Power Density Simulation Report

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Google LLC

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1. Numerical modeling for Power Density (PD) calculations

1.1 Full-wave numerical computation tool

To calculate the Power Density (PD) of the phone at FR2 frequencies, a commercial software called HFSS [1], which is a part of ANSYS Electronics Desktop 2021 R2 package, is used. This software is a 3D full-wave electromagnetic (EM) computational solver based on the Finite Element Method (FEM).

1.2 Full-wave simulation setup

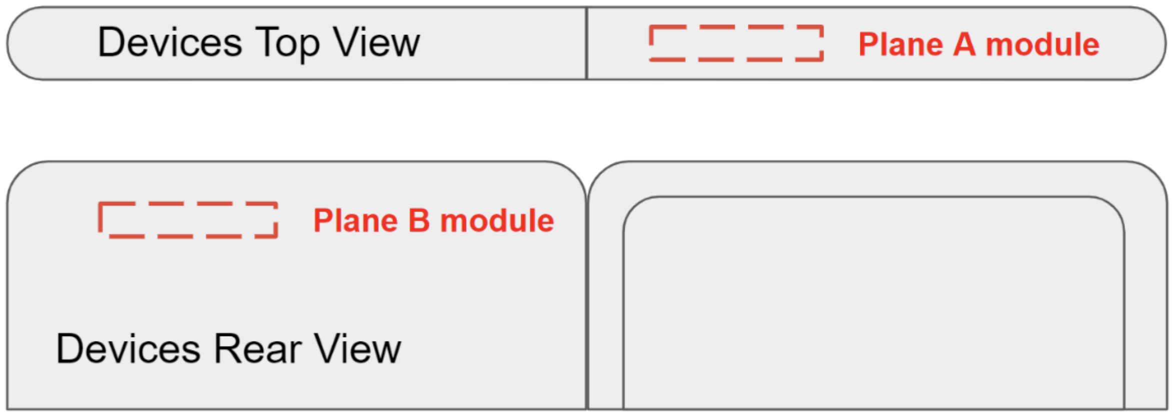
1.2.1 Simulation model

The device includes one L-shaped mmWave module that consists of Plane A sub-module (Plane A Module) and Plane B sub-module (Plane B Module), located at the top and the back side of the device, respectively, as shown in Figure 1-1. In order to obtain accurate PD calculations, it is necessary to have accurate modeling of the mmWave antennas, as well as all other components of the device in close proximity to the mmWave antennas. The simulation model therefore must include all components of the device located within a distance of at least one wavelength from the mmWave module. A list of the components included in the simulation model includes housing, mmWave antenna module, sub6 antennas, PCB, shield cans, Flexible Printed Circuits (FPCs), battery, all components having metallic parts, etc.

1.2.2 Mesh settings and solution setup

ANSYS HFSS features an automatic adaptive mesh refinement algorithm that refines the computational mesh iteratively in regions with strong EM fields and thereby generates very accurate high-frequency simulation results. The steps of adaptive mesh refinement algorithm execution are as follows. First, an initial computational mesh is created, based on the solution setup parameters entered by the user, and is then used to obtain the initial solution for the EM fields of the simulation model. The algorithm then adaptively refines the mesh in each subsequent iteration until a desired solution accuracy, specified by the user, is achieved. The solution accuracy is commonly defined by a convergence parameter called ΔS, which is a variation in the magnitude of all S-parameters between the consecutive iterations of the algorithm [1]. The ΔS parameter specified for all PD simulations presented in this report is 0.02. Figure 1-2 shows an example cut surface in the model showing a tetrahedral computational mesh created by the adaptive mesh refinement algorithm in one of the HFSS simulation models. A radiation boundary with Absorbing Boundary Condition (ABC) is assigned to the outer surface of an air-box surrounding the simulation model, which allows the EM waves to propagate outward from the boundary of the domain without generating any reflected EM waves.

Open Mode:



Closed Mode:

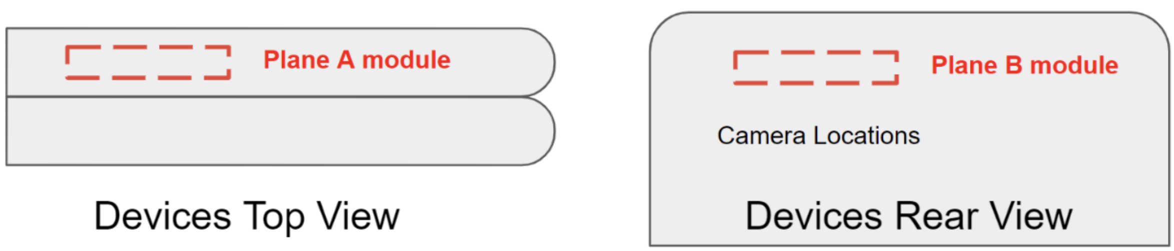


Figure 1-1 Placement of the L-shaped mmWave module in Closed and Open mode, called Plane-A sub-module and Plane-B sub-module, at the top and the back side of the device, respectively.

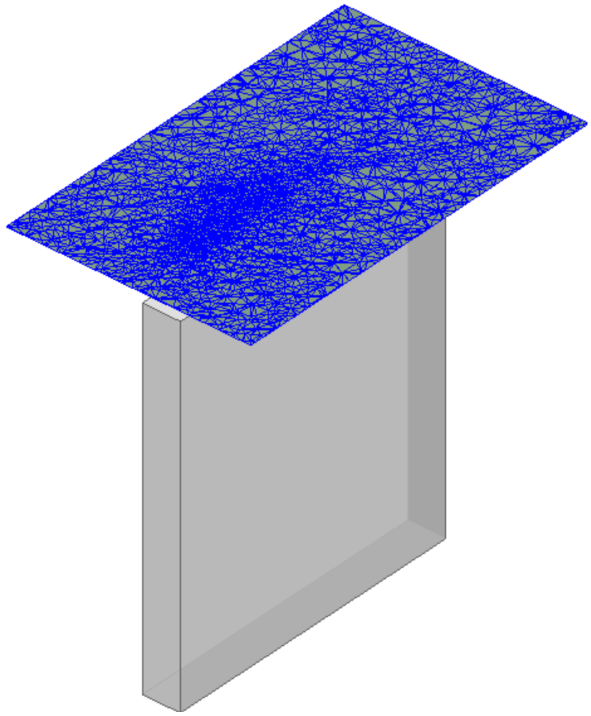


Figure 1-2 An example cut surface in an HFSS simulation model showing the tetrahedral mesh created by the adaptive mesh refinement algorithm.

The FEM simulations are performed for the mmWave module that includes Plane A sub-module and Plane B sub-module, as shown in Figure 1-1. In the simulation, 32 wave-ports are assigned to the feed points of the mmWave antenna arrays. Each sub-module has 16 feeding ports. Specifically, eight of them excite the vertical polarization on the antenna array, called V-pol, and the other eight wave-ports excite the horizontal polarization, called H-pol. After the FEM simulations are completed and full-wave EM solutions are obtained, the magnitude and phase values of the 32 wave-ports excitation signals are sequentially assigned for each of the beams in the codebook. This is accomplished as a post-processing step by using the "Edit post process sources" tab in the HFSS environment, as shown in Figure 1-3 for one of the beams from the codebook.

Spectral Fields | Source Contexts

	Source	Type	Magnitude	Unit	Phase	Unit
1	HFSSDesign1_1_1:1	Port	0	W	0	deg
2	HFSSDesign1_1_2:1	Port	0	W	0	deg
3	HFSSDesign1_1_3:1	Port	0	W	0	deg
4	HFSSDesign1_1_4:1	Port	0	W	0	deg
5	HFSSDesign1_1_5:1	Port	0	W	0	deg
6	HFSSDesign1_1_6:1	Port	0	W	0	deg
7	HFSSDesign1_1_7:1	Port	0	W	0	deg
8	HFSSDesign1_1_8:1	Port	0	W	0	deg
9	HFSSDesign1_1_9:1	Port	0	W	0	deg
10	HFSSDesign1_1_10:1	Port	0	W	0	deg
11	HFSSDesign1_1_11:1	Port	0	W	0	deg
12	HFSSDesign1_1_12:1	Port	0	W	0	deg
13	HFSSDesign1_1_13:1	Port	0	W	0	deg
14	HFSSDesign1_1_14:1	Port	0	W	0	deg
15	HFSSDesign1_1_15:1	Port	0	W	0	deg
16	HFSSDesign1_1_16:1	Port	0	W	0	deg
17	HFSSDesign1_1_17:1	Port	0	W	0	deg
18	HFSSDesign1_1_18:1	Port	0	W	0	deg
19	HFSSDesign1_1_19:1	Port	0	W	0	deg
20	HFSSDesign1_1_20:1	Port	0	W	0	deg
21	HFSSDesign1_1_21:1	Port	0	W	0	deg
22	HFSSDesign1_1_22:1	Port	0	W	0	deg
23	HFSSDesign1_1_23:1	Port	0	W	0	deg
24	HFSSDesign1_1_24:1	Port	0	W	0	deg
25	HFSSDesign1_1_25:1	Port	0	W	0	deg
26	HFSSDesign1_1_26:1	Port	0	W	0	deg
27	HFSSDesign1_1_27:1	Port	0	W	0	deg
28	HFSSDesign1_1_28:1	Port	0	W	0	deg
29	HFSSDesign1_1_29:1	Port	0	W	0	deg
30	HFSSDesign1_1_30:1	Port	1	W	0	deg
31	HFSSDesign1_1_31:1	Port	0	W	0	deg
32	HFSSDesign1_1_32:1	Port	0	W	0	deg

Figure 1-3 An example of magnitude and phase assignments to the wave-ports in the “Edit post process sources” tab in the HFSS environment.

1.2.3 Time-averaged PD calculation

After the convergence criterion is achieved in the last iterative pass, that is Max{|ΔS|} is smaller than the specified value of the convergence parameter ΔS (that being 0.02 in this report, as mentioned above), the values of the electric and magnetic field vectors $\vec{E}$ and $\vec{H}$ respectively, are calculated, and then used to calculate the *PD* by the following formula:

$$PD = \frac{1}{2}\left|Re\left\{\overrightarrow{E} \times \overrightarrow{H}^*\right\}\right|$$

Based on the calculated *PD*, the time-averaged *PD* (PD_{ave}) over a surface *A* can be obtained as:

$$PD_{ave} = \frac{1}{2A}\int_A \left|Re\left\{\overrightarrow{E} \times \overrightarrow{H}^*\right\}\right| \cdot dS$$

In order to determine the RF exposure from the mmW antennas in the device, the values of the electric and magnetic field vectors at the six surfaces S1, S2, S3, S4, S5, and S6 shown in Figure 1-4 are needed. Depending on the simulation or measurement setting, the distance from these six surfaces to the device is set to be either 2 mm or 10 mm. As long as the distance between mmWave sub-module and any six surfaces is greater than 25mm, the surface integration terms in the above formula for the PD_{ave} corresponding to some of these six surfaces are negligible, and thus can be excluded from the PD_{ave} calculation. Using square markings, Table 1-1 specifies which one of the six surfaces needs to be used in the above formula for the PD_{ave} calculation. As seen, the surfaces S1, S2, S4, and S5 need to be used in the PD_{ave} calculations for both planes.

In the spatially averaged power density calculations, the surface *A* is a circle in the evaluation plane with an area of 4 cm^2. Furthermore, PD_{ave} is calculated at the points of a grid with 0.1 mm step size defined in each evaluation plane.

