



A2484_5G_Product-mmWave-MPE_Simulation_Report- withsimPDPlots

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1 Introduction

This document provides an overview of the methodology used for MPE (averaged power density) RF exposure compliance of the 5G mmWave radios on next generation iPhone.

Due to the presence of multiple antenna arrays, and multiple antenna beams for each antenna array, we propose to use a combination of simulation and measurement to demonstrate MPE (PD) compliance. At a high level, the discussion is grouped into the following topics:

- Brief introduction to MPE simulation methodologies
- Explanation of the approach to demonstrate MPE (PD) compliance in a device with measurement to validate simulation
- Brief review of the device configuration and operation, and detailed description of the simulation methodology and results

A few things to be noted are

1. The simulation and validation methods described herein follow QC guidance for SAR Char and PD Char for determining the worst-case beam for static transmission measurements.
2. The PD simulation models are built with different CAD models for different programs.
3. Based on guidance, we intend to characterize the three highest MPE beams per polarization per module in order to choose the scaling factor for all other beams on that module/polarization.

2 MPE Simulation Methodology

3D full-wave simulation is used to evaluate power density (MPE) for each antenna array module's beam. Each beam is created by invoking a pre-defined codebook that has the proper array elements' excitation (i.e., magnitude and phase) to create the beam.

As is shown in Figure 1, the following steps are taken to verify the validity of the model used for MPE simulations and then the verified model is used for the MPE calculations:

1) EM Simulation:

- Import a CAD model that represents the actual product in the simulation tool
- Define material properties inside the product based on vendor's inputs
- Perform mesh seeding and solve

2) Apply Codebook:

- Apply array elements' excitation from the codebook and extract the fields
- Codebook shows the magnitude and phase of each antenna element, which determines each beam of the antenna array
- Codebook is generated to automate the simulation of different beams

3) MPE Calculations:

- Post-process the extracted fields including averaging the power density on the evaluation surface
- Averaging area is 4 cm²



- Calculate average power density (MPE)
- 4) **Validate Simulation Model:**
- Measure MPE
 - Compare measurement vs simulation
 - Once a correlation is established, and model's accuracy is verified, this model will be used for computational MPE assessments

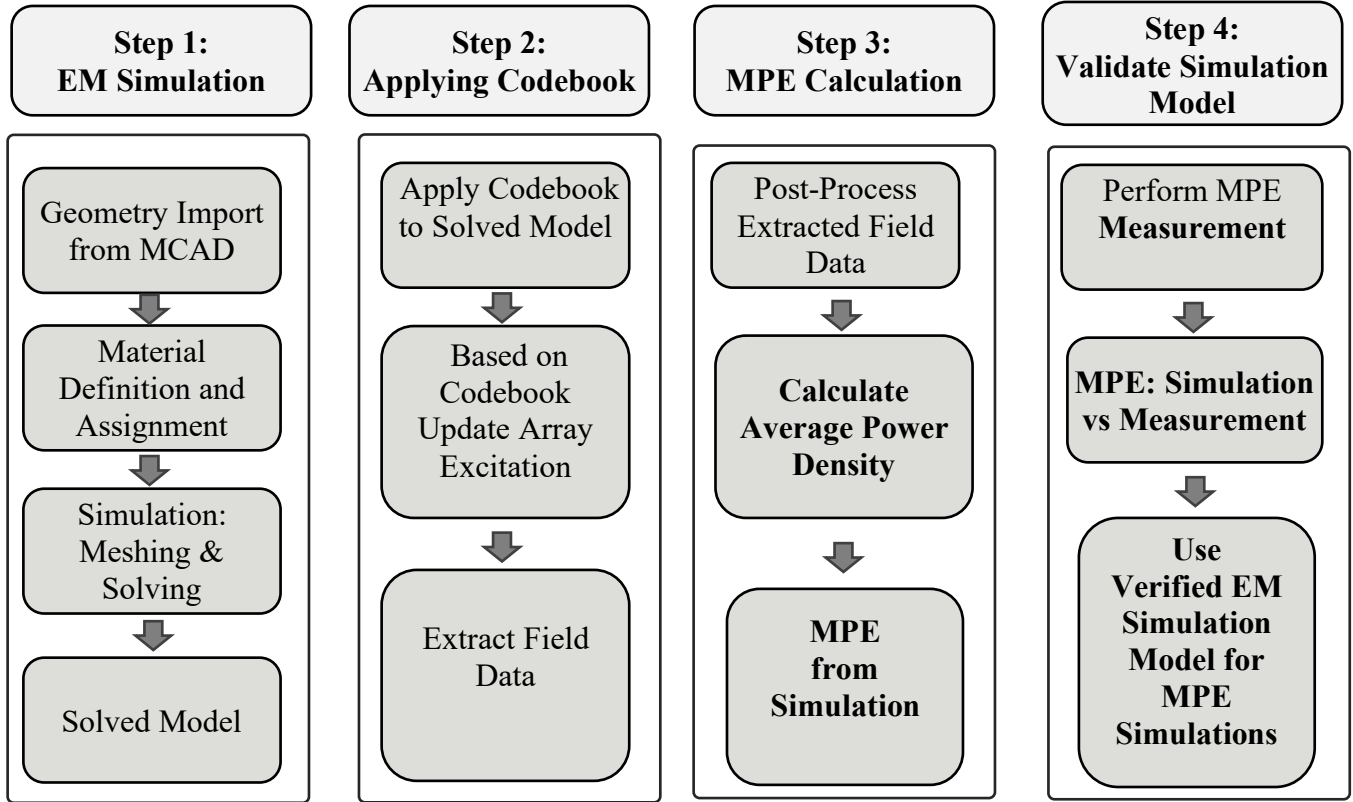


Figure 1. Model validation workflow for MPE simulation and evaluation.

3 MPE Measurements

A mmWave DAE SN 1411 module from SPEAG is used to measure the MPE (PD) above the DUT. Figure 2 shows the setup of measurement. The mmWave E-field probe is used to measure the electric field above DUT. The near-field magnetic field and MPE are further obtained using this setup. The measurement algorithm can be found in¹ in detail.

¹ S. Pfeifer , E. Carrasco, P. Crespo-Valero, E. Neufeld, S. Kuhn, T. Samaras, A. Christ, M. H. Capstick, and N. Kuster, "Total field reconstruction in the near field using pseudo-vector E-field measurement," *IEEE Trans. Electromagn. Compat.*, vol. 61, no. 2, pp. 476–486, Apr. 2019.

