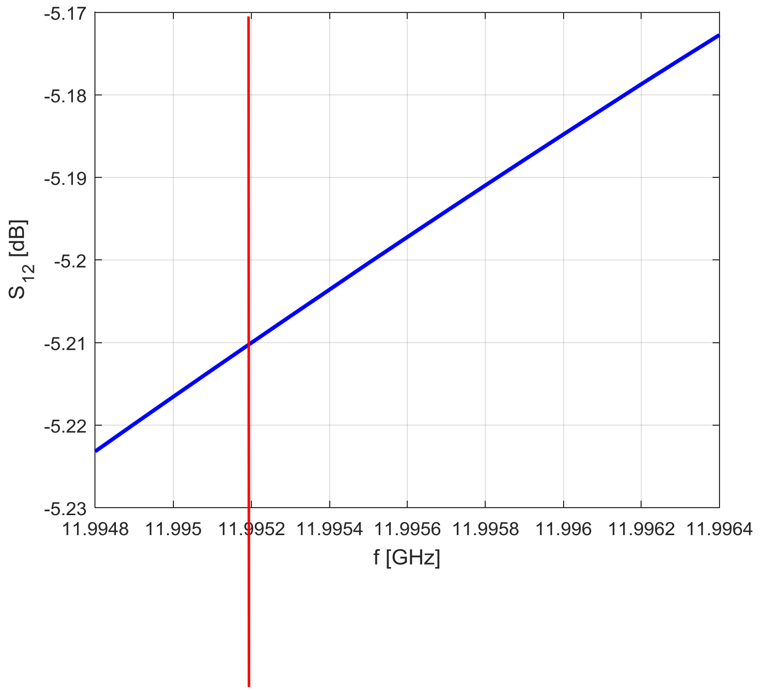


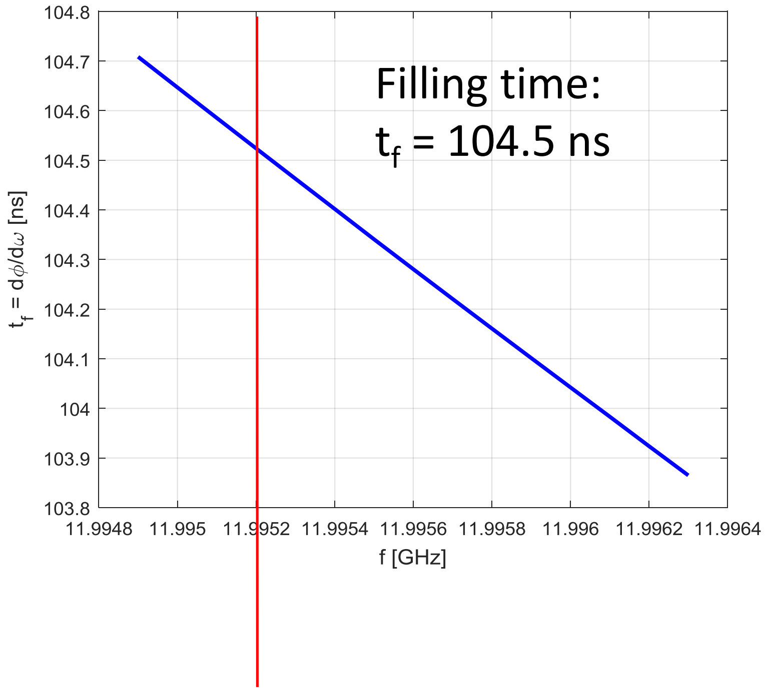
7/3/2017, A. Grudiev

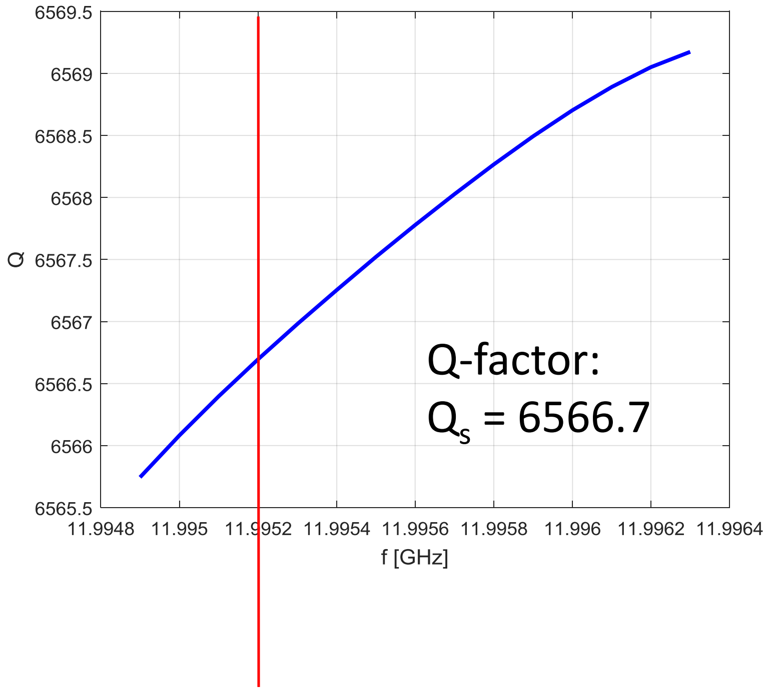
S-pars of the full length Cu structure: bm=14.8867mm, Nc=96, dsurf=5um



S12, filling time and Q-factor in full length Cu structure: bm=14.8867mm, Nc=96, dsurf=5um







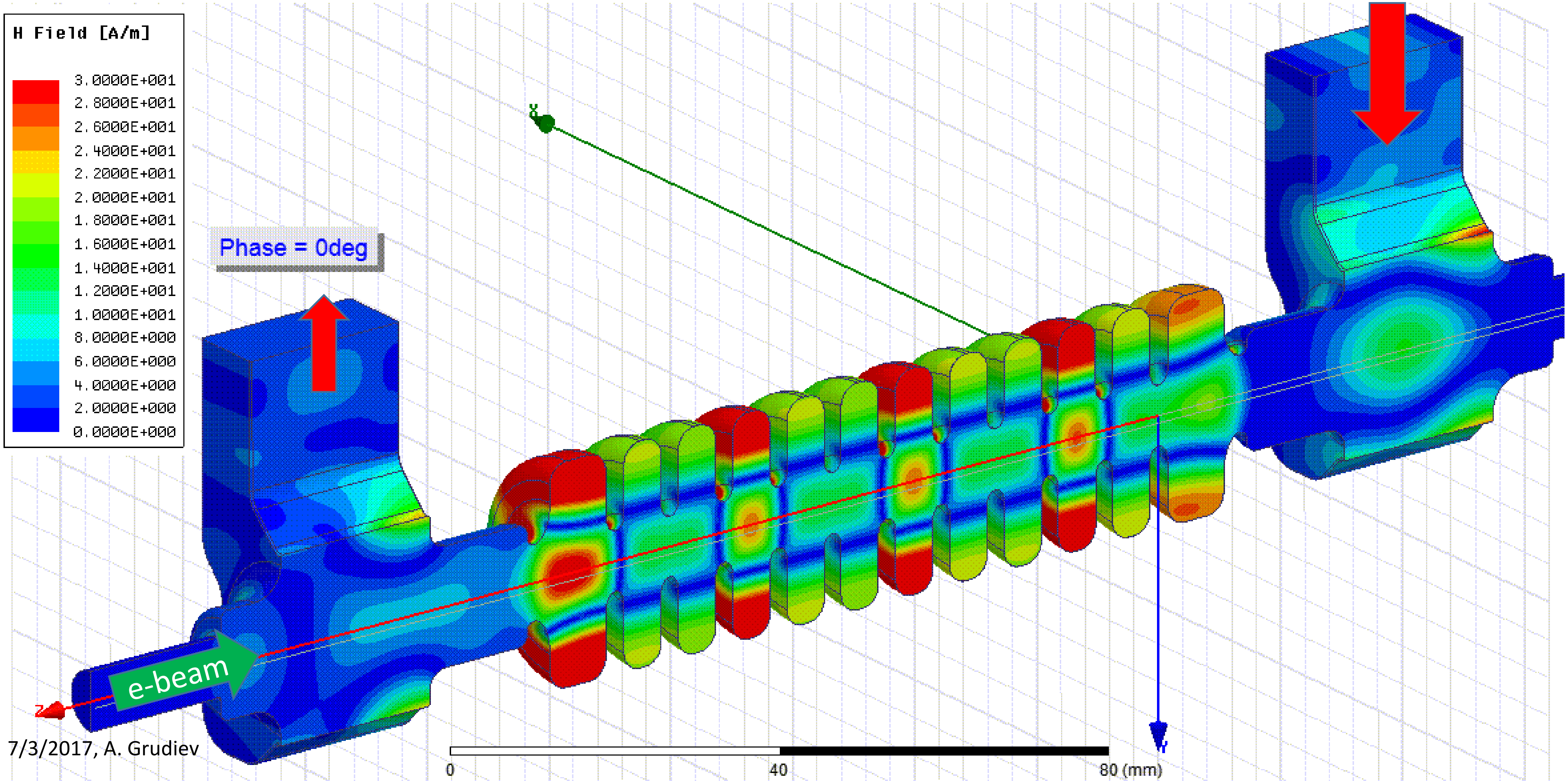
Complex $S_{12}(f)$ => $t_f(f) = d\varphi/d\omega = d(-\mathrm{ang}[S_{12}(f)])/d(2\pi f)$ $Q_s(f) = \pi f t_f/\tau_s = \pi f t_f(f)/[-\log(|S_{12}(f)|)]$

Cell parameters at f=11.9952 GHz => $t_f(96\text{cells}) = 96h/v_g = 100.0$ ns Q = 6490

RF parameters for X-band TDS system

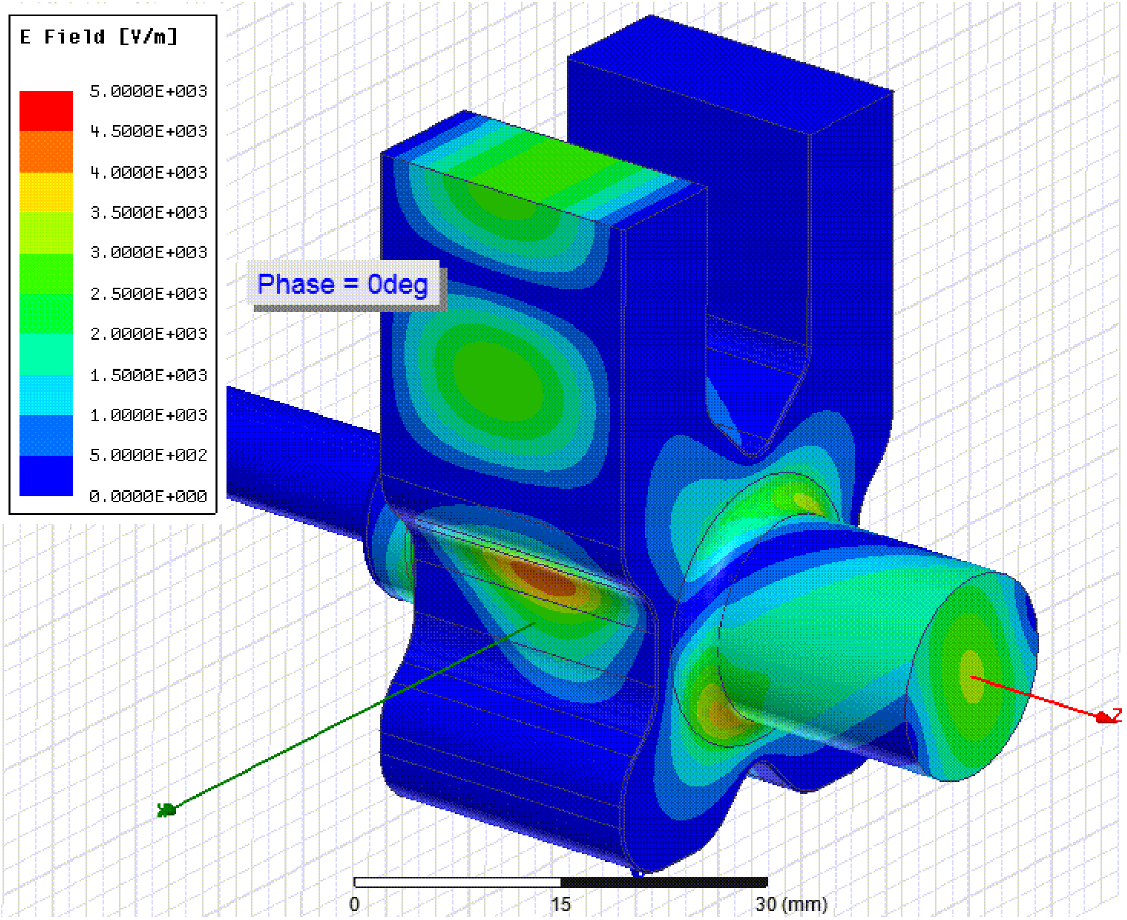
Parameters			comments
f_0 [GHz]	11.9952		
T [degree C]	30		
Cell parameters			
a [mm]	4		
$\Delta\phi_0$ [degree]	120		
Q	6490		
v_g/c [%]	-2.666		
R_x [MΩ/m]	50		
TDS along parameters	Base line	Option	
N_c	96	120	Number of regular cells
L_s [m]	0.8	1	Active length
L [m]	0.98	1.18	Preliminary total length (flange2flange)
t_f [ns]	104.5	129.5	Filling time
R_s [MΩ]	27.3	37.5	Shunt impedance of TDS
V_d [MV] @ P_k = 6 MW	12.8	15.0	
TDS+PC parameters			PC = Pulse compressor
Q_0	180000		Q-factor of the PC
Q_{ext}	20100		External Q-factor of PC
t_k [ns]	1500		Klystron pulse length
R_s [MΩ]	145	182	Effective Shunt impedance of TDS+PC
V_d [MV] @ P_k = 6 MW	29.5	33.0	

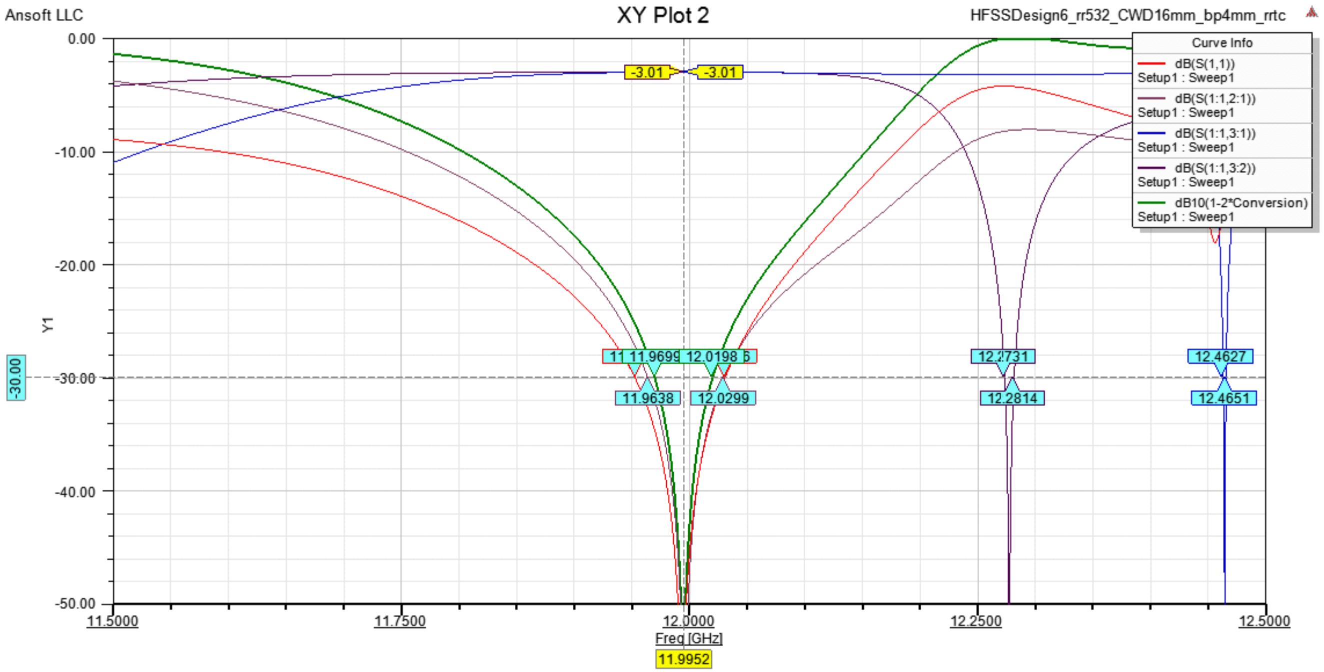
H-field in Backward Travelling Wave TDS: N_c=10



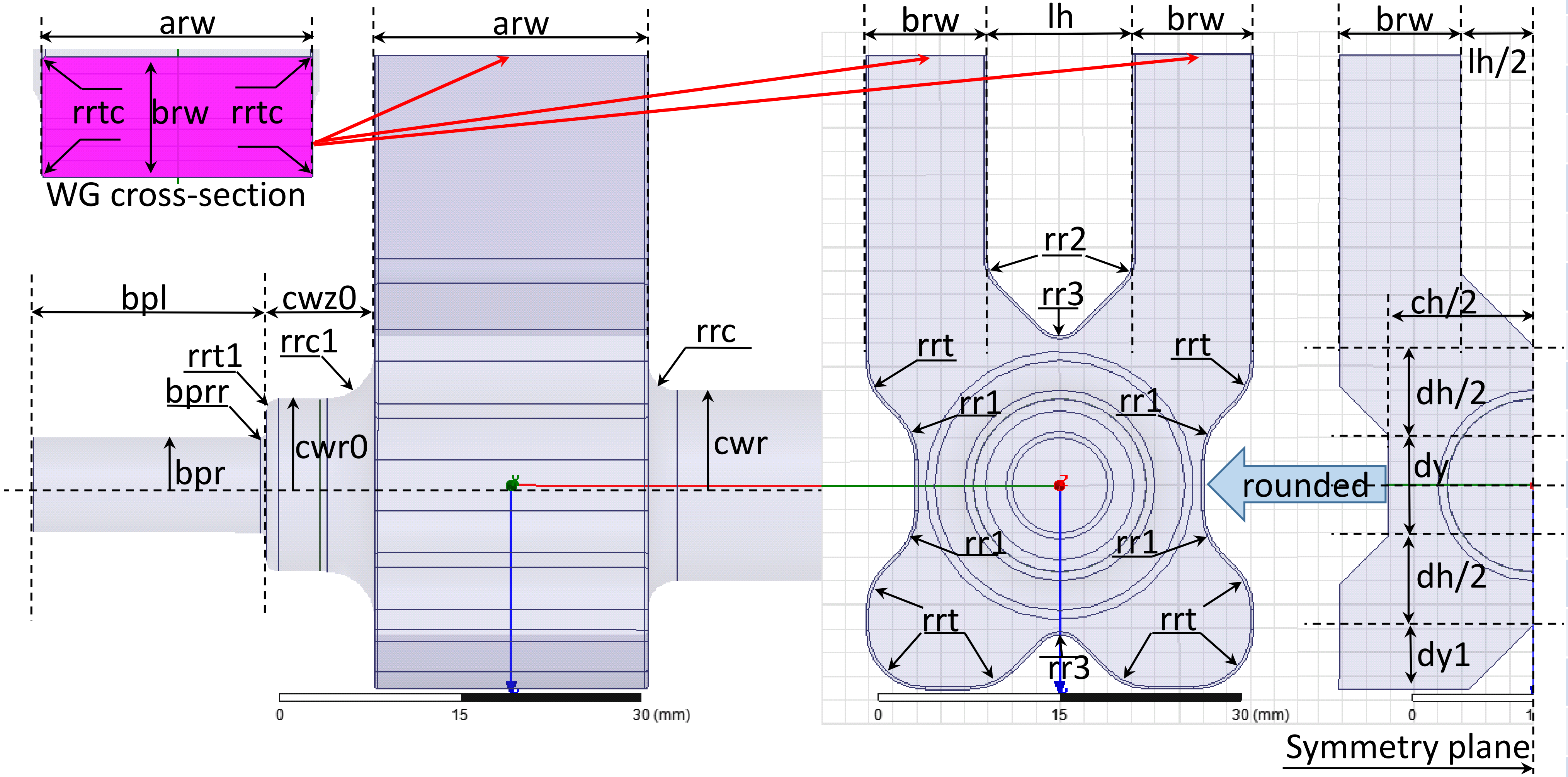
Spare slides

RF design of the E-rotator with beam pipe





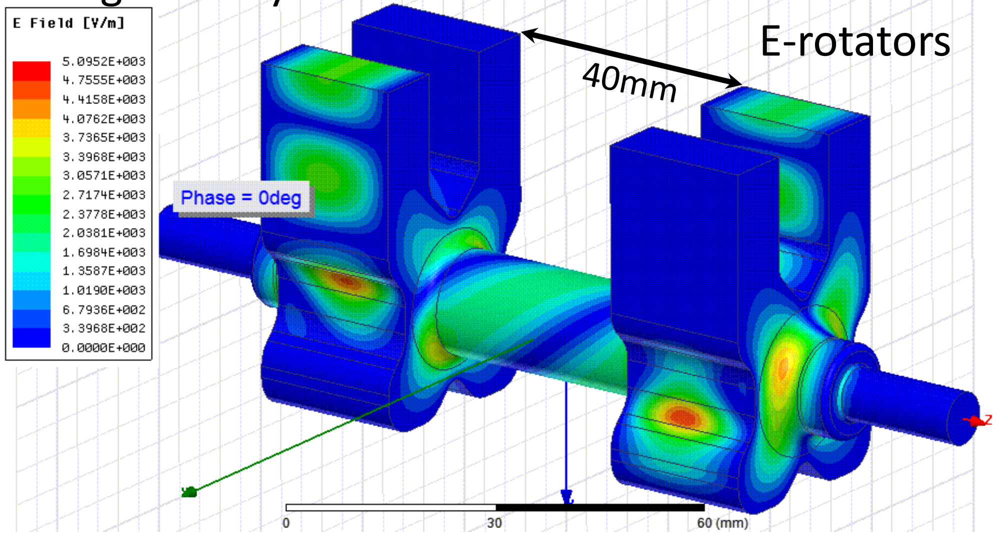
Geometry of the E-rotator with beam pipe