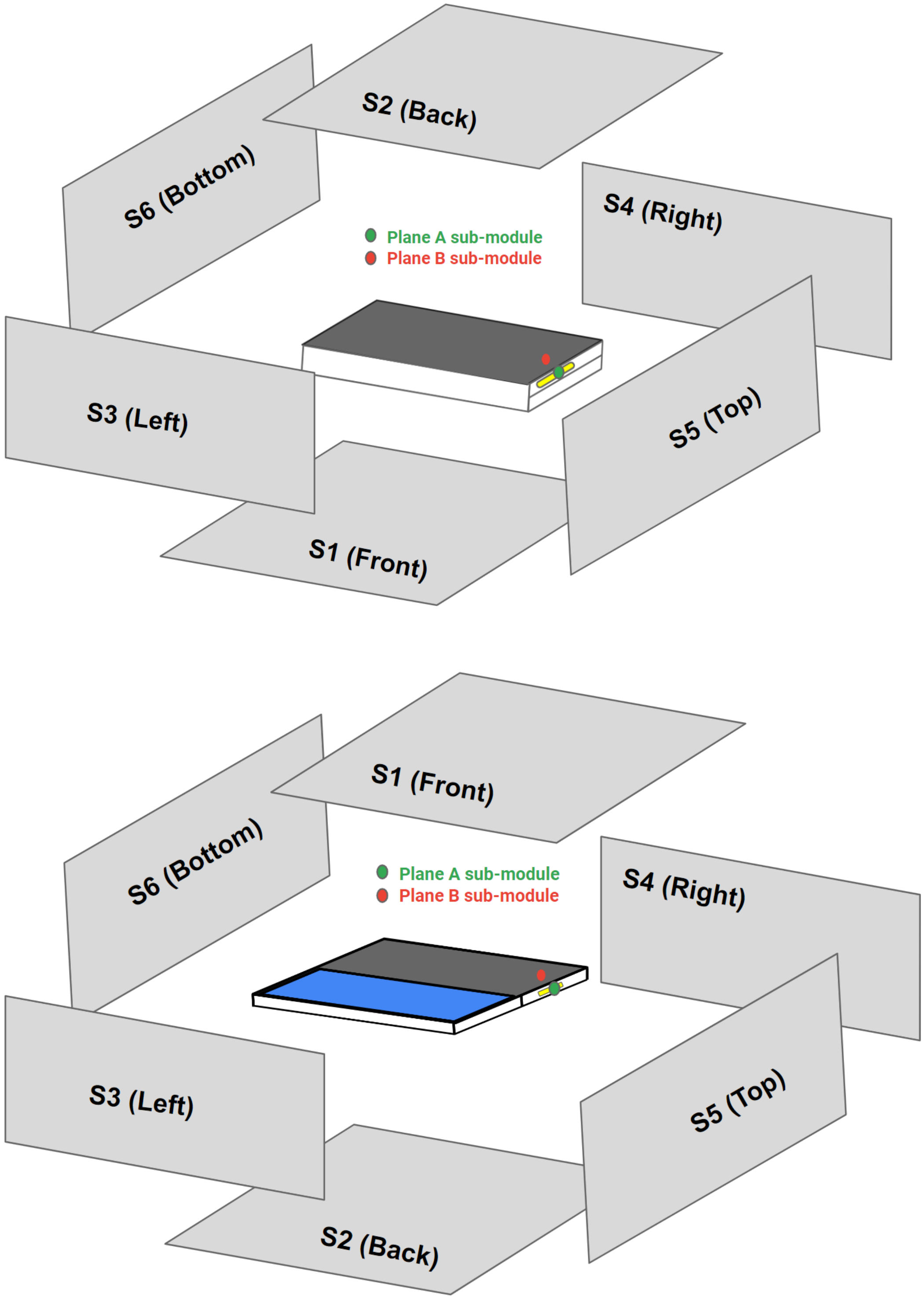


Figure 1-4 *PD* evaluation surfaces. Averaged power densities (PD_{ave}) are calculated and measured on the specified surfaces (S1, S2, S4, and S5) surrounding the DUT.

Table 1-1 *PD* evaluation surfaces considered for each mmWave module in the device.

	S1 (front)	S2 (back)	S3 (left)	S4 (right)	S5 (top)	S6 (bottom)
Plane A Module			✗			✗
Plane B Module			✗			✗

2. Simulation and modeling validation

2.1 Comparison between simulation and measurement

Following the time-average *PD* calculation procedure described in section 1.2.3, the distributions of *PD* and PD_{ave} are calculated in the evaluation planes and are compared with the measurements for a selected number of beams, with the highest PD_{ave} values compared to the other beams, whose IDs are listed in Table 2-1 (a),(b) for both closed and open mode. Also shown in this table are simulated and measured results for the PD_{ave} for n261, n260, and n258 frequency bands, as well as Horizontal, Vertical, and Horizontal + Vertical (Simultaneous Transmit) polarizations, denoted as H, V and H+V, respectively. For Plane B Module, PD_{ave} of 2mm from DUT is used for calculating minimum target power while PD_{ave} of 2mm from Visor Surface is used to derive the correction factor. Figure 2-1 (a),(b) shows orientation of the device for the *PD* and PD_{ave} distribution plots in both closed and open mode presented in Figures 2-2 to 2-73. The presented plots demonstrate a good agreement between simulated and measured results for both *PD* and PD_{ave}.

(a) Closed mode

Test Number	Antenna Module	H Pol Beam ID	V Pol Beam ID	Band	Frequency (GHz)	Exposure Surface	Reference Plane	Test Separation	Measured results Savg @ 4cm^2 (W/m2)	Simulated results Savg @ 4cm^2 (W/m2)	Sim. – Meas. (dB)
1	Plane A sub-module	3	-	n261	27.925	Top (S5)	EUT Surface	10mm	6.1	4.46	-1.360
2	Plane A sub-module	-	4	n261	27.925	Top (S5)	EUT Surface	10mm	6.95	5.13	-1.319
3	Plane A sub-module	4	4	n261	27.925	Top (S5)	EUT Surface	10mm	10.3	10.89	0.242
4	Plane B sub-module	3	-	n261	27.925	Back (S2)	EUT Surface	10mm	4.87	4.62	-0.229
5	Plane B sub-module	-	3	n261	27.925	Back (S2)	EUT Surface	10mm	4.74	4.56	-0.168
6	Plane B sub-module	3	3	n261	27.925	Back (S2)	EUT Surface	10mm	8.28	9.66	0.669
7	Plane A sub-module	2	-	n260	38.5	Top (S5)	EUT Surface	10mm	4.31	5.37	0.955
8	Plane A sub-module	-	4	n260	38.5	Top (S5)	EUT Surface	10mm	3.54	5.06	1.551
9	Plane A sub-module	4	4	n260	38.5	Top (S5)	EUT Surface	10mm	6.78	10.29	1.812
10	Plane B sub-module	5	-	n260	38.5	Back (S2)	EUT Surface	10mm	4.3	2.1	-3.112
11	Plane B sub-module	-	2	n260	38.5	Back (S2)	EUT Surface	10mm	2.02	2.11	0.189
12	Plane B sub-module	2	2	n260	38.5	Back (S2)	EUT Surface	10mm	5.29	4.93	-0.306
13	Plane A sub-module	3	-	n258	24.75	Top (S5)	EUT Surface	10mm	7.19	5.06	-1.526
14	Plane A sub-module	-	3	n258	24.75	Top (S5)	EUT Surface	10mm	6.27	4.42	-1.518
15	Plane A sub-module	3	3	n258	24.75	Top (S5)	EUT Surface	10mm	15.9	14.35	-0.445
16	Plane B sub-module	4	-	n258	24.75	Back (S2)	EUT Surface	10mm	3.43	4.29	0.972
17	Plane B sub-module	-	6	n258	24.75	Back (S2)	EUT Surface	10mm	3.17	4.3	1.324
18	Plane B sub-module	5	5	n258	24.75	Back (S2)	EUT Surface	10mm	5.61	8.58	1.845

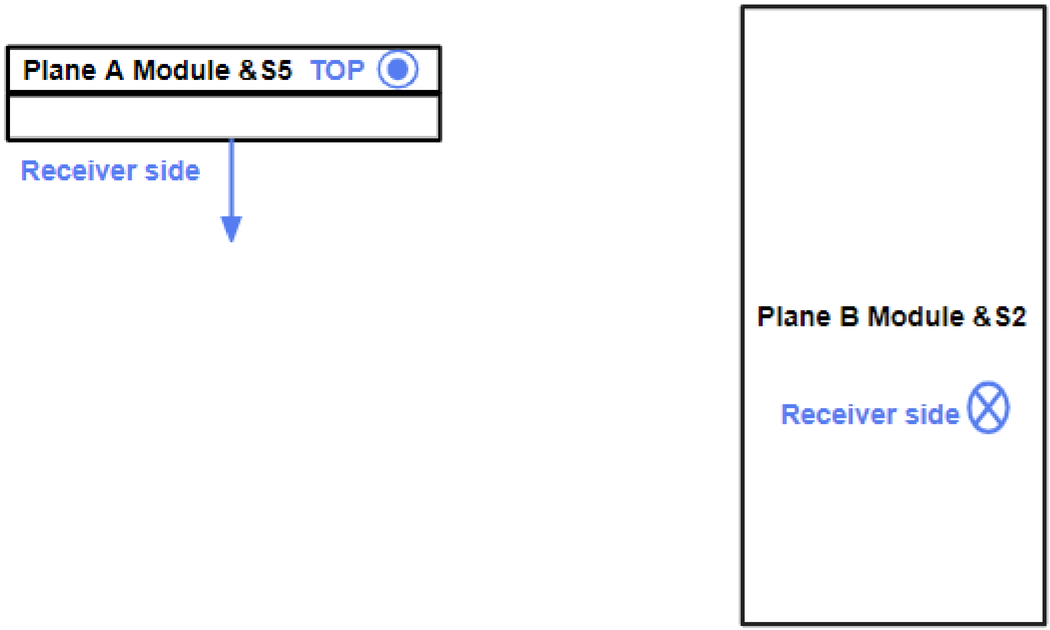
(b) Open mode

Test Number	Antenna Module	H Pol Beam ID	V Pol Beam ID	Band	Frequency (GHz)	Exposure Surface	Reference Plane	Test Separation	Measured results Savg @ 4cm^2 (W/m2)	Simulated results Savg @ 4cm^2 (W/m2)	Sim. – Meas. (dB)
19	Plane A sub-module	3	-	n261	27.925	Top (S5)	EUT Surface	2mm	8.35	8.87	0.262
20	Plane A sub-module	-	4	n261	27.925	Top (S5)	EUT Surface	2mm	8.43	9.51	0.524
21	Plane A sub-module	3	3	n261	27.925	Top (S5)	EUT Surface	2mm	17.9	21.59	0.814
22	Plane B sub-module	3	-	n261	27.925	Front (S1)	Visor Surface	2mm	5.81	5.85	0.030
23	Plane B sub-module	-	2	n261	27.925	Front (S1)	Visor Surface	2mm	5.89	6.14	0.181
24	Plane B sub-module	2	2	n261	27.925	Front (S1)	Visor Surface	2mm	10.9	13.01	0.769
25	Plane A sub-module	1	-	n260	38.5	Top (S5)	EUT Surface	2mm	6.32	8.29	1.178
26	Plane A sub-module	-	5	n260	38.5	Top (S5)	EUT Surface	2mm	5.28	7.86	1.728

27	Plane A sub-module	4	4	n260	38.5	Top (S5)	EUT Surface	2mm	9.07	15.8	2.410
28	Plane B sub-module	5	-	n260	38.5	Front (S1)	Visor Surface	2mm	5.83	3	-2.885
29	Plane B sub-module	-	2	n260	38.5	Front (S1)	Visor Surface	2mm	2.87	3.08	0.307
30	Plane B sub-module	5	5	n260	38.5	Front (S1)	Visor Surface	2mm	6.92	6.3	-0.408
31	Plane A sub-module	3	-	n258	24.75	Top (S5)	EUT Surface	2mm	12.7	9.98	-1.047
32	Plane A sub-module	-	3	n258	24.75	Top (S5)	EUT Surface	2mm	11.2	10.03	-0.479
33	Plane A sub-module	3	3	n258	24.75	Top (S5)	EUT Surface	2mm	31.7	28.43	-0.473
34	Plane B sub-module	4	-	n258	24.75	Front (S1)	Visor Surface	2mm	5.72	6.17	0.329
35	Plane B sub-module	-	6	n258	24.75	Front (S1)	Visor Surface	2mm	5.57	6.94	0.955
36	Plane B sub-module	6	6	n258	24.75	Front (S1)	Visor Surface	2mm	9.05	13.71	1.804

Table 2-1 (a),(b) Simulated and measured PD_{ave} for selected beams with 17dBm and 20dBm target power at boresight for single and H+V polarization.

(a) Closed mode:



(b) Open mode

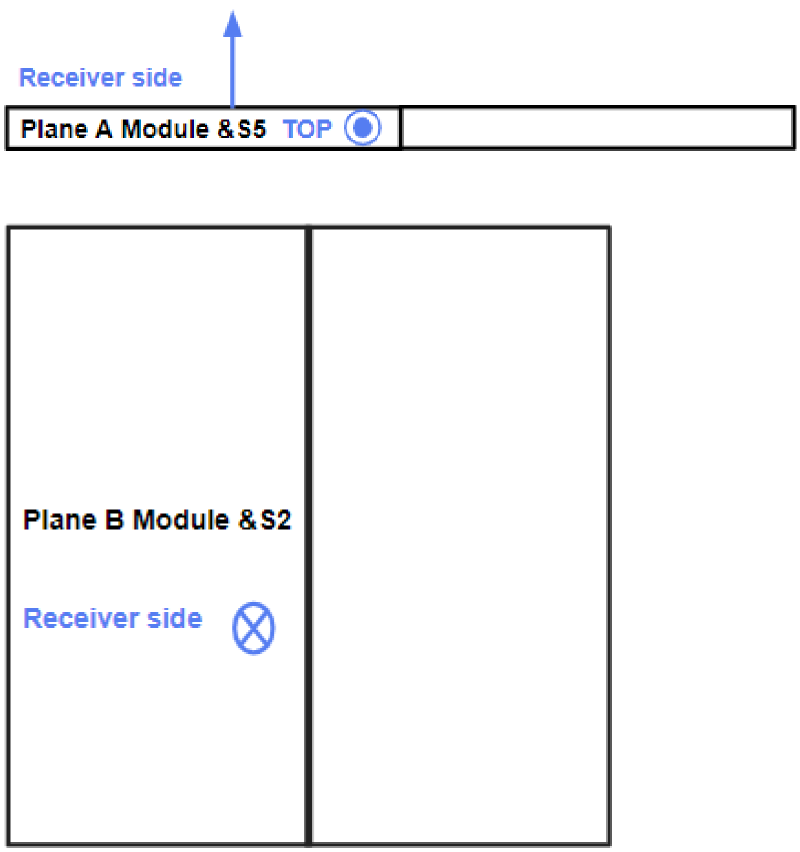
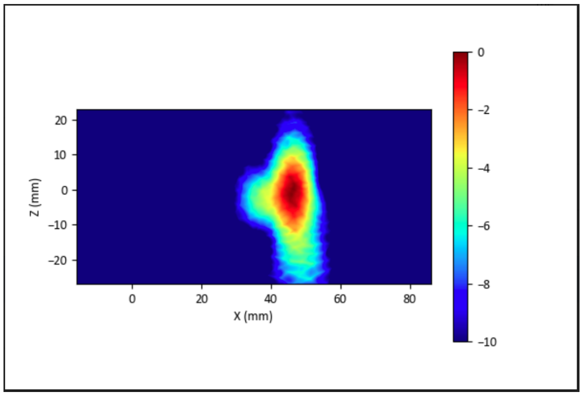


Figure 2-1 (a),(b) Orientation of the device for the *PD* distribution plots both closed & open mode.