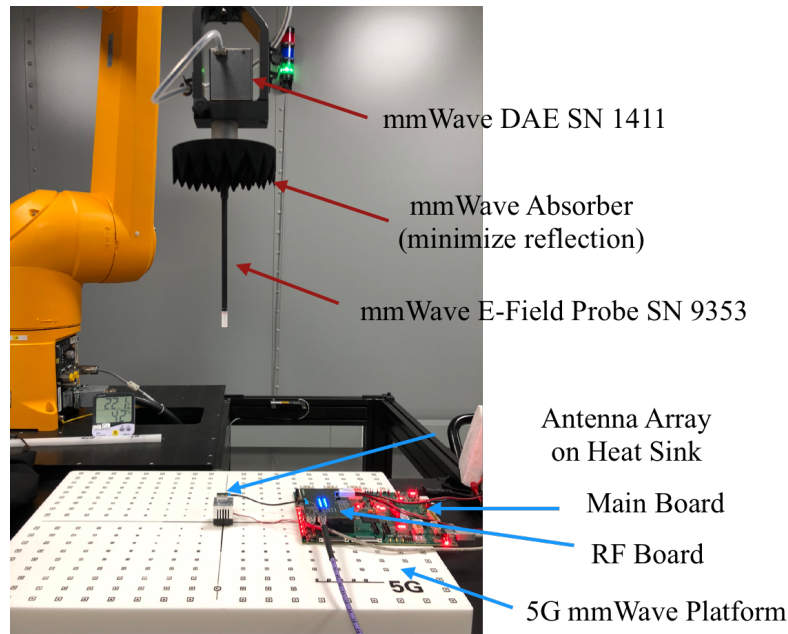


Figure 2. MPE measurement setup.

The distance from probe sensor tip to the edge of the housing is 1.5 mm, and there is 0.5 mm gap between probe tip and the DUT surface to prevent mechanical damage. Therefore, the closest distance that the setup can measure is 2 mm as shown below in Figure 3.

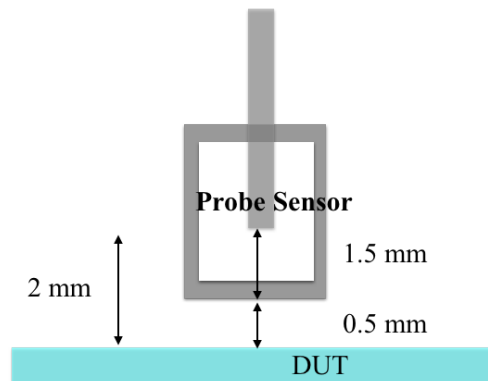


Figure 3. Sketch of the probe showing that the minimum measurable distance is 2 mm.

4 MPE (PD) Simulations

In 5G, MIMO antennas are designed to orient the beam to specific directions in order to improve link budgets. Most MIMO can be configured by using the codebook with each code resulting in a different exposure. The number of codes in the codebook can be very large and measurements of all possible configurations have been shown to be impractical. Therefore, simulation is used to determine the modes/configurations that result in the highest MPE.

All elements are dual polarized patch antennas with horizontal and vertical feeds.



Simulation Models

Figure 4 is a schematic of the simulation model. There are three antenna arrays in the phone, which are back-firing array 1, back-firing array 2 and side-firing array.

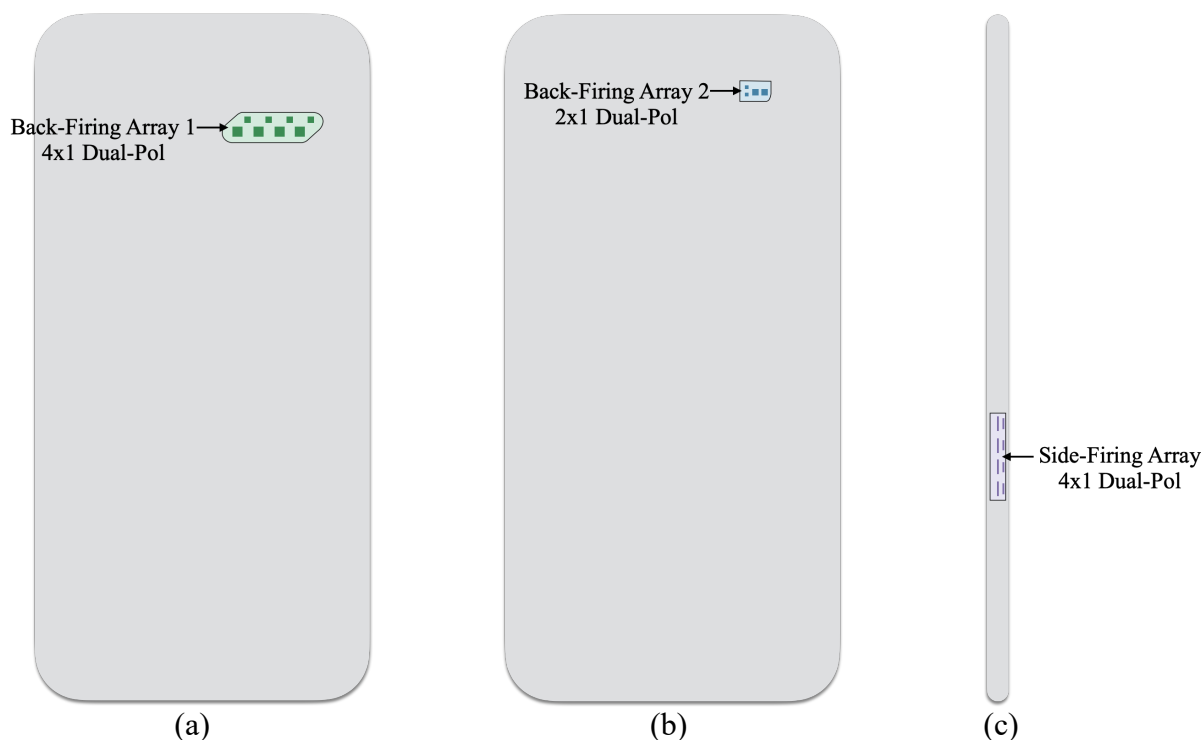


Figure 4. Schematic of the simulation mode, which consists of three 5G antenna arrays, (a) back-firing array 1 (rear view), (b) back-firing array 2 (rear view), and (c) side-firing array (side view).

The measurements and simulations are correlated across different evaluating surfaces 2 mm away from each DUT surface (drawn not to scale), as shown in Figure 5 below. Six surfaces will be evaluated, respectively: front (S1), back (S2), left (S3), right (S4), top (S5) and bottom (S6). As Table 1 shows, for the three antenna arrays, only the evaluating planes within 2.5 cm from the edges of the antenna modules will be considered. This does not apply to the back-to-front or front-to-back condition since fields from the back module will be blocked at the front evaluating plane (and vice versa) by the metal parts (such as battery, MLB) in between.

