T24_vg1.8_disk

11WNSDVG1.8

CLIC_G un-damped @ 11.424 GHz

measurements versus simulations

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CERN

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Acknowledgements

CERN:
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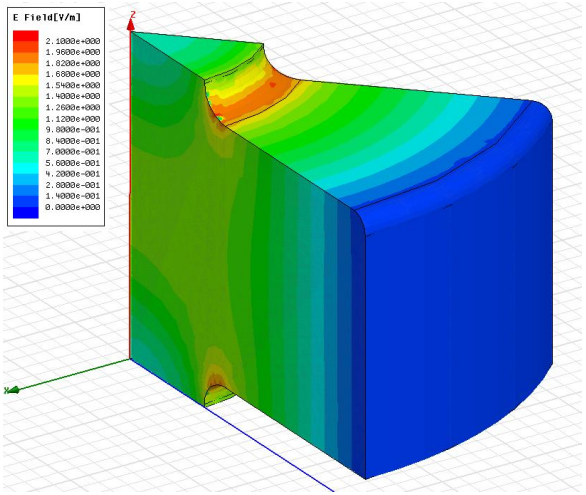
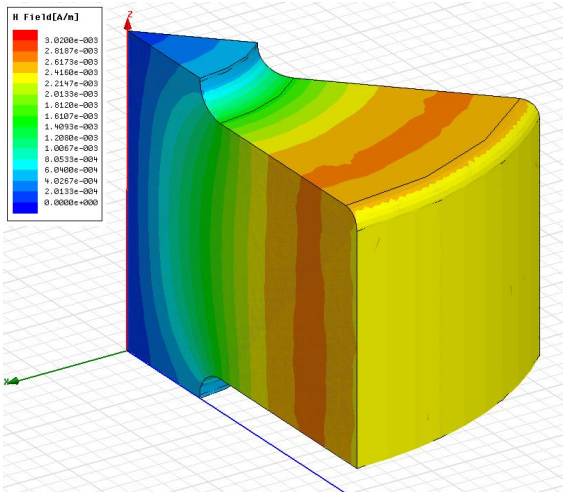
SLAC:
Z. Li

First cell

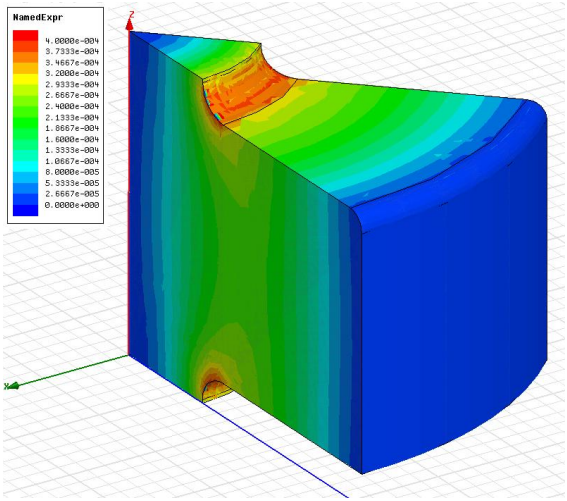
E_s/E_a



H_s/E_a



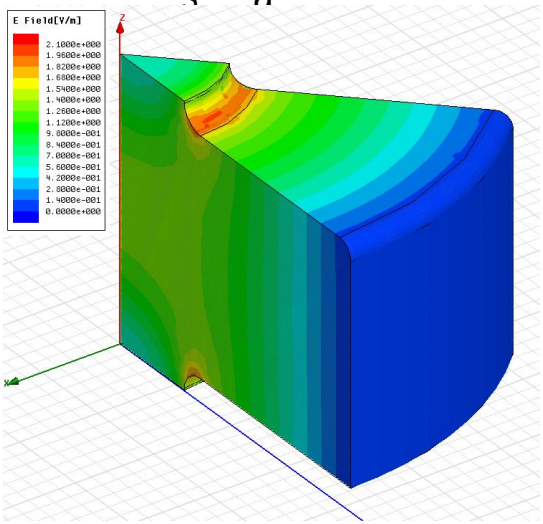
S_c/E_a^2



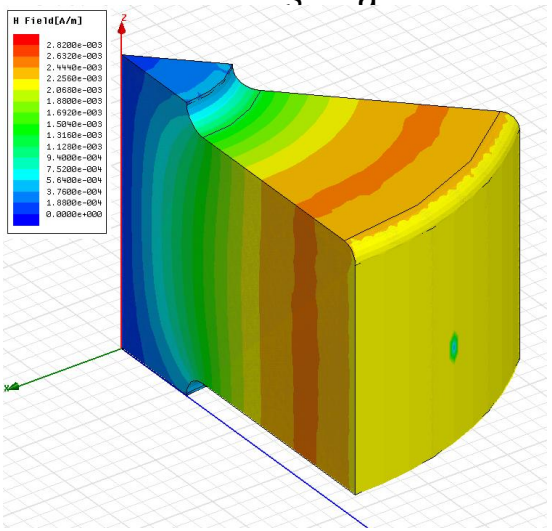
a [mm]	3.307
d [mm]	1.753
e	1.16
f [GHz]	11.433
Q(Cu)	6814
vg/c [%]	1.83
r'/Q [LinacΩ/m]	15198
Es/Ea	1.95
Hs/Ea [mA/V]	2.6
Sc/Ea^2 [mA/V]	0.37

Middle cell

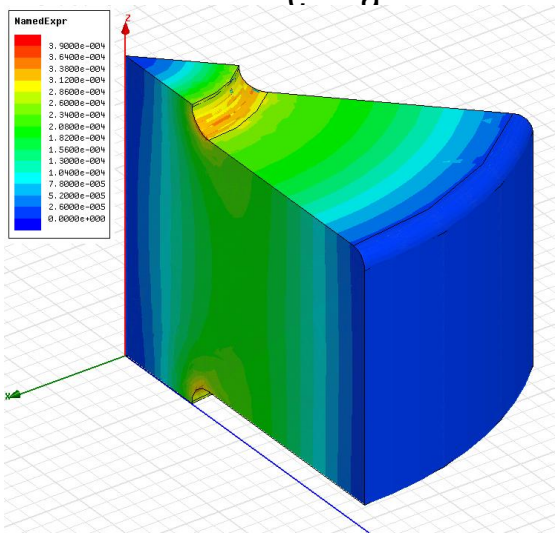
E_s/E_a



H_s/E_a



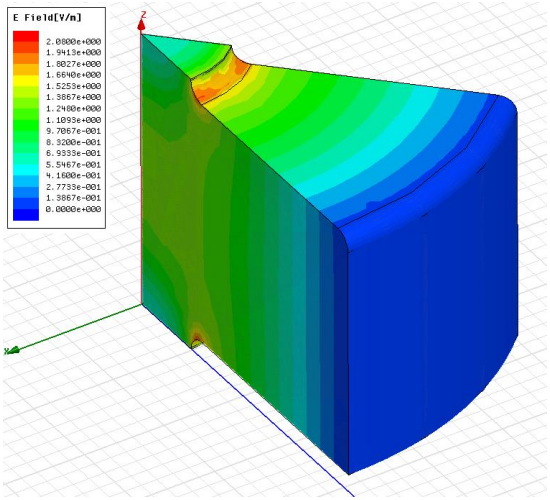
S_c/E_a^2



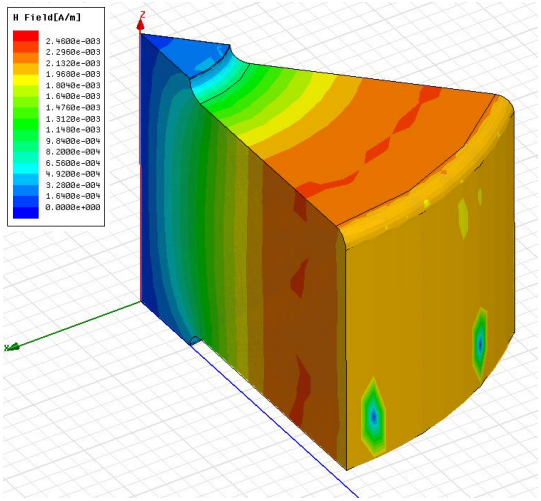
a [mm]	2.887
d [mm]	1.402
e	1.15
f [GHz]	11.432
Q(Cu)	6980
vg/c [%]	1.33
r'/Q [LinacΩ/m]	16960
Es/Ea	1.95
Hs/Ea [mA/V]	2.45
Sc/Ea^2 [mA/V]	0.34