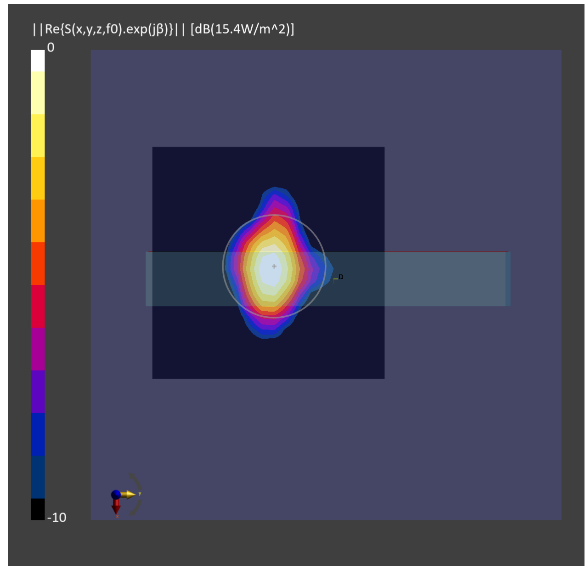
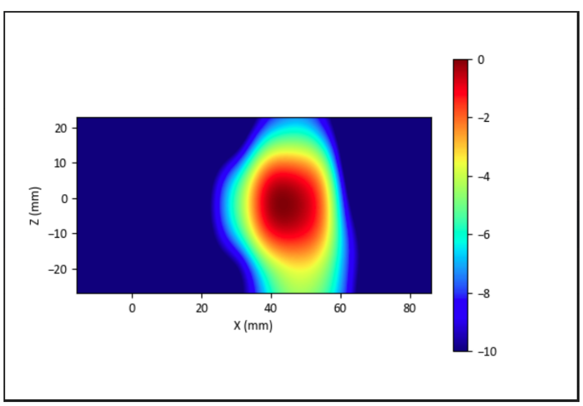


Figure 2-2 Simulated (left) and measured (right) *PD* distribution for the following configuration: Band n261, MID Channel, Beam ID 3, H polarization, Plane A Module, plotted on the surface S5 (top) with 10mm separation distance to the DUT in the Closed Mode.



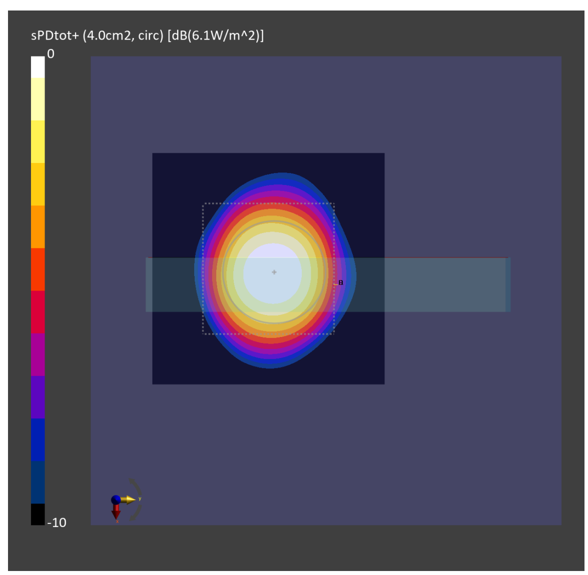


Figure 2-3 Simulated (left) and measured (right) averaged *PD* distribution for the following configuration: Band n261, MID Channel, Beam ID 3, H polarization, Plane A Module, plotted on the surface S5 (top) with 10mm separation distance to the DUT in the Closed Mode.

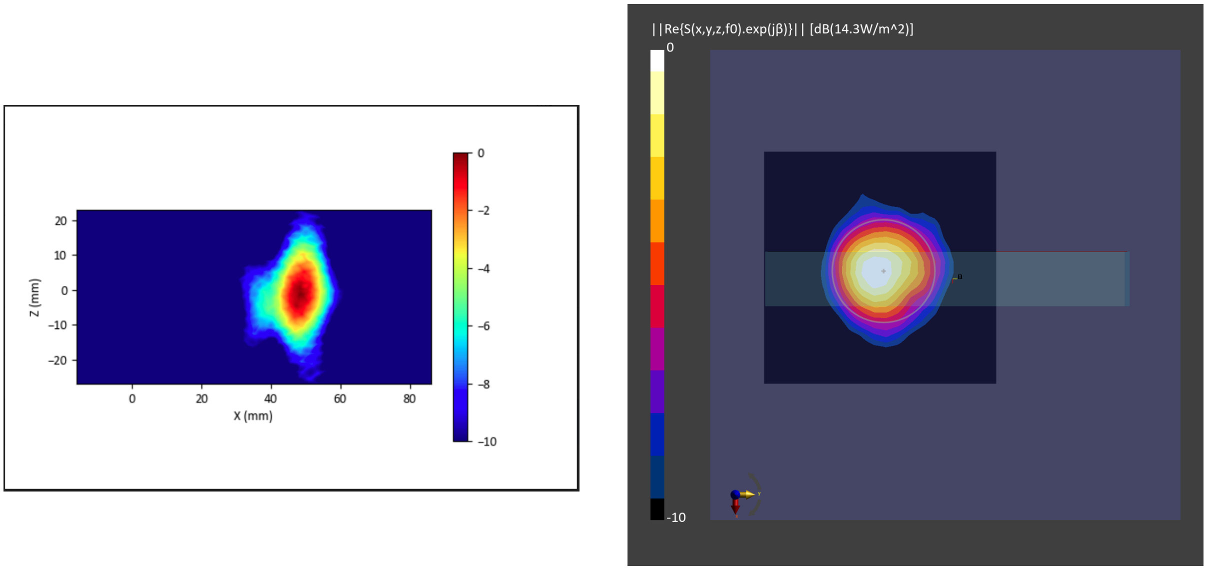


Figure 2-4 Simulated (left) and measured (right) *PD* distribution for the following configuration: Band n261, MID Channel, Beam ID 4, V polarization, Plane A Module, plotted on the surface S5 (top) with 10mm separation distance to the DUT in the Closed Mode.

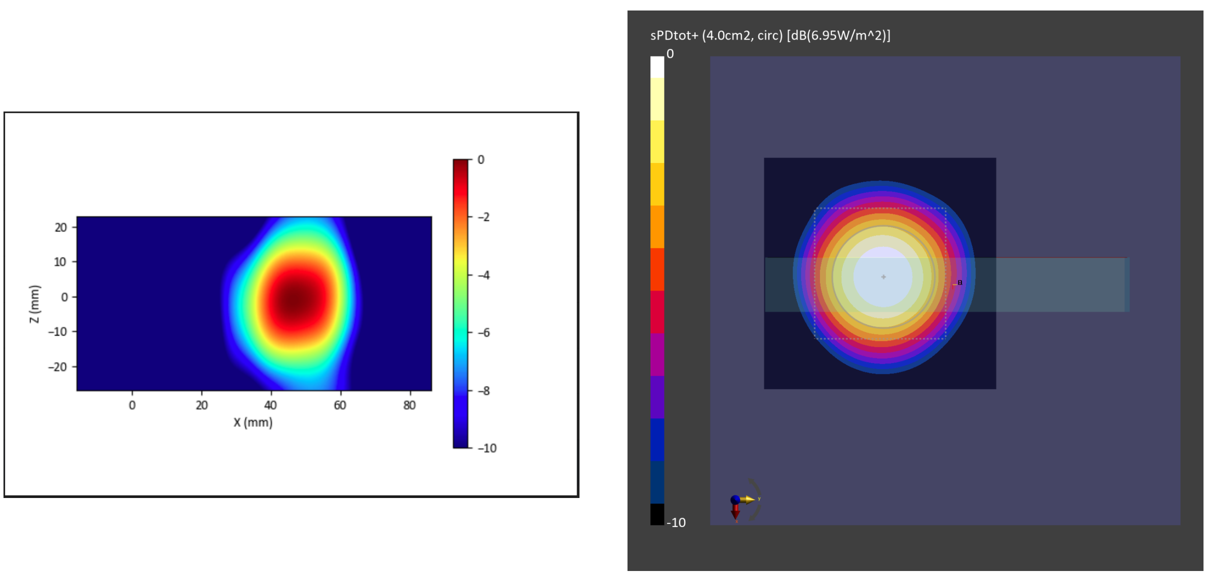


Figure 2-5 Simulated (left) and measured (right) averaged *PD* distribution for the following configuration: Band n261, MID Channel, Beam ID 4, V polarization, Plane A Module, plotted on the surface S5 (top) with 10mm separation distance to the DUT in the Closed Mode.

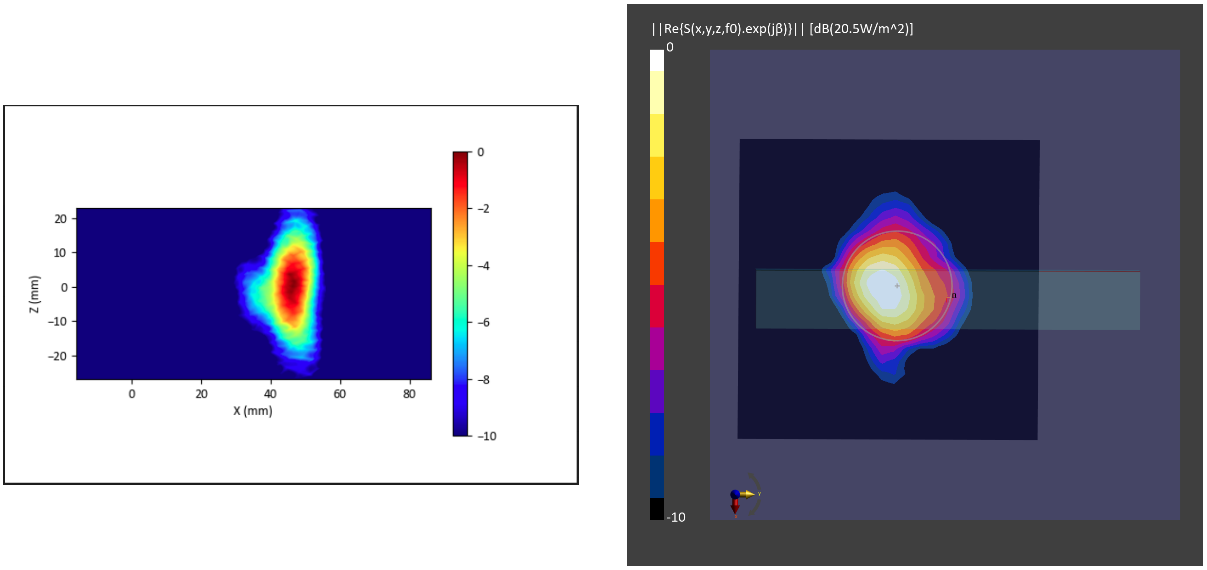


Figure 2-6 Simulated (left) and measured (right) *PD* distribution for the following configuration: Band n261, MID Channel, Beam ID 4, H+V polarization, Plane A Module, plotted on the surface S5 (top) with 10mm separation distance to the DUT in the Closed Mode.