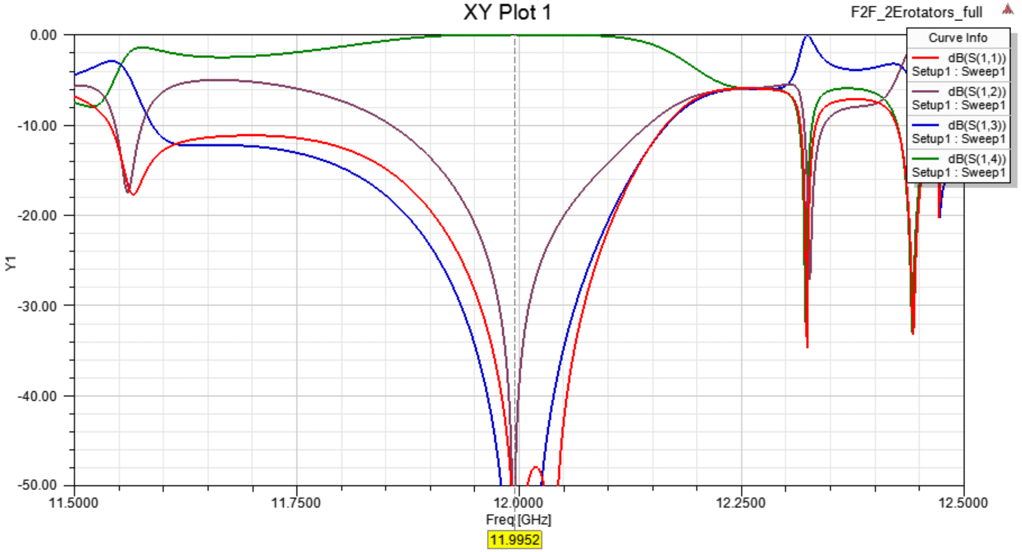


Pars	
arw [mm]	22.86
brw [mm]	10.16
rrtc [mm]	0.25
lh [mm]	12.21
ch [mm]	24.27
dh [mm]	15.02
dy [mm]	8.37
dy1 [mm]	5.41
rrt [mm]	5
rr1 [mm]	5
rr2 [mm]	3
rr3 [mm]	2
rrc [mm]	2.5
rrc1 [mm]	4
rrt1 [mm]	1
cwr0 [mm]	7.25
cwz0 [mm]	9.12
bpr [mm]	4
bprr [mm]	0.5
bpl [mm]	>10

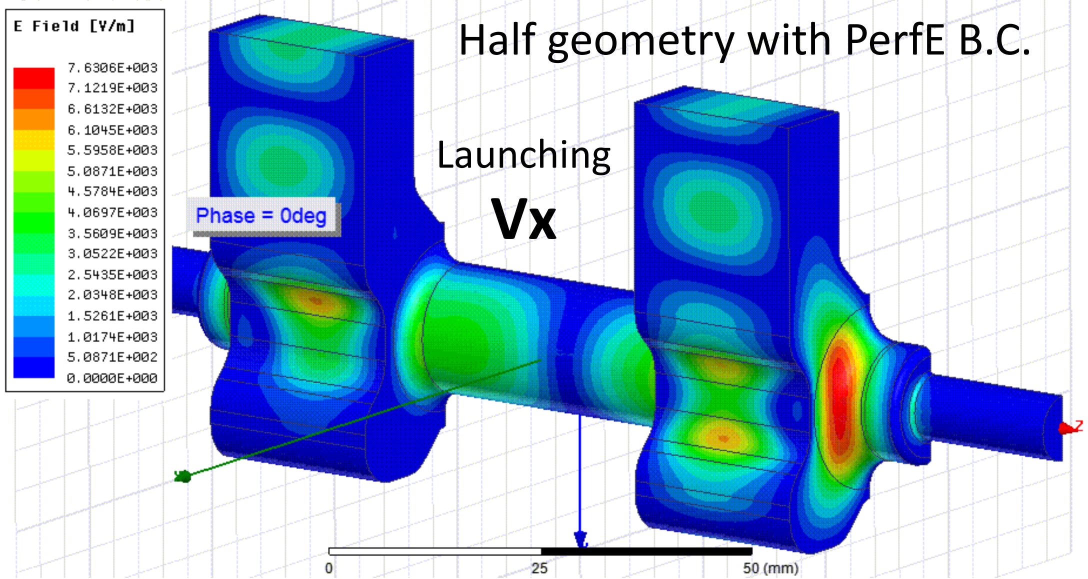
Two E-rotators face-to-face

Full geometry for a face-to-face RF check of two E-rotators

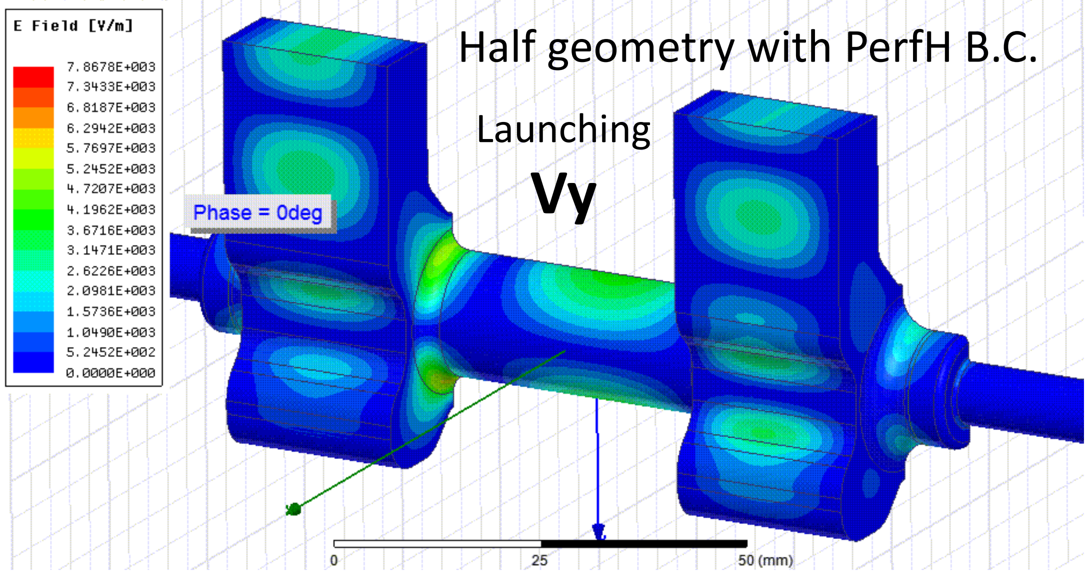




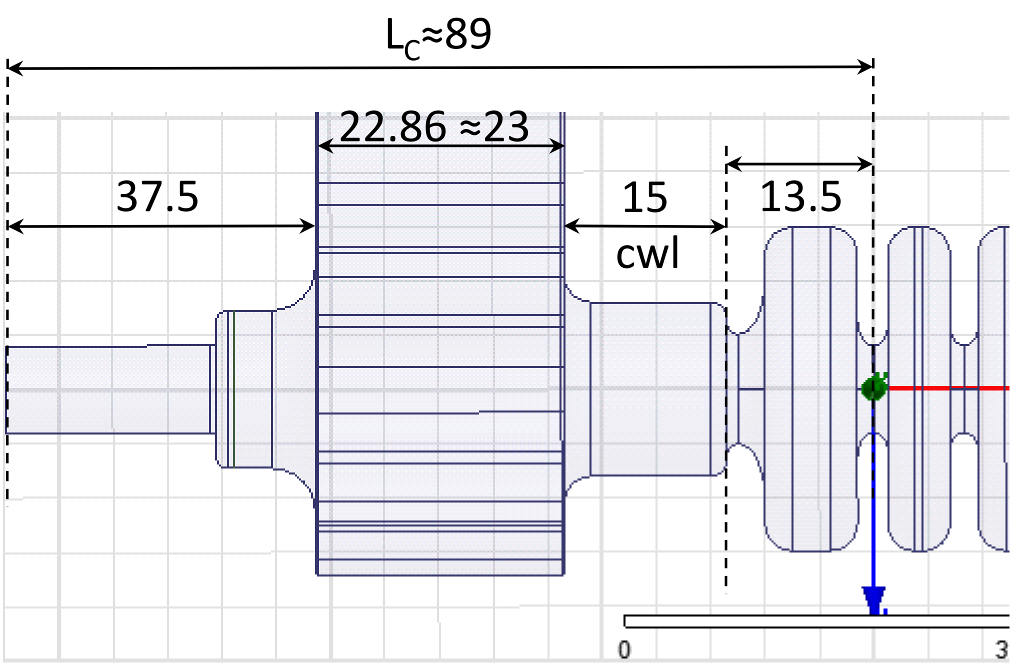
Half geometry with PerfE B.C.

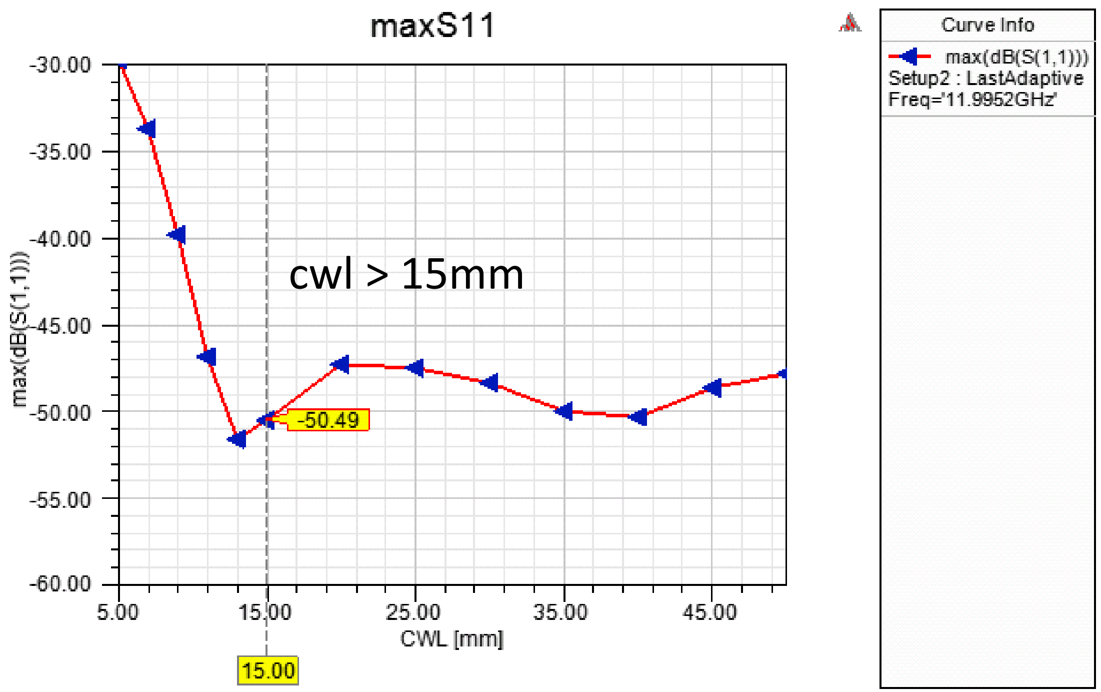


Half geometry with PerfH B.C.



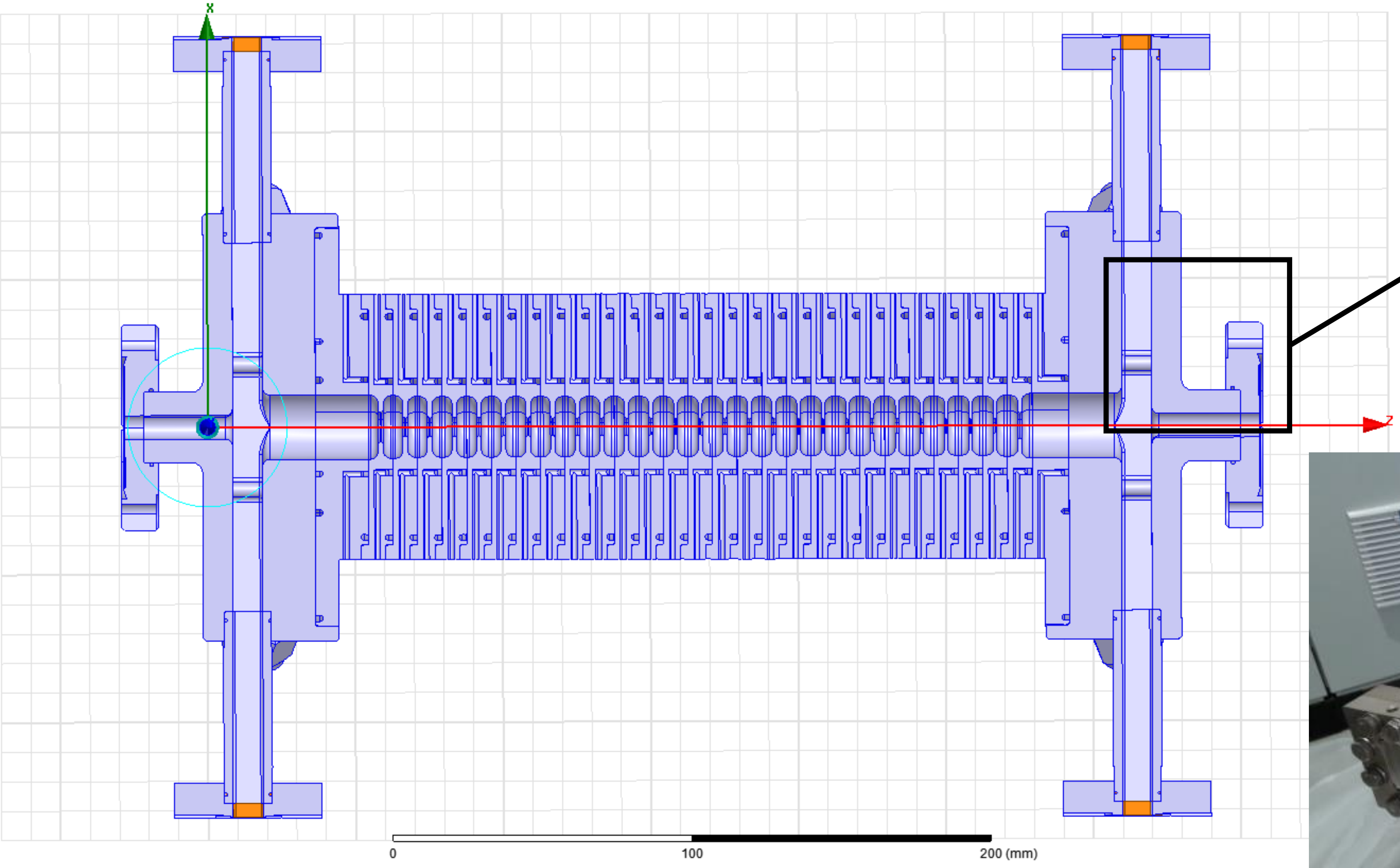
Distance between E-rotator and the Cells: cwl



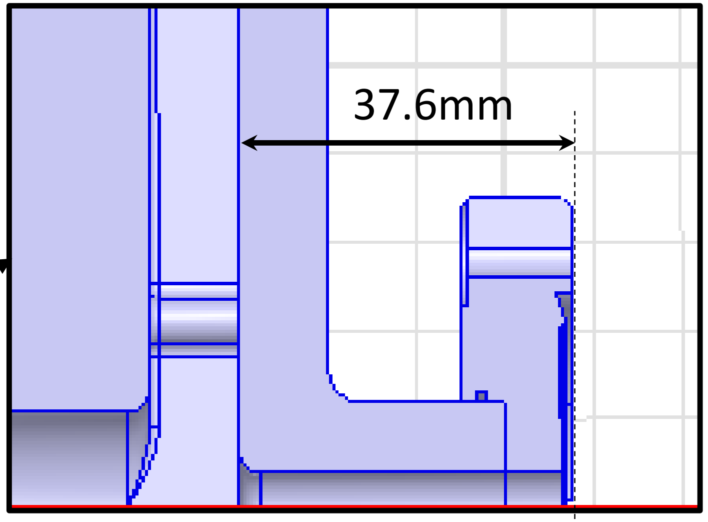


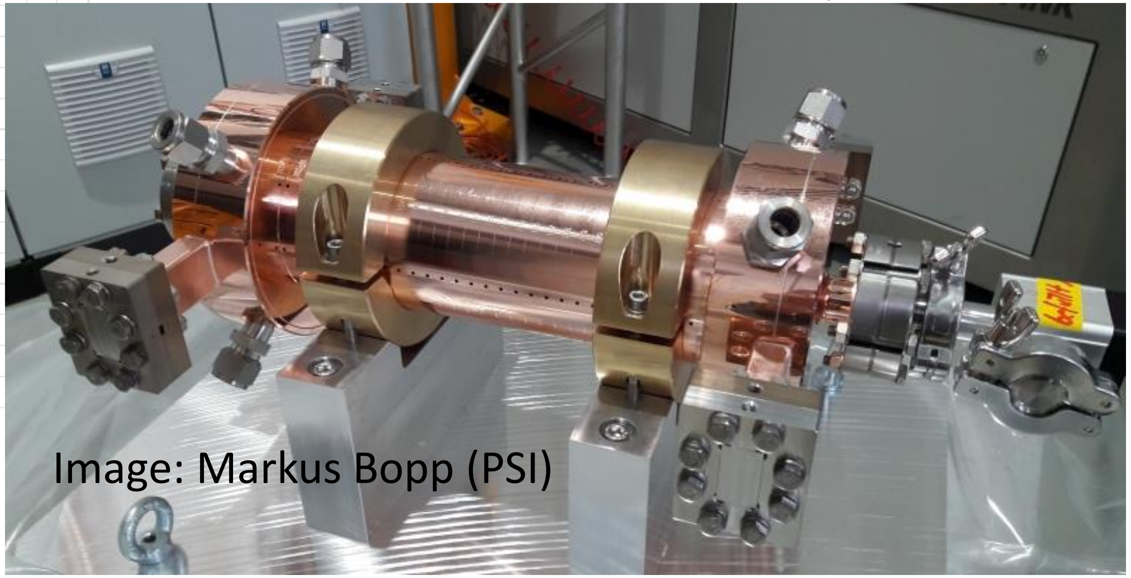
Number of regular cells: N_c	96	112	120	144
Active length (all regular cells): $L_s = h*N_c$ [m]	0.8	0.927	1.0	1.2
Total length (flange-to-flange): $L = L_s + 2L_C$ [m]	0.978	1.111	1.178	1.378