Last cell

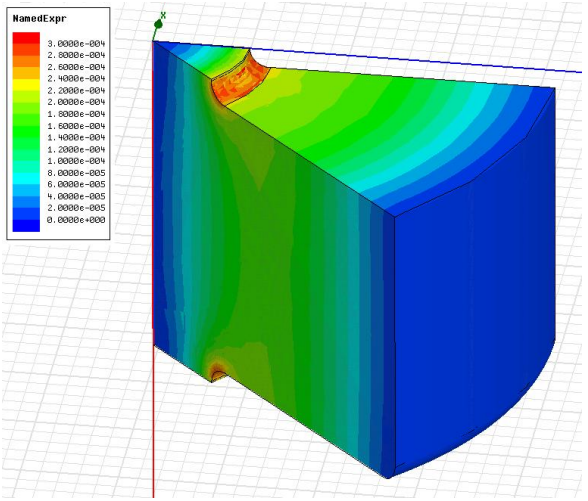
E_s/E_a



H_s/E_a



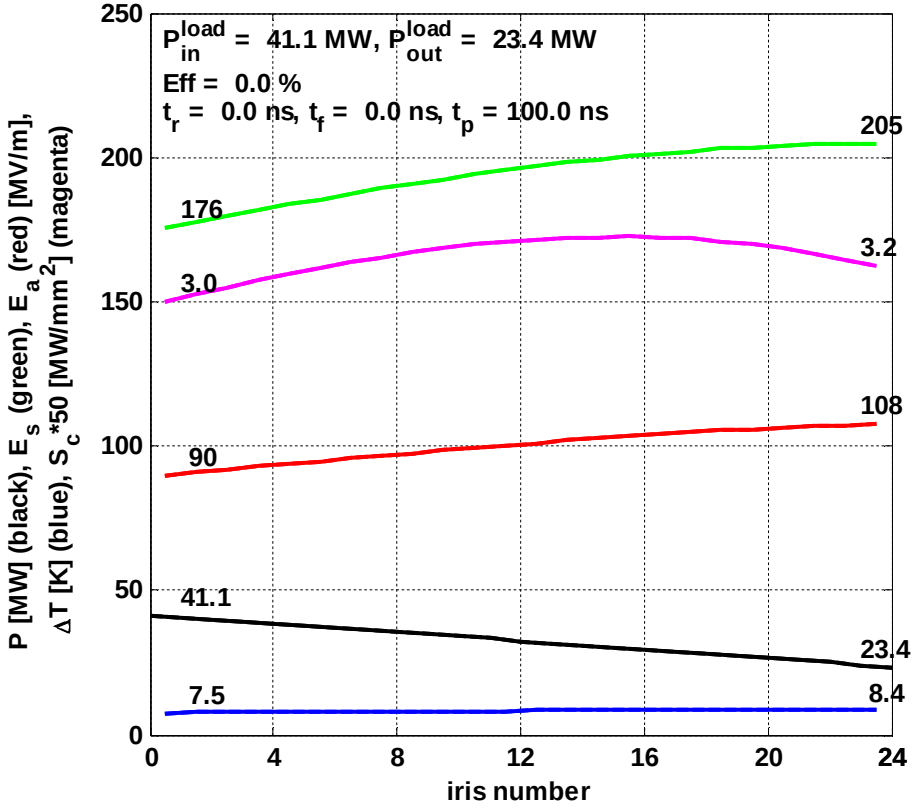
S_c/E_a^2



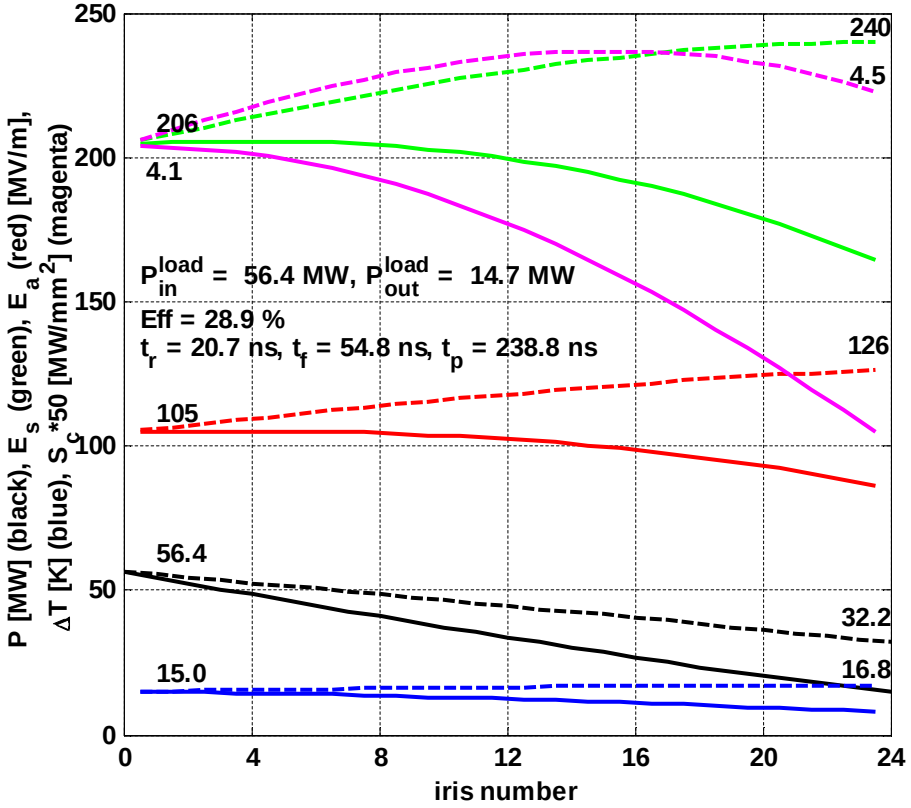
a [mm]	2.467
d [mm]	1.05
e	1.13
f [GHz]	11.426
Q(Cu)	7157
vg/c [%]	0.92
r'/Q [LinacΩ/m]	18713
Es/Ea	1.9
Hs/Ea [mA/V]	2.3
Sc/Ea^2 [mA/V]	0.28

Gradient in 24 regular cells

Average unloaded of 100 MV/m



Average loaded of 100 MV/m



$$\frac{dP}{dz} = -\frac{\omega}{Qv_g}P - \sqrt{\frac{\omega}{v_g}\frac{R'}{Q}}\, I\, P^{\frac{1}{2}}$$

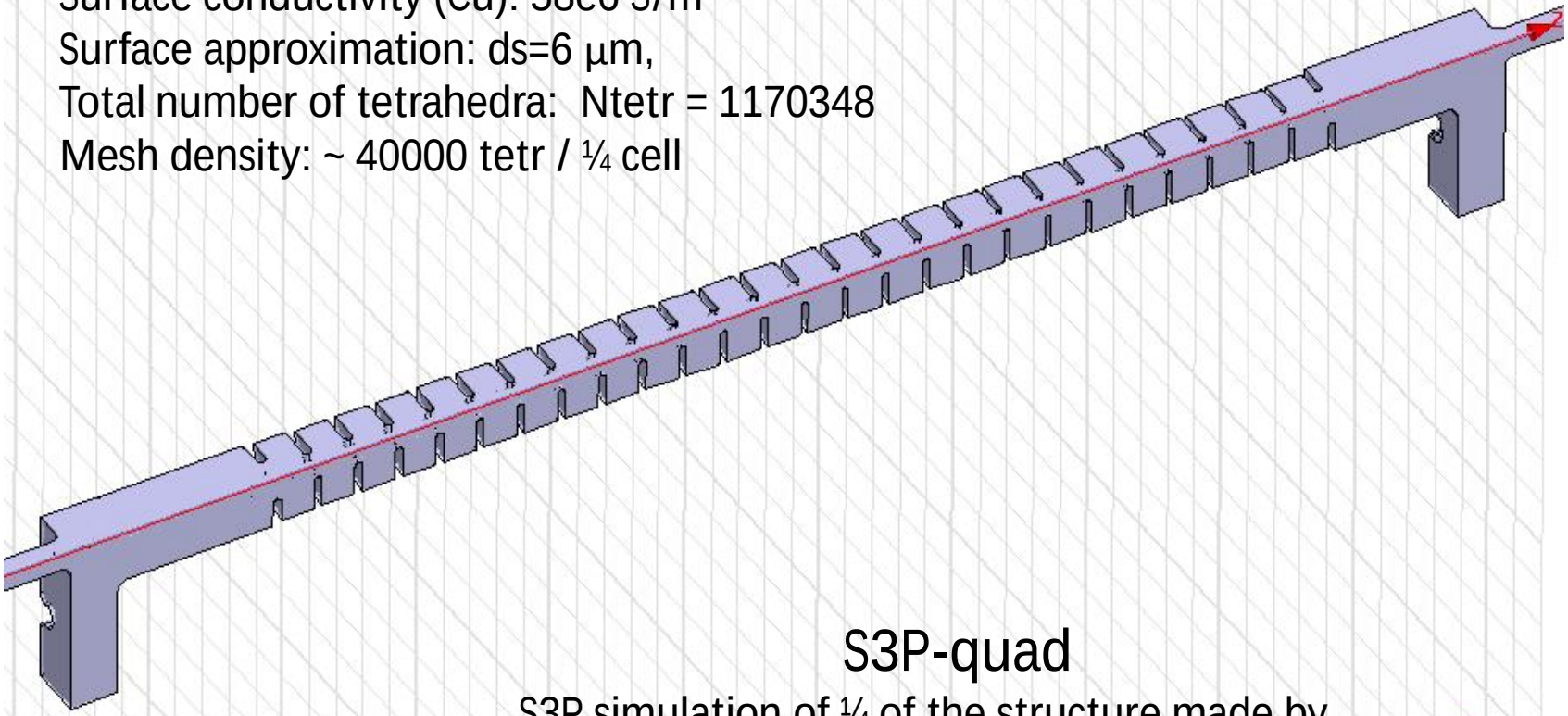
Number of regular cells: Nc	24
Bunch population: N	3.72×10^9
Number of bunches: Nb	312
Bunch separation: Ncycl	6 rf cycles

Simulation setup 1 & 2

HFSS-quad

HFSS v10.1

HFSS simulation of ¼ of the structure:
Surface conductivity (Cu): 58e6 S/m
Surface approximation: ds=6 μm,
Total number of tetrahedra: Ntetr = 1170348
Mesh density: ~ 40000 tetr / ¼ cell



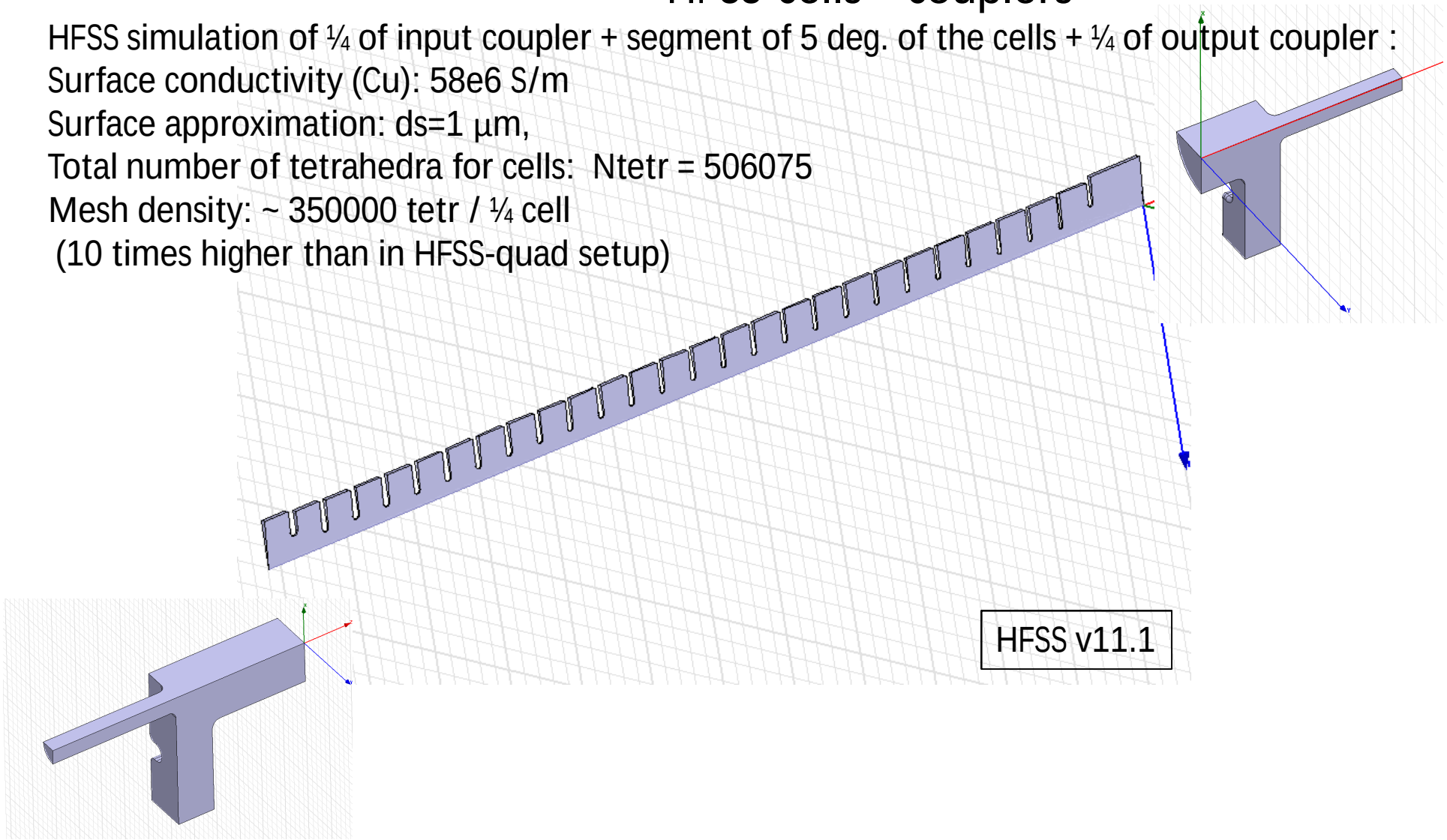
S3P-quad

S3P simulation of ¼ of the structure made by Zenghai Li at SLAC-ACD
Surface conductivity (Cu): 57e6 S/m different