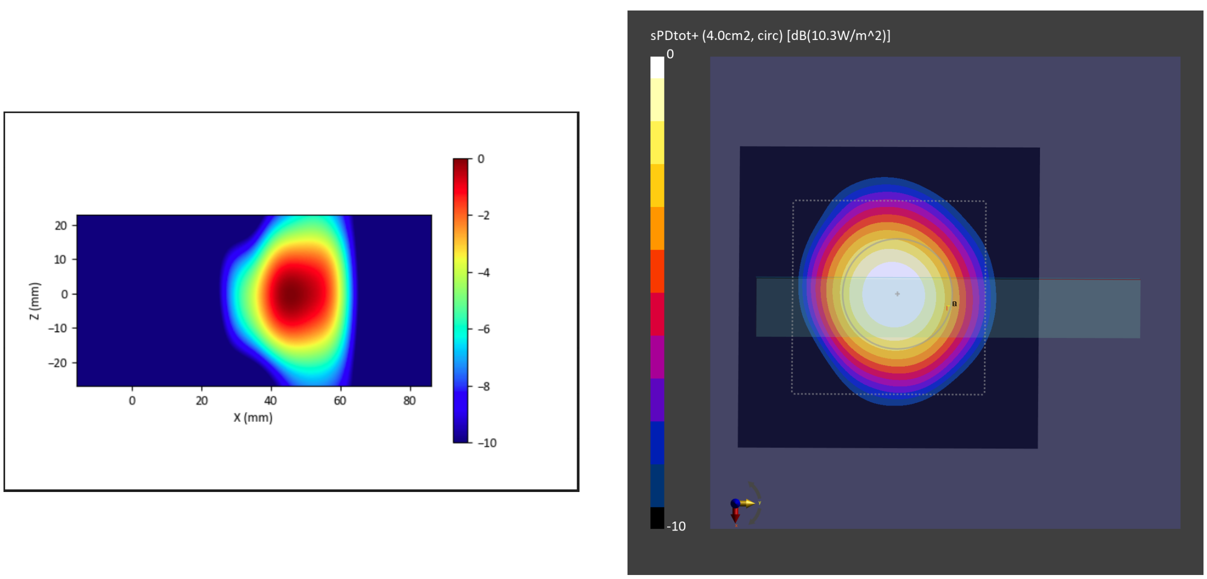


Figure 2-7 Simulated (left) and measured (right) averaged *PD* distribution for the following configuration: Band n261, MID Channel, Beam ID 4, H+V polarization, Plane A Module, plotted on the surface S5 (top) with 10mm separation distance to the DUT in the Closed Mode.

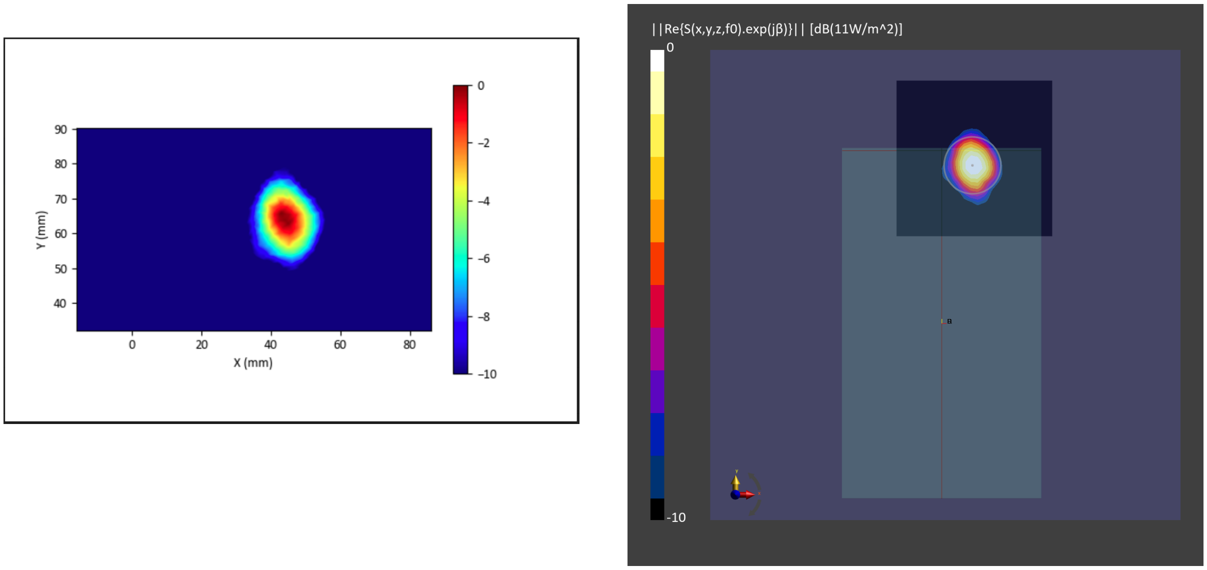


Figure 2-8 Simulated (left) and measured (right) *PD* distribution for the following configuration: Band n261, MID Channel, Beam ID 3, H polarization, Plane B Module, plotted on the surface S2 (back) with 10mm separation distance to the DUT.

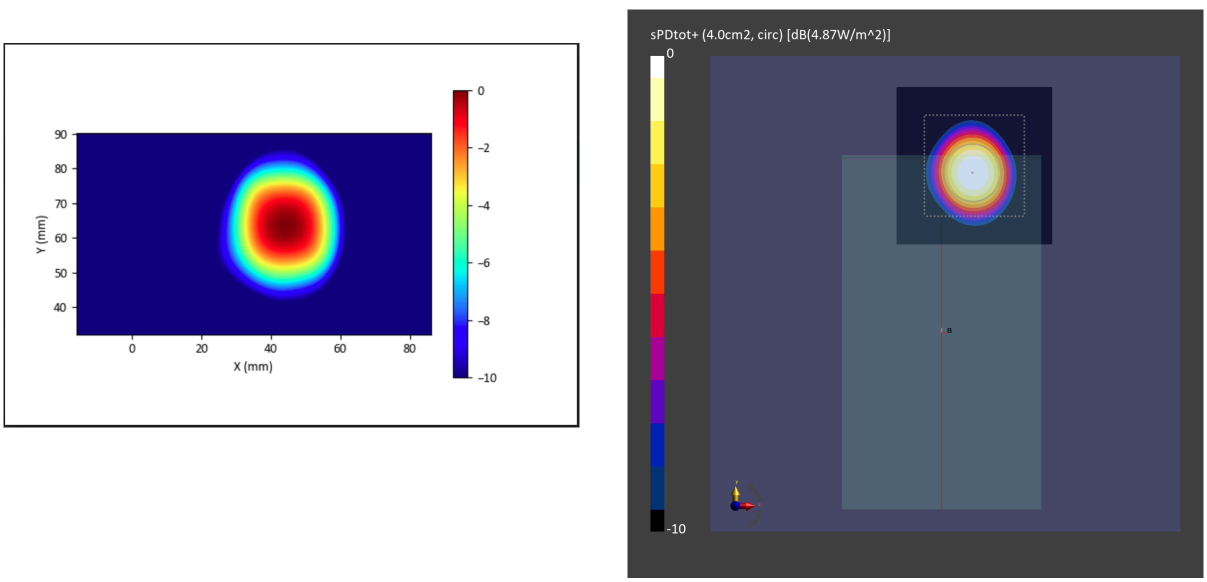


Figure 2-9 Simulated (left) and measured (right) averaged *PD* distribution for the following configuration: Band n261, MID Channel, Beam ID 3, H polarization, Plane B Module, plotted on the surface S2 (back) with 10mm separation distance to the DUT.

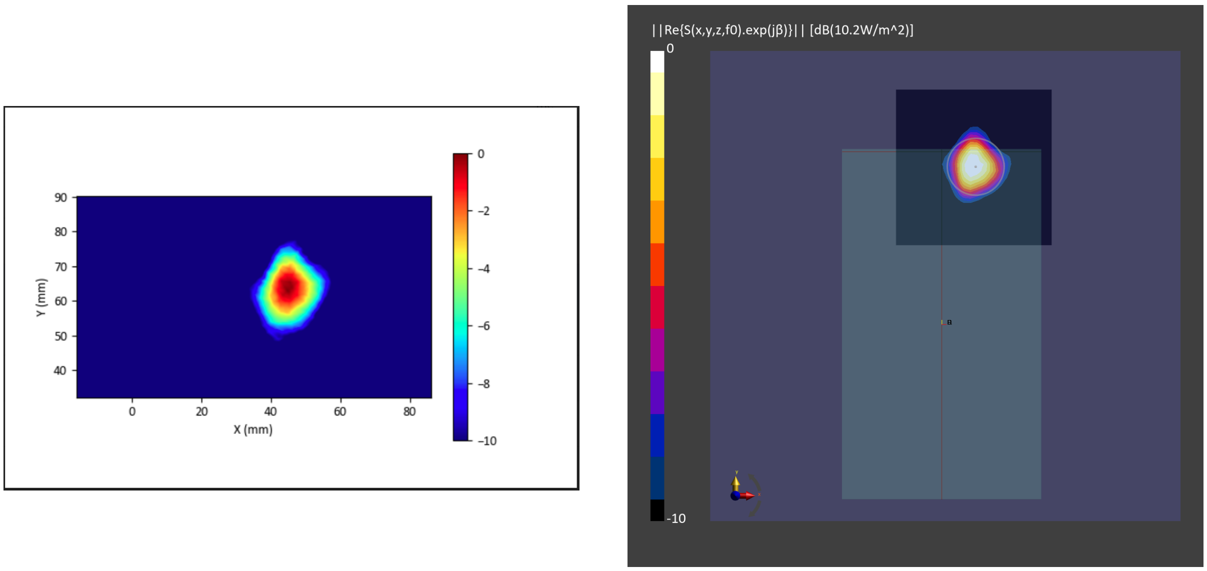


Figure 2-10 Simulated (left) and measured (right) *PD* distribution for the following configuration: Band n261, MID Channel, Beam ID 3, V polarization, Plane B Module, plotted on the surface S2 (back) with 10mm separation distance to the DUT in the Closed Mode.

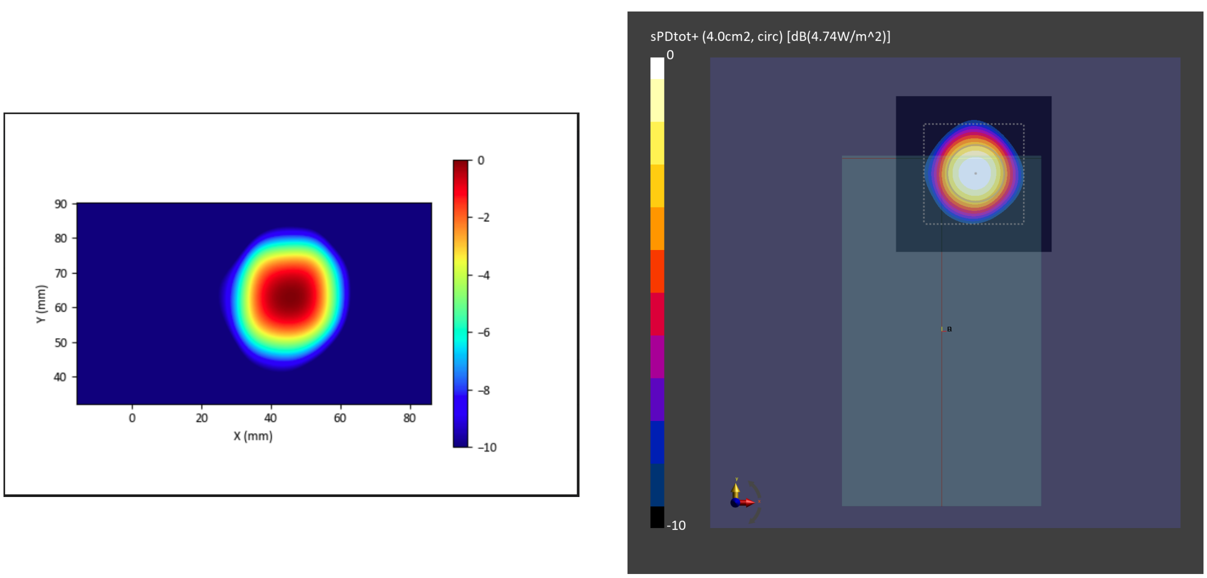


Figure 2-11 Simulated (left) and measured (right) averaged *PD* distribution for the following configuration: Band n261, MID Channel, Beam ID 3, V polarization, Plane B Module, plotted on the surface S2 (back) with 10mm separation distance to the DUT in the Closed Mode.

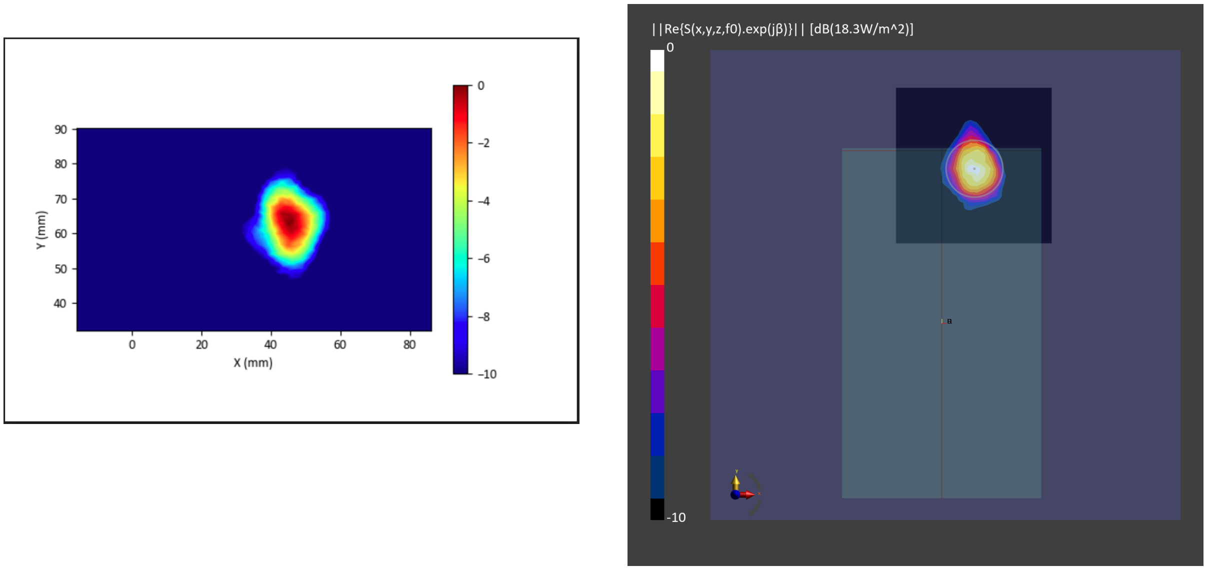


Figure 2-12 Simulated (left) and measured (right) *PD* distribution for the following configuration: Band n261, MID Channel, Beam ID 3, H+V polarization, Plane B Module, plotted on the surface S2 (back) with 10mm separation distance to the DUT in the Closed Mode.