T24_PSI x-band accelerating structure prototype layout



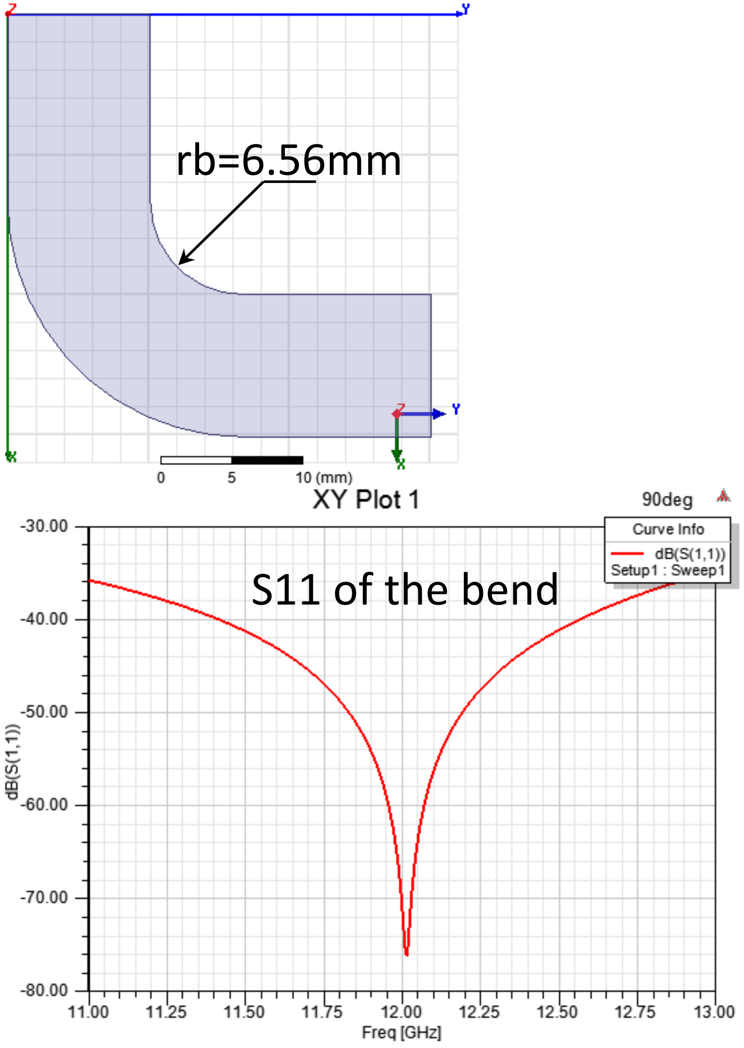
Beam pipe length

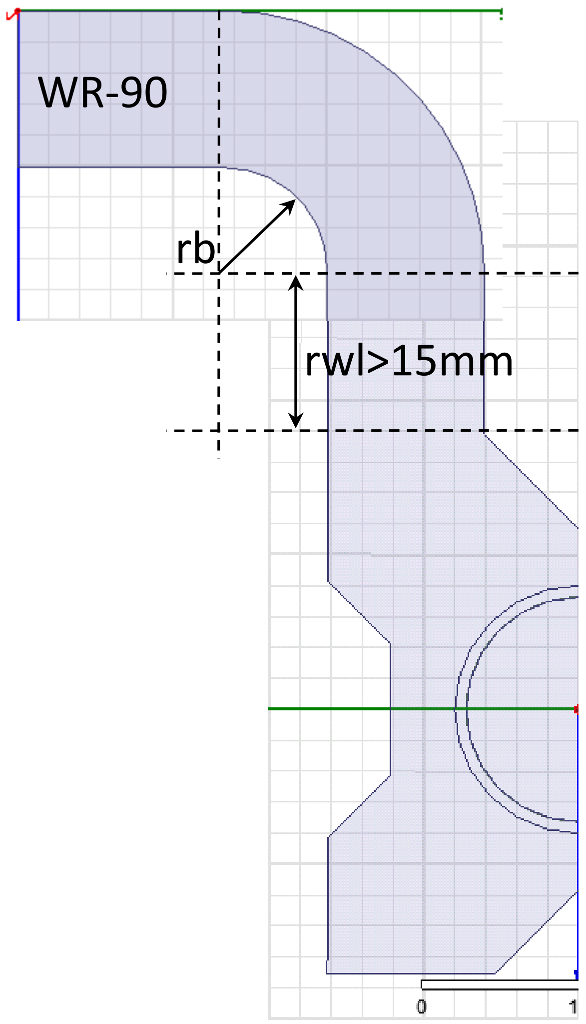


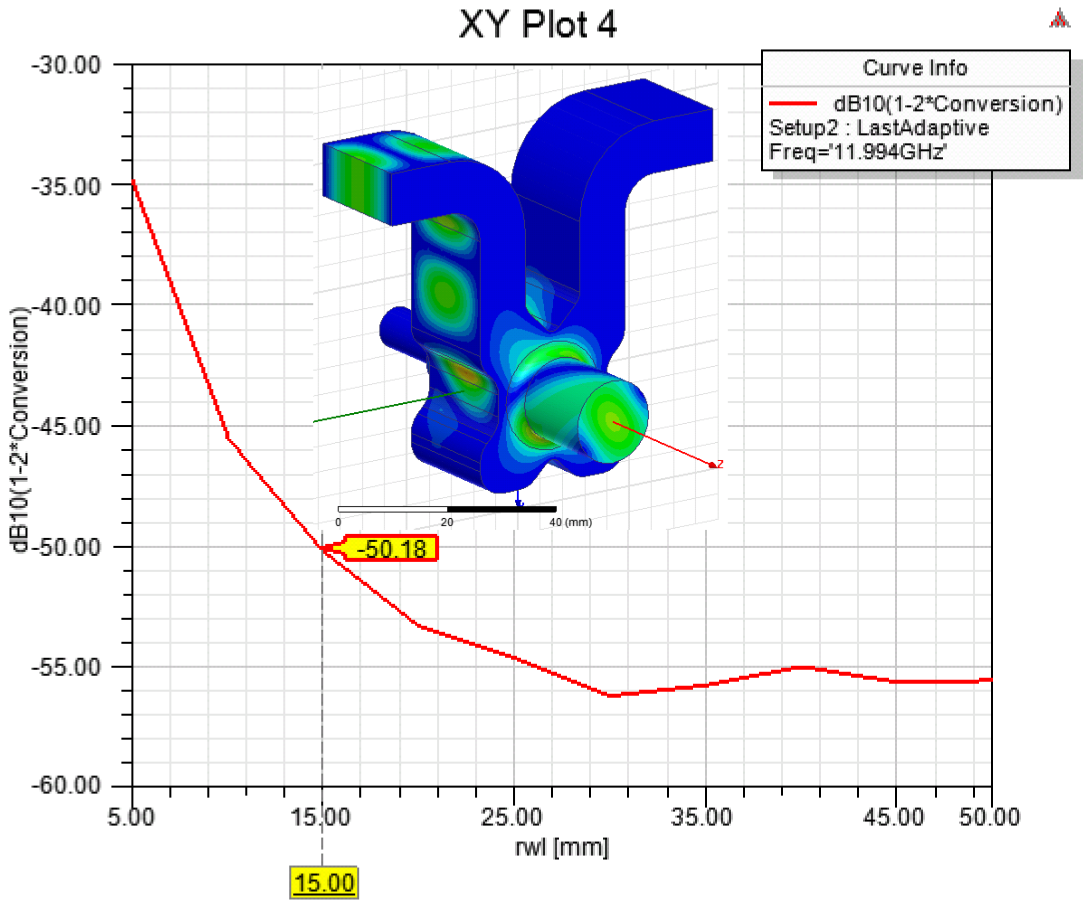


18/05/2016, A. Grudiev

Adding 90 degree bends to WR-90

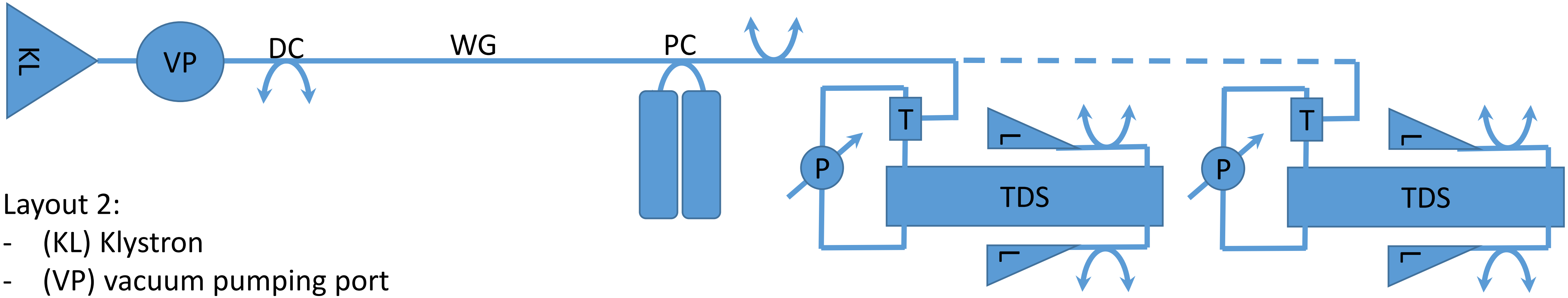






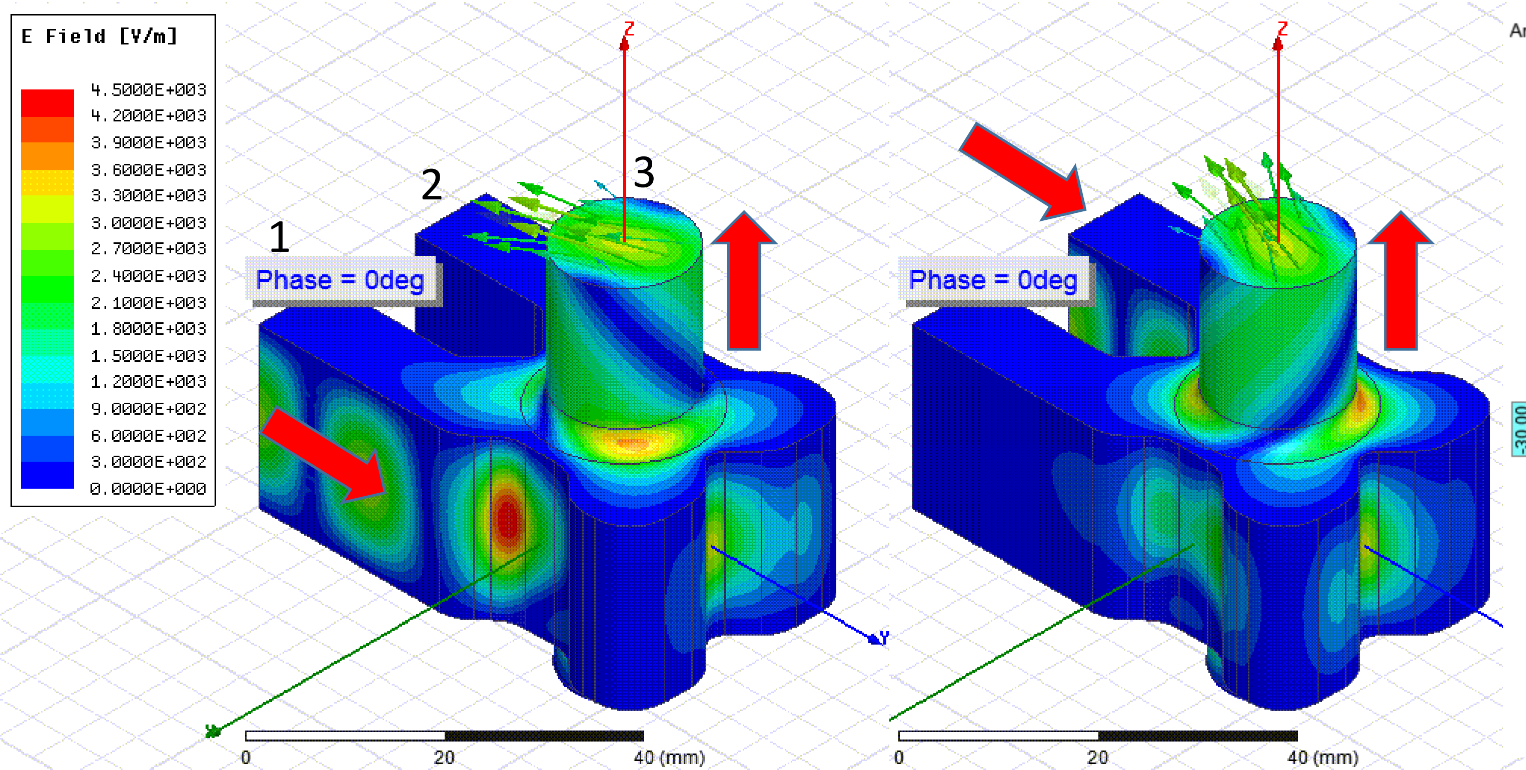
Schematic layout of an X-band TDS system

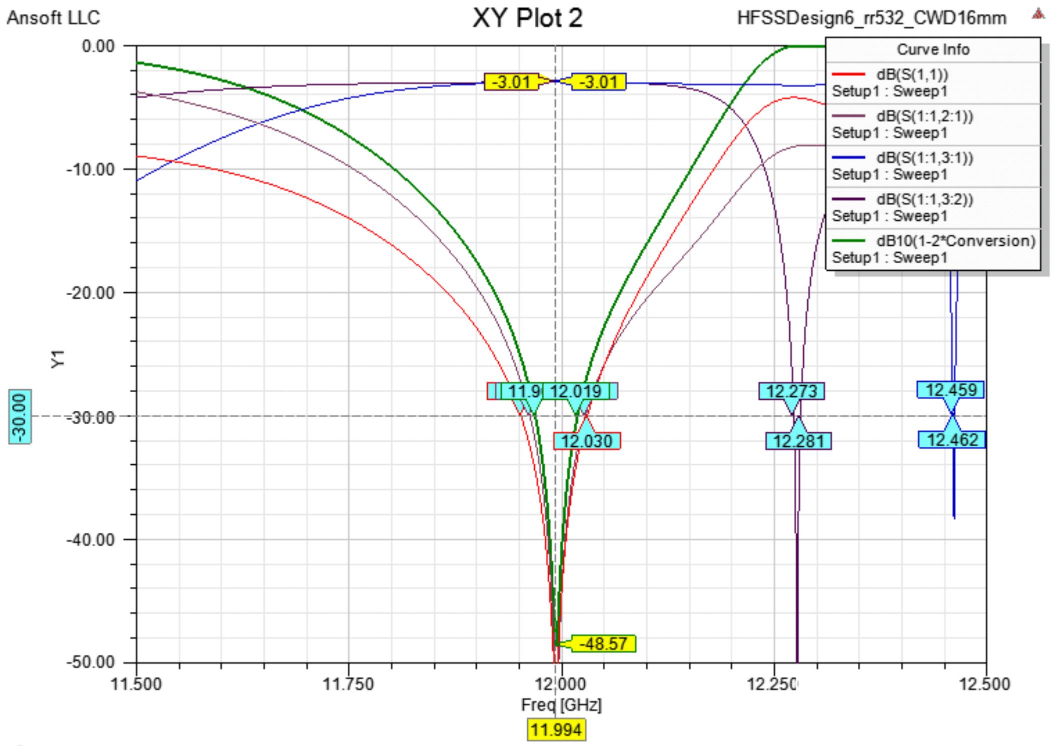
Basic layout + pulse compressor (PC)



Layout 2:
- (KL) Klystron
- (VP) vacuum pumping port
- (WG) waveguide network
- (PC) Pulse compressor
- (DC) Bi-directional couplers
- (T) waveguide splitter
- (P) Variable phase shifter
- (L) RF load

Compact E-plane circular TE11 rotating mode launcher (E-Rotator)

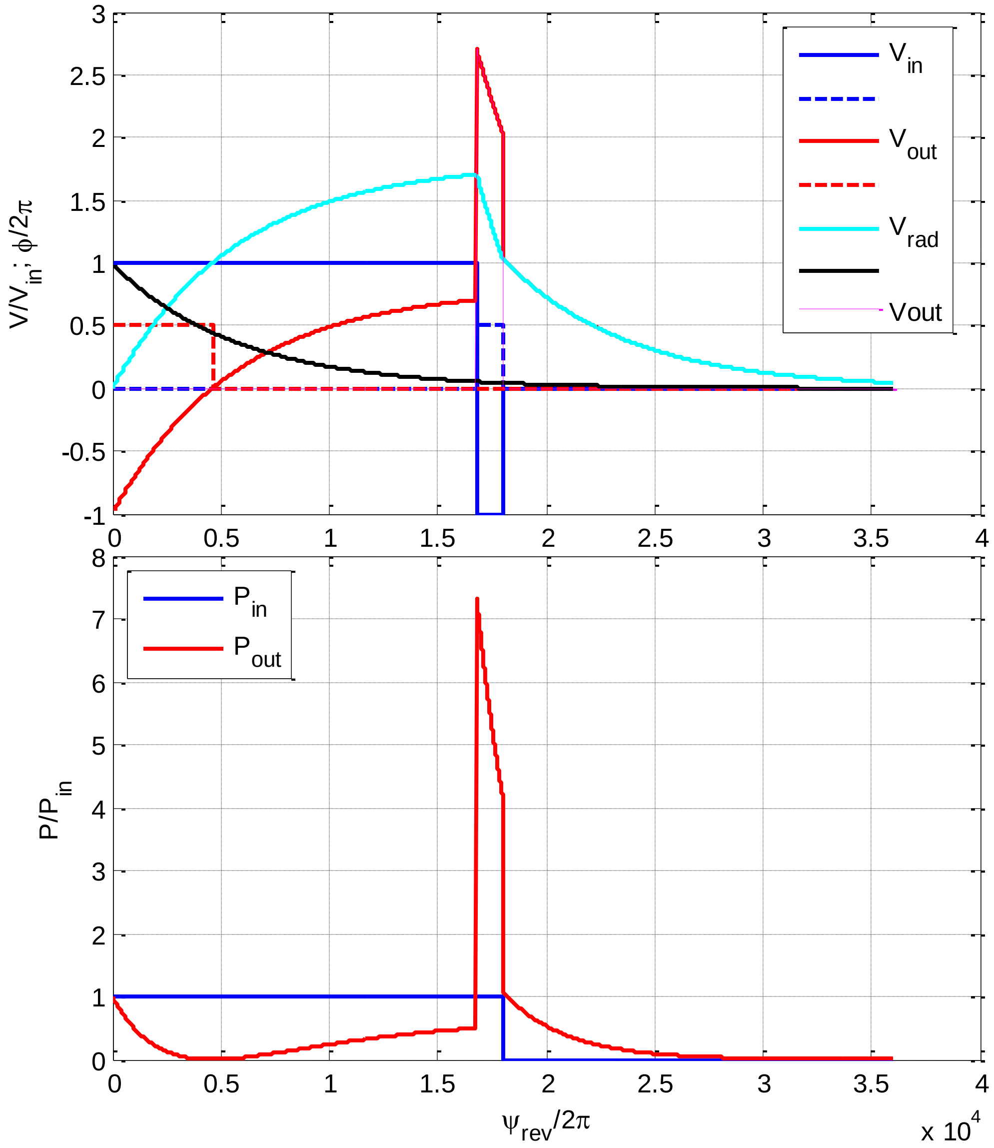




Design goal function:
Conversion = 0.5 =
|Re{S13x}Im{S13y}+Im{S13x}Re{S13y}|

Bandwidth at -30 dB	[MHz]	Max Surface Fields	at Pin=1W	at Pin=100MW
S11	78	E [MV/m]	0.0051	51
S12	65	H [kA/m]	0.018	180
1-2Conversion	50	S [MW/mm^2]	2e-8	2

Pulse compression: example

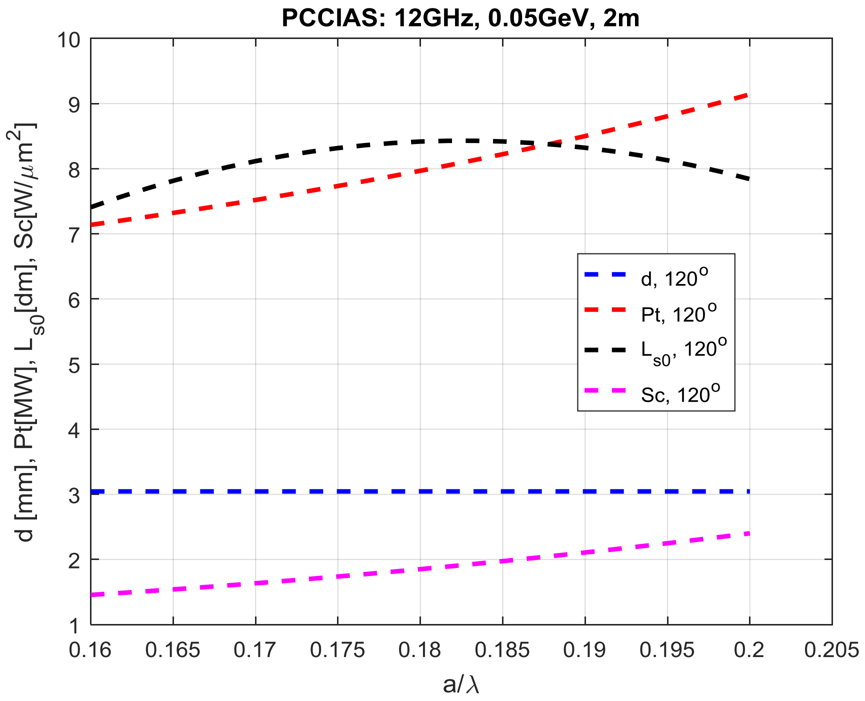


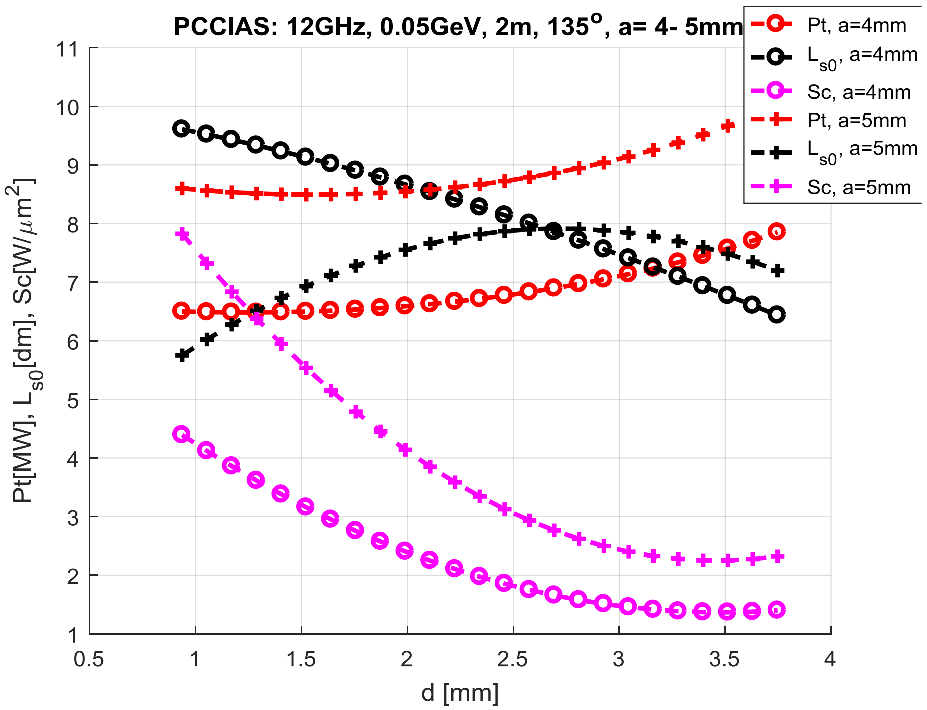
Example at 12 GHz:

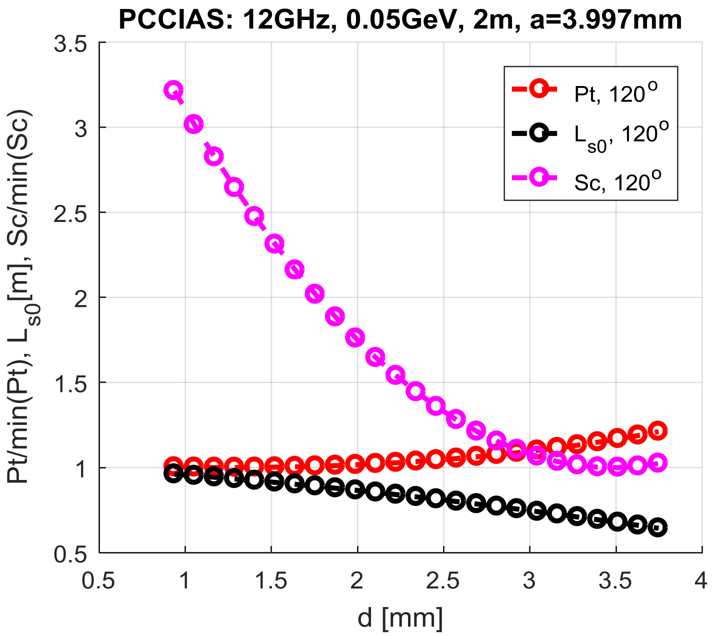
Q_0 = 180000; Q_e = 20000
t_k = 1500 ns klystron pulse length
t_p = 100 ns compressed pulse length

Average power gain =
= average power in compressed pulse
/ input power = 5.6
Average power efficiency =
= compressed pulse energy
/ input pulse energy = 34.7 %

TDS parameters versus cell geometry, (Δϕ =135°)

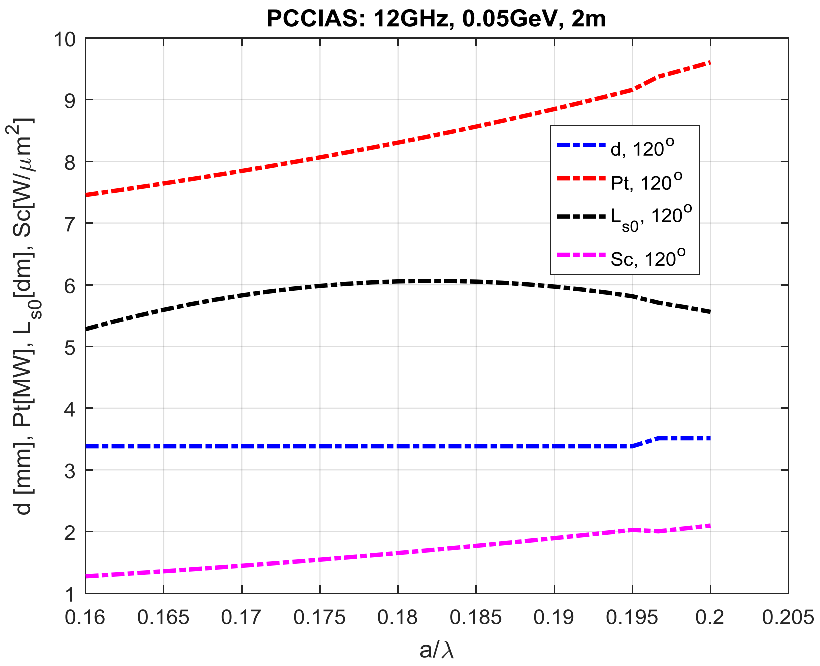


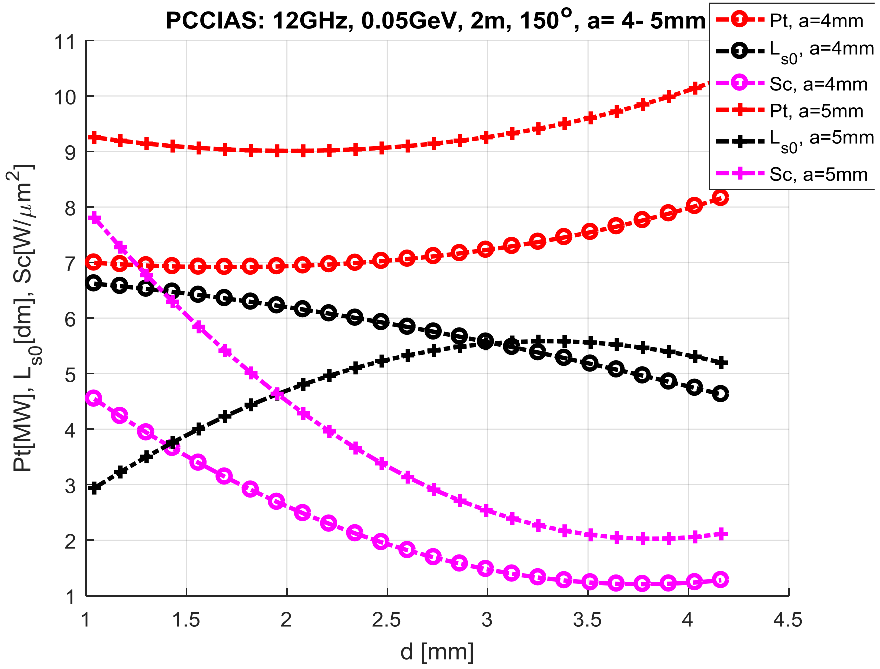


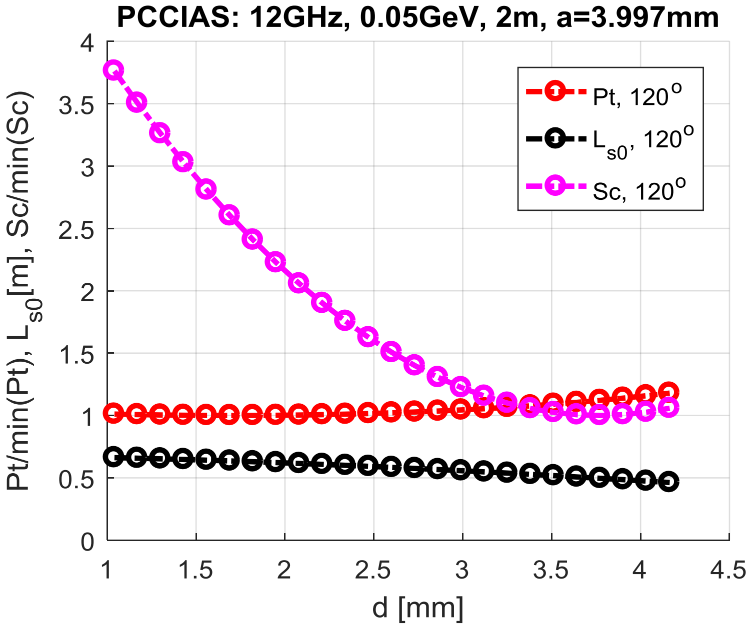


a=4mm;
d=3mm;
Ls = 747mm

TDS parameters versus cell geometry ($\Delta\phi$ =150^o)

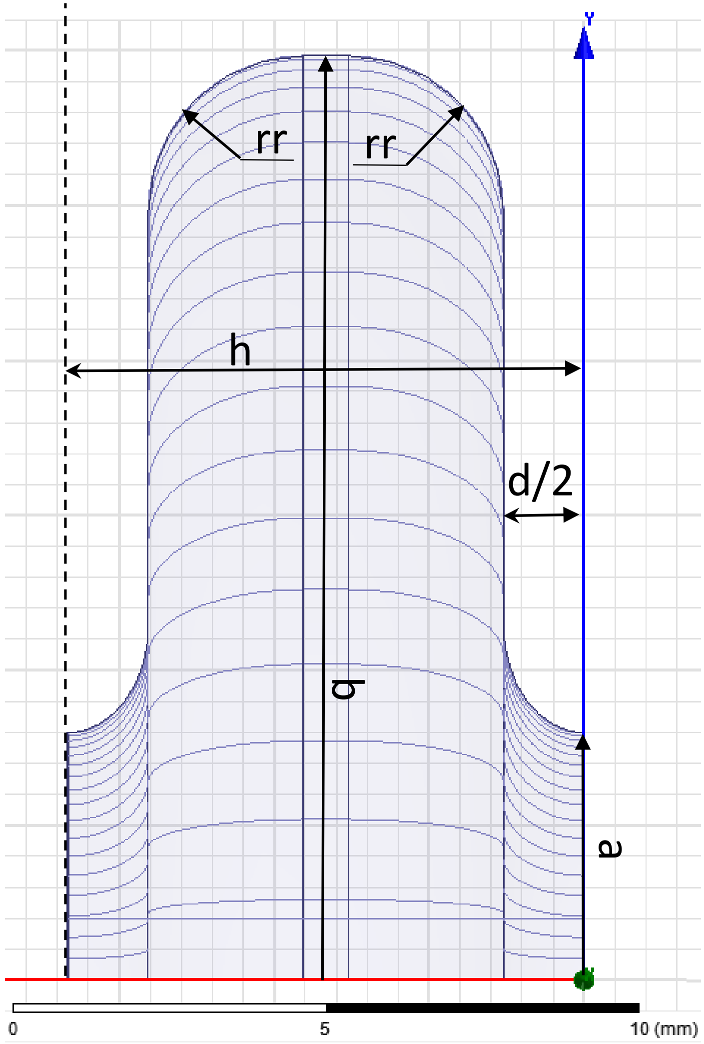


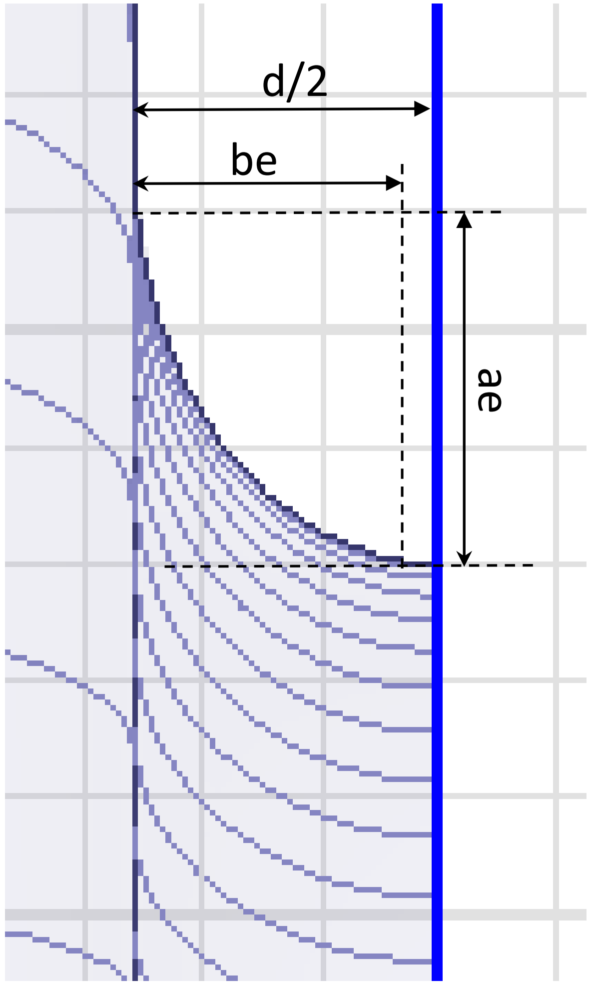




a=4mm;
d=3.4mm;
Ls = 527mm

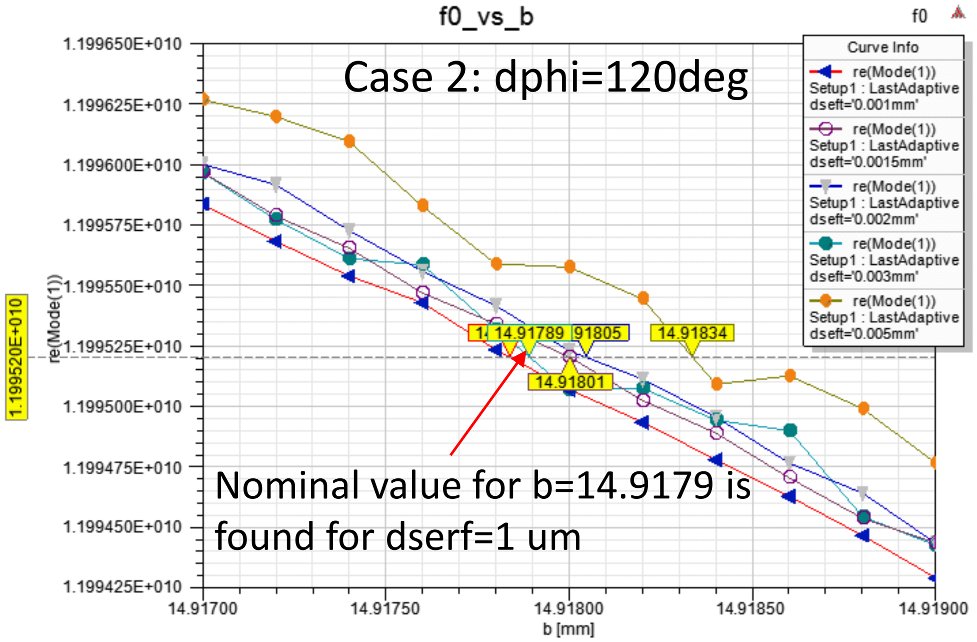
3D design of the case 2 and 3 TDS (HFSS)

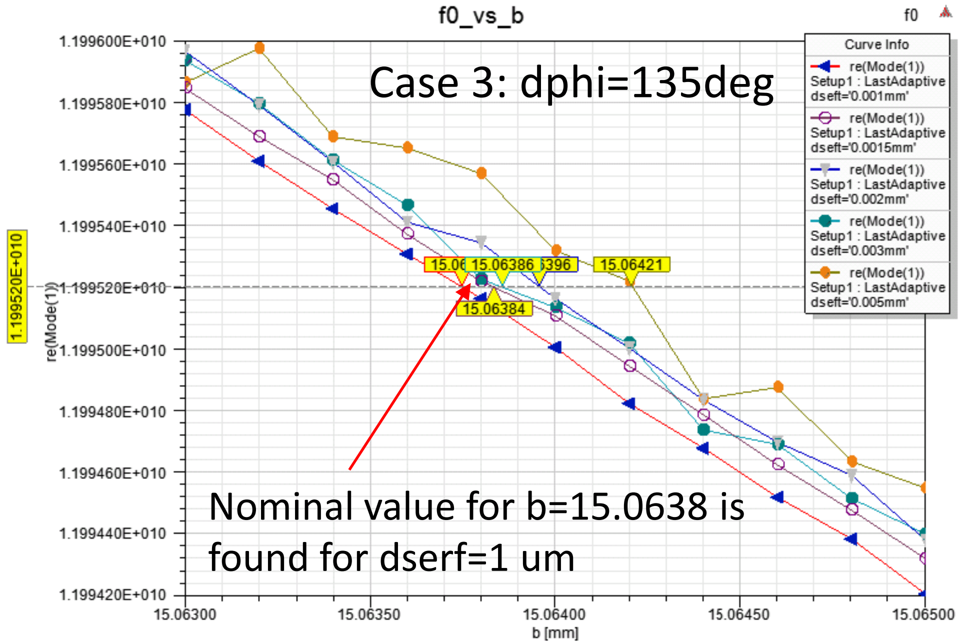




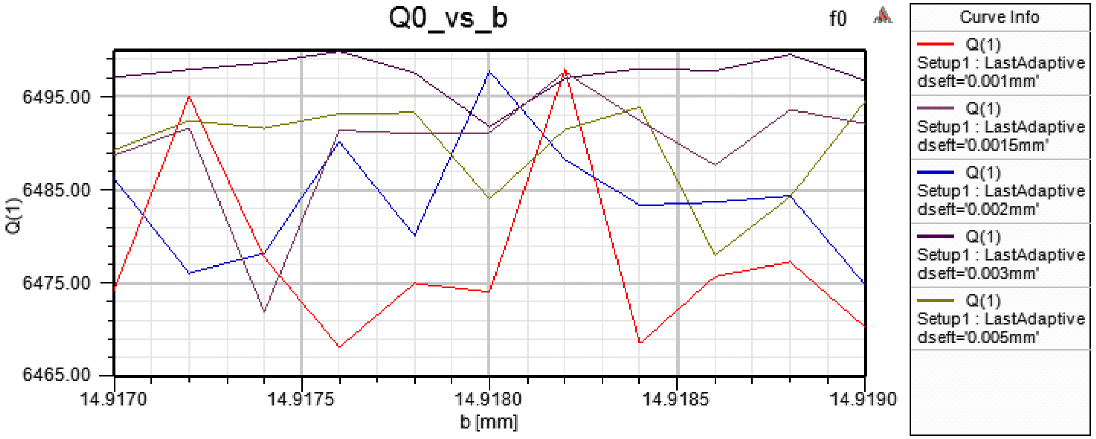
Pars		
f_0 [GHz]	11.9952	
T [degree C]	30	
$\Delta\phi_0$ [degree]	120	135
a [mm]	4	
h [mm]	8.3309	9.3723
rr [mm]	2.5	3
b [mm]	14.9179	15.0638
d [mm]	2.6	3
s	0.01	
e	1.35	1.4
be [mm]	d/2*(1-s)	
ae [mm]	be*e	

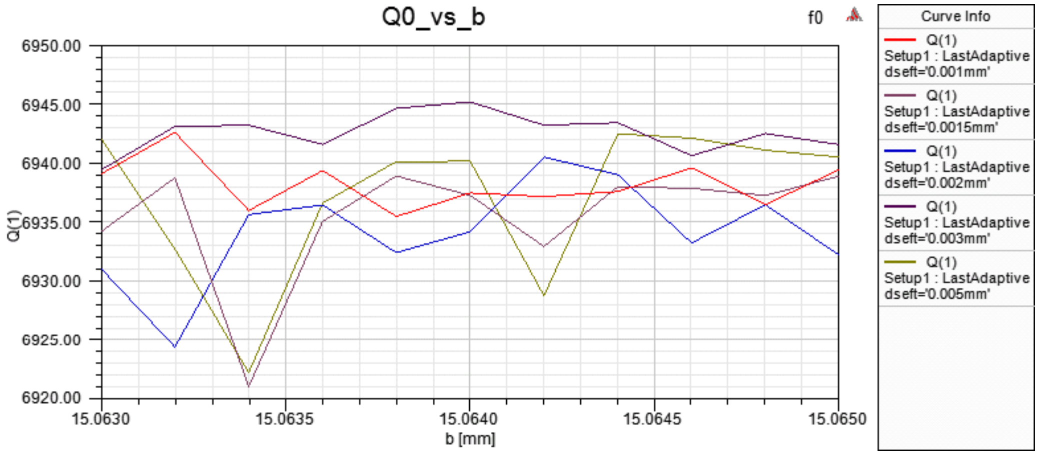
Dependence of the frequency f0 on surface approximation dserf. (AnsysEM v17.2)





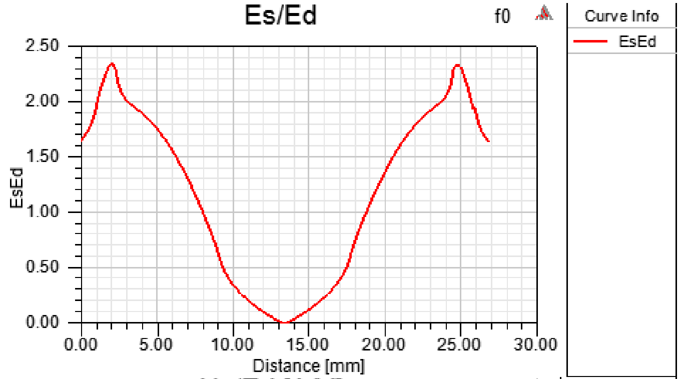
- dserf=2 um is also OK and can be used for tolerance studies