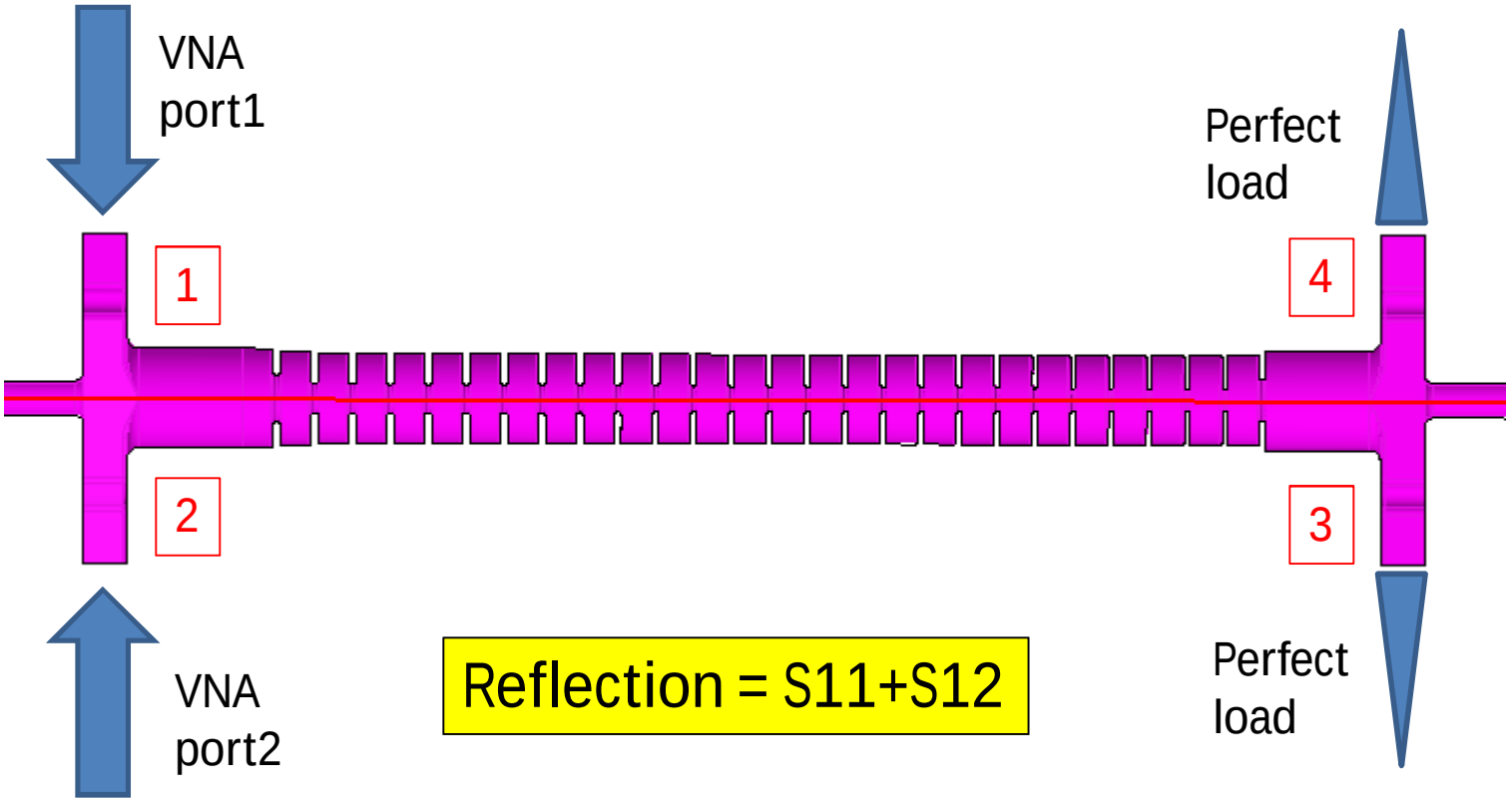
Simulation setup 3

HFSS-cells + couplers

HFSS simulation of ¼ of input coupler + segment of 5 deg. of the cells + ¼ of output coupler :
Surface conductivity (Cu): 58e6 S/m
Surface approximation: ds=1 μm,
Total number of tetrahedra for cells: Ntetr = 506075
Mesh density: ~ 350000 tetr / ¼ cell
(10 times higher than in HFSS-quad setup)

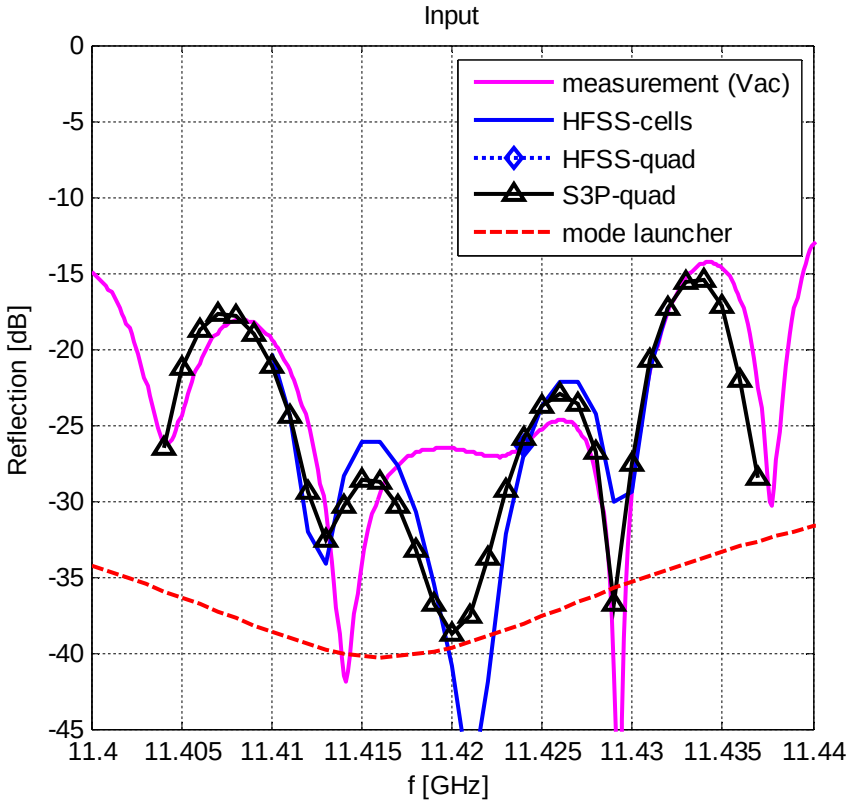


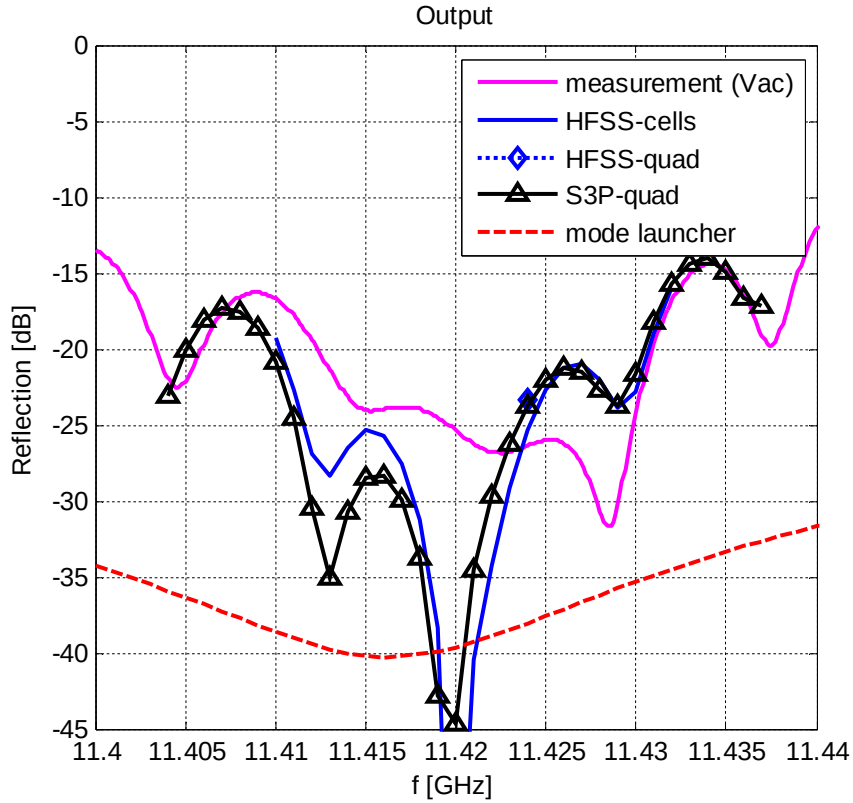
Measurement setup 1 (reflections)



Frequency correction due to air (ε = 1.00059)
Frequency in vacuum: f' = f*sqrt(1.00059) ≈ f + 3.5 MHz @ X-band