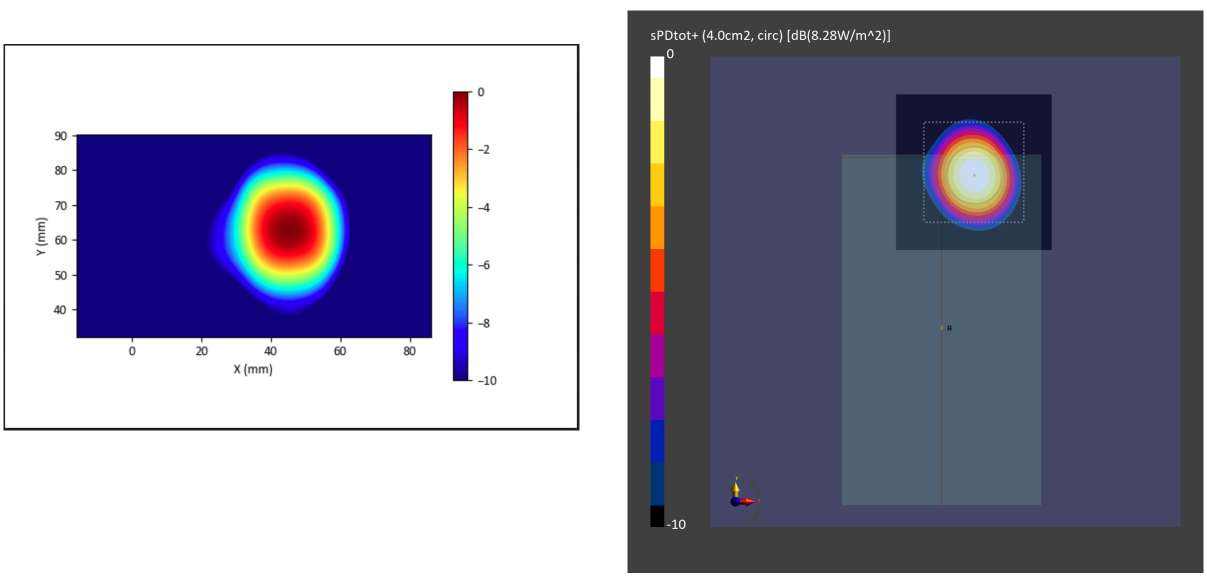
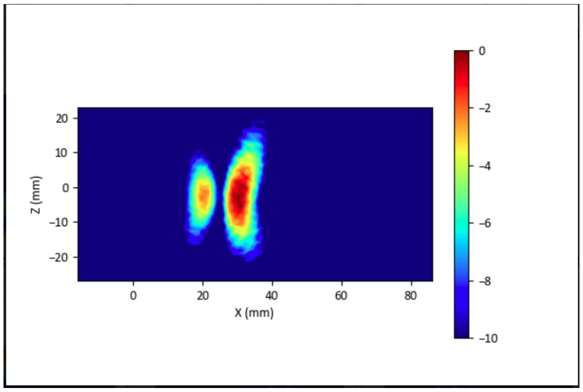


Figure 2-13 Simulated (left) and measured (right) averaged *PD* distribution for the following configuration: Band n261, MID Channel, Beam ID 3, H+V polarization, Plane B Module, plotted on the surface S2 (back) with 10mm separation distance to the DUT in the Closed Mode.



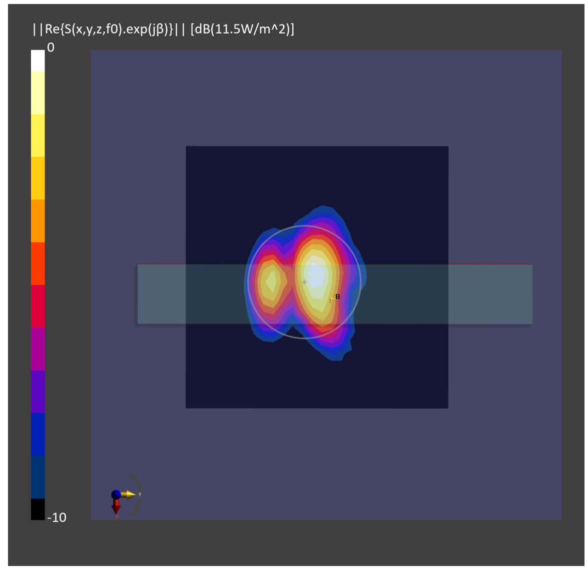
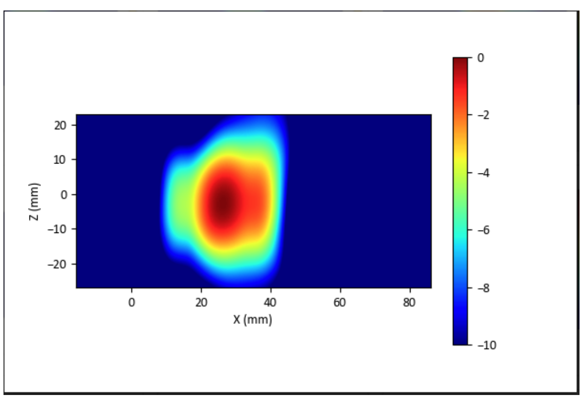


Figure 2-14 Simulated (left) and measured (right) *PD* distribution for the following configuration: Band n260, MID Channel, Beam ID 2, H polarization, Plane A Module, plotted on the surface S5 (top) with 10mm separation distance to the DUT in the Closed Mode .



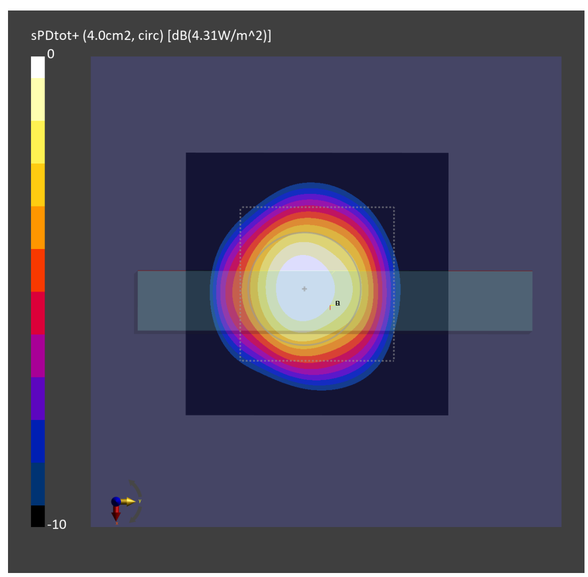


Figure 2-15 Simulated (left) and measured (right) averaged *PD* distribution for the following configuration: Band n260, MID Channel, Beam ID 2, H polarization, Plane A Module, plotted on the surface S5 (top) with 10mm separation distance to the DUT in the Closed Mode .

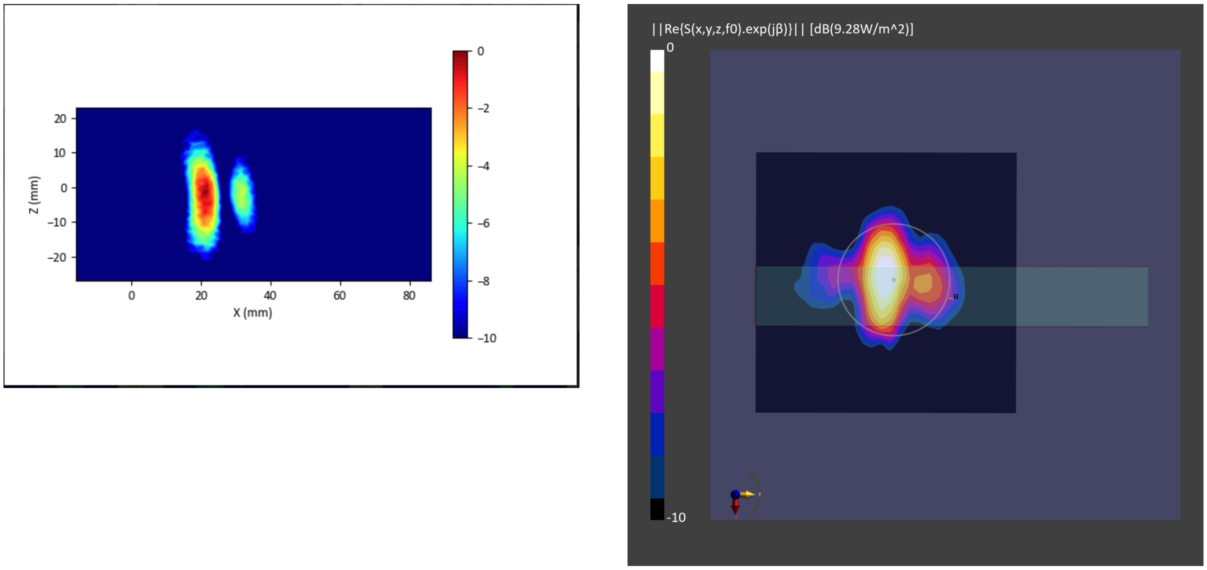


Figure 2-16 Simulated (left) and measured (right) *PD* distribution for the following configuration: Band n260, MID Channel, Beam ID 4, V polarization, Plane A Module, plotted on the surface S5 (top) with 10mm separation distance to the DUT in the Closed Mode.

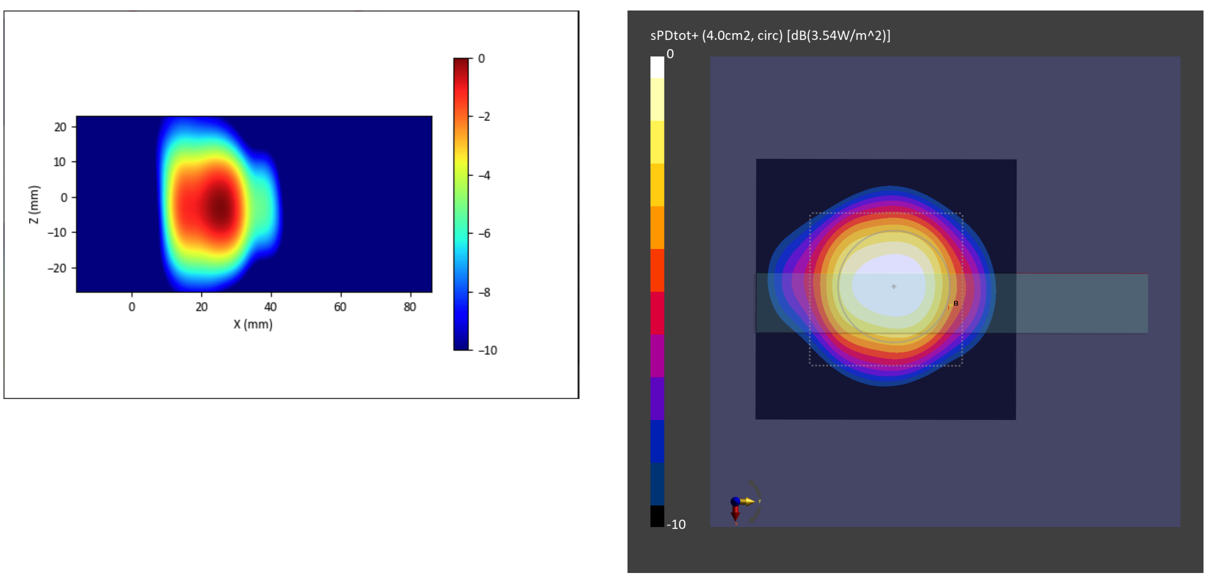
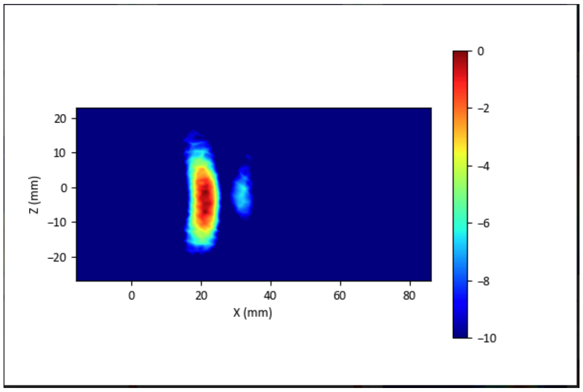


Figure 2-17 Simulated (left) and measured (right) averaged *PD* distribution for the following configuration: Band n260, MID Channel, Beam ID 4, V polarization, Plane A Module, plotted on the surface S5 (top) with 10mm separation distance to the DUT in the Closed Mode.