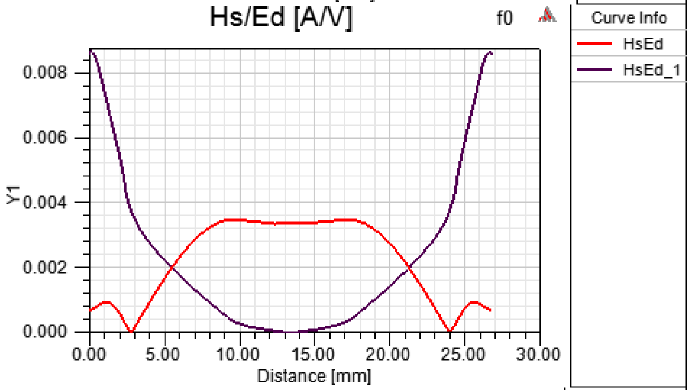


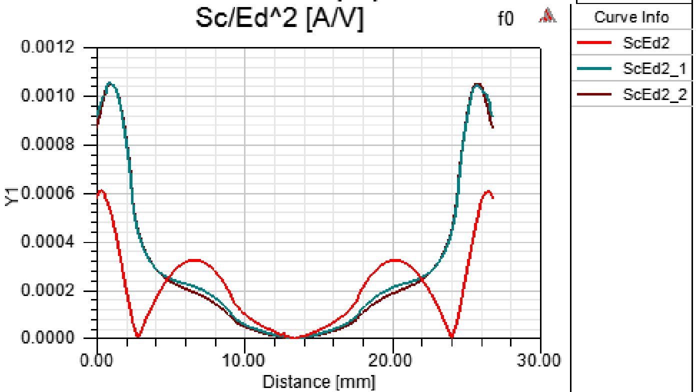


Surface fields normalized to the deflecting field. dserf=1um

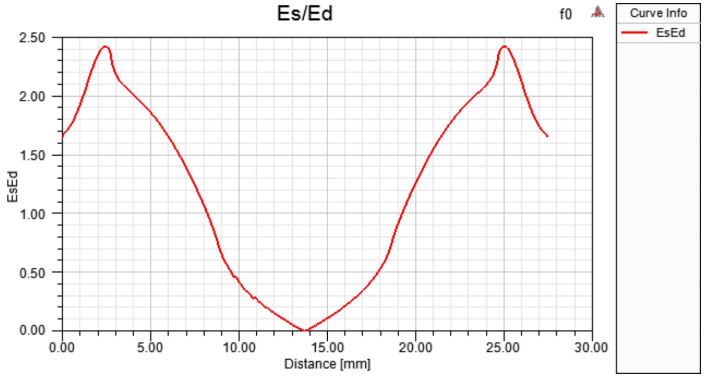
Case 2: dphi=120deg

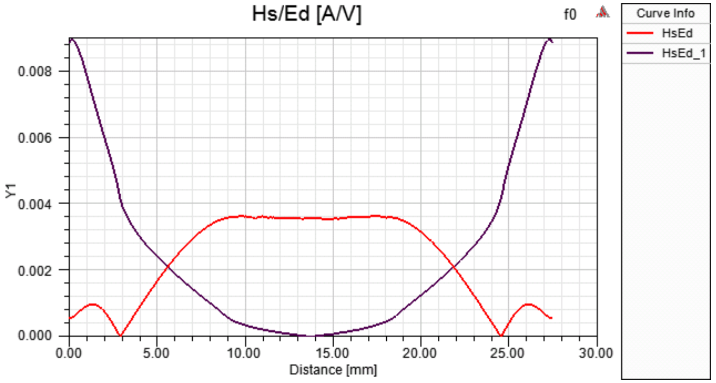


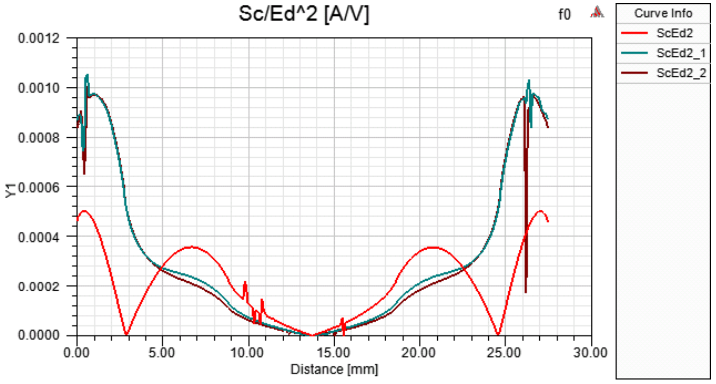




Case 3: dphi=135deg



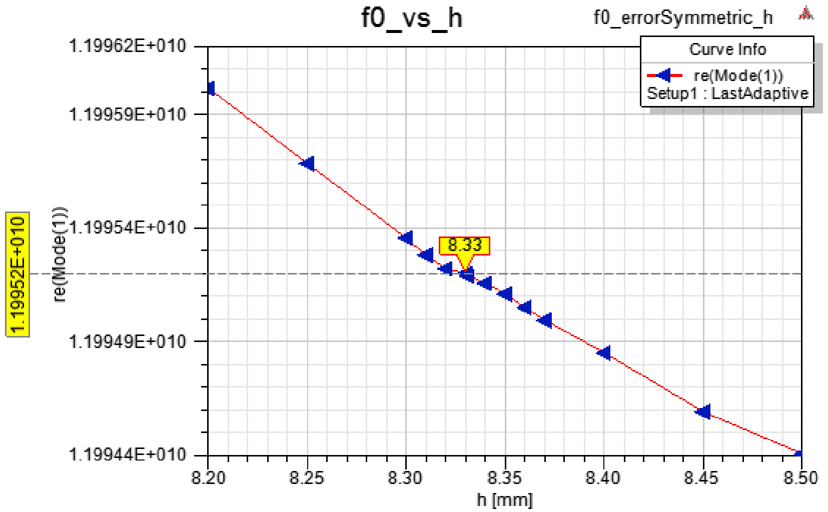


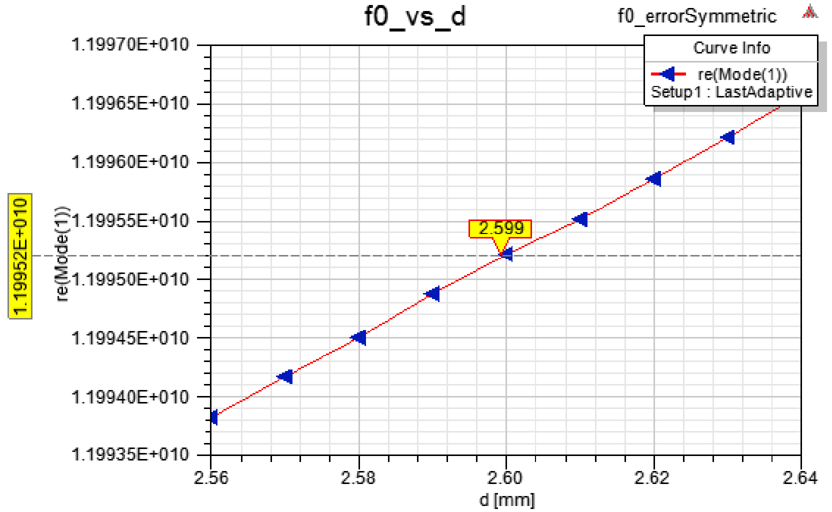


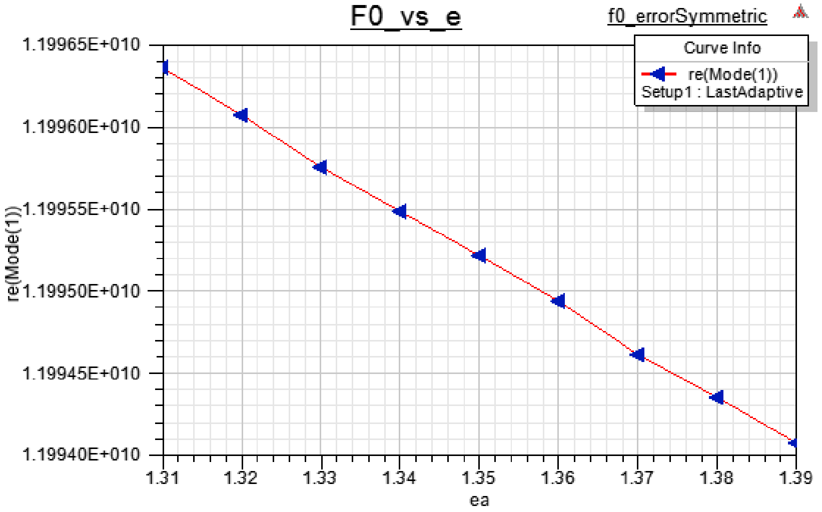
Pars		
f_0 [GHz]	11.9952	
T [degree C]	30	
$\Delta\phi_0$ [degree]	120	135
Q	6490	6940
v_g/c [%]	-2.666	-2.063
R_x/Q [Ω/m]	7706	7076
Es/Ed	2.35	2.4
Hs/Ed [mA/V]	8.7	9.0
Sc/Ed^2 [mA/V]	1.05	0.98

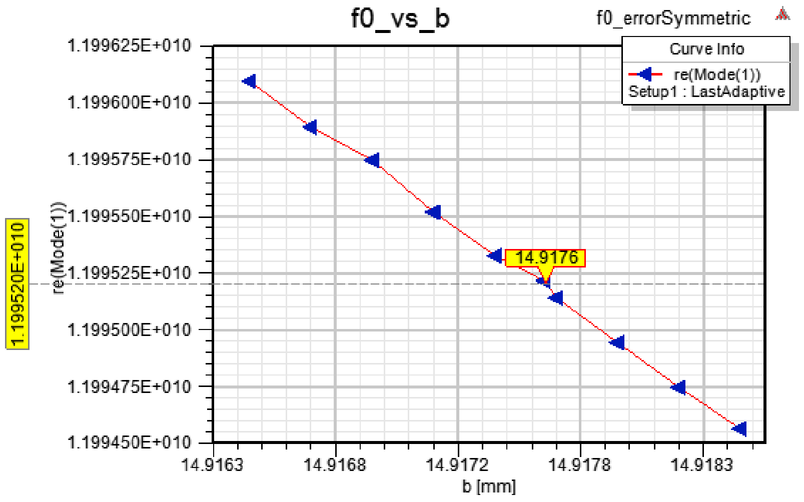
Frequency sensitivity to the axially symmetric errors.

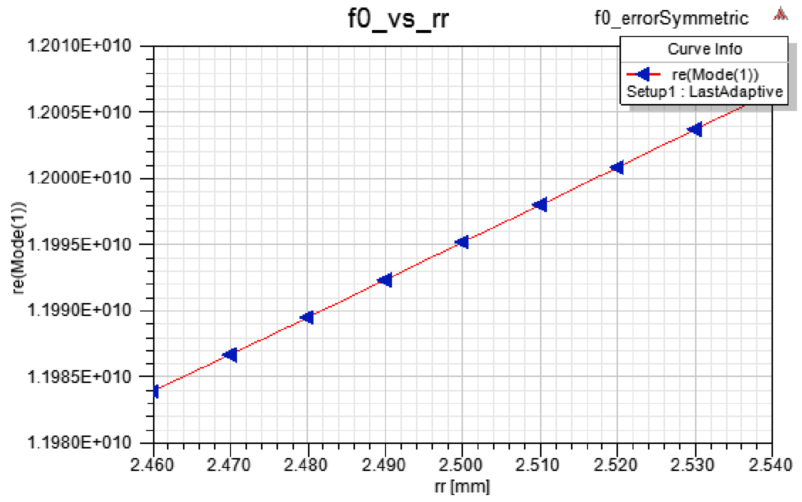
$\Delta\phi_0$ = 120 degree, dserf=1um,

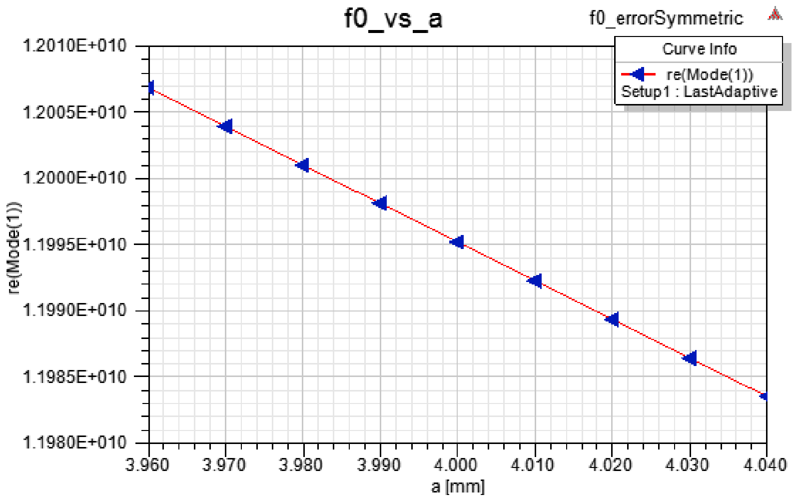




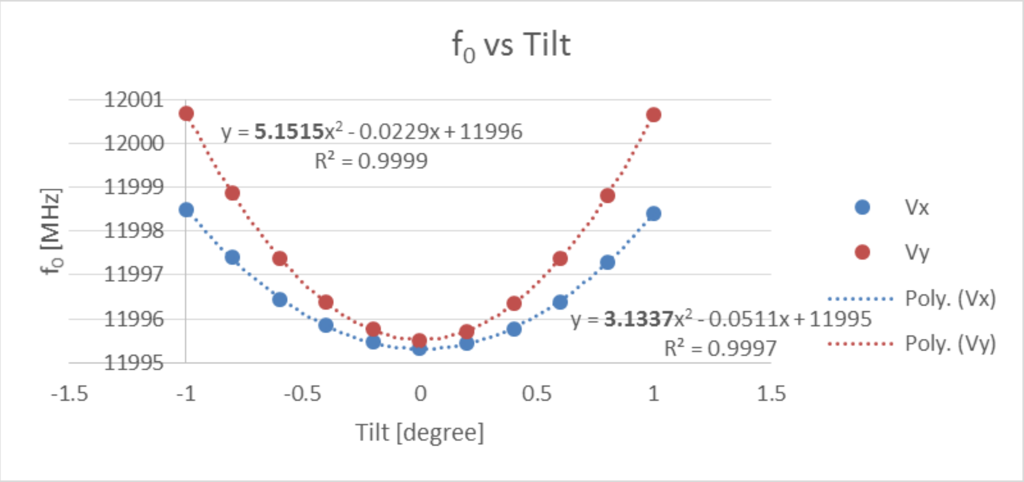


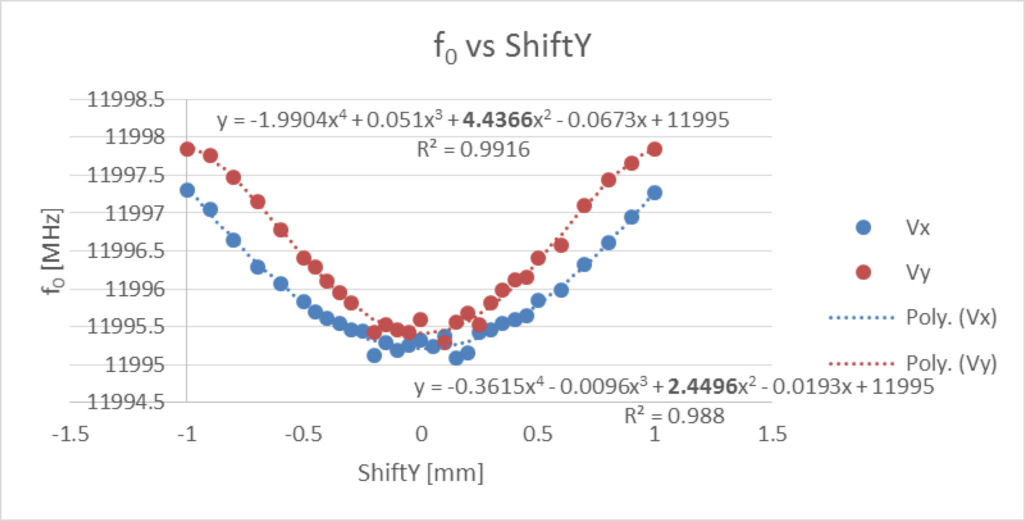






Frequency sensitivity to the non-axially symmetric errors. $\Delta\phi_0$ = 120 degree, dserf=2um,



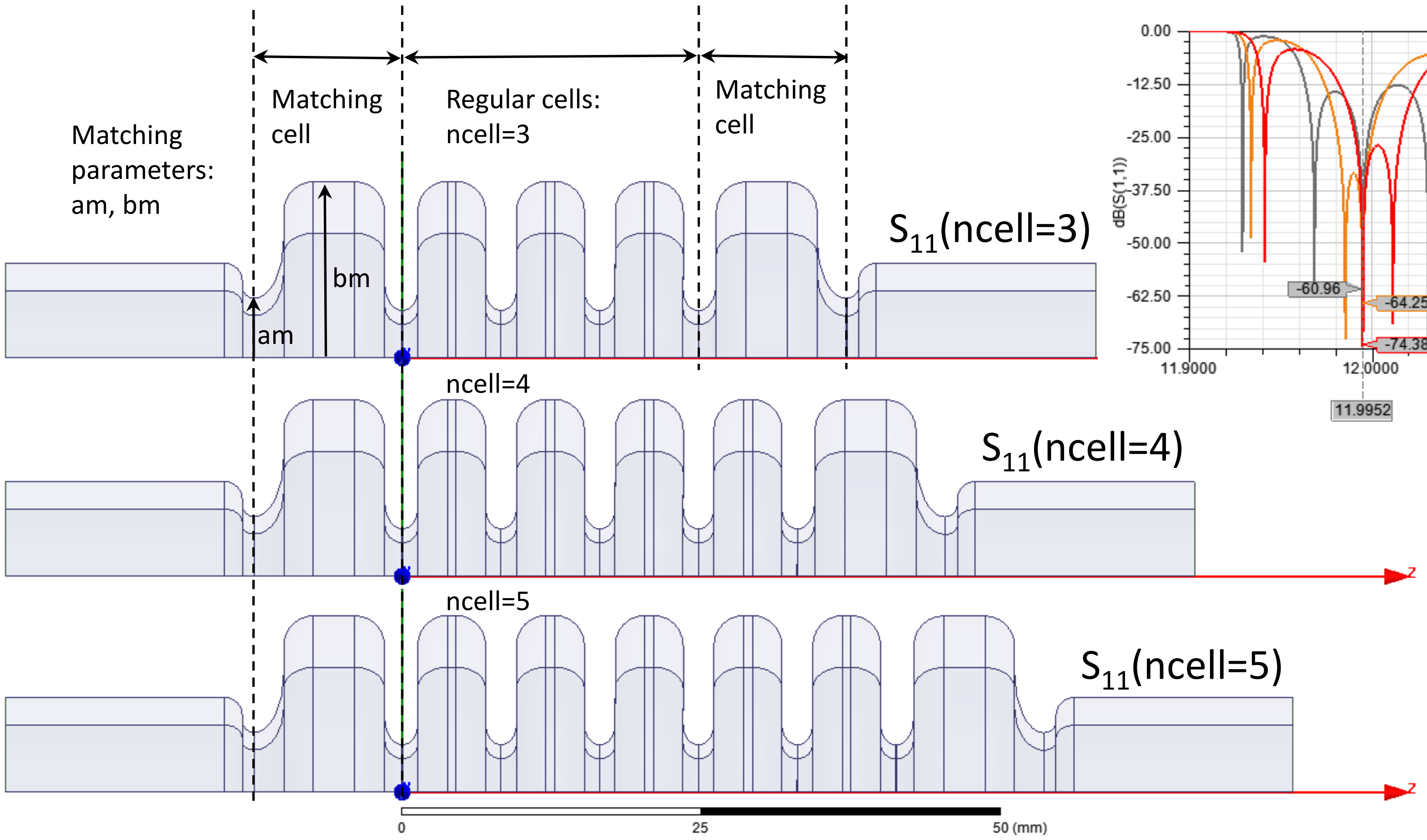


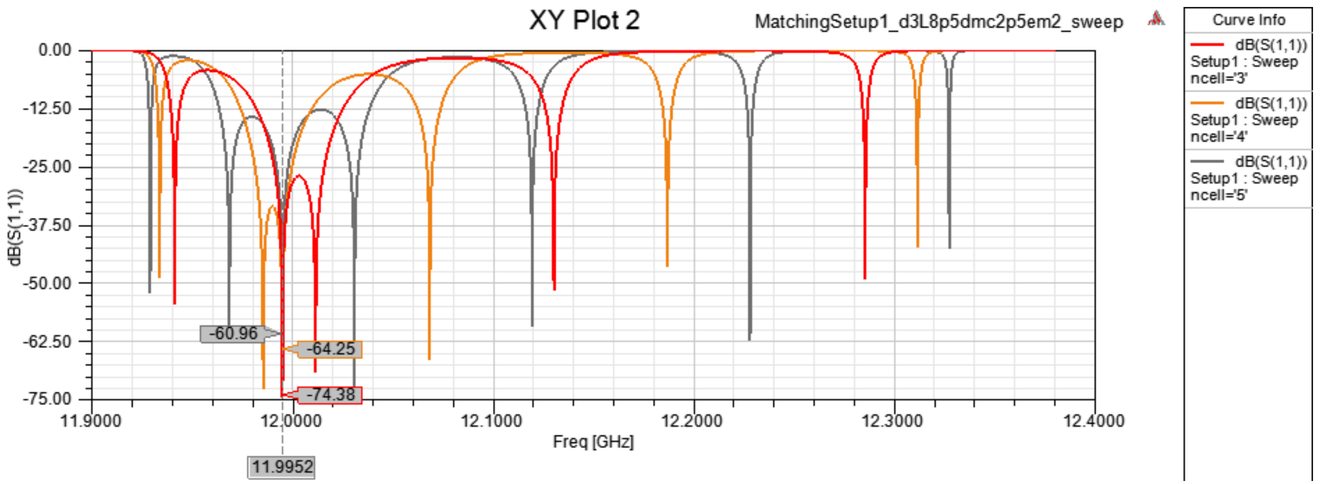
						dV/V [%]	-1	-2	-5		-1	-2	-5
						$d(\Delta\phi_0)*N_c$	11.46497	16.21391	25.63645		11.46497	16.21391	25.63645
						L_s=0.8m, N_c=96				L_s=1m, N_c=120			
	z	α [deg]	d^2f/dz^2 [MHz/deg^2]	Comments	$d^2(\Delta\phi_0)/dz^2$ [deg/deg^2]		dz [±deg]	dz [±deg]	dz [±deg]		dz [±deg]	dz [±deg]	dz [±deg]
1	Tilt Vx	90	3.13		1.174513316		0.318876	0.37921	0.476831		0.285211	0.339175	0.42649
2	Tilt Vy	0	5.15	more critical	1.932505936		0.248594	0.29563	0.371735		0.222349	0.264419	0.332489
3		45	4.261419951		1.599071718		0.273286	0.324993	0.408657		0.244434	0.290683	0.365514
			d^2f/dz^2 [MHz/mm^2]		$d^2(\Delta\phi_0)/dz^2$ [deg/mm^2]		dz [±mm]	dz [±mm]	dz [±mm]		dz [±mm]	dz [±mm]	dz [±mm]
4	Shift Vx	90	2.45		0.919347484		0.360422	0.428616	0.538956		0.322371	0.383366	0.482057
5	Shift Vy	0	4.44	more critical	1.666082787		0.267733	0.31839	0.400355		0.239468	0.284777	0.358088
6		45	3.585812321		1.345554096		0.29792	0.354289	0.445495		0.266468	0.316886	0.398463