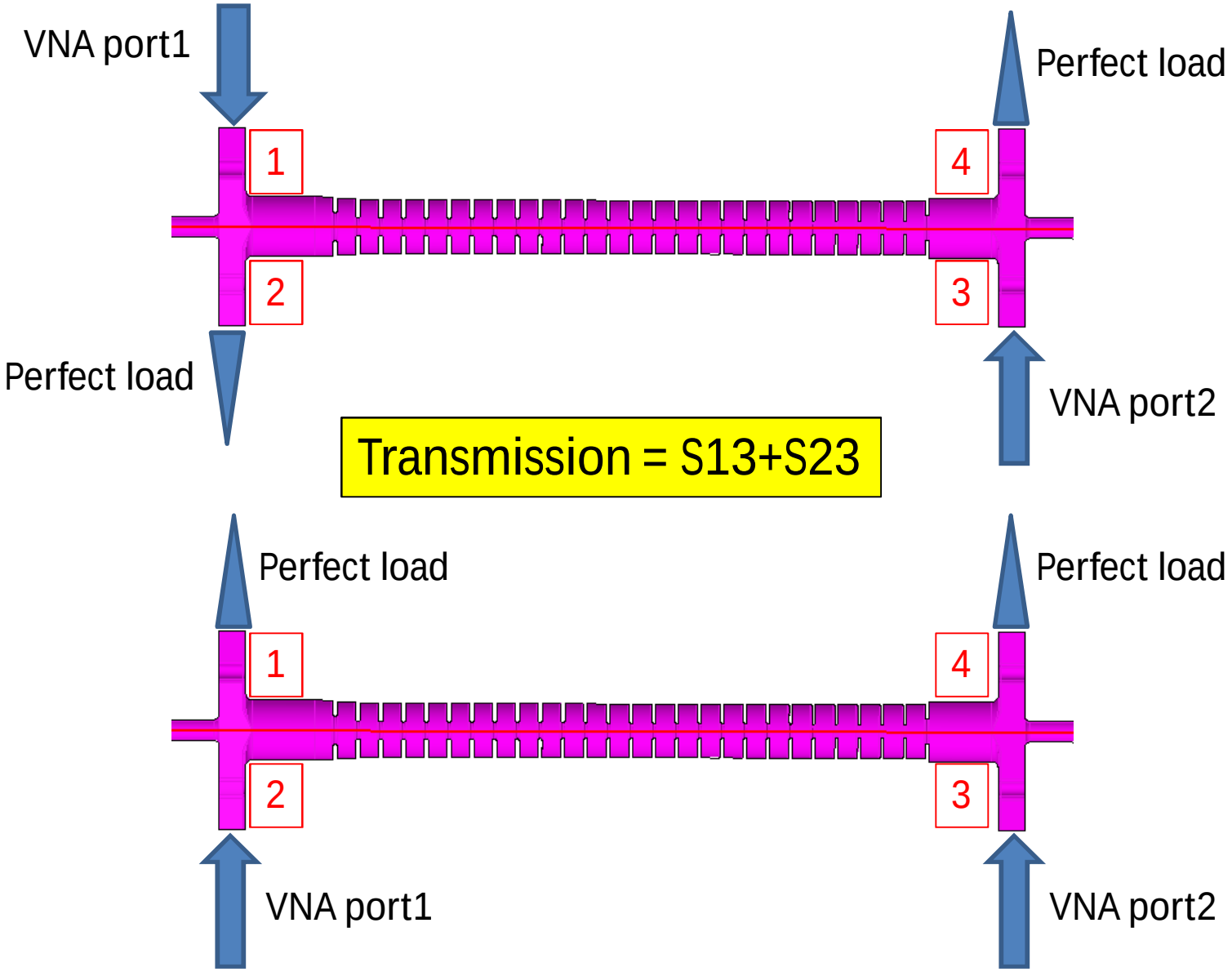
Reflection: comparison



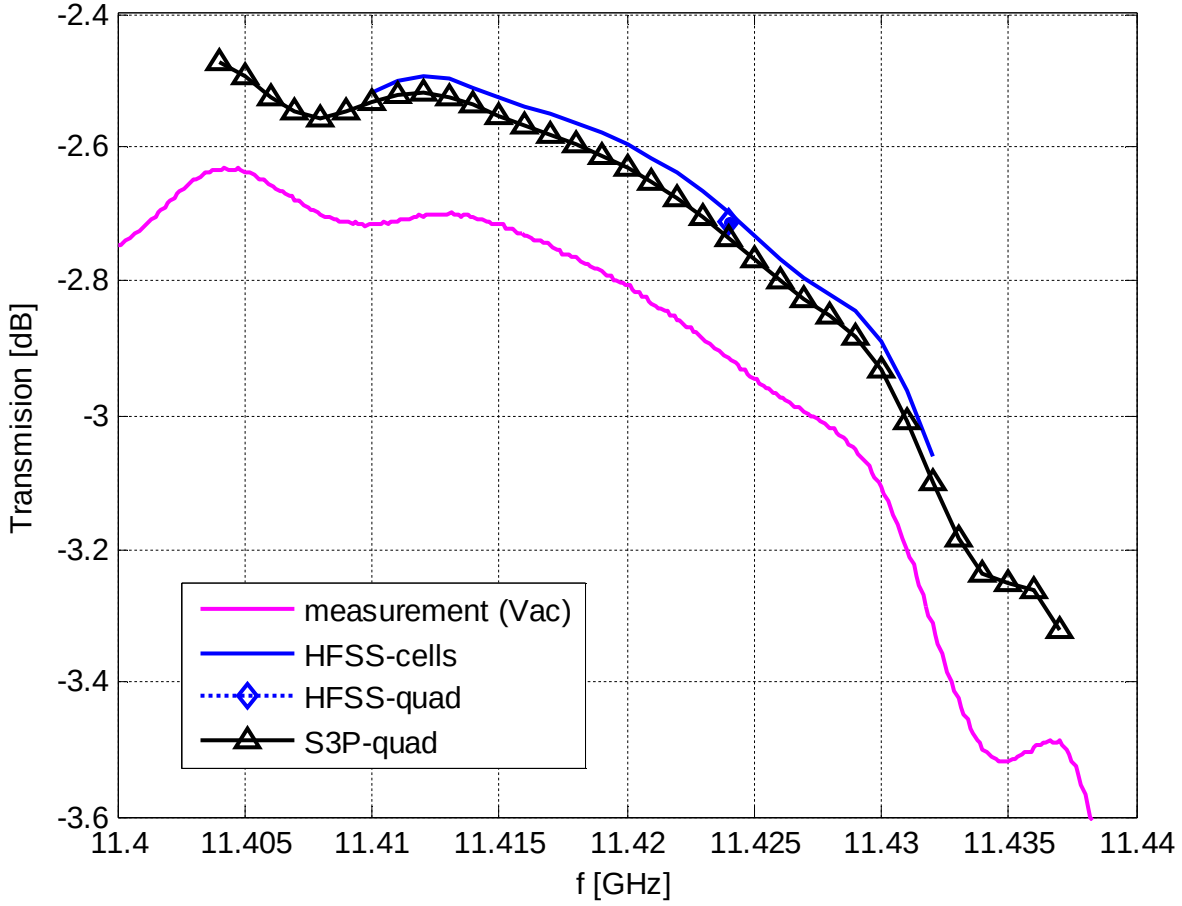


There is very small (~1MHz) or no difference in frequency between simulations and the air corrected measurements

Measurement setup 2 (transmission)



Transmission: comparison



- There is small difference between HFSS and S3P simulation results due to different conductivity used in the simulations
- Both simulation results show higher transmission than air corrected measurements by about 0.2 dB

Some useful equations

$$P_{out} = P_{in} e^{-2\tau} \text{ where } \tau = \ln|S_{12}| \text{ attenuation}$$

On the other hand

$$P_{out} = P_{in} e^{-\frac{\omega t_f}{Q}} \text{ where } Q = \frac{\omega W}{P_{loss}} \text{ - average quality factor}$$

$$t_f = \frac{W_0}{P_{in}} \equiv \frac{d(\phi = \arg S_{12})}{d\omega} \text{ - filling time } \equiv \text{ group delay}$$