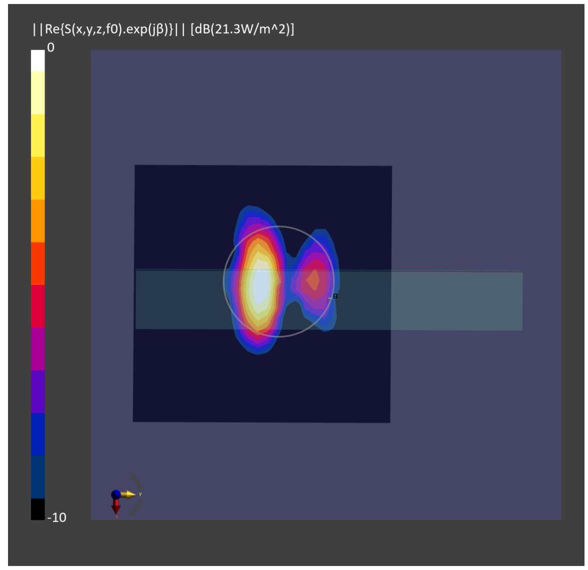
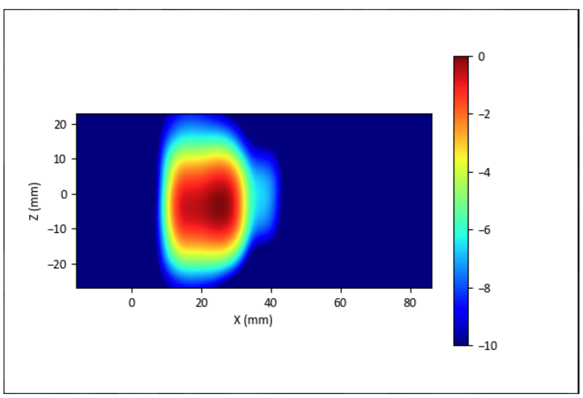


Figure 2-18 Simulated (left) and measured (right) *PD* distribution for the following configuration: Band n260, MID Channel, Beam ID 4, H+V polarization, Plane A Module, plotted on the surface S5 (top) with 10mm separation distance to the DUT in the Closed Mode.



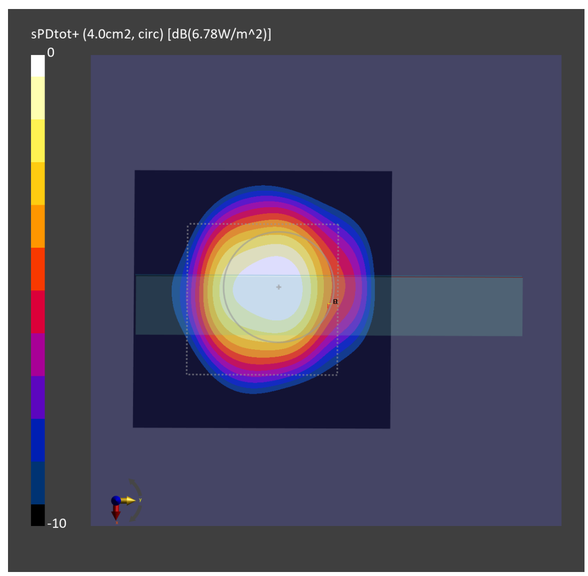


Figure 2-19 Simulated (left) and measured (right) averaged *PD* distribution for the following configuration: Band n260, MID Channel, Beam ID 4, H+V polarization, Plane A Module, plotted on the surface S5 (top) with 10mm separation distance to the DUT in the Closed Mode.

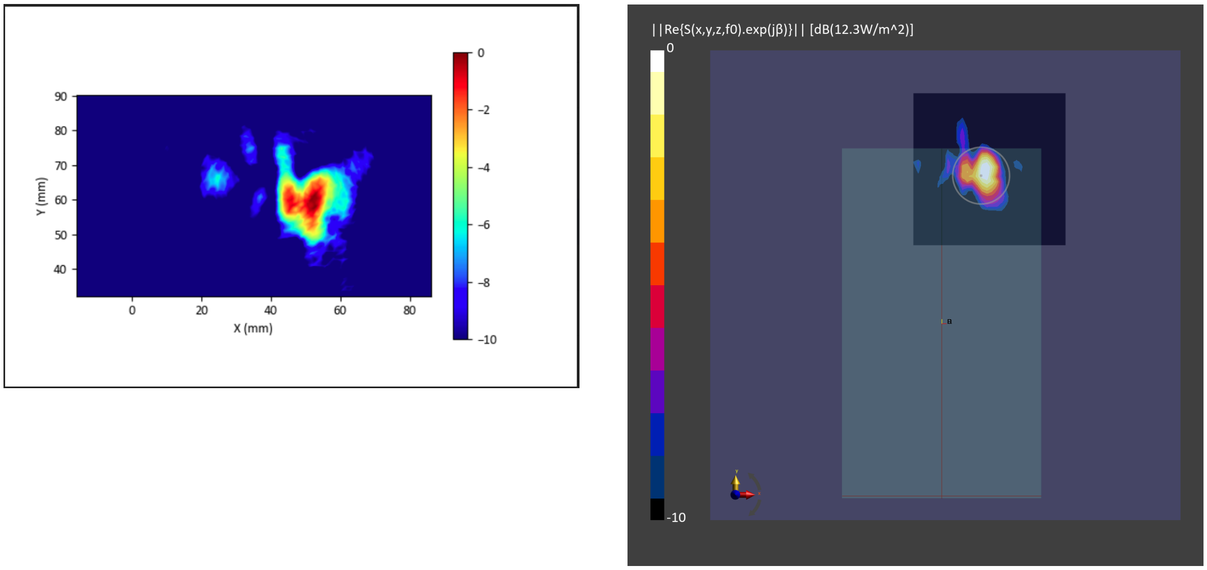


Figure 2-20 Simulated (left) and measured (right) *PD* distribution for the following configuration: Band n260, MID Channel, Beam ID 5, H polarization, Plane B Module, plotted on the surface S2 (back) with 10mm separation distance to the DUT in the Closed Mode.

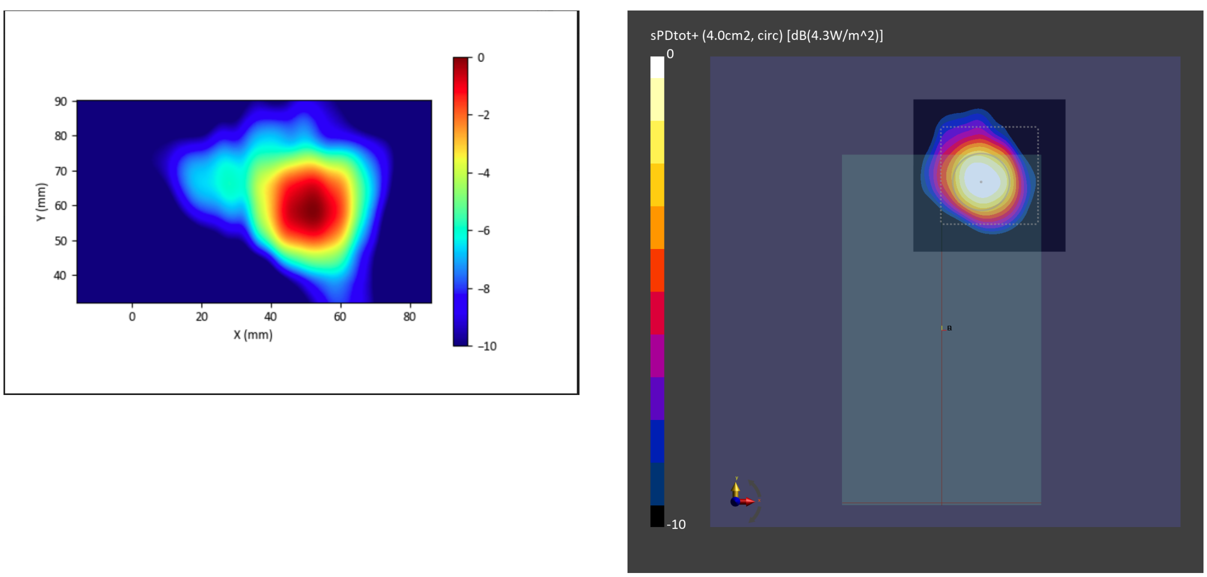


Figure 2-21 Simulated (left) and measured (right) averaged *PD* distribution for the following configuration: Band n260, MID Channel, Beam ID 5, H polarization, Plane B Module, plotted on the surface S2 (back) with 10mm separation distance to the DUT in the Closed Mode.

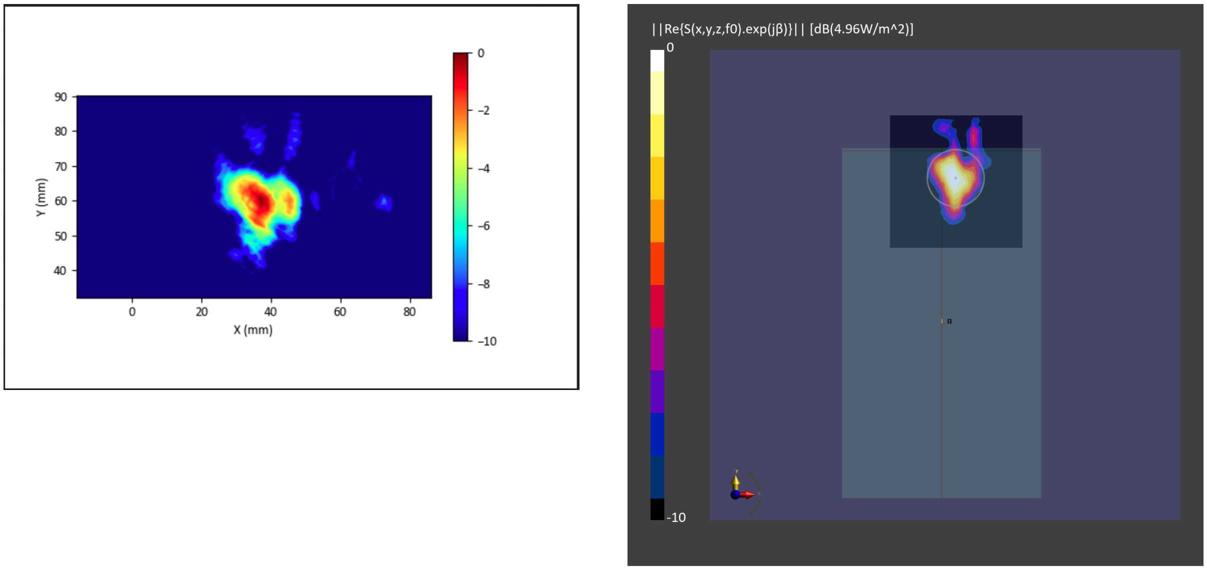


Figure 2-22 Simulated (left) and measured (right) *PD* distribution for the following configuration: Band n260, MID Channel, Beam ID 2, V polarization, Plane B Module, plotted on the surface S2 (back) with 10mm separation distance to the DUT in the Closed Mode.

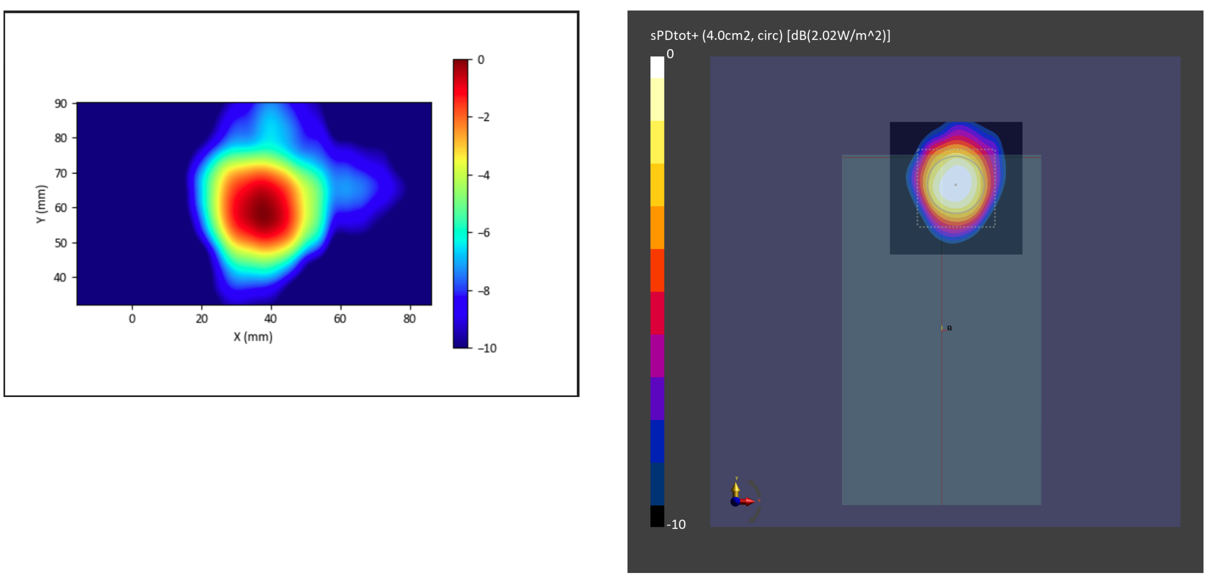


Figure 2-23 Simulated (left) and measured (right) averaged *PD* distribution for the following configuration: Band n260, MID Channel, Beam ID 2, V polarization, Plane B Module, plotted on the surface S2 (back) with 10mm separation distance to the DUT in the Closed Mode.