The same tilt in each cell -> “banana”

The same shift in each cell -> “book shelfing”

Matching Disk-loaded waveguide to a Circular waveguide

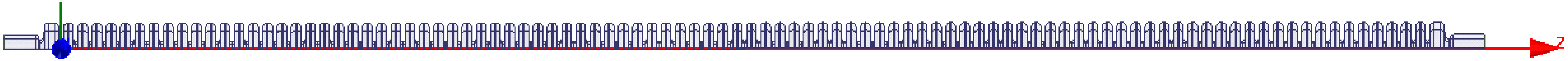


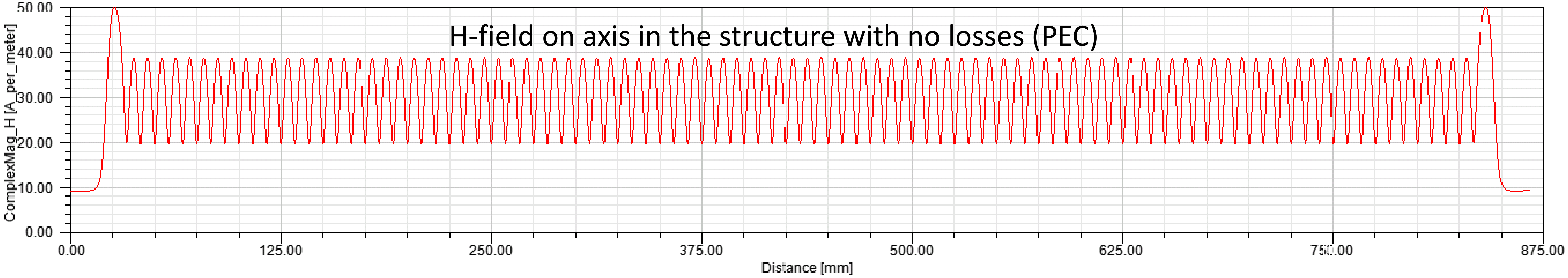


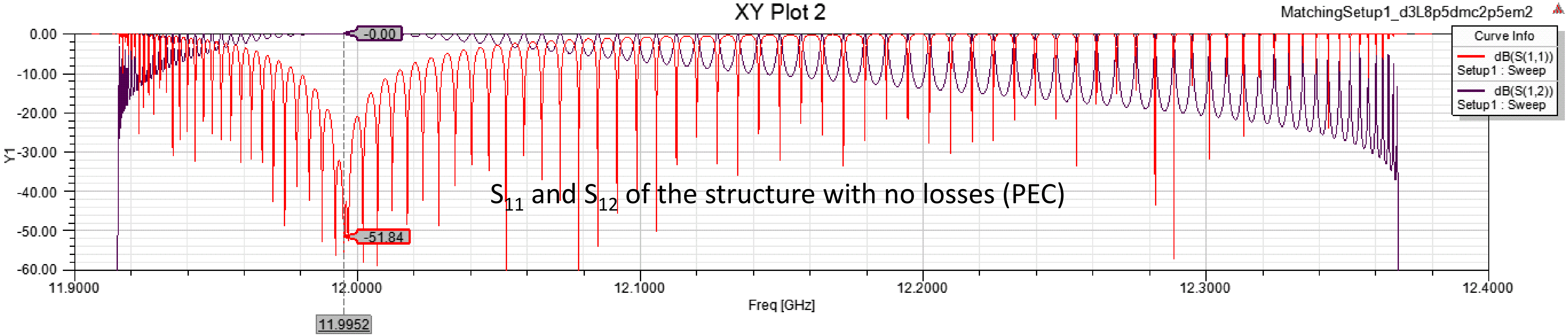
Matching condition:
Envelope of three curves above goes to 0 =>

Max{S_{11}(ncell=3,4,5)} -> 0

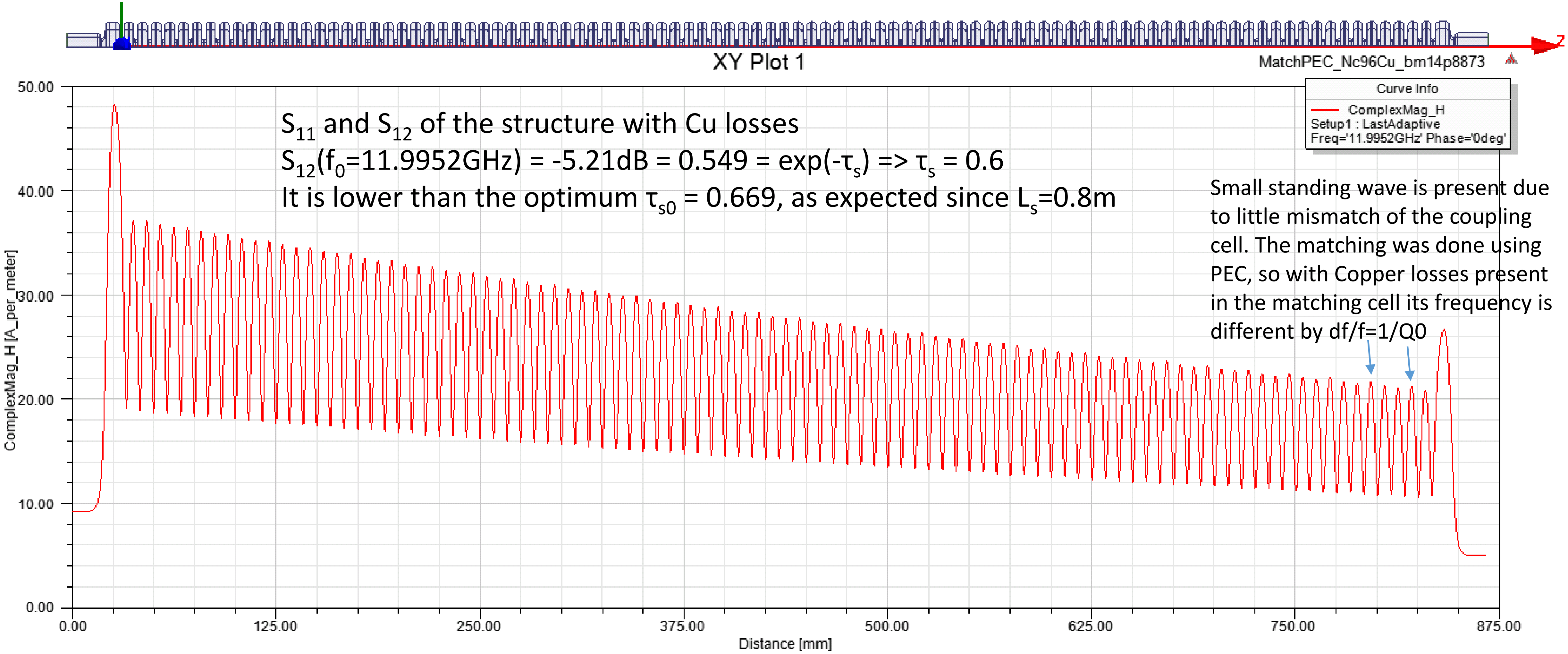
Field distribution and S-pars in full length structure (PEC): bm=14.8873mm, Nc=96, dsurf=5um







Field distribution in full length Cu structure: bm=14.8873mm, Nc=96, dsurf=5um



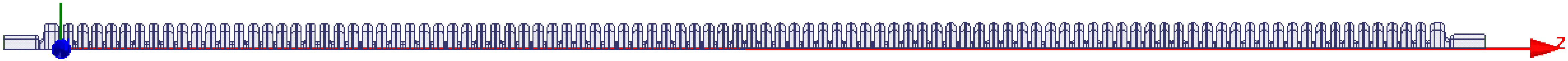
S_{11} and S_{12} of the structure with Cu losses

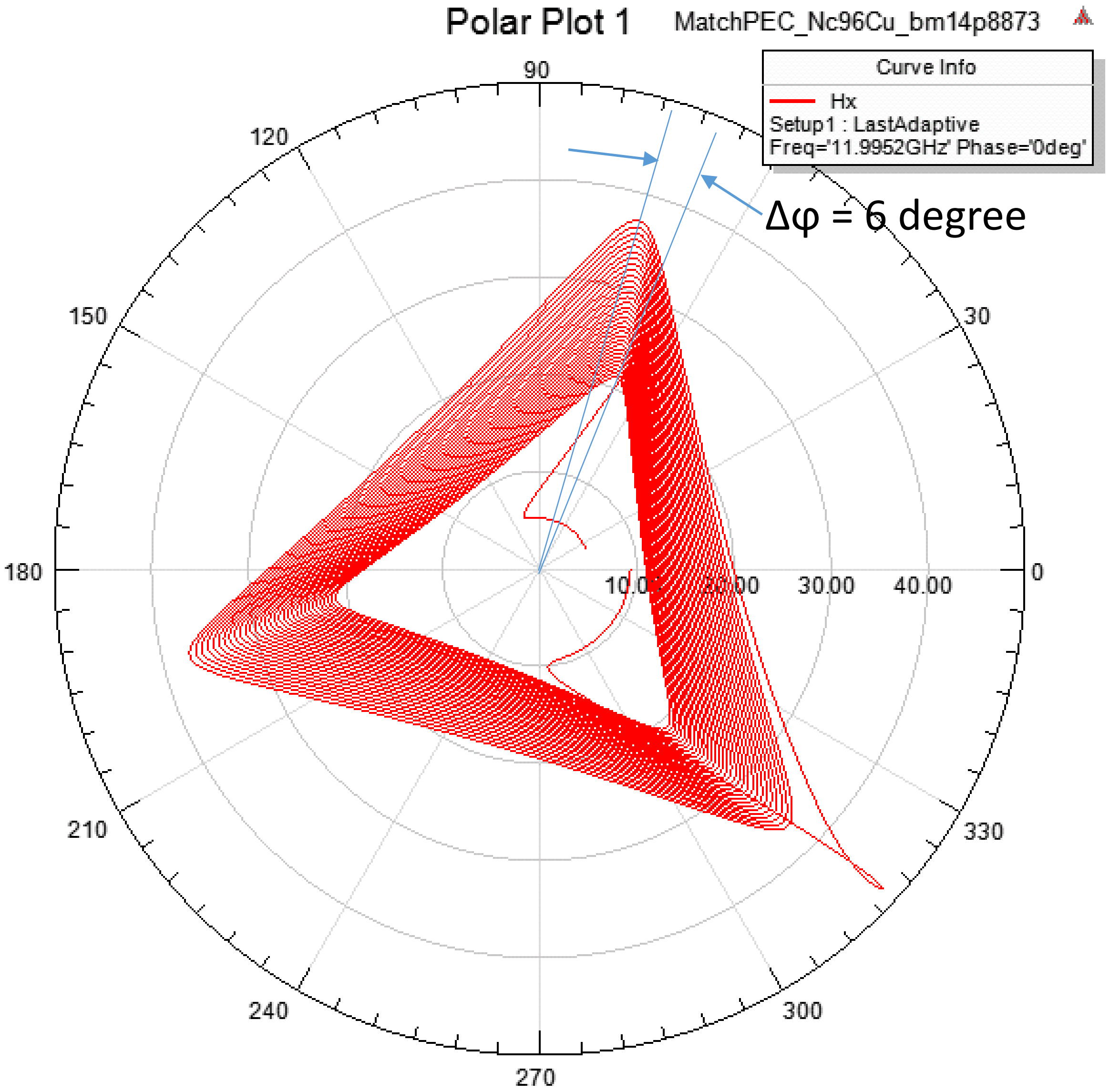
$S_{12}(f_0=11.9952\text{GHz}) = -5.21\text{dB} = 0.549 = \exp(-\tau_s) \Rightarrow \tau_s = 0.6$

It is lower than the optimum $\tau_{s0} = 0.669$, as expected since $L_s=0.8\text{m}$

Small standing wave is present due to little mismatch of the coupling cell. The matching was done using PEC, so with Copper losses present in the matching cell its frequency is different by df/f=1/Q0

Field distribution in full length structure in Cu: bm=14.8873mm, Nc=96, dsurf=5um





The phase advance error of 6 degree over 96 cells corresponds to numerical frequency error per cell:
6deg/120deg/96cells*0.02666*11.9952GHz = 0.2MHz
This correspond to 0.2um error in b,
Well within error related to mesh
Much smaller than the target machining tolerances
The effect on the RF performance is negligible

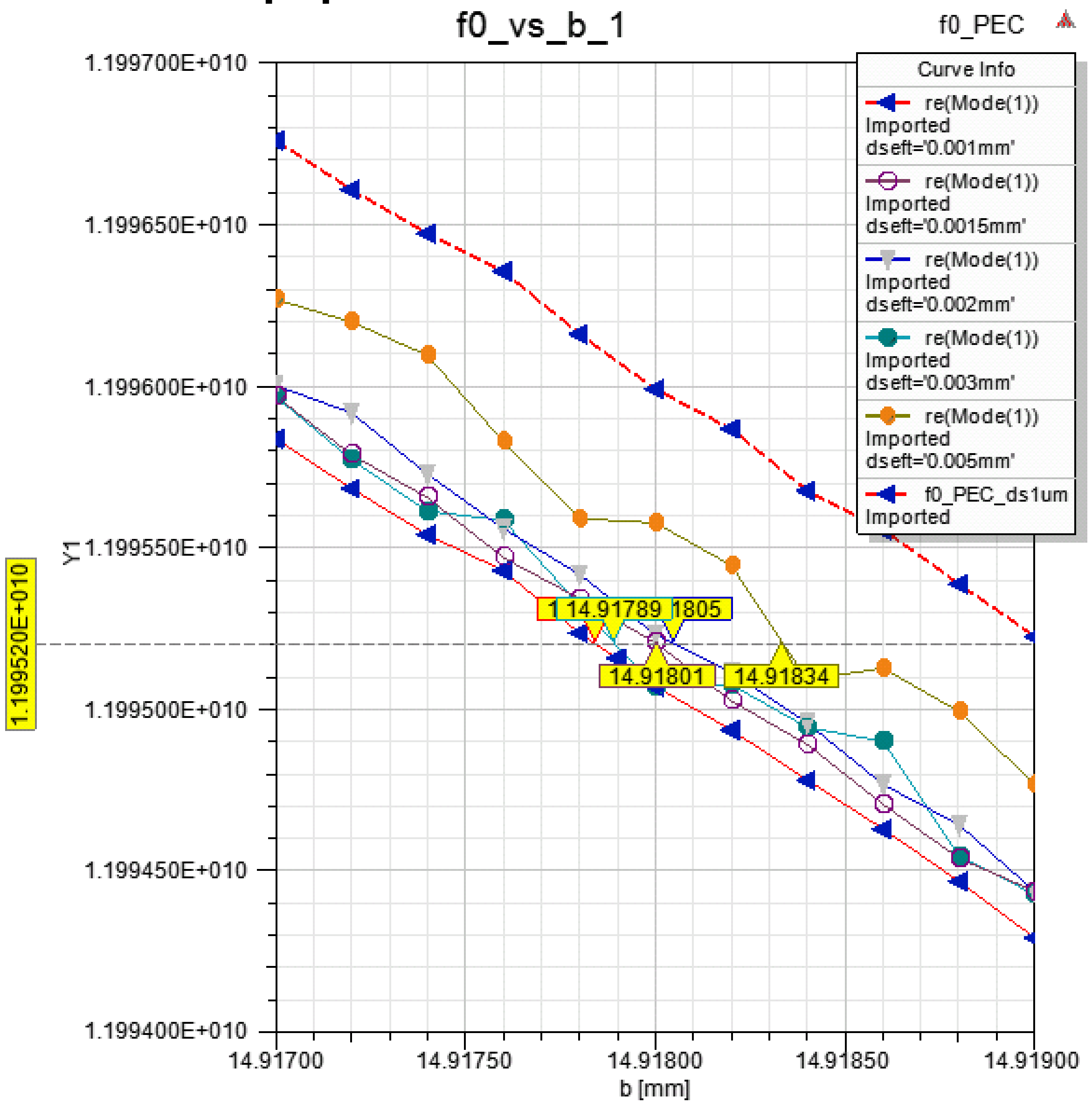
Conclusion: Dimensions of the cell found in eigenmode solver are confirmed in the S-pars solver

Vy [V] for Pin=6MW

	Freq [GHz]	Vym*sqrt(1.5)*1000 Setup1 : Sweep1 Phase='0deg'
1	11.995000	12861891.596793
2	11.995100	12864489.886917
3	11.995200	12862455.911294
4	11.995300	12855803.262451
5	11.995400	12844548.142562

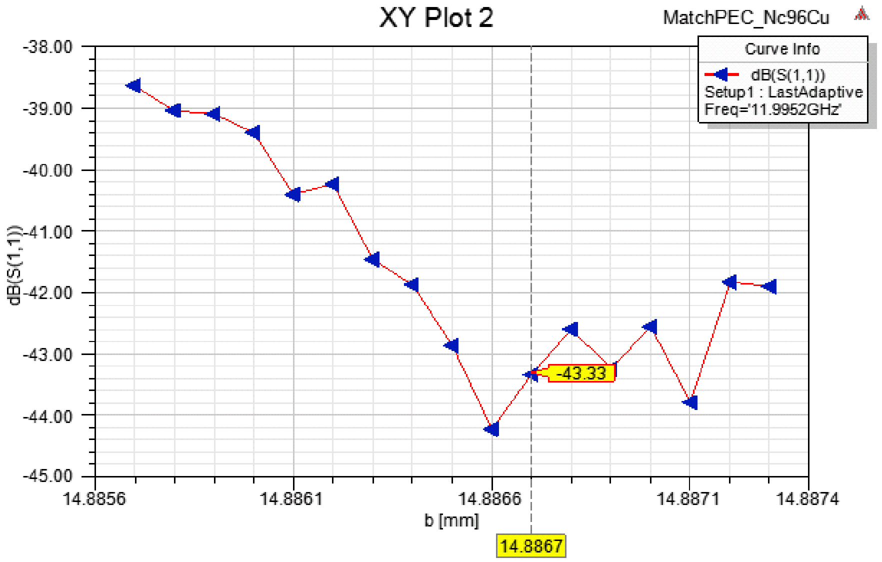
Tuning matching cell with copper losses

- Effect of the copper losses on the regular cell frequency
- Due to copper losses frequency decreases by df/f~1/Q0 => -0.9 MHz
- This corresponds to 0.9 um correction in b
- In order to correct the matching cell frequency (matched using PEC) in the presence of copper losses bm must be reduce by ~0.9um
- This is an estimate