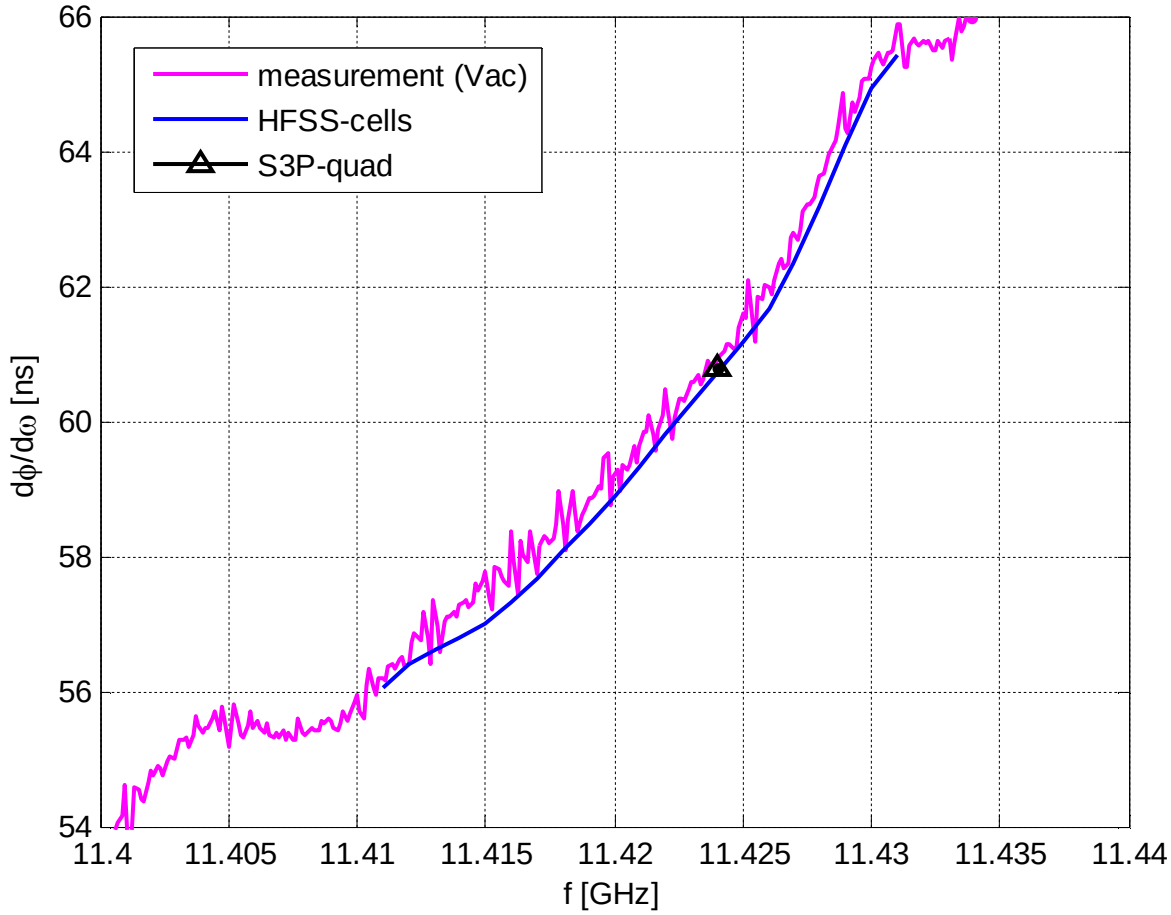
W - stored energy in lossy structure

W_0 - stored energy in lossfree structure

Finally

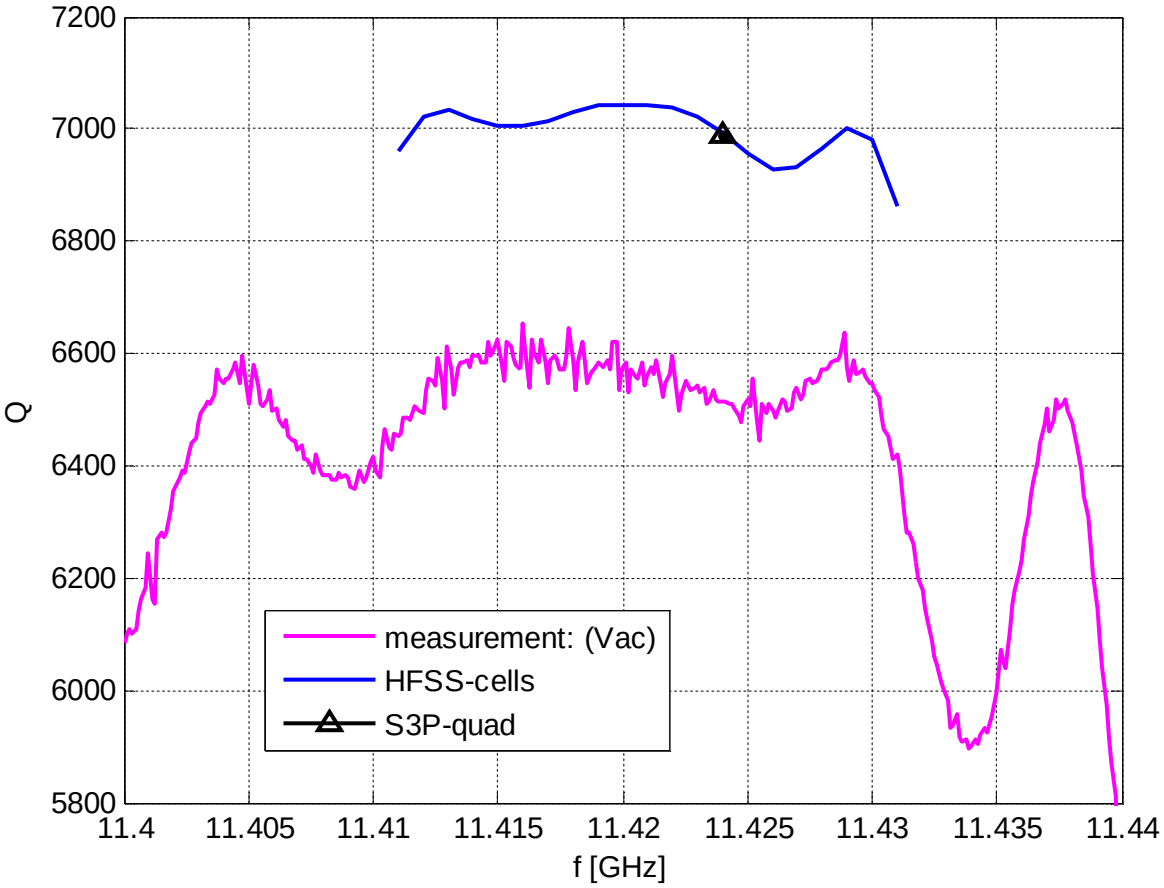
$$Q = \frac{\omega t_f}{2\tau}$$

Transmission: comparing group delay



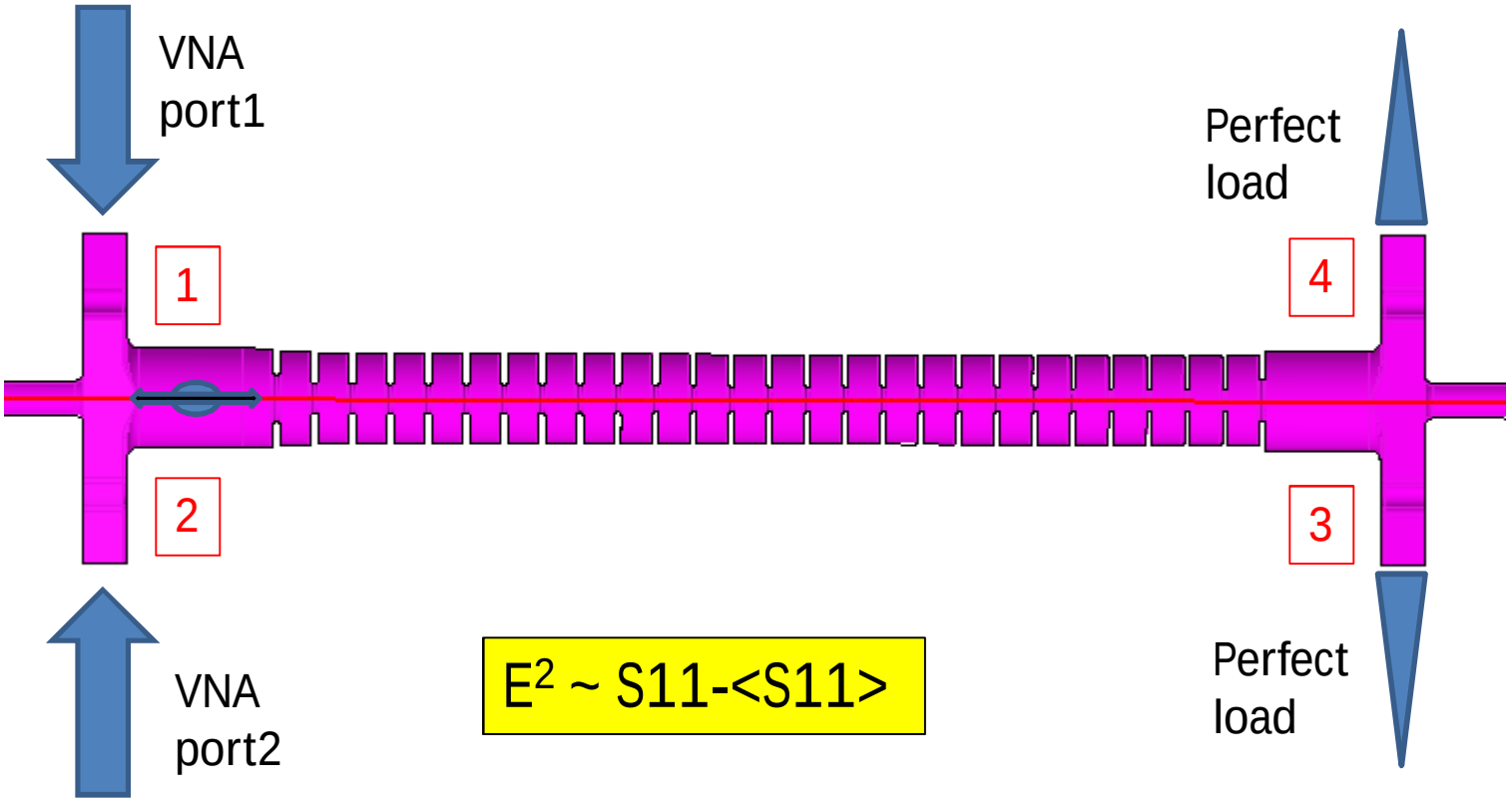
There is no difference between both HFSS and S3P simulations and the air corrected measurements

Transmission: comparing Q-factor

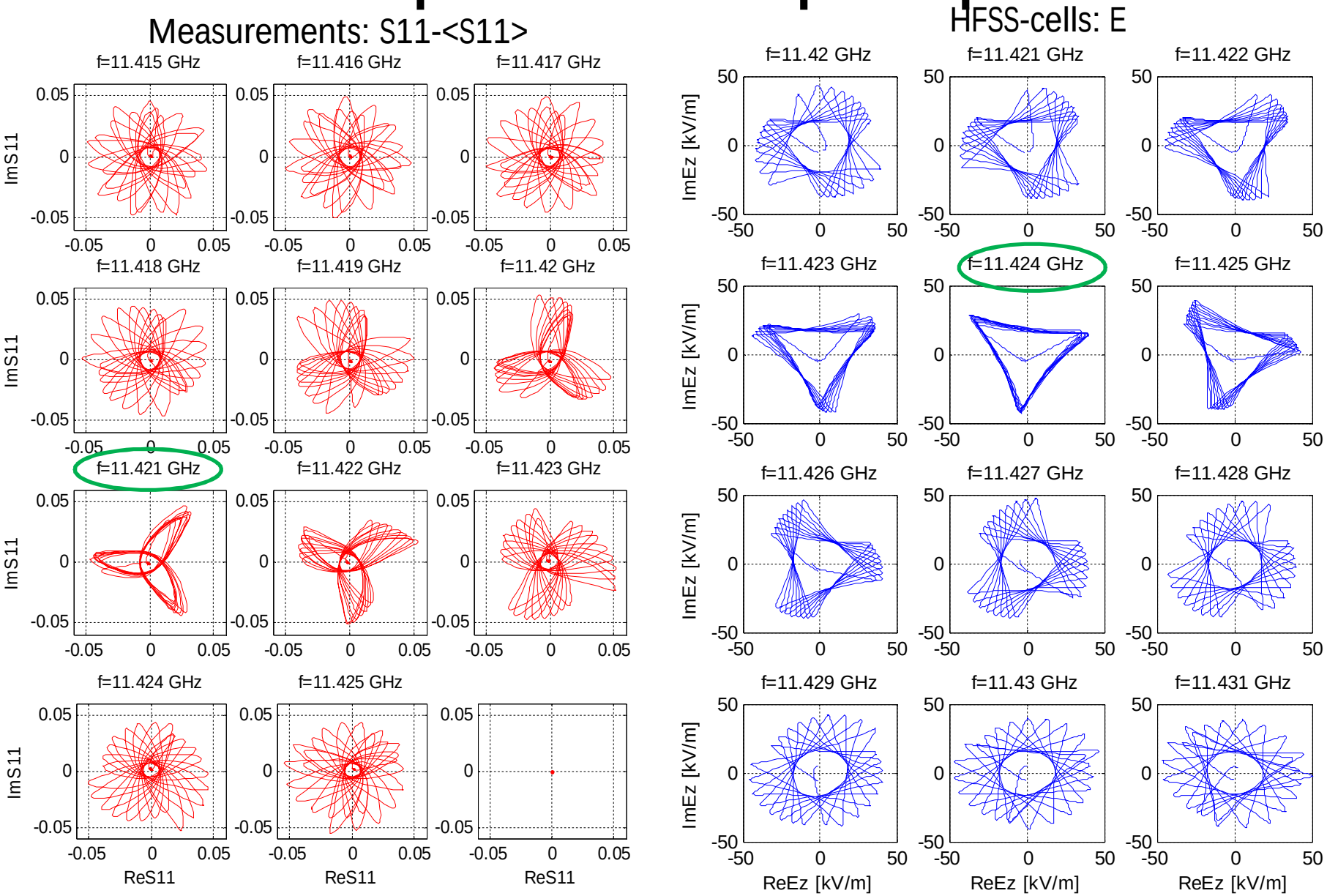


- There is no difference in Q-factor (~7000) between HFSS and S3P simulations.
- The measured Q-factor of about 6600 is lower than the simulated value by about 6 %.

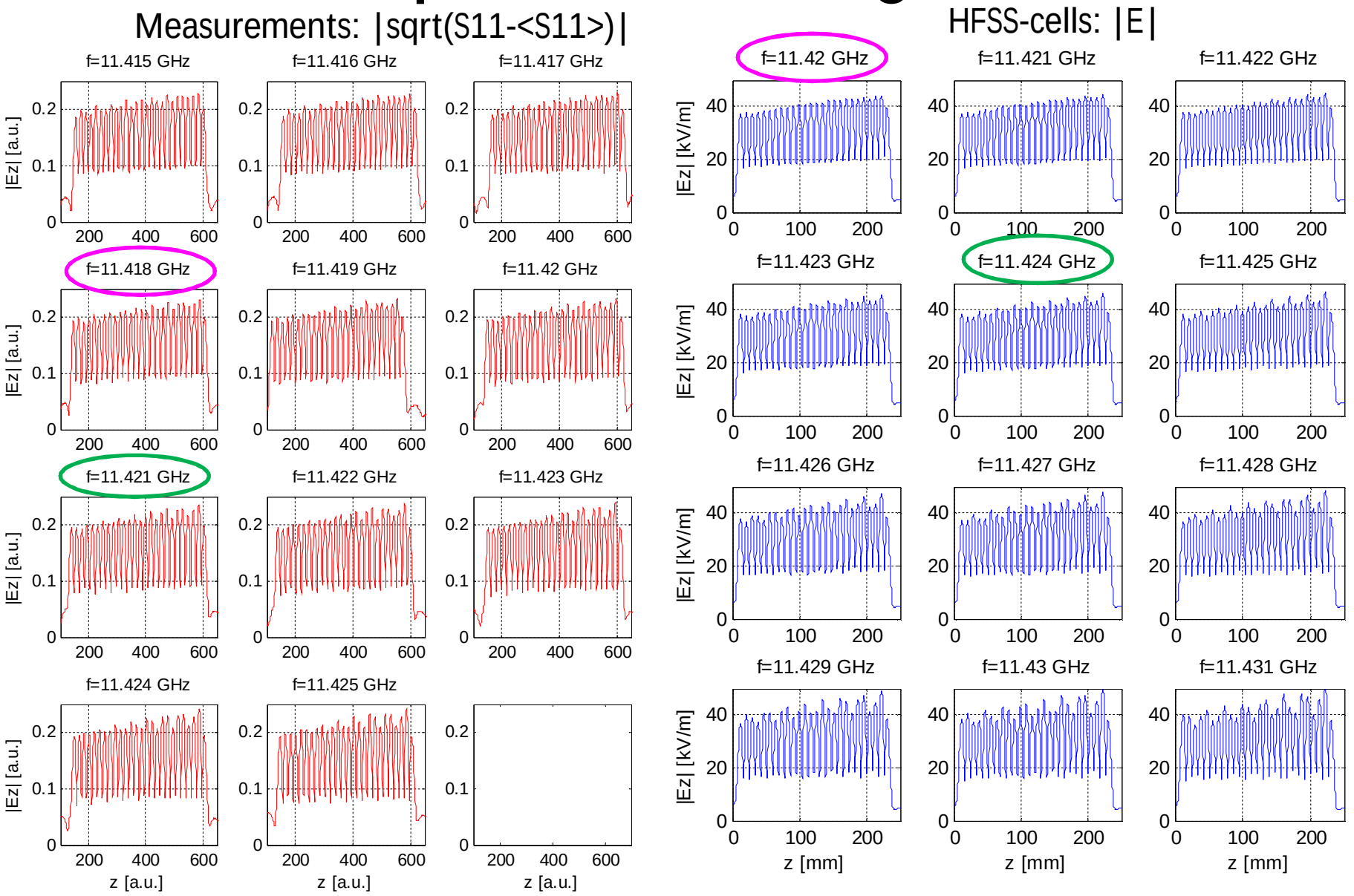
Measurement setup 3 (bead pull)