The “left” and “right” edges in the report are defined relative to the front of the device.

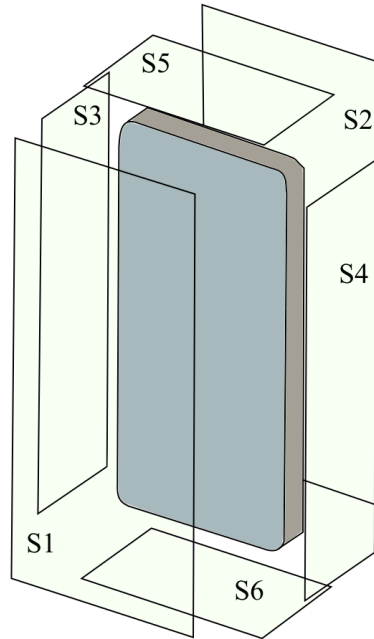


Figure 5. Evaluating surfaces for MPE (PD).

Table 1 - PD Evaluation Planes

	Front (S1)	Rear (S2)	Left from Front View (S3)	Right from Front View (S4)	Top (S5)	Bottom (S6)
Side Array	Yes (0.4 cm)	Yes (0.4 cm)	No (7 cm)	Yes (0 cm)	No (8 cm)	No (4 cm)
Back Array 1	No (0.6 cm)	Yes (0 cm)	Yes (0.9 cm)	No (4 cm)	No (2.7 cm)	No (12 cm)
Back Array 2	No (0.6 cm)	Yes (0 cm)	Yes (0.9 cm)	No (4 cm)	Yes (0.8 cm)	No (12 cm)

MPE (PD) Definition

After solving the 3D full-wave electromagnetic simulation, various physical quantities can be derived. To calculate PD evaluation, two physical quantities, an electric field $\vec{E}$ and a magnetic field $\vec{H}$ are needed. The actual consumption power can be expressed as the real term of the Poynting vector $\vec{S}$ from the cross product of $\vec{E}$ and complex conjugation of $\vec{H}$ as shown below:

$$\vec{S} = \frac{1}{2} \text{Re}(\vec{E} \times \vec{H}^*)$$

$\vec{S}$ can be expressed as localized power density based on a peak value of each spatial point on mesh grid, and obtained directly from ANSYS Electromagnetics suite version 19.2 (HFSS).



From the localized power density $\vec{S}$, the spatial-averaged power density (PD) on an evaluated area (A) can be shown as below

$$PD = \frac{1}{A} \int_A \vec{S} \cdot d\vec{A} = \frac{1}{2A} \int_A \text{Re}(\vec{E} \times \vec{H}^*) \cdot d\vec{A}$$

For the purposes of these simulations, PD is the total power density value considering the contributions of x, y, and z components of localized power density $\vec{S}$. The evaluated area A is 4 cm². To capture worst-case power density conditions, simulations and measurements were performed assuming a 100% duty cycle.

Mesh and Convergence Criteria:

HFSS adapts the mesh based on field strength. The determination parameter of the number of iterations in HFSS is defined by the convergence criteria, ΔS , and the iterative adaptive mesh process repeats until ΔS is met, which in this case is 0.001. Figure 6 is an example of the final adaptive mesh of the device (cross-section of top view). The simulation results of this report are all calculated with a ΔS target of 0.02.

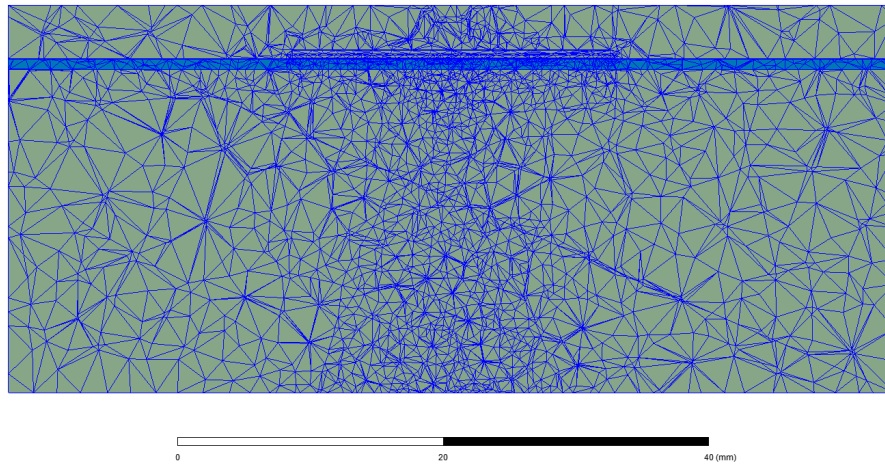


Figure 6. Example of the adaptive mesh technique (top view)

It is important to make sure the mesh is refined to capture MPE (PD) accurately. This can be done by monitoring MPE (PD) levels vs. different mesh densities, as Figure 7 depicts, showing that a fine enough mesh is needed to guarantee that the simulation gives converged and correct results. The first row in Figure 7 is simulation with coarse mesh, and the last row is with fine mesh. From the results we can see that for the third mesh, the simulated result is within 1% of the result for the finest mesh. In these simulations, the mesh in the third row is applied to ensure an accurate result with the shortest processing time.

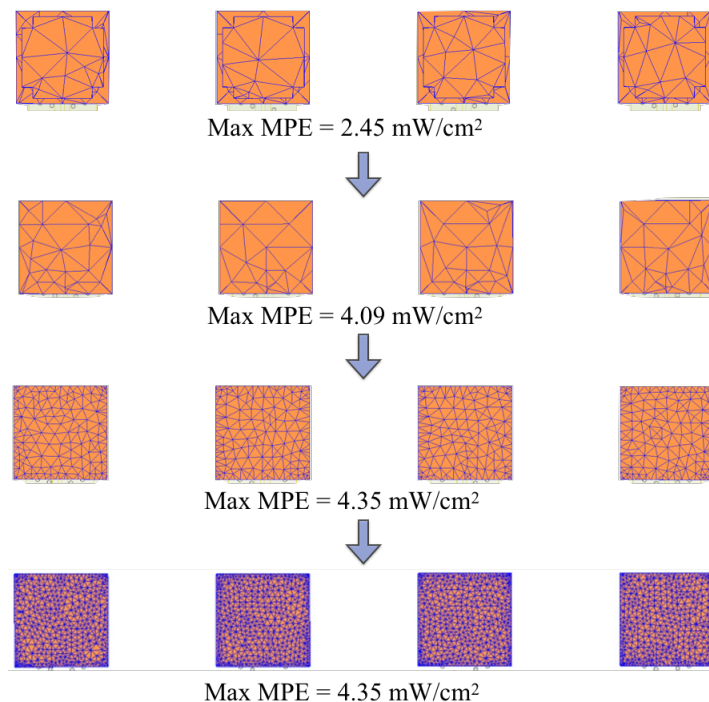


Figure 7. HFSS adaptive mesh shows that when the mesh is fine enough, MPE results will converge.