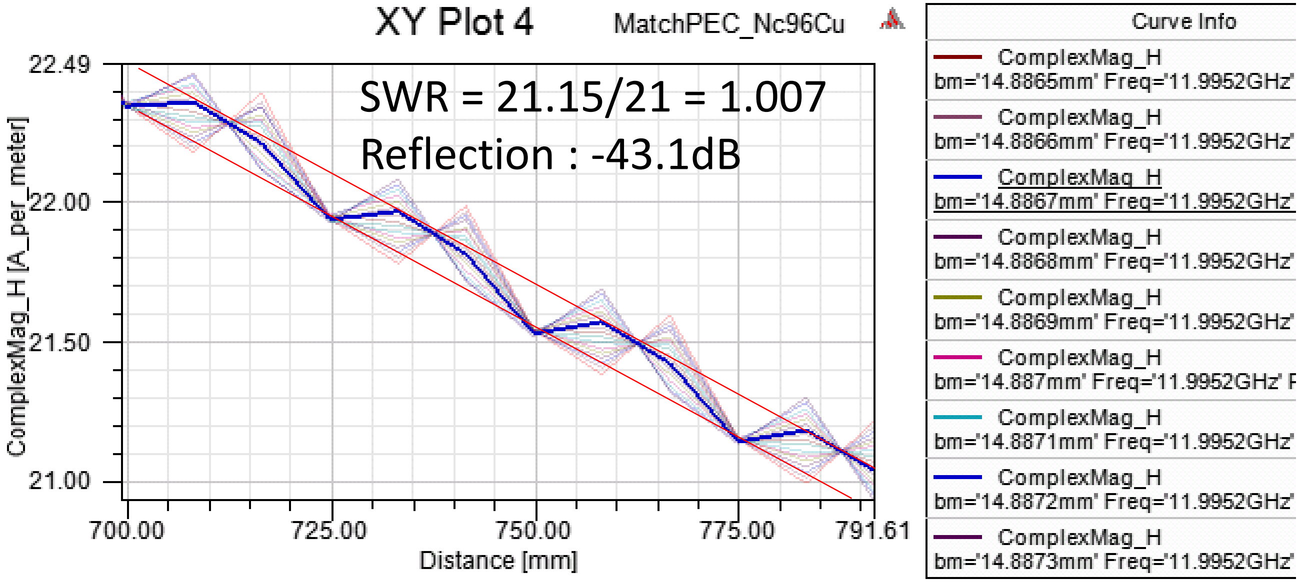


Tuning matching cell with copper losses

S11 versus the matching cell radius bm

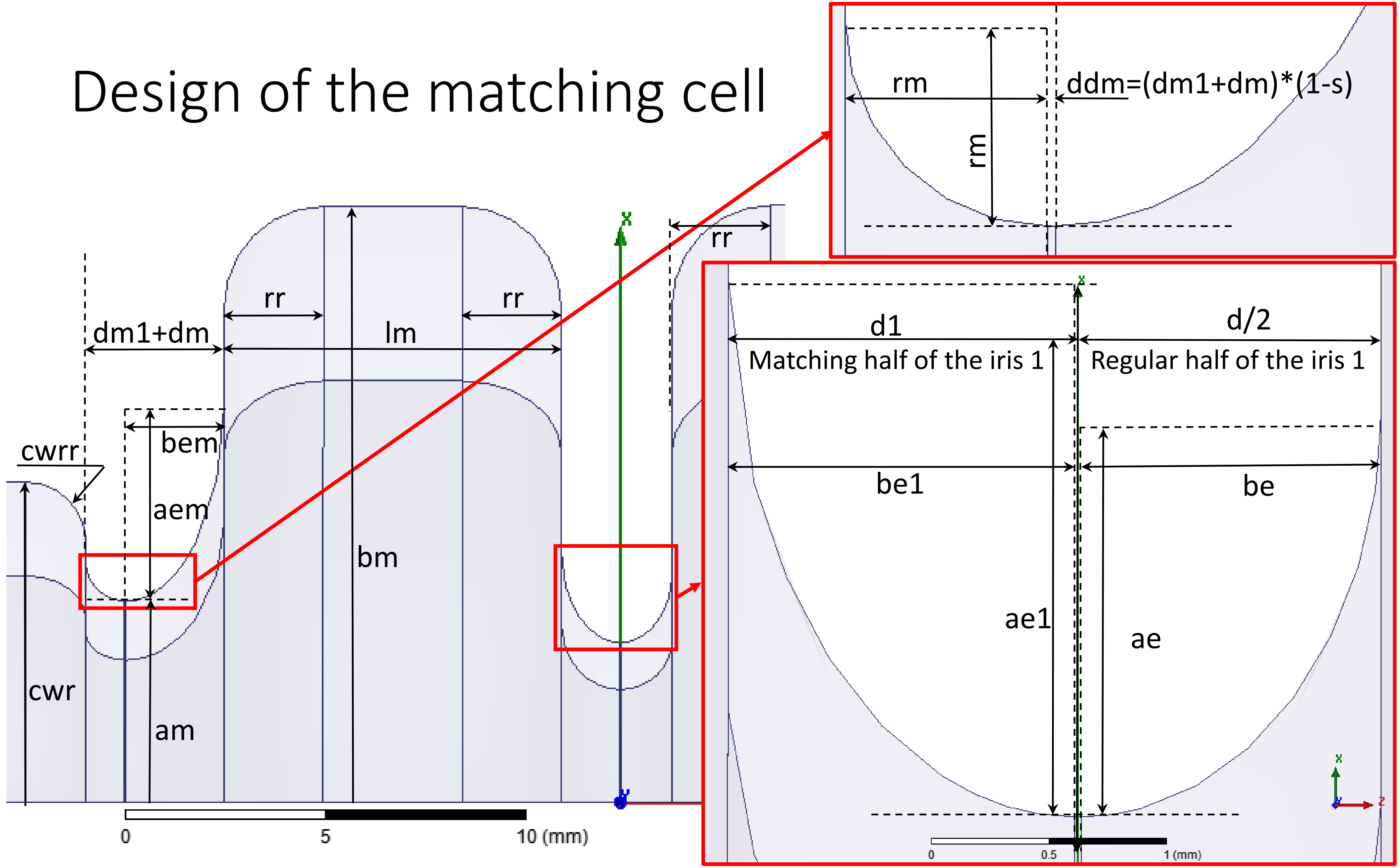


Mag of H-field on axis in the middle of the last 12 regular cells



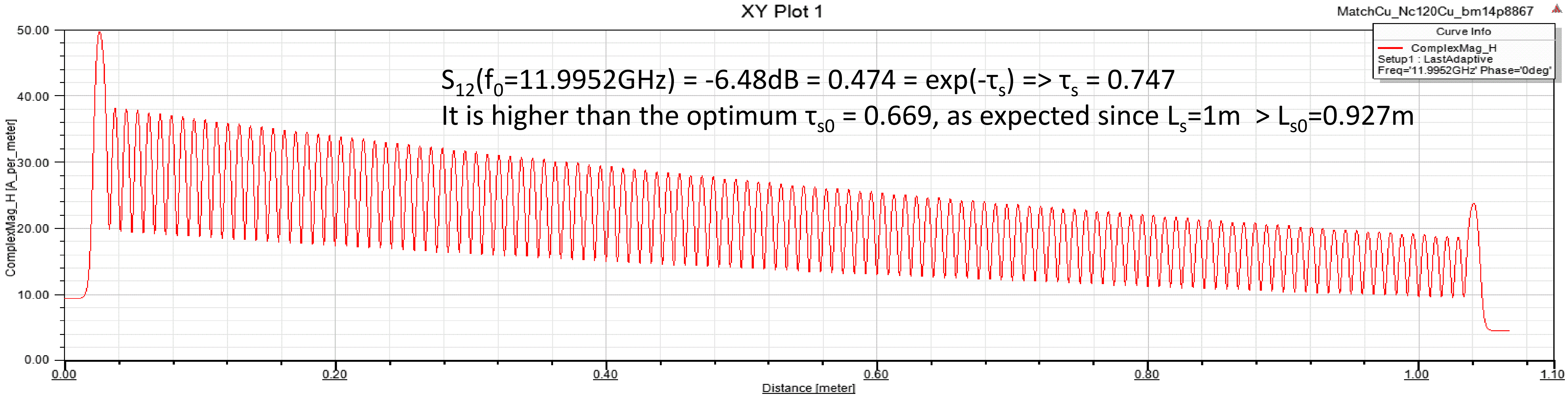
- Both the S11,S22 (reflection from the matching cell into the waveguide) and the standing wave (reflection form matching cell into the periodic structure) is minimized for **bm=14.8867 mm** to about the same level of -43 dB
- It is still higher than reflection in the PEC structure: -60dB mainly due to mismatch in the mating iris radius
- BUT corrections of the matching iris radius to minimize S11 and standing wave have different sign. So it is impossible to set both to 0 in the symmetric structure, where input and output matching iris are the same.
- Since it is very small (<-43dB) and the corrections would be below the machining tolerances level, we neglect this tiny mismatch

Design of the matching cell



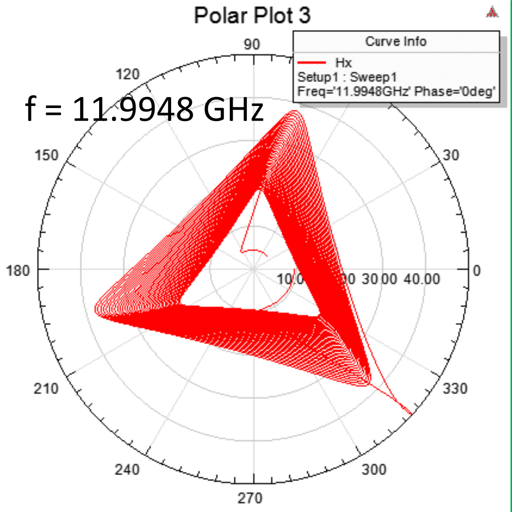
Matching Pars	
f_0 [GHz]	11.9952
T [degree C]	30
am [mm]	5.0322
lm [mm]	8.5
bm [mm]	14.8867
dm [mm]	2.5
em	2
bem [mm]	dm*(1-s)
aem [mm]	bem*em
dm1 [mm]	1
rm [mm]	dm1*(1-s)
d1 [mm]	1.5
e1	e*2*d1/d
be1 [mm]	d1*(1-s)
ae1 [mm]	be1*e1
cwr [mm]	8
cwrr [mm]	1.5

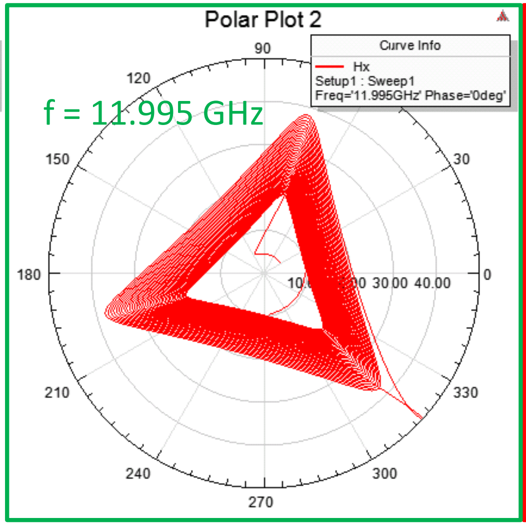
Field distribution in full length Cu structure: bm=14.8867mm, Nc=120, dsurf=5um

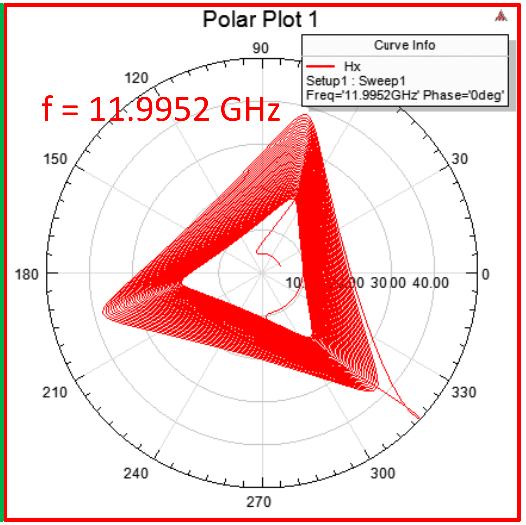


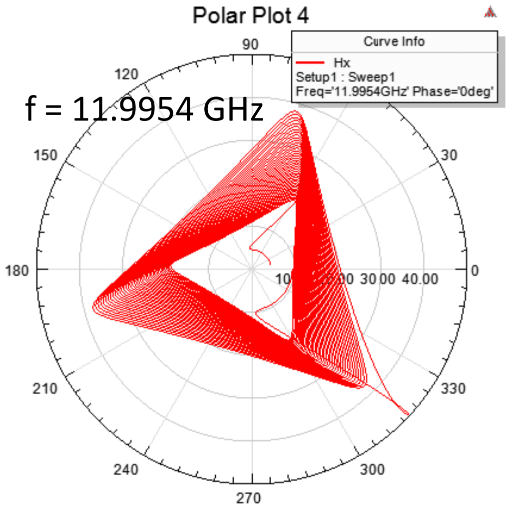
$S_{12}(f_0=11.9952\text{GHz}) = -6.48\text{dB} = 0.474 = \exp(-\tau_s) \Rightarrow \tau_s = 0.747$

It is higher than the optimum $\tau_{s0} = 0.669$, as expected since L_s=1m > L_{s0}=0.927m

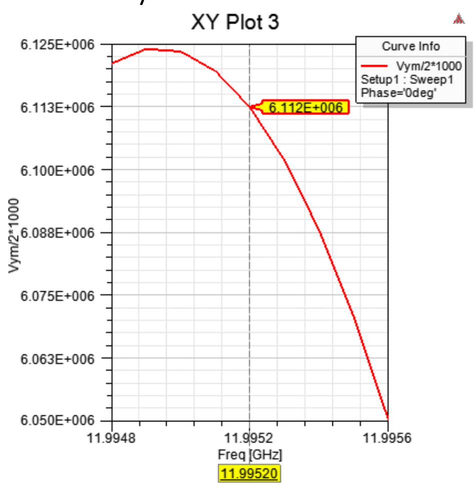








V_y for P_{in} = 1MW



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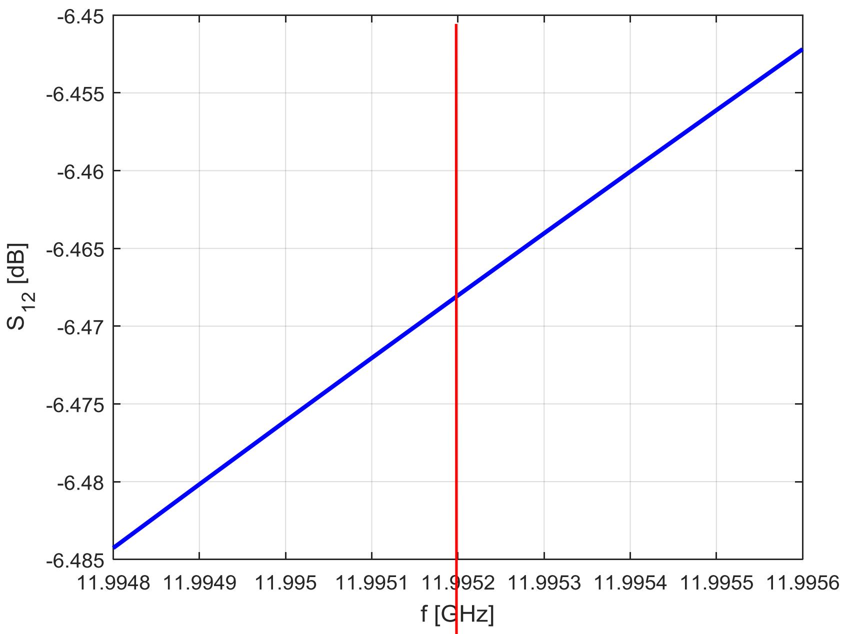
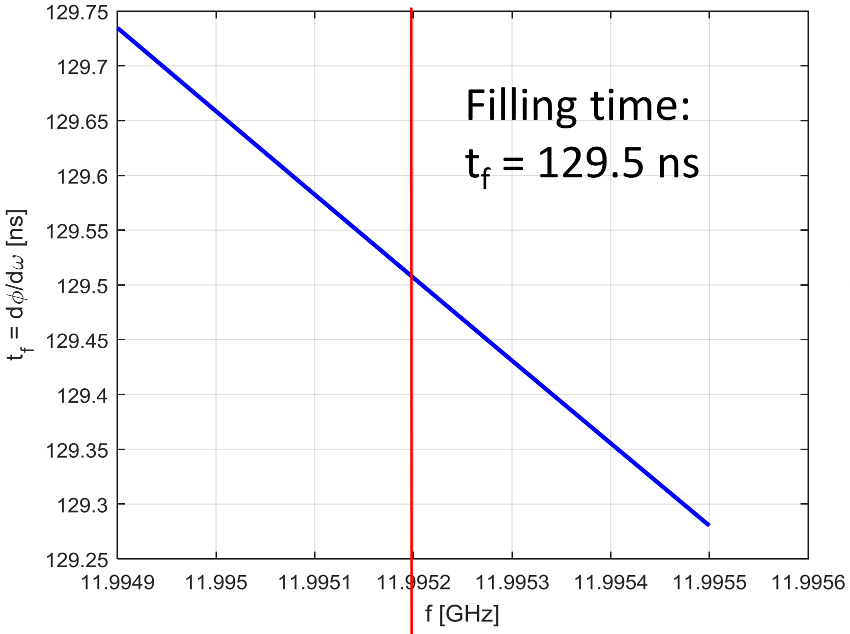
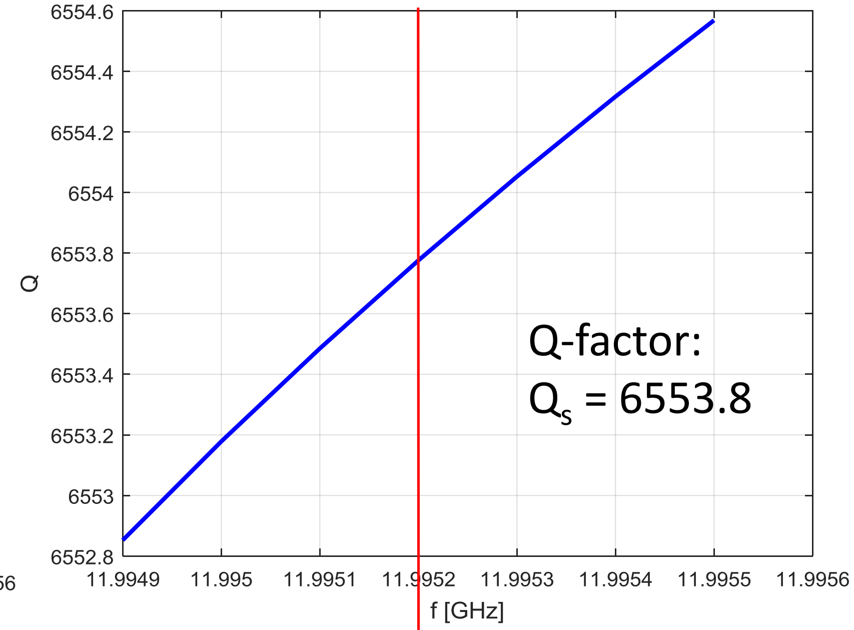
S12, filling time and Q-factor in full length Cu structure: bm=14.8867mm, Nc=120, dsurf=5um







S-pars solver: S12 for 96 and 120 cells give the regular cell parameters =>

v_g in regular cell from S12:
$v_g/c = (120\text{-}96)h/c[t_f(120) - t_f(96)]$
$= 24h/c25[\text{ns}] =$ **0.02667**

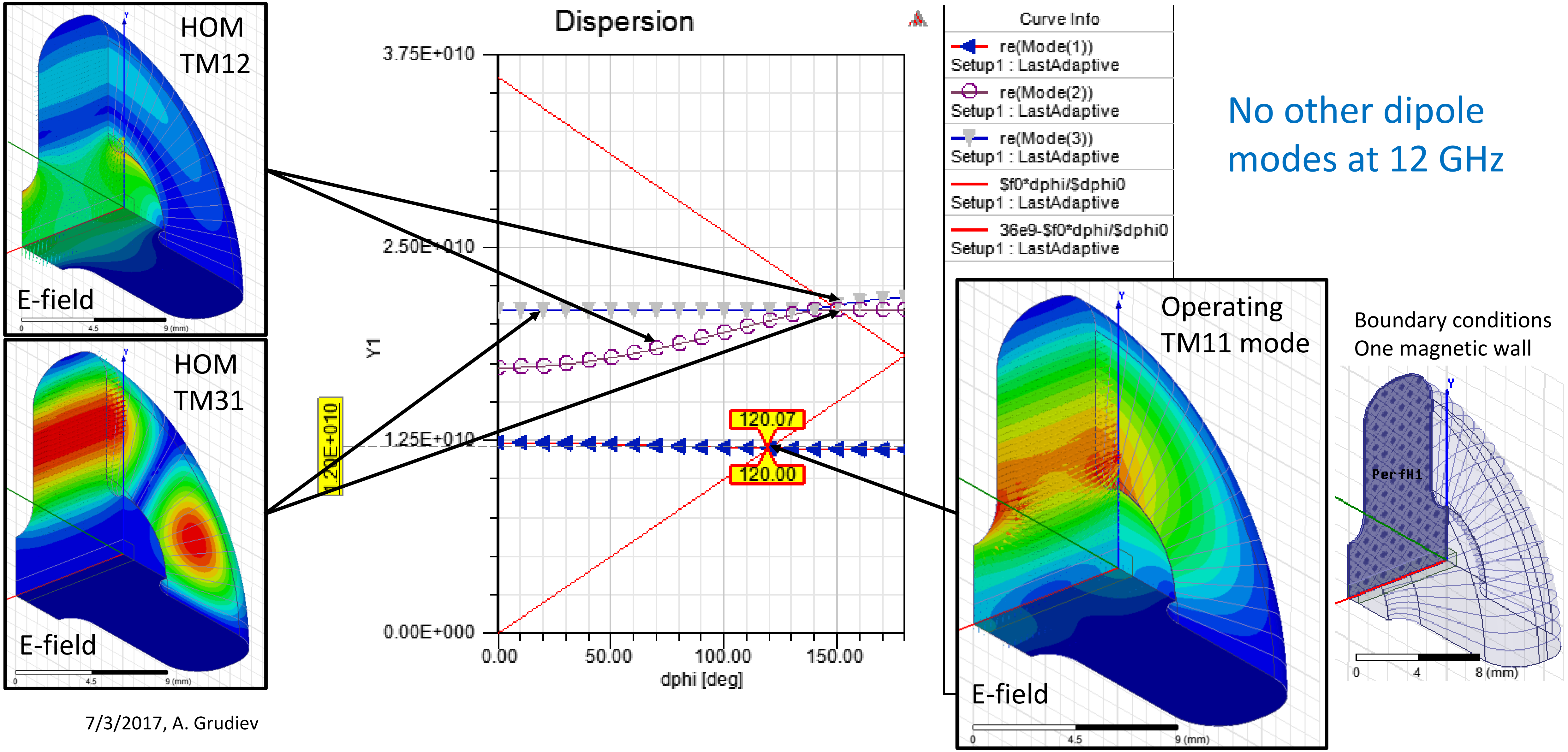
Q-factor in the regular cell from S12:
$Q = \pi f[t_f(120)\text{-}t_f(96)]/[\tau_s(120)\text{-}\tau_s(96)]$
$= \pi f[t_f(120)\text{-}t_f(96)]/[\log(|S_{12}(96)/S_{12}(120)|)]$
$= \pi*12[\text{GHz}]*25[\text{ns}]/\log(0.548/0.474) =$ **6497**