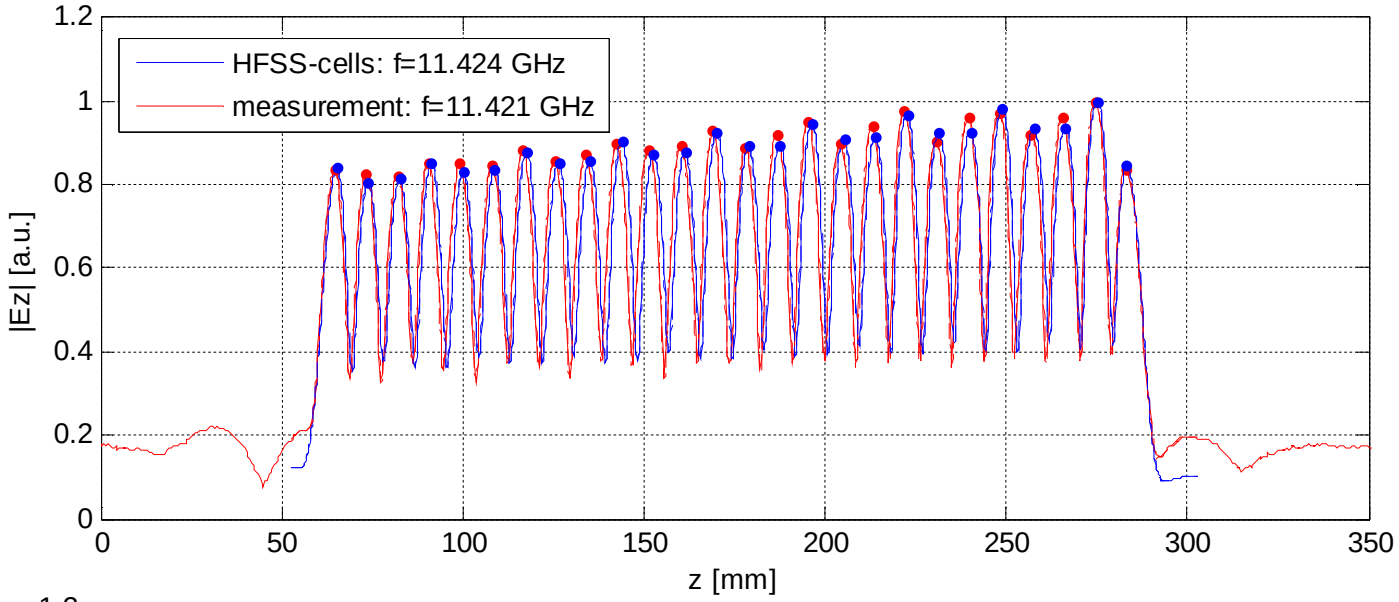
Bead pull in complex plane



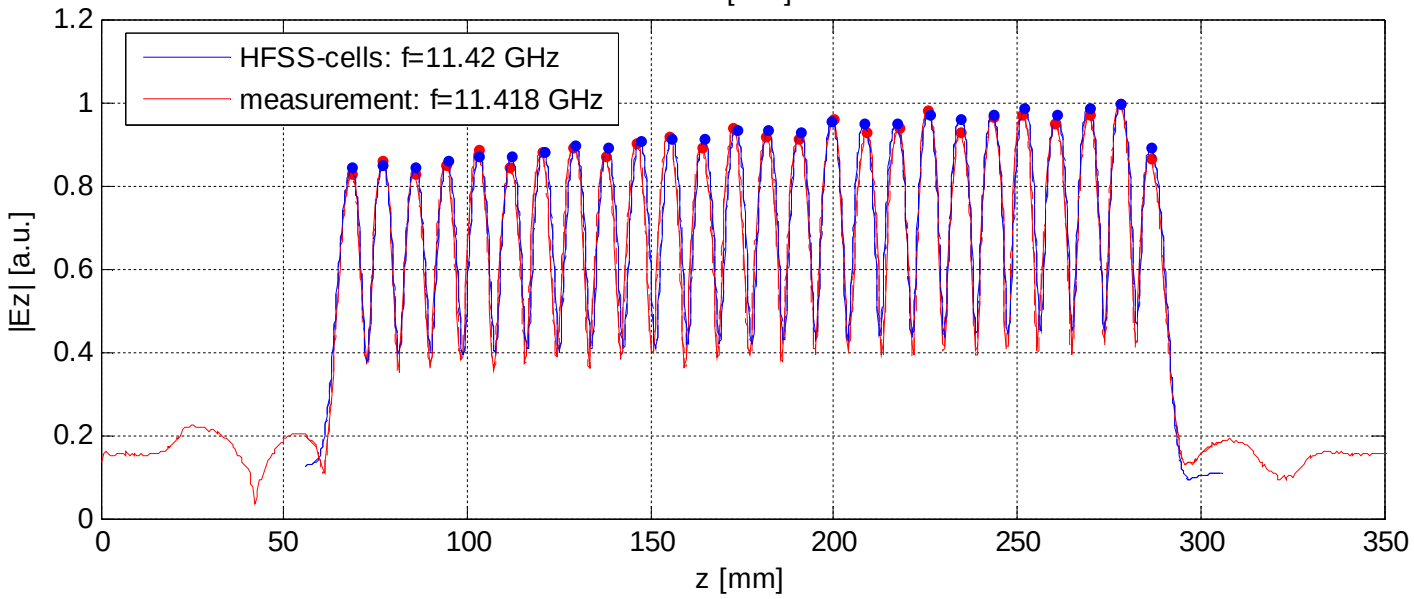
Bead pull: field magnitude



Field distribution at different frequencies

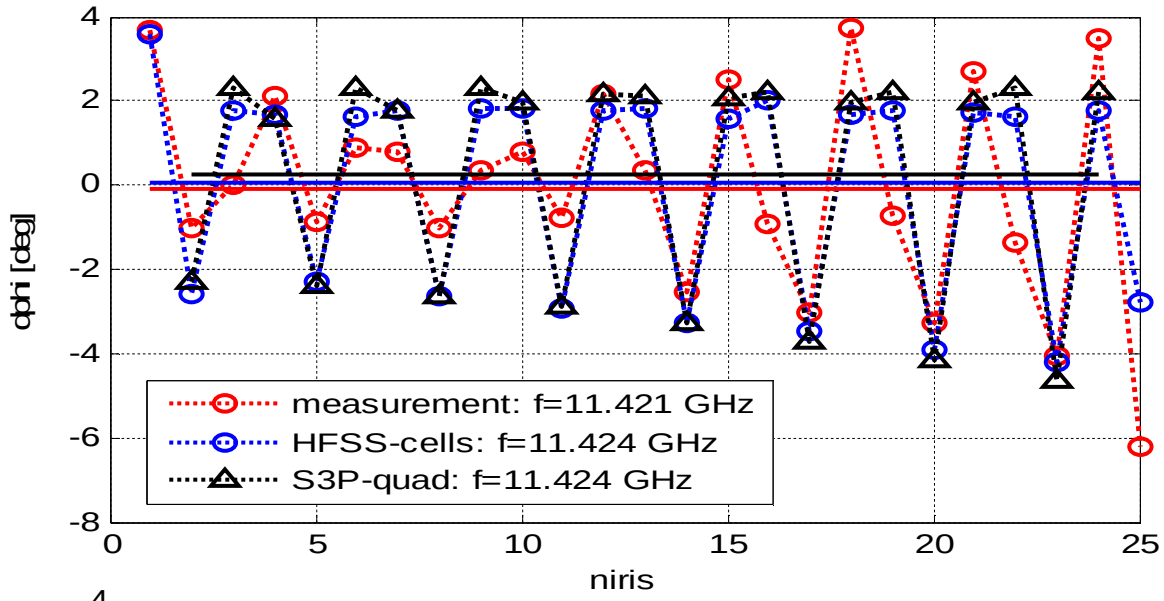


120^{o} rf phase advance per cell frequency 11.424 GHz

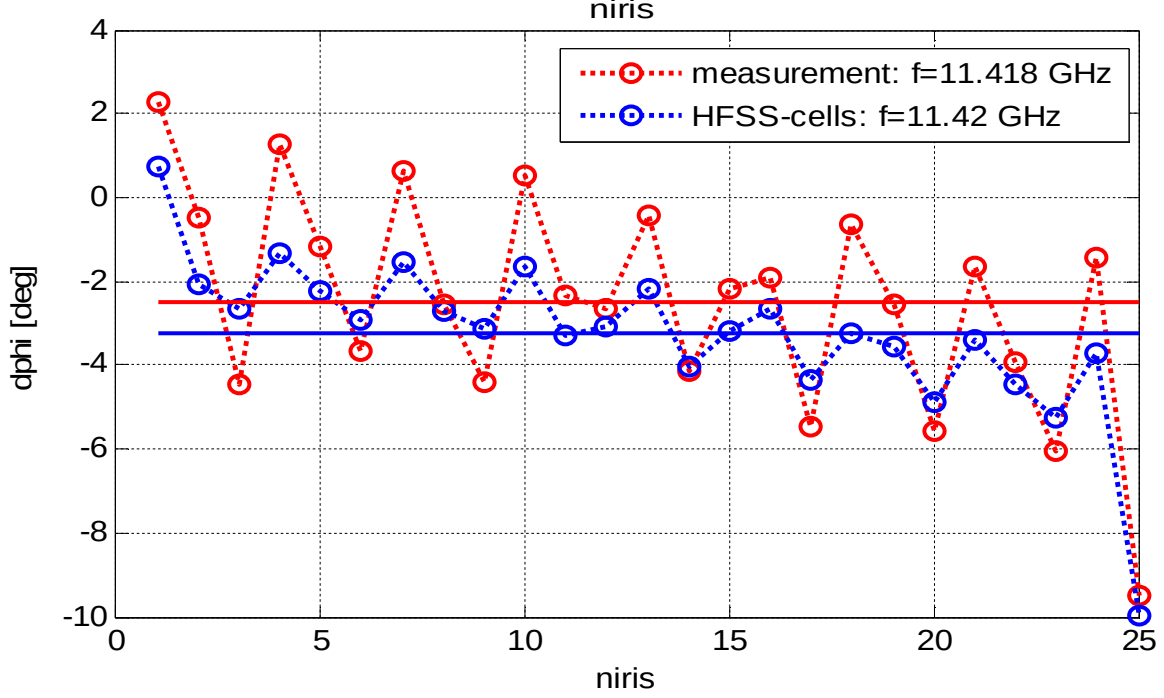


Best match frequency 11.420 GHz

RF phase advance per cell at different frequencies



120^{o} rf phase advance per cell frequency: 11.424 GHz



Best match frequency: 11.420 GHz

Summary table for T24_vg1.8_disk

	S12	Pout/ Pin	τ=0.5ln (Pout/ Pin)	tf=dϕ/ dω [ns]	tf=W0 /Pin [ns]	Q=ωtf/2τ	Q=ωW /(Pin-Pout)	Q=ωW /Ploss	Pin100 24 cells [MW]
Measure ments (Vac)	0.715	0.511	0.336	60.9	-	6600	-	-	
HFSS ¼	0.732	0.536	0.312	-	58.4	6720	7010	7010	
HFSS InCoup OutCoup Cells 24+2	0.731 0.99875 0.99889 0.733	0.534 0.9975 0.9978 0.537	0.313 0.0013 0.0011 0.311	60.7 <- <- 59.9	59.8 0.46 0.36 59.0	6960 12700 11800 6910	6940 13000 12300 6880	6640 13200 12300 6580	42.2
3-cells model		0.569-0.533	0.282-0.315	-	54.8-59.37	6974-6764	6980		41.1
S3P (SLAC)	0.730	0.533	0.315	60.8		6927(σ=57e6) 6988(σ=58e6)			42.4