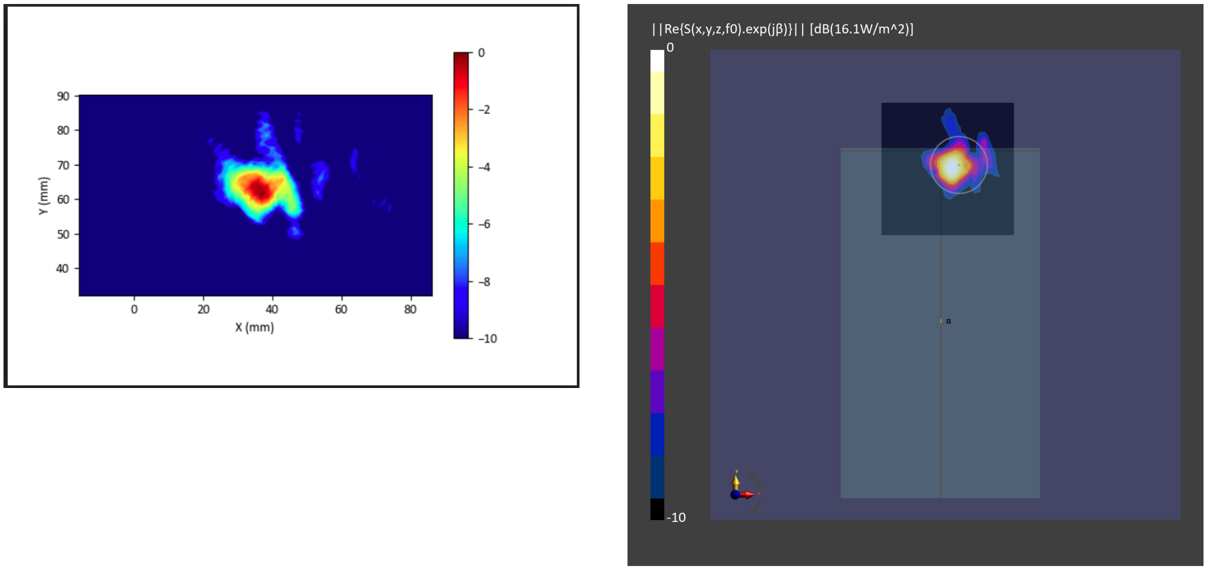


Figure 2-24 Simulated (left) and measured (right) *PD* distribution for the following configuration: Band n260, MID Channel, Beam ID 2, H+V polarization, Plane B Module, plotted on the surface S2 (back) with 10mm separation distance to the DUT in the Closed Mode.

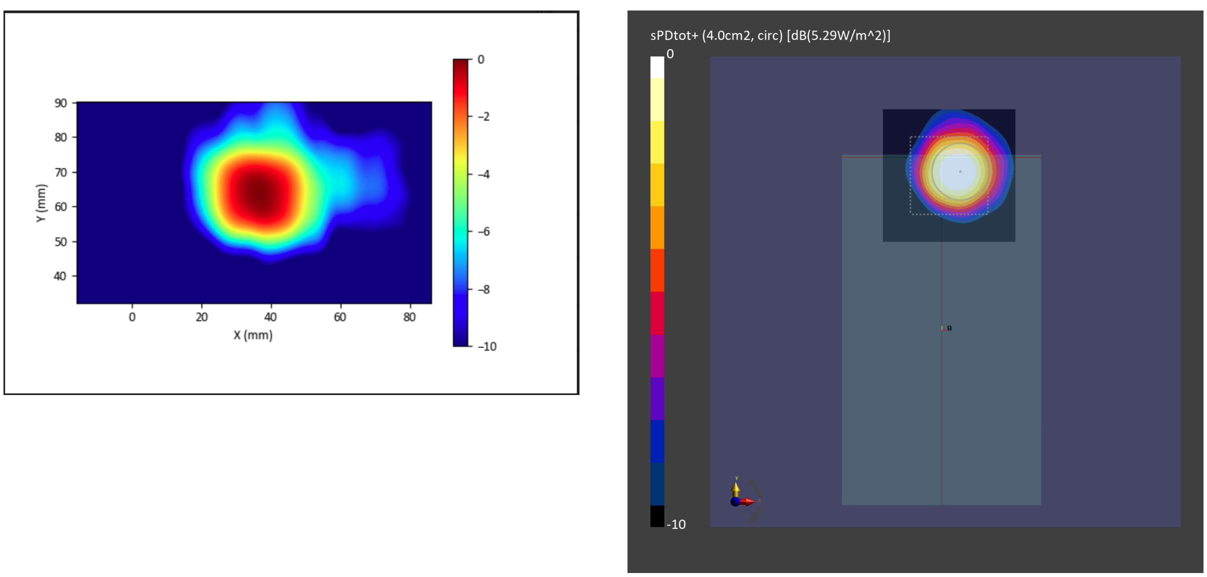


Figure 2-25 Simulated (left) and measured (right) averaged *PD* distribution for the following configuration: Band n260, MID Channel, Beam ID 2, H+V polarization, Plane B Module, plotted on the surface S2 (back) with 10mm separation distance to the DUT in the Closed Mode.

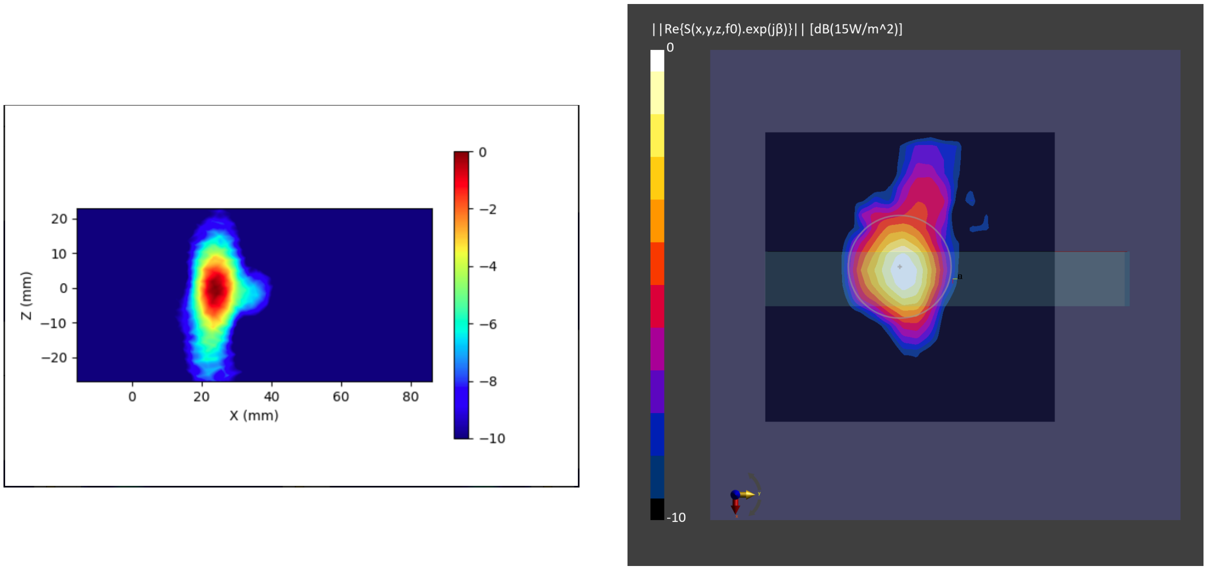


Figure 2-26 Simulated (left) and measured (right) *PD* distribution for the following configuration: Band n258, MID Channel, Beam ID 3, H polarization, Plane A Module, plotted on the surface S5 (top) with 10mm separation distance to the DUT in the Closed Mode.

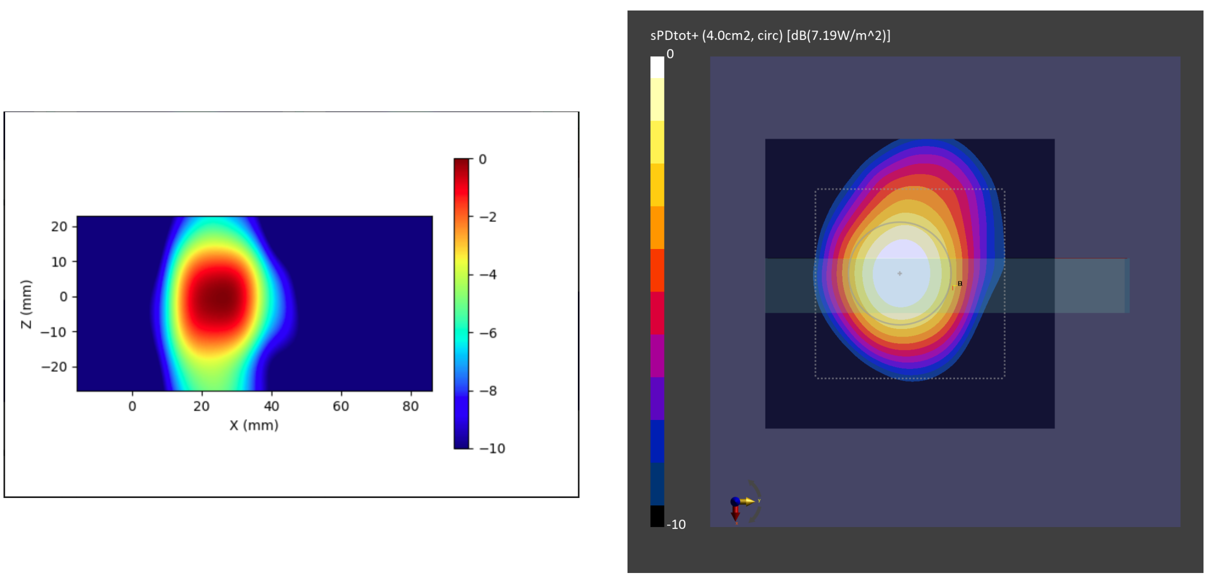


Figure 2-27 Simulated (left) and measured (right) averaged *PD* distribution for the following configuration: Band n258, MID Channel, Beam ID 3, H polarization, Plane A Module, plotted on the surface S5 (top) with 10mm separation distance to the DUT in the Closed Mode.

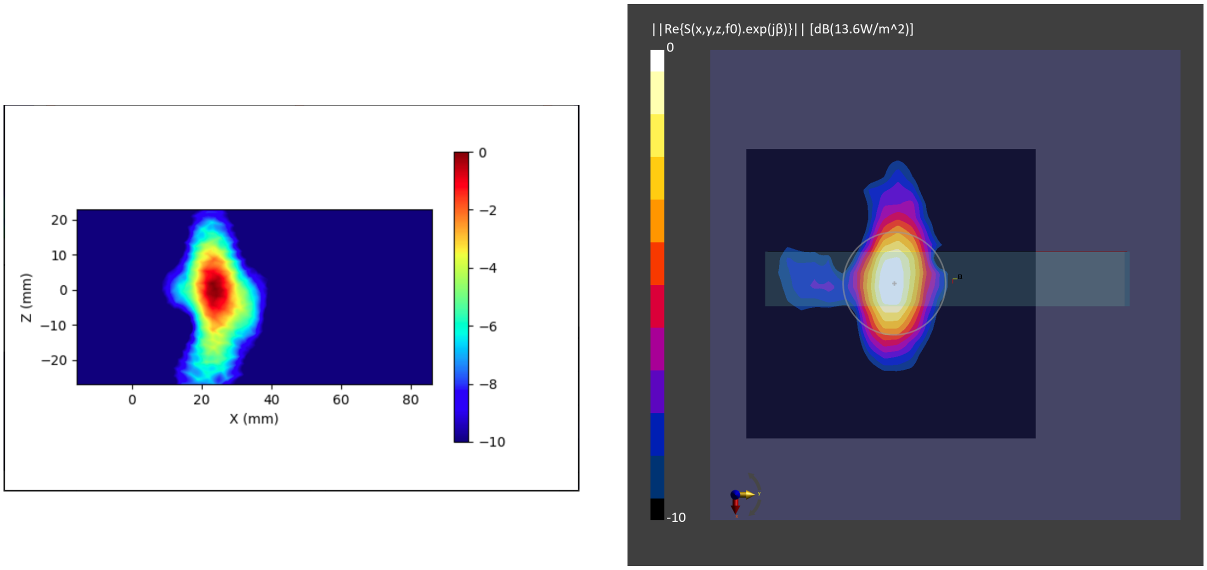


Figure 2-28 Simulated (left) and measured (right) *PD* distribution for the following configuration: Band n258, MID Channel, Beam ID 3, V polarization, Plane A Module, plotted on the surface S5 (top) with 10mm separation distance to the DUT in the Closed Mode.

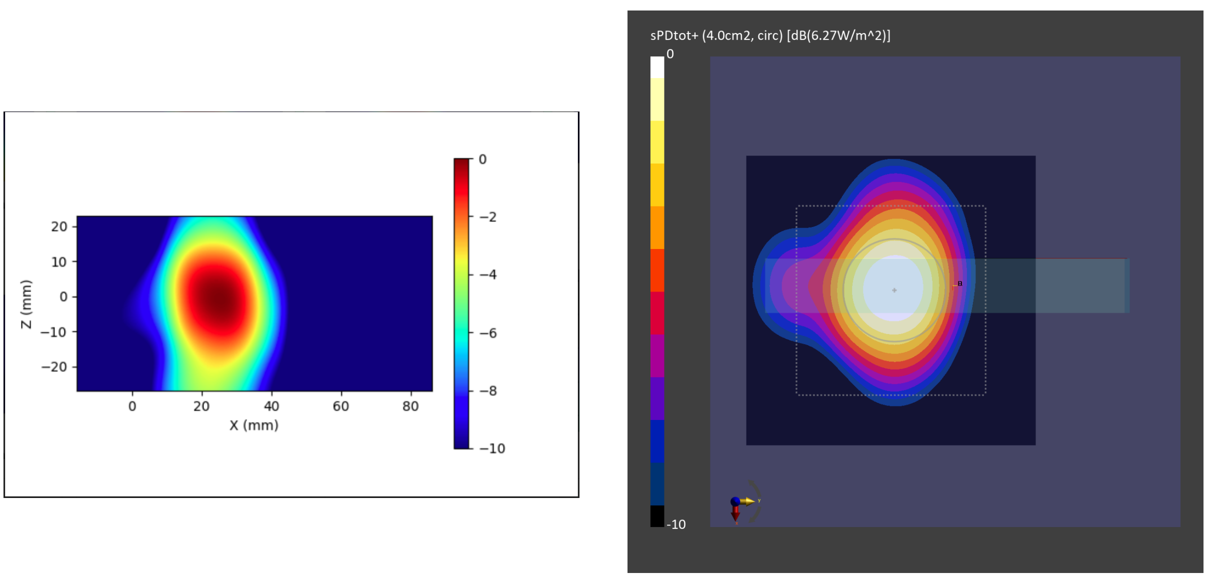


Figure 2-29 Simulated (left) and measured (right) averaged *PD* distribution for the following configuration: Band n258, MID Channel, Beam ID 3, V polarization, Plane A Module, plotted on the surface S5 (top) with 10mm separation distance to the DUT in the Closed Mode.

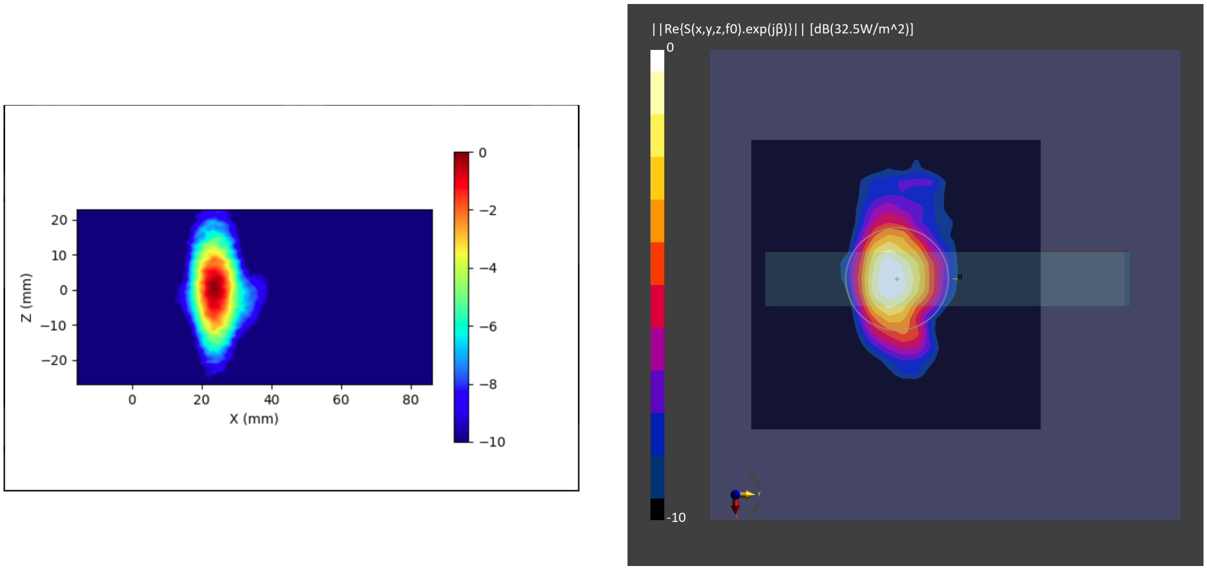


Figure 2-30 Simulated (left) and measured (right) *PD* distribution for the following configuration: Band n258, MID Channel, Beam ID 3, H+V polarization, Plane A Module, plotted on the surface S5 (top) with 10mm separation distance to the DUT in the Closed Mode.

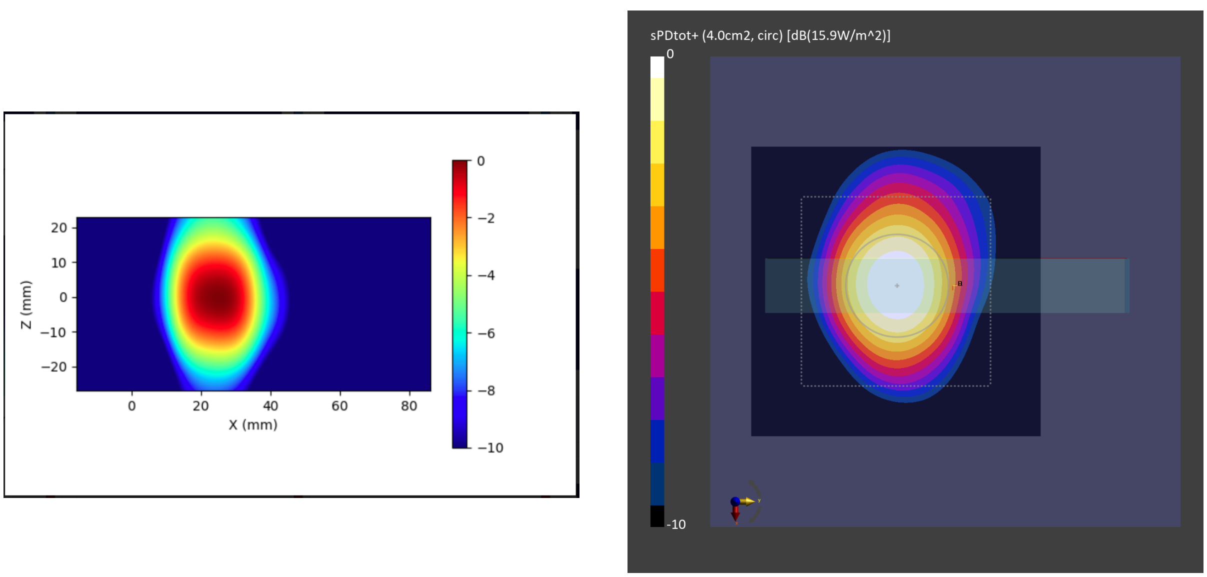


Figure 2-31 Simulated (left) and measured (right) averaged *PD* distribution for the following configuration: Band n258, MID Channel, Beam ID 3, H+V polarization, Plane A Module, plotted on the surface S5 (top) with 10mm separation distance to the DUT in the Closed Mode.

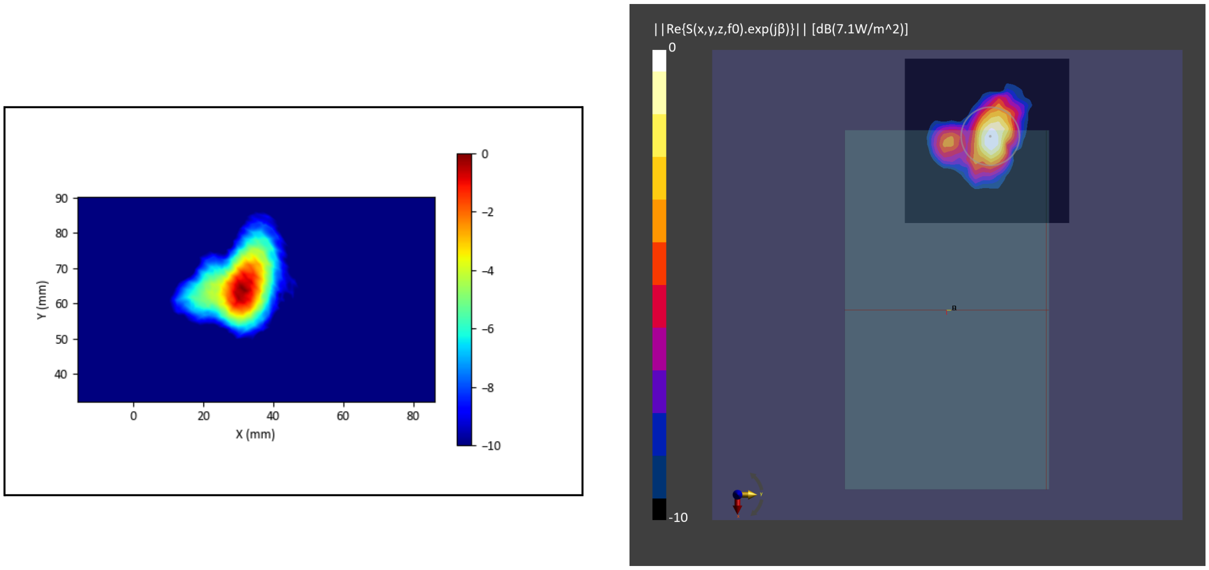


Figure 2-32 Simulated (left) and measured (right) *PD* distribution for the following configuration: Band n258, MID Channel, Beam ID 4, H polarization, Plane B Module, plotted on the surface S2 (back) with 10mm separation distance to the DUT in the Closed Mode.

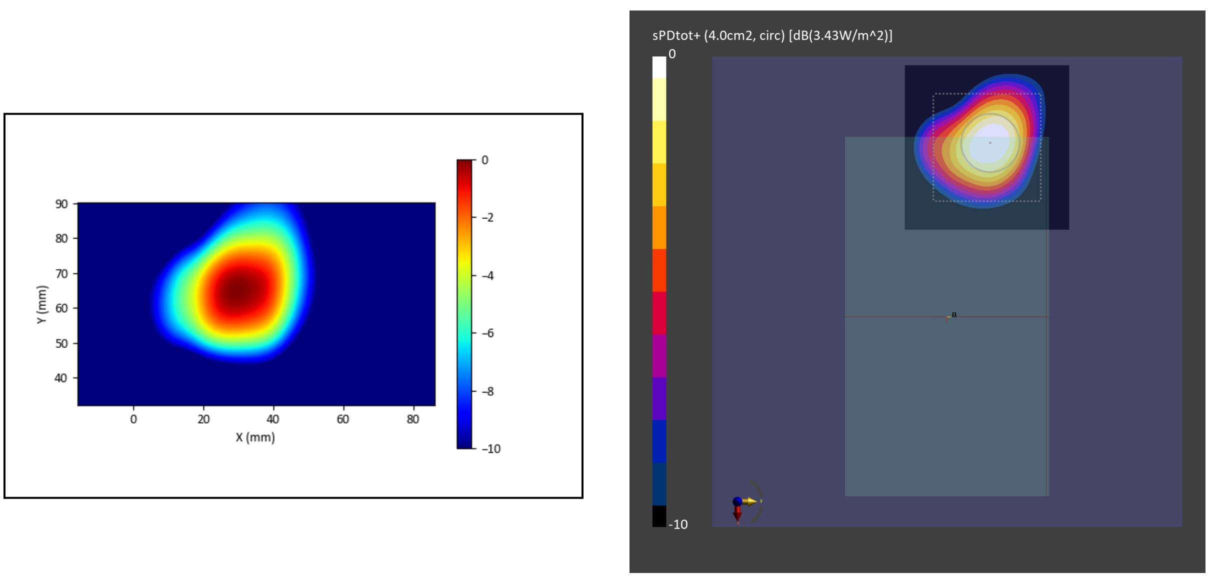


Figure 2-33 Simulated (left) and measured (right) averaged *PD* distribution for the following configuration: Band n258, MID Channel, Beam ID 4, H polarization, Plane B Module, plotted on the surface S2 (back) with 10mm separation distance to the DUT in the Closed Mode.