Boundary Conditions:

The boundary condition for simulating electromagnetic behavior in HFSS is to allow electromagnetic waves to be electrically open at the boundary and radiated far away without reflection. HFSS can support the absorption boundary condition (ABC) for radiation boundary and normally requires a quarter-wave separation from the structure. In this report, in order to cover all beamforming cases, a spacing of four full wavelengths is used.

Source Excitation and Example Codebook:

Figure 8 shows an example of the codebook for the antenna modules. The first column of the codebook is the beam ID. “Amplitude” and “Phase” are the excitation amplitude and phase for each antenna element. Each beam has a “Paired_With” beam for concurrent MIMO streams. The last column is the index of the beam which is paired with the index shown in the second column. The “Amplitude” is in dBm, and “Phase” is in degrees. In real applications, amplitude of the input power for n257 and n261 is 12 dBm, and for n260 is 11 dBm.



Band	Beam_ID	Module	Ant_Group	Subarray	Ant_Type	Ant_Feed	Amplitude	Phase	Paired_With
257	0	0	0	7	PATCH	10	0	0	128
257	1	0	0	9	PATCH	12	0	0	129
257	2	1	0	11	PATCH	13	0	0	130
257	3	0	0	7	PATCH	9	0	0	131
257	4	0	0	9	PATCH	11	0	0	132
257	5	1	0	11	PATCH	14	0	0	133
257	6	0	0	7	PATCH	10;9	0;0	202.5;11.25	134
257	7	0	0	7	PATCH	10;9	0;0	281.25;22.5	135
257	8	0	0	7	PATCH	10;9	0;0	0;0	136
257	9	0	0	7	PATCH	10;9	0;0	281.25;213.75	137
257	10	0	0	9	PATCH	12;11	0;0	112.5;56.25	138
257	11	0	0	9	PATCH	12;11	0;0	67.5;225	139
257	12	1	0	11	PATCH	9;13	0;0	303.75;45	140
257	13	1	0	11	PATCH	10;9	0;0	225;0	141
257	14	1	0	11	PATCH	9;13	0;0	168.75;78.75	142
257	15	1	0	11	PATCH	13;14	0;0	11.25;0	143
257	16	0	0	7	PATCH	10;9	0;0	78.75;225	144
257	17	0	0	7	PATCH	10;9	0;0	326.25;22.5	145
257	18	0	0	7	PATCH	10;9	0;0	213.75;168.75	146
257	19	0	0	9	PATCH	12;11	0;0	45;78.75	147
257	20	1	0	11	PATCH	9;13	0;0	281.25;0	148
257	21	1	0	11	PATCH	13;14	0;0	236.25;0	149
257	22	1	0	11	PATCH	10;9	0;0	213.75;191.25	150
257	23	0	0	7	PATCH	10;13;9;14	0;0;0;0	315;258.75;112.5;0	151
257	24	0	0	7	PATCH	10;13;9;14	0;0;0;0	191.25;348.75;281.25;0	152
257	25	0	0	7	PATCH	10;13;9;14	0;0;0;0	78.75;90;78.75;0	153
257	26	0	0	7	PATCH	10;13;9;14	0;0;0;0	247.5;112.5;180;0	154

Figure 8. An example version of the antenna codebook.

One thing to be noted is that the codebook is defined at the chipset, not at the antenna elements.

Averaging the Power Density for MPE (PD):

Spatial averaging is needed to determine the MPE values from power density simulation results over the 4 cm² area required by the FCC. Figure 9 illustrates how averaging is conducted inside the software.

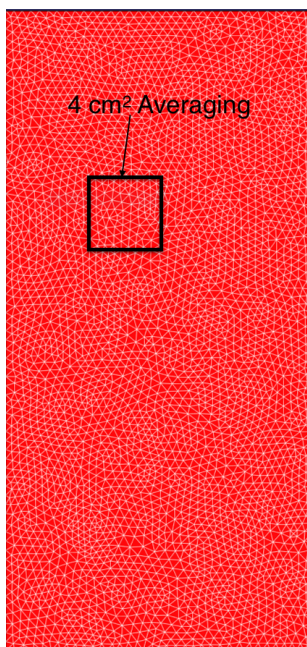


Figure 9. Averaging power density of 4cm^2 area to get MPE (PD) results.

5 Uncertainty Budget for Simulation

5.1 Mesh resolution

5.1.1 FEM meshes

Either of the two strategies described below shall be applied to determine FEM mesh resolution, depending on whether the code used for the evaluation of the *psPD* employs adaptive mesh refinement or not.

If the applied finite-element code does not employ adaptive mesh refinement, the number of mesh elements per wavelength (material dependent) used for the initial mesh shall be set to a) 1.15 times and then to b) 1.3 times the value.

If the applied finite-element code uses adaptive mesh refinement, additional adaptive passes shall be performed until the number of mesh elements has increased by at least 20%.

In either case, the maximum deviation of the *psPD* shall be reported in Table assuming normal probability distribution.

5.2 Absorbing boundary conditions

The impact of the absorbing boundaries conditions should be determined by moving the boundaries outward by a $\lambda/4$ and $5\lambda/4$ spacing in all directions. The maximum deviation of the *psPD* shall be reported in Table assuming rectangular probability distribution.

NOTE: The location of the maximum electric or magnetic energy at the boundary may correspond to the main beam of a radiating structure or to its reactive field.



5.3 Power budget

The power fed into the computational domain shall be recorded at the sources (P_M or P_O). The sum of the power absorbed in the lossy dielectrics, lossy conductors and passive components in the computational domain and radiated into the ABCs shall be recorded and compared to P_M or P_O . The deviation shall be reported in Table assuming normal probability distribution.