Summary on comparison

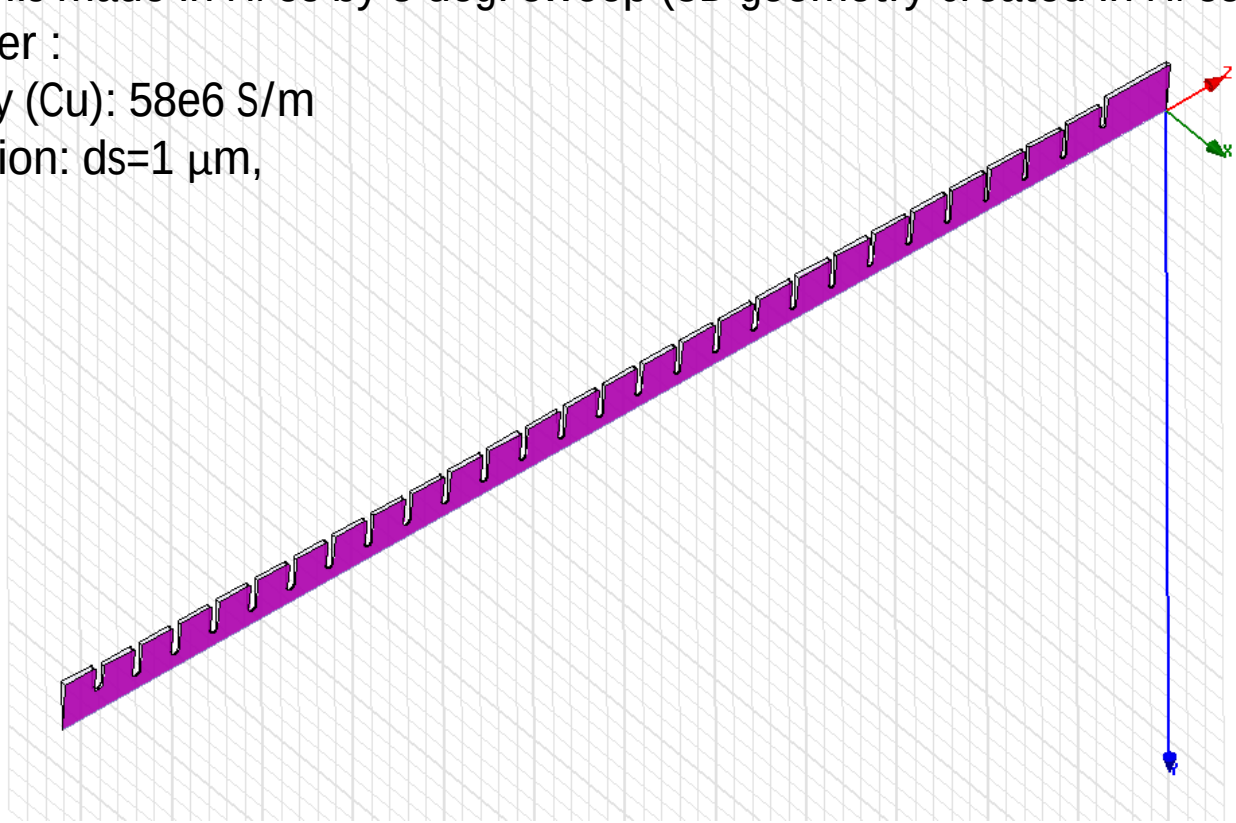
- Simulation results of HFSS and S3P show very good agreement
- Q-factor
  - All 3 different ways of calculating Q-factor: S3P, HFSS-S-parameter solver and HFSS-eigenmode solver give very close values of about 7000
  - The measurements of the T24_vg1.8_disk structure made at CERN show 6 % lower Q-factor of 6600
- RF phase advance
  - Both HFSS and S3P simulations and air corrected measurements simulations show 120^{o} rf phase advance frequency of 11.424 GHz which is the design frequency
  - Good agreement (± 0.5 MHz) between simulations and measurements demonstrates extremely high (sub-micron) precision of machining. For example, it is equivalent to ± 0.6 μm tolerance on the outer wall radius RF phase advance
- Structure matching
  - There is a design error in structure matching of about 4 MHz. The match frequency is 11.420 GHz . To some extent this is also in agreement with the measurements

HFSS S-par solver: v10.1 versus v11.1

Simulation setup 4

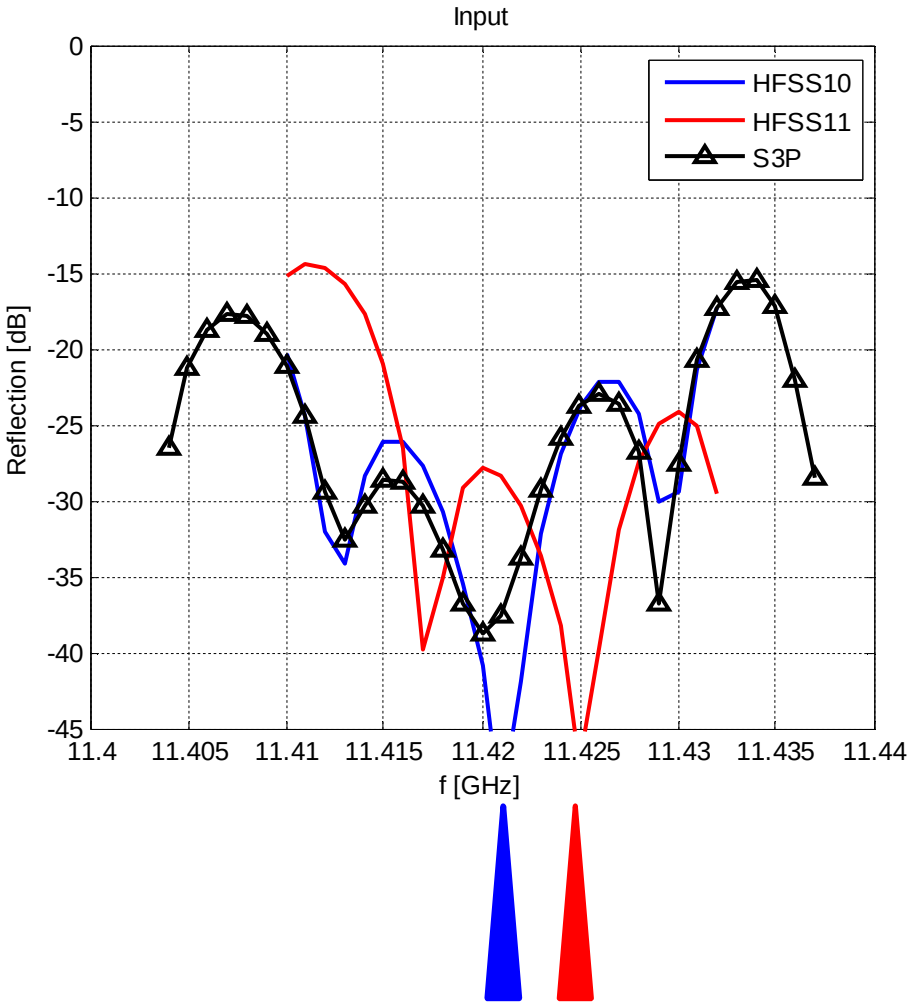
HFSS-cells + couplers

HFSS simulation of ¼ of input coupler
+ segment of the cells made in HFSS by 5 deg. Sweep (3D geometry created in HFSS)
+ ¼ of output coupler :
Surface conductivity (Cu): 58e6 S/m
Surface approximation: ds=1 μm,