Cell parameters at f=11.9952 GHz => from eigenmode solver

$v_g/c =$ **2.666** %

Q = **6490**

Dispersion diagram for 3 lowest dipole and sextupole TM modes



No other dipole modes at 12 GHz

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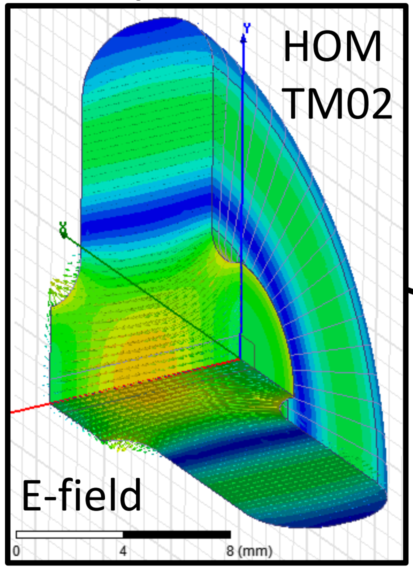
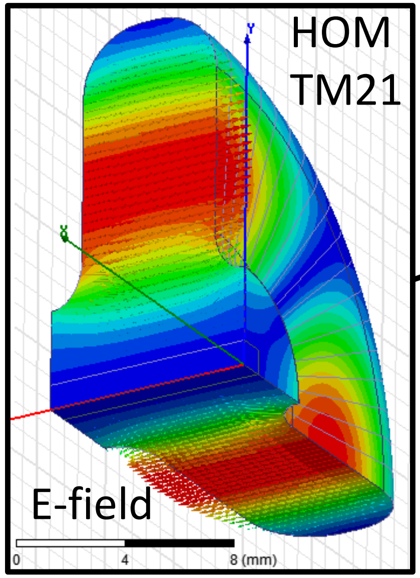
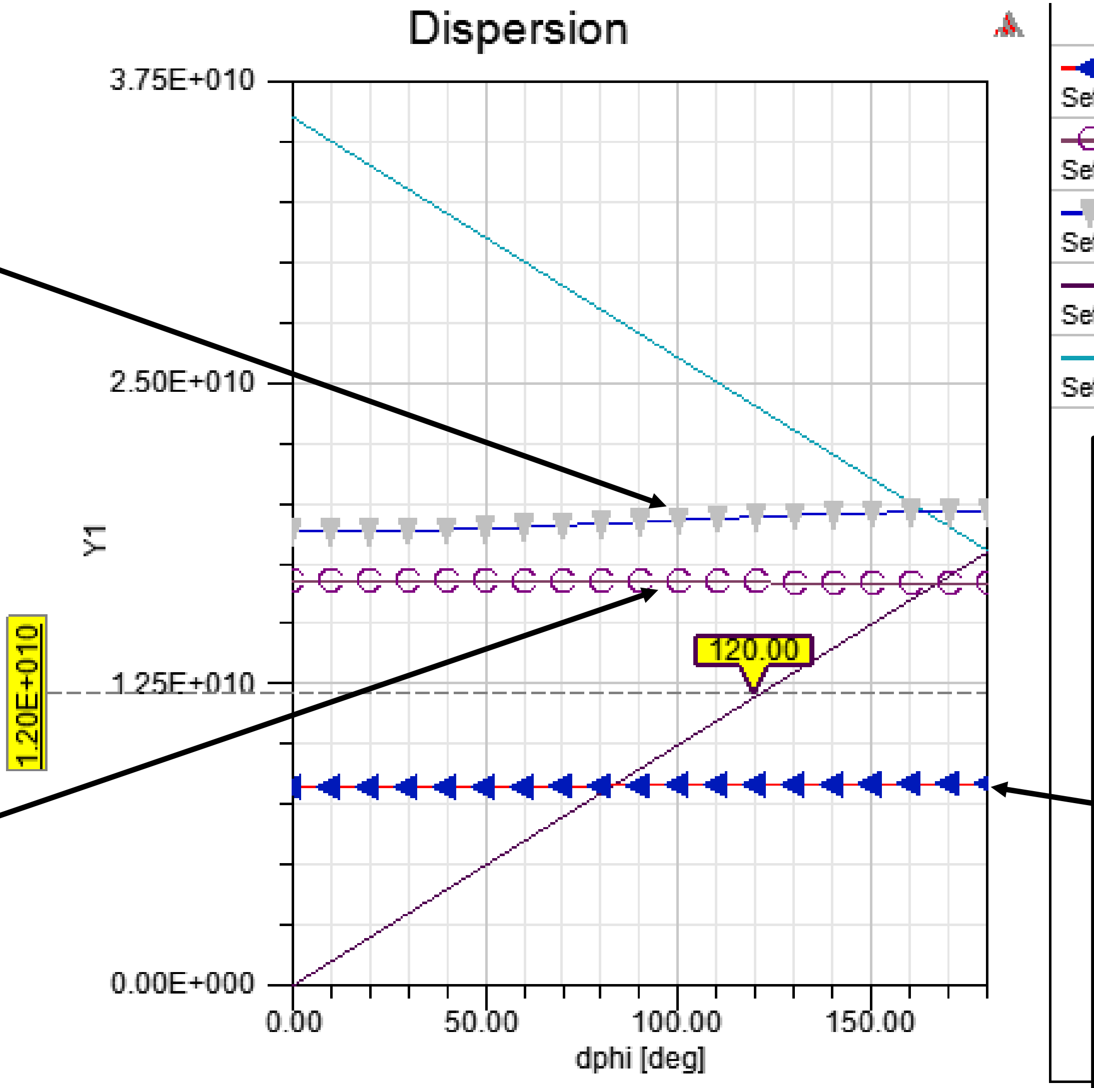
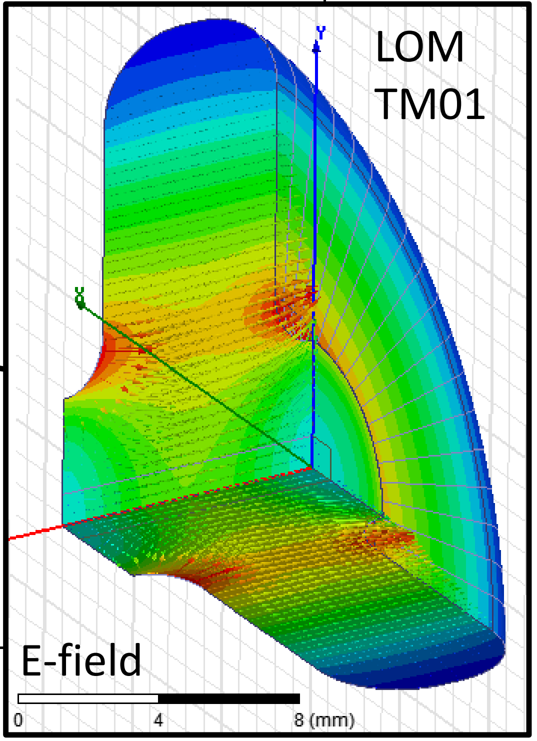
Dispersion diagram for 3 lowest monopole and quadrupole TM modes



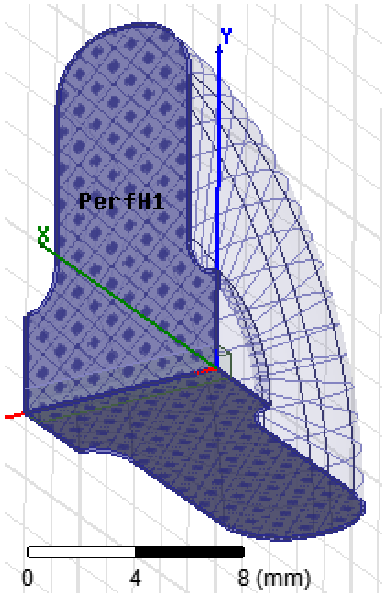




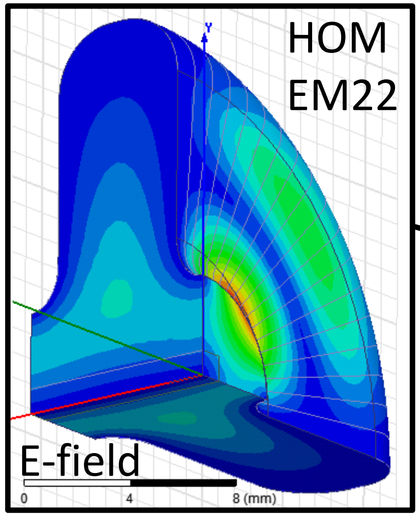
No modes at 12 GHz

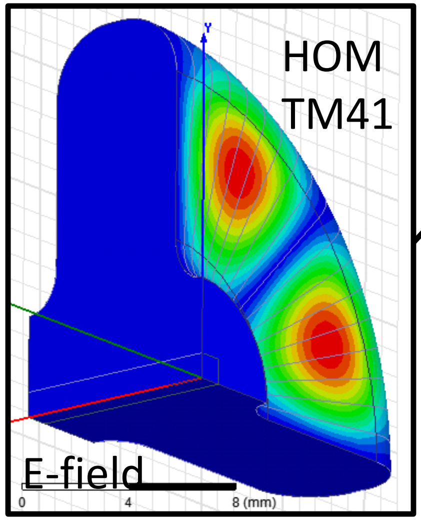


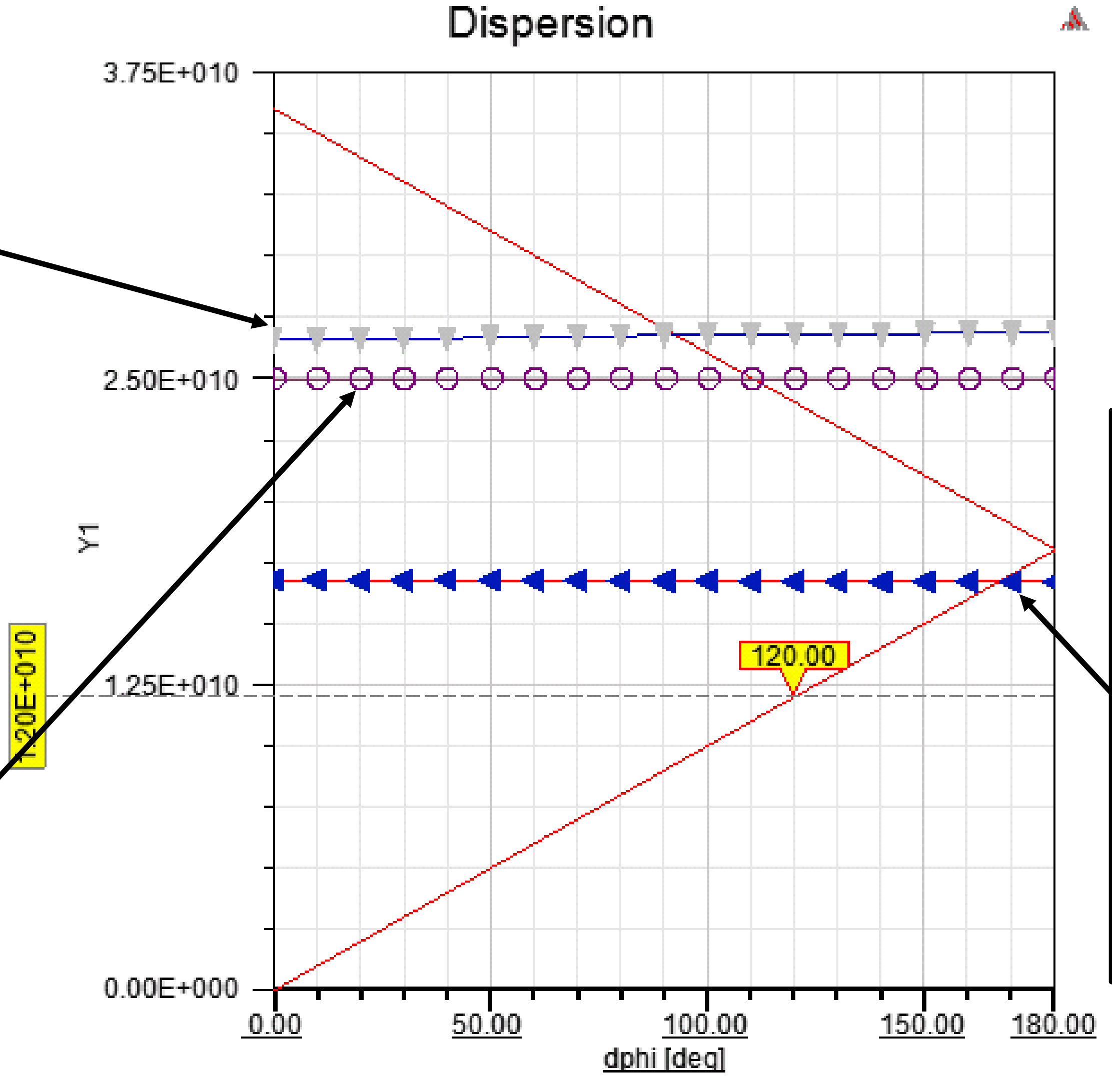
Boundary conditions
Two magnetic walls

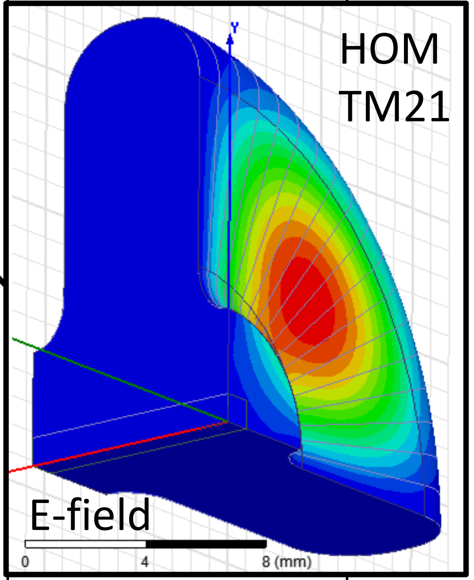


Dispersion diagram for 3 lowest quadrupole, octupole TM modes and hybrid TE/TM mode



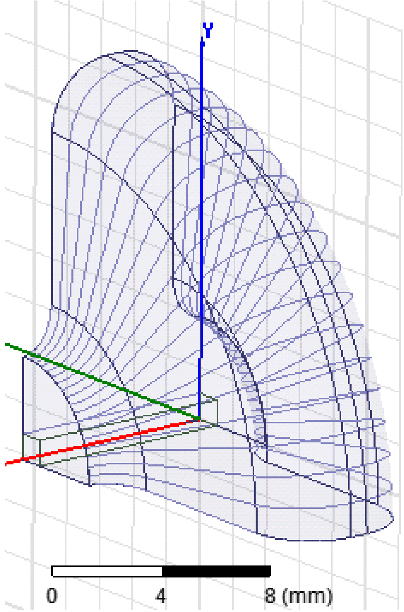






No modes at 12 GHz

Boundary conditions
Two electric walls



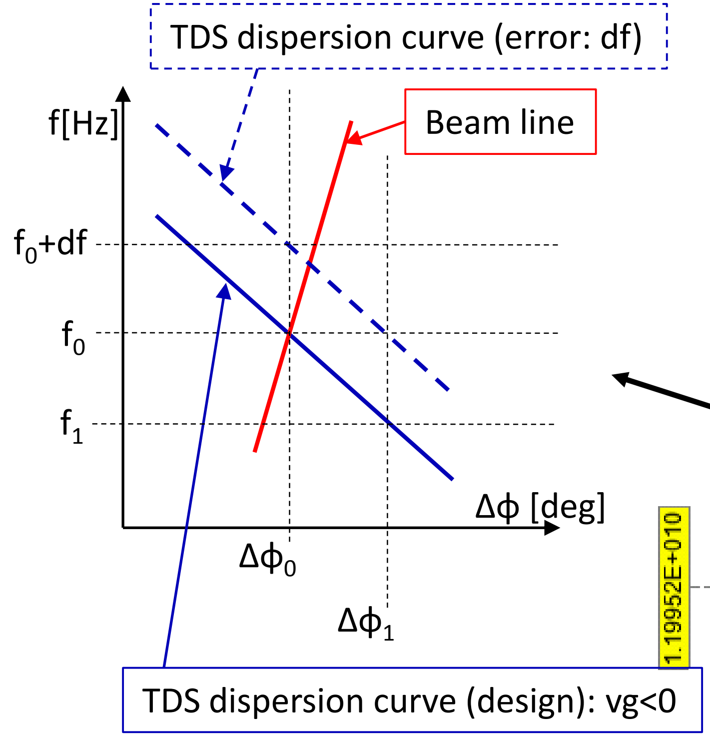
Relationship between synchronous phase and frequency errors

Beam line:
$f=c/h*\Delta\phi/360$

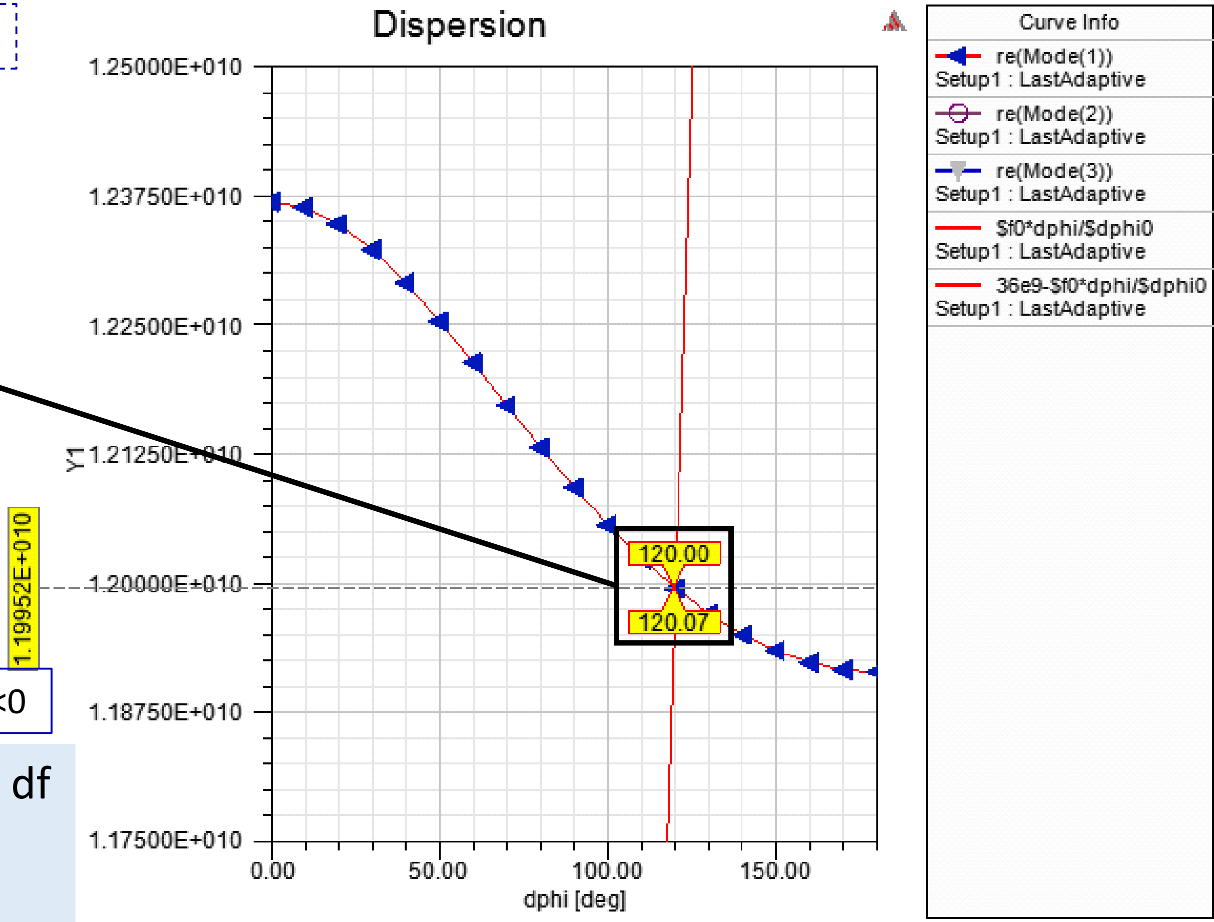
TDS dispersion curve (design):
In linear approximation near synchronous point: $f_0=c/h*\Delta\phi_0/360$

$f = f_0 + v_g/h*(\Delta\phi-\Delta\phi_0)/360$
=>
$(f_1-f_0)/f_0 = v_g/c*(\Delta\phi_1-\Delta\phi_0)/\Delta\phi_0$

For TDS dispersion curve with error df:
$df = f_0-f_1$
=>
$$\mathbf{df/f_0 = -v_g/c*(\Delta\phi_1-\Delta\phi_0)/\Delta\phi_0}$$



Dispersion curve of operating TM11 mode



For tolerances study eigenmode setup is used with dphi0 where df is calculated for both polarizations as a function of geometrical errors