NOTE: When simulating devices with multiple sources operating simultaneously, it is recommended to excite each port separately while loading the inactive ports with the reference impedance in order to compute the full S-matrix of the multiport system. As such, the *psPD* and the power budget for a given excitation vector can be calculated by superimposing the fields for any excitation vector and load. For details refer to:

IEC Technical Report 62630, "Guidance for evaluating exposure from multiple EM sources"
IEC TC106 WG4, December 2009.

Kozlov, M. and Tumer, R., "SAR in interleaved excitation of an MRI RF array"
Antennas and Propagation Society International Symposium (APSURSI), 2012 IEEE.

5.4 Convergence

5.4.1 Frequency domain FEM solvers

If the FEM solver has adaptive mesh refinement, the E-field vector components shall be recorded in the region (the relevant region) where the *psPD* is expected. The field components shall be recorded on a subvolume of this region, and the maximum element size in this subvolume shall be smaller than 20% of the maximum element size of the computational domain. (The element size is defined by the radius of a sphere circumscribed around the element.) The absolute value of the complex field vectors shall be calculated in each adaptive step. For a sufficiently converged adaptive process, the maximum field value shall be at the same mesh point and the deviation of this maximum field value from their mean value in the last two adaptive steps shall not be larger than 2%.

If the FEM solver does not have adaptive mesh refinement, the solution shall be generated on two meshes where the second mesh shall contain 30% more elements in the relevant region (e.g., in regions of high energy or fine geometrical details where the refinement is expected to have the biggest impact) than the first mesh does. The element number should be increased in the relevant region in a way that the maximum element size does not increase. Then the convergence shall be evaluated as in the adaptive refinement case.

5.4.2 Reporting the convergence uncertainty

The deviation shall be reported in Table 2 as uncertainty with rectangular probability distribution. Since the location of the *psPD* may not be known beforehand, it is recommended to select the relevant region large enough to avoid repeated simulation. Testing simulations with coarser meshes or simplified geometry may help to limit the computational expenses to identify the relevant regions for the recording of the signals.



5.5 Dielectric properties

The dielectric properties of the DUT model are usually affected by uncertainties according to their specification. The impact of these uncertainties on the *psPD* shall be evaluated by applying the minimum and maximum conductivity and permittivity (four different combinations). The minimum and maximum shall be chosen according to the uncertainty that is reported in the reference documentation of the dielectric properties *e.g.*, data sheet or other publication. In order to avoid excessive numbers of simulations for structures with a large number of different dielectrics, the changes in conductivity and permittivity may be limited to the region where most of the electromagnetic energy is confined or absorbed, or advanced statistical methods may be applied for the quantification of the uncertainty. In such cases, an appropriate rationale shall be given. The deviation shall be reported in Table as uncertainty with normal probability distribution.

5.6 Lossy conductors

The finite conductivity of the conductors of the DUT shall be varied according to their specification. The impact of these uncertainties shall be evaluated by applying the minimum and maximum conductivity of all conductors of the DUT (two simulations). The minimum and maximum shall be chosen according to the uncertainty that is reported in the reference documentation of the conductors, *e.g.*, data sheet, publication. The deviation shall be reported in Table 2 as uncertainty with rectangular probability distribution.

Table 2 – Preliminary budget of the uncertainty contributions of the numerical algorithm for the validation- or testing-setup

Uncertainty component	Subclause	Probability distribution	Divisor $f(d, h)^1$	C_i^2	Uncertainty %
Mesh resolution	5.1	Normal	1	1	0.7%
ABC	5.2	Normal	1	1	0.7%
Power budget	5.3	Normal	1	1	0.5%
Convergence	5.5	Rectangular	1,73	1	0.1%
DUT dielectrics	5.6	Normal	1	1	5.5%
Lossy conductors	5.7	Rectangular	1,73	1	3.5%
Combined standard uncertainty ($k = 1$)					11.0%

Note 1: The divisor is a function of the probability distribution and degrees of freedom (ν_i and ν_{eff}).

Note 2: c_i is the sensitivity coefficient that is applied to convert the variability of the uncertainty component into a variability of *psPD*.

6 Simulation vs. Measurement

To validate the accuracy of the model, measured MPE and simulated MPE values for n258 are summarized below in Table 3, with unit mW/cm^2 . The difference between simulated and measured



MPE values is in dB. Please be noted due to timeline, the simulation and measurement comparison is done not using the final version of codebook.

a) Side-Firing Array, n258

Beam ID	Ant Pol	Simulation (mW/cm ²)	Measurement (mW/cm ²)	Delta = Sim – Meas. (dB)
		S4	S4	S4
35	V	9.38	6.12	1.85
43	V	8.19	5.36	1.84
44	V	9.85	6.64	1.71
161	H	5.89	3.95	1.74
163	H	5.20	4.52	0.61
170	H	5.30	5.08	0.18

b) Back-Firing Array 1, n258

Beam ID	Ant Pol	Simulation (mW/cm ²)	Measurement (mW/cm ²)	Delta = Sim – Meas. (dB)
		S2	S2	S2
29	V	7.49	5.04	1.72
30	V	8.45	4.76	2.49
38	V	7.58	5.40	1.47
157	H	6.27	5.64	0.46
158	H	6.92	6.64	0.18
168	H	8.18	7.40	0.44

c) Back-Firing Array 2, n258

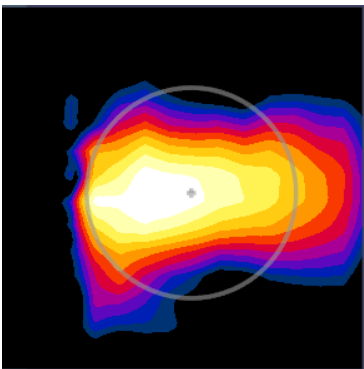
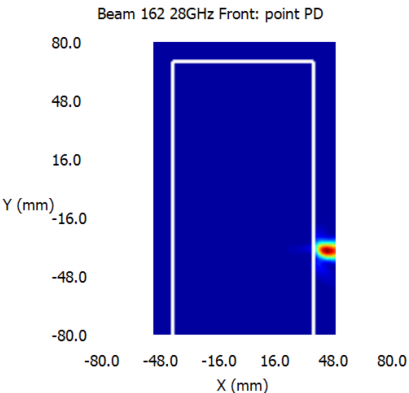
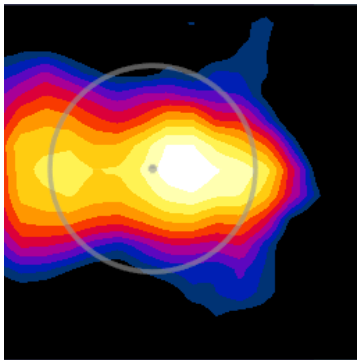
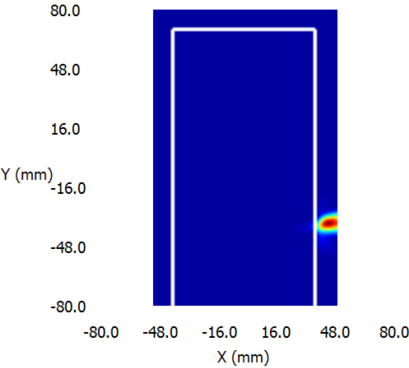
Beam ID	Ant Pol	Simulation (mW/cm ²)	Measurement (mW/cm ²)	Delta = Sim – Meas. (dB)
		S2	S2	S2
11	V	2.32	1.32	2.45
21	V	2.37	1.16	3.10
22	V	2.29	1.26	2.59
139	H	2.30	2.54	-0.43
140	H	2.34	2.71	-0.64
150	H	2.42	2.86	-0.73

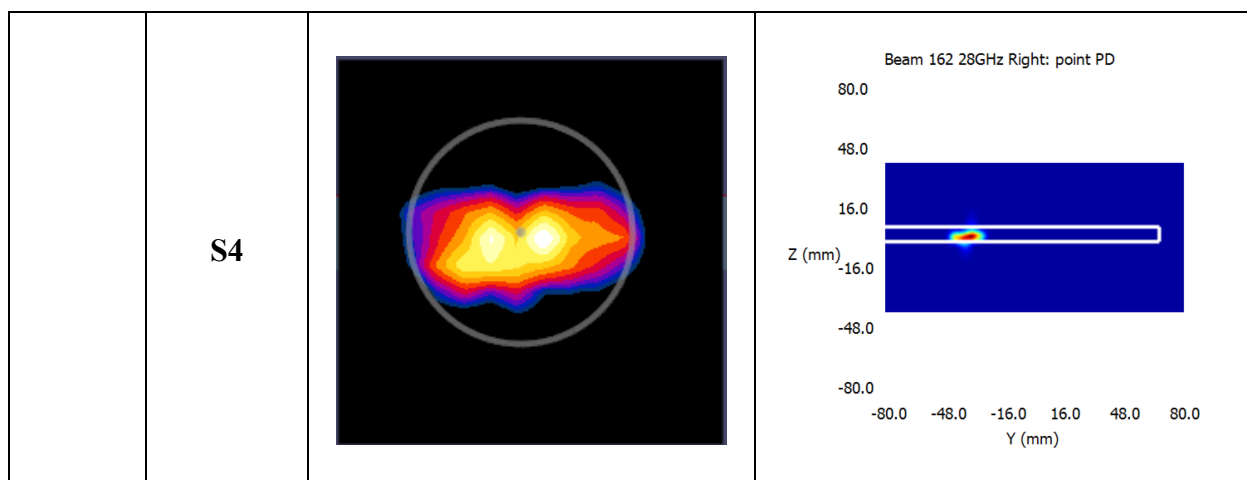
Table 3 - Simulated and measured n258 MPE (PD) at 2 mm away from DUT.



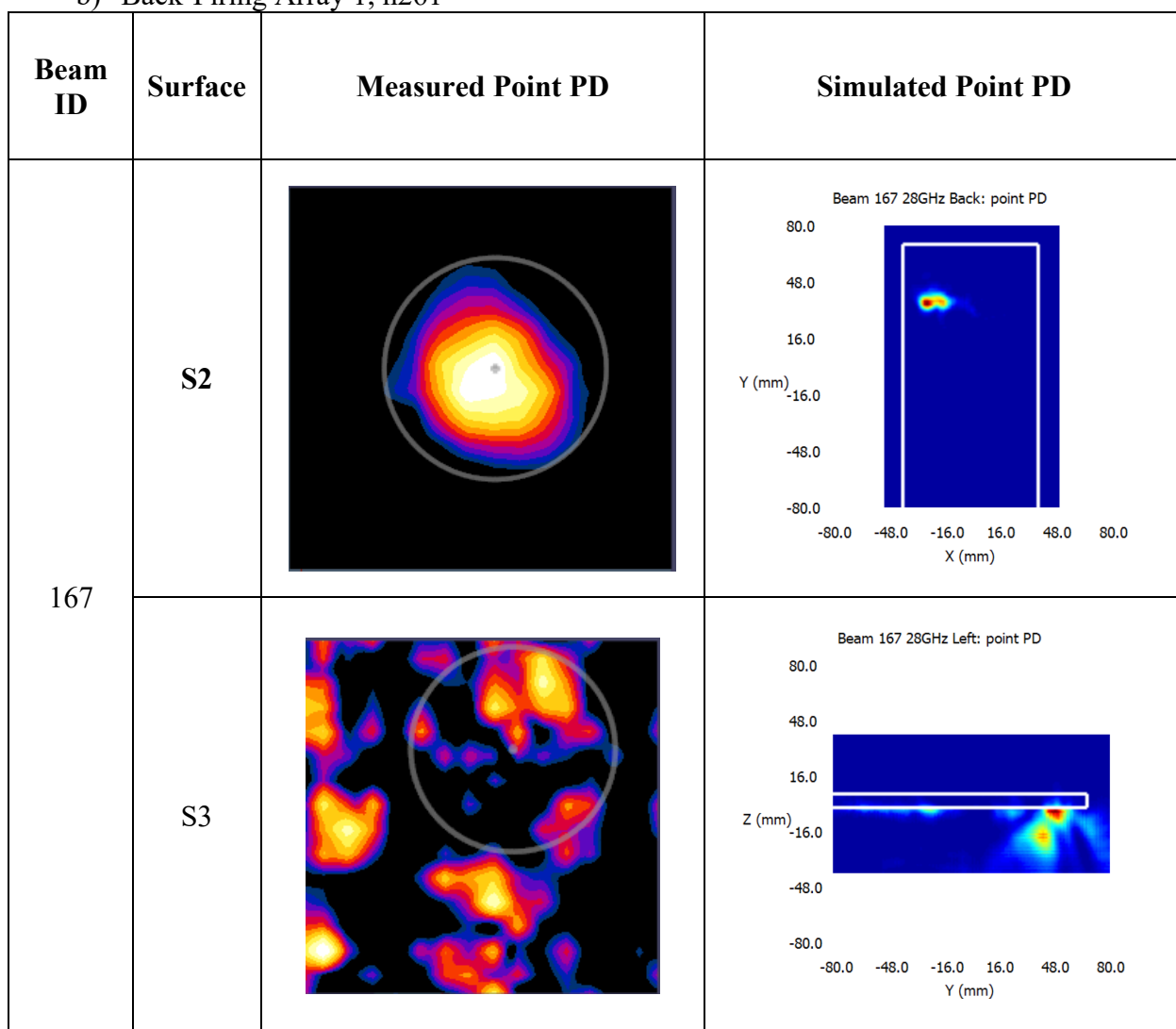
To validate the accuracy of the model, measured point PD patterns for the three arrays were compared to simulated point PD patterns for different beams for n261, as is shown in Figure 10. The plotted point PD pattern are normalized to its own maximum value, respectively. Please be noted due to timeline, the simulation and measurement comparison is done not using the final version of codebook.

a) Side-Firing Array, n261

Beam ID	Surface	Measured Point PD	Simulated Point PD
162	S1		 Beam 162 28GHz Front: point PD
	S2		 Beam 162 28GHz Back: point PD



b) Back-Firing Array 1, n261





c) Back-Firing Array 2, n261

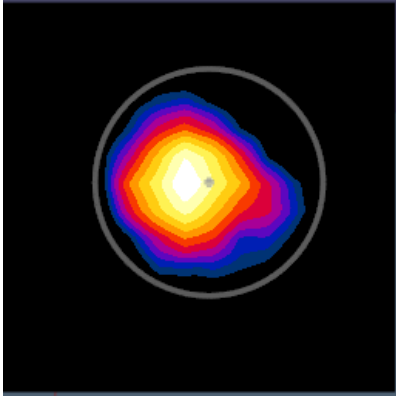
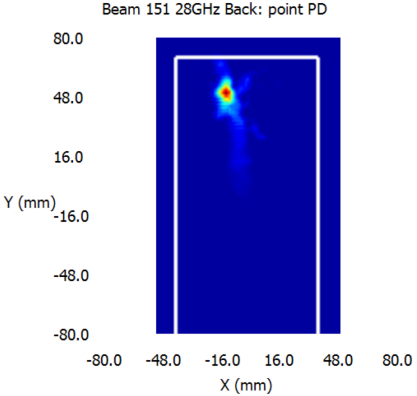
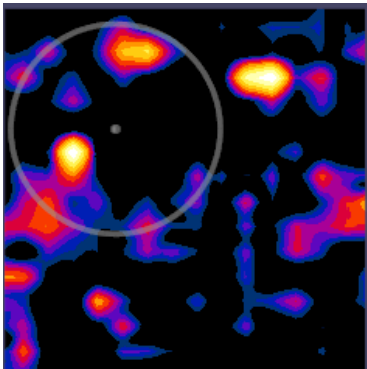
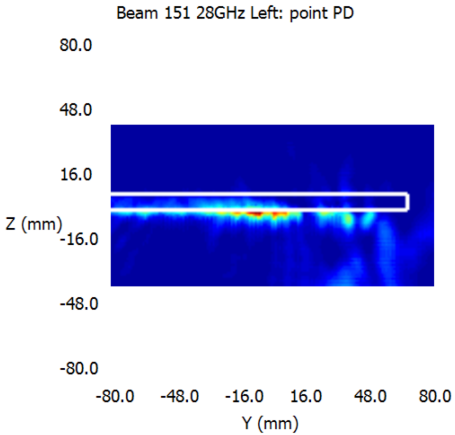
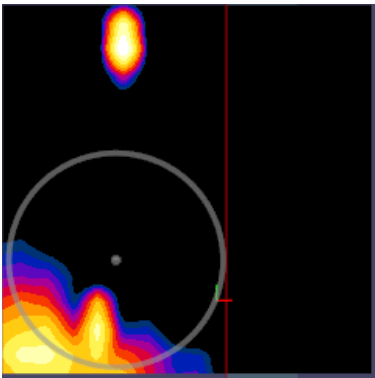
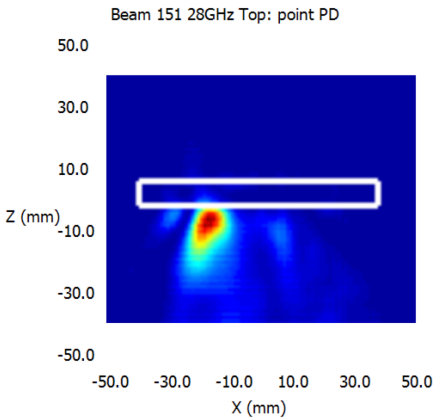
Beam ID	Surface	Measured Point PD	Simulated Point PD
151	S2		
	S3		
	S5		

Figure 10. Simulated and measured point PD for different beams for n261.



Measured MPE and simulated MPE values for n261 are summarized below in Table 4, with unit mW/cm². The difference between simulated and measured MPE values is in dB.

a) Side-Firing Array, n261

Beam ID	Ant Pol	Simulation (mW/cm ²)	Measurement (mW/cm ²)	Delta = Sim – Meas. (dB)
		S4	S4	S4
34	V	8.72	4.84	2.56
42	V	8.82	4.60	2.83
43	V	8.68	5.40	2.06
162	H	7.44	6.16	0.82
170	H	7.70	5.76	1.26
171	H	7.23	5.64	1.08

b) Back-Firing Array 1, n261

Beam ID	Ant Pol	Simulation (mW/cm ²)	Measurement (mW/cm ²)	Delta = Sim – Meas. (dB)
		S2	S2	S2
29	V	6.38	3.88	2.16
39	V	6.29	3.77	2.22
40	V	6.65	3.36	2.96
156	H	5.37	4.72	0.56
158	H	5.44	4.44	0.88
167	H	5.58	4.88	0.58

c) Back-Firing Array 2, n261

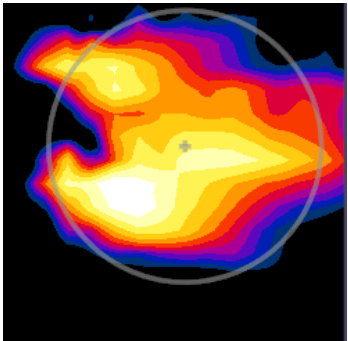
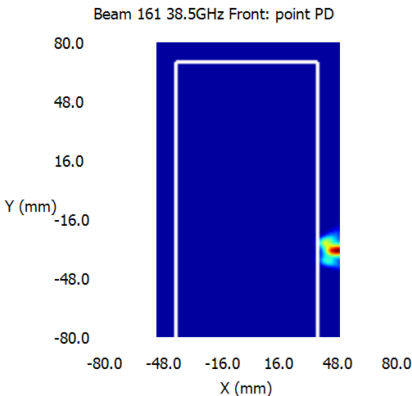
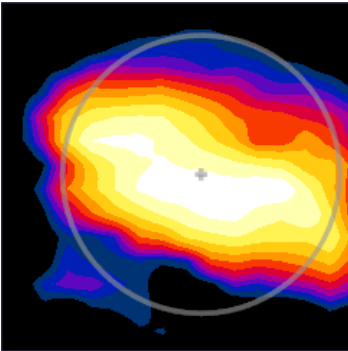
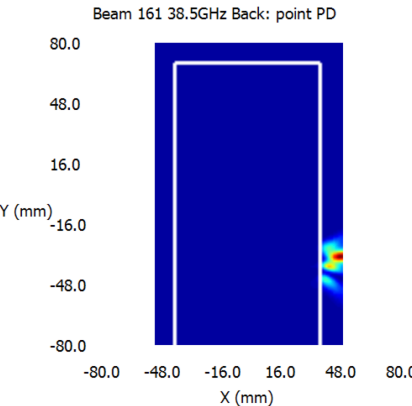
Beam ID	Ant Pol	Simulation (mW/cm ²)	Measurement (mW/cm ²)	Delta = Sim – Meas. (dB)
		S2	S2	S2
12	V	1.66	1.29	1.10
22	V	1.69	1.21	1.45
23	V	1.79	1.19	1.77
140	H	1.83	1.89	-0.14
150	H	1.75	1.97	-0.51
151	H	1.86	1.82	0.09

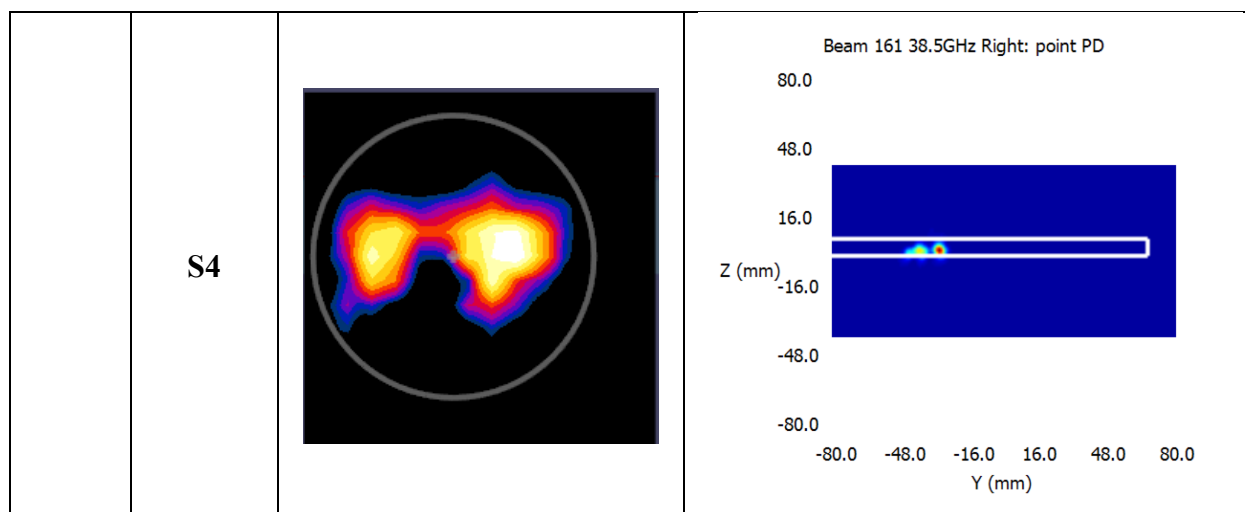
Table 4 - Simulated and measured n261 MPE (PD) at 2 mm away from DUT.



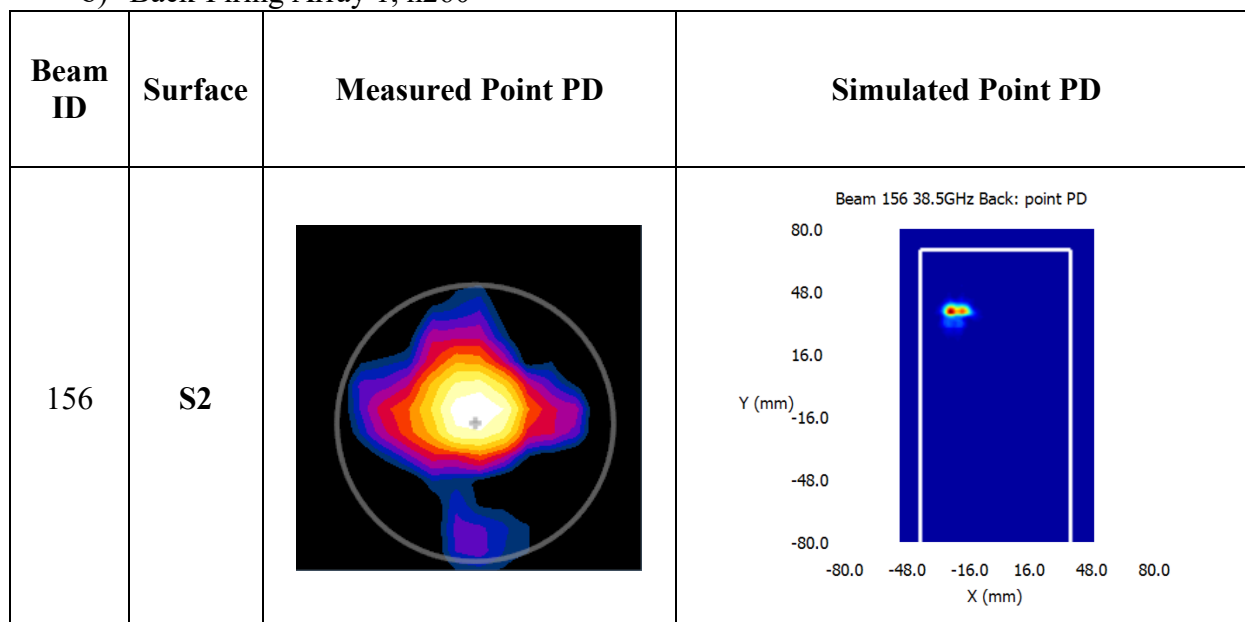
To validate the accuracy of the model, measured point PD patterns for the three arrays were compared to simulated point PD patterns for different beams for n260, as is shown in Figure 11. The plotted point PD patterns are normalized to their own maximum value, respectively. Please be noted due to timeline, the simulation and measurement comparison is done not using the final version of codebook.