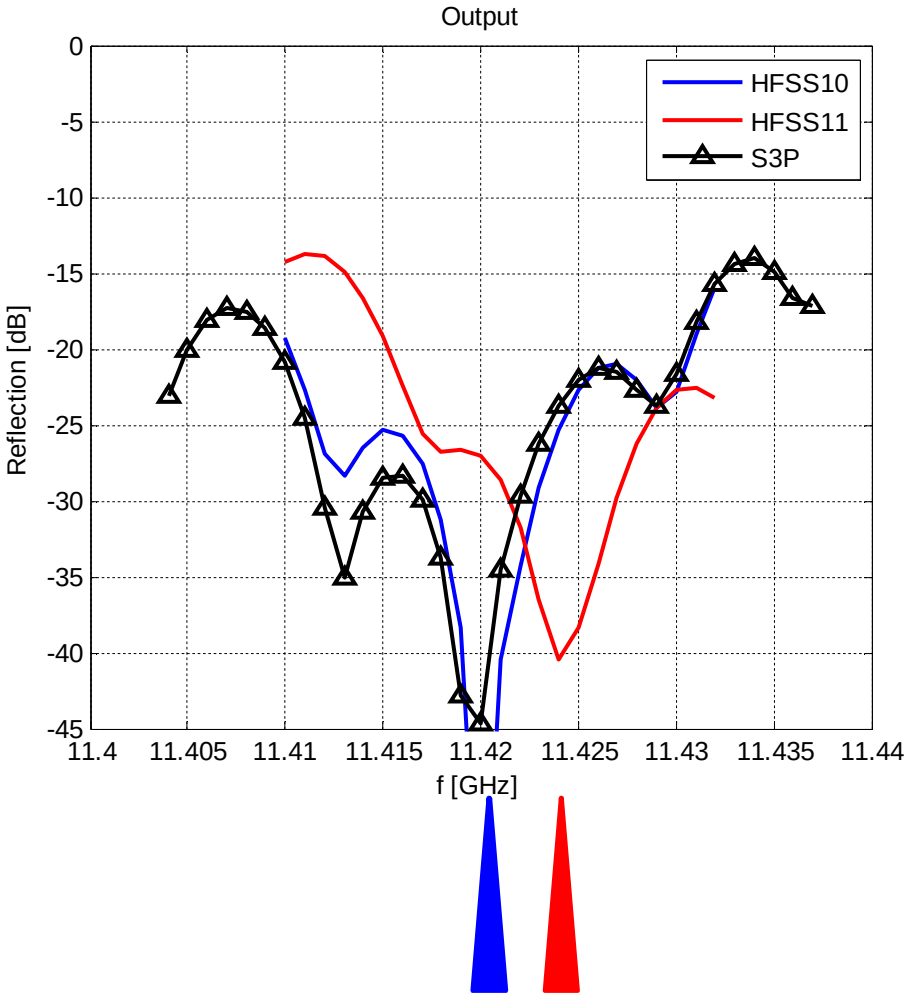


HFSS v11.1 versus HFSS v10.1

Reflection

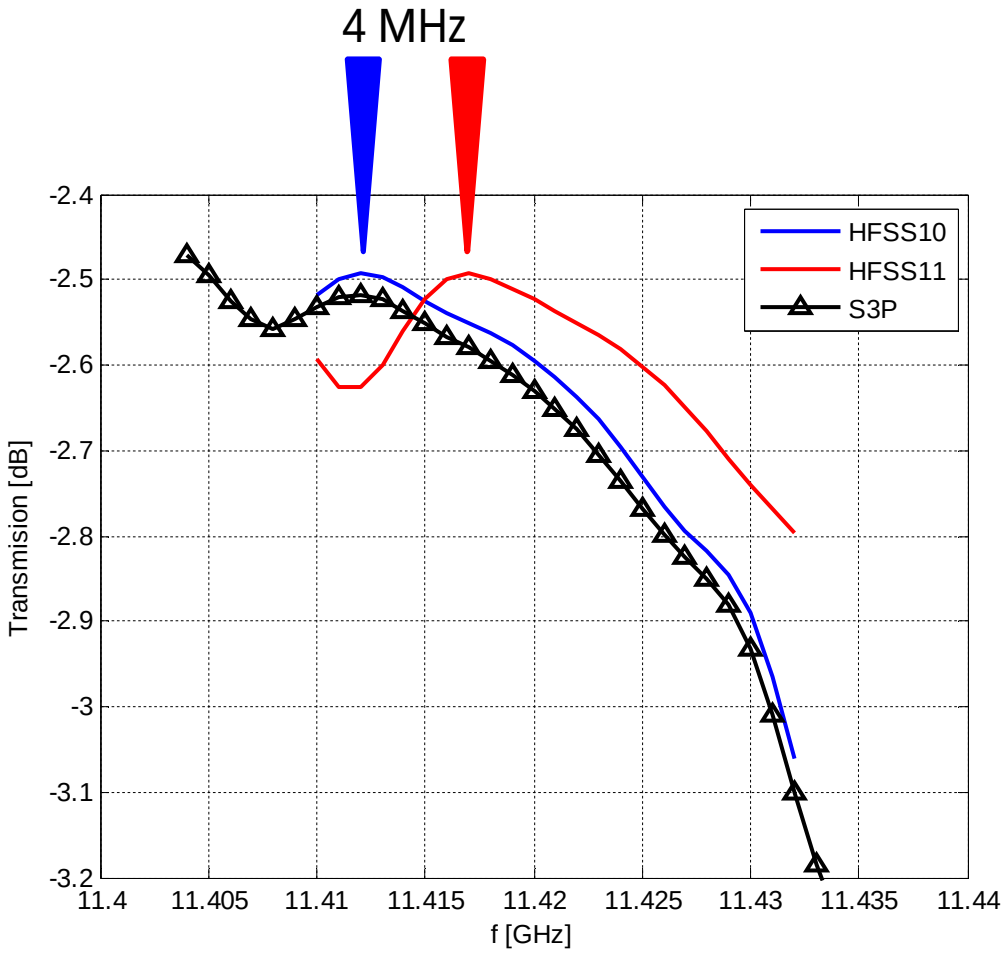


4 MHz

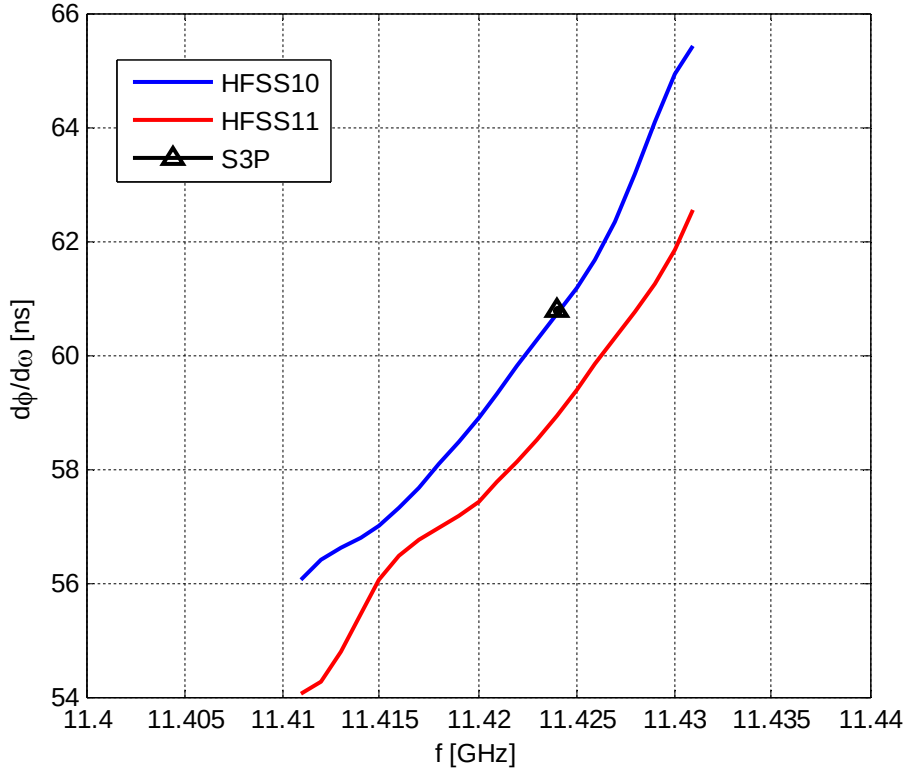


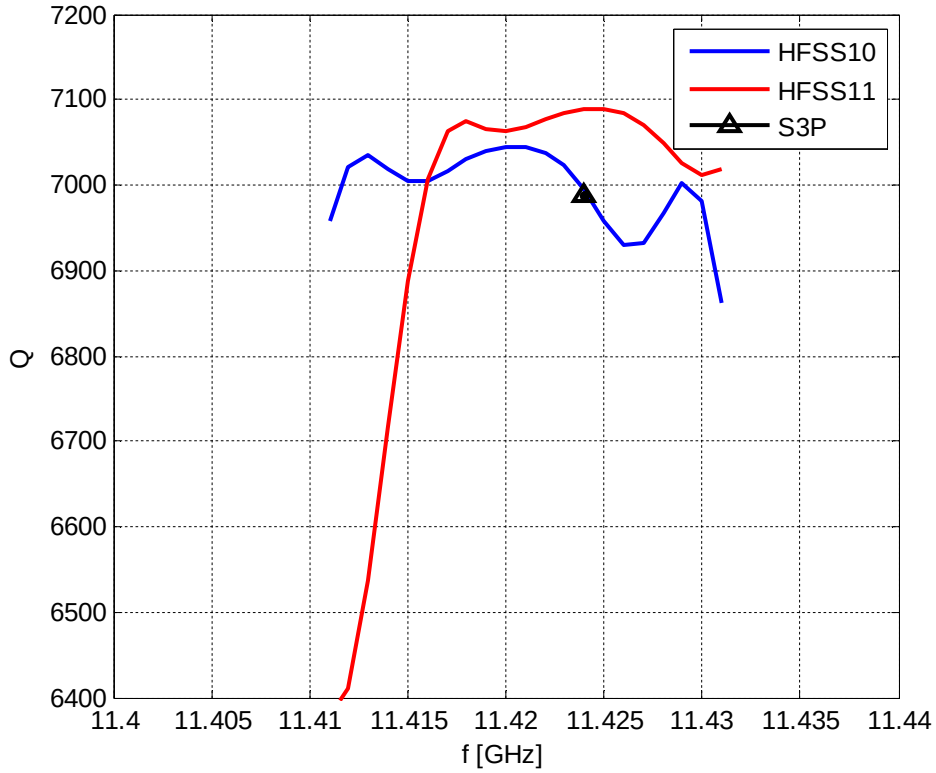
4 MHz

Transmission



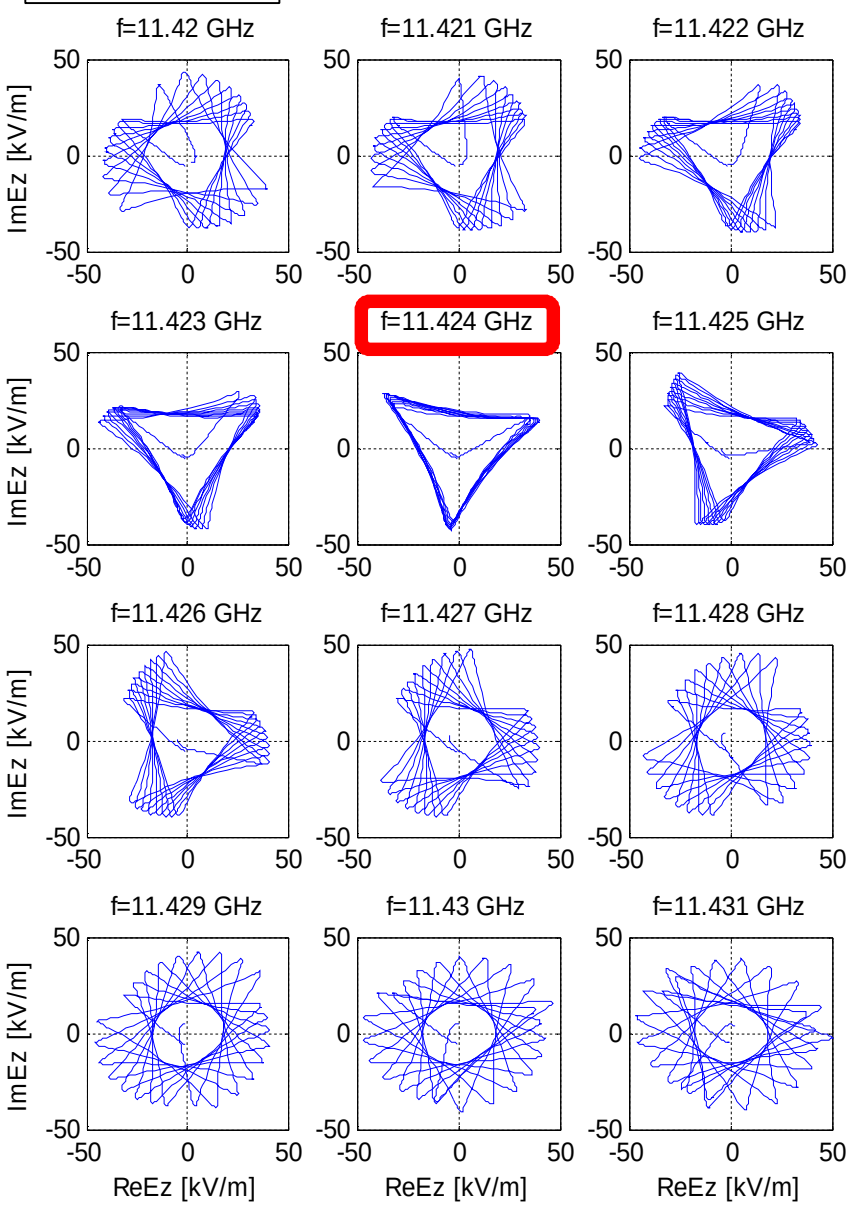
Group delay and Q-factor



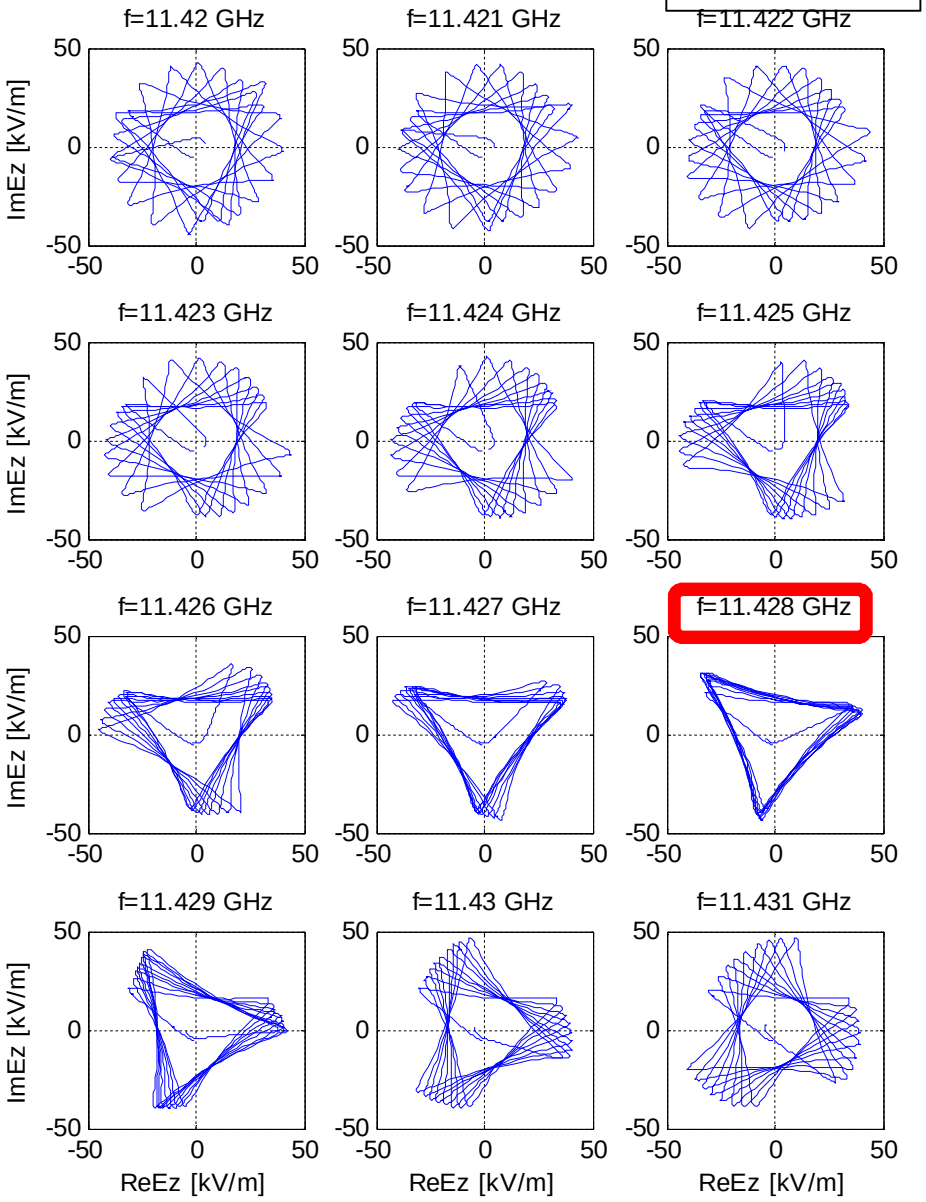


RF phase advance per cell

HFSS v10.1



HFSS v11.1



Summary on HFSS

- It seems that there is a bug in HFSS v11.
- The results of the simulations using HFSS v11 are shifted up in frequency by 4 MHz with respect to the results of the simulations using HFSS v10 or S3P
- Use HFSS-S-parameter solver VERSION 10 or S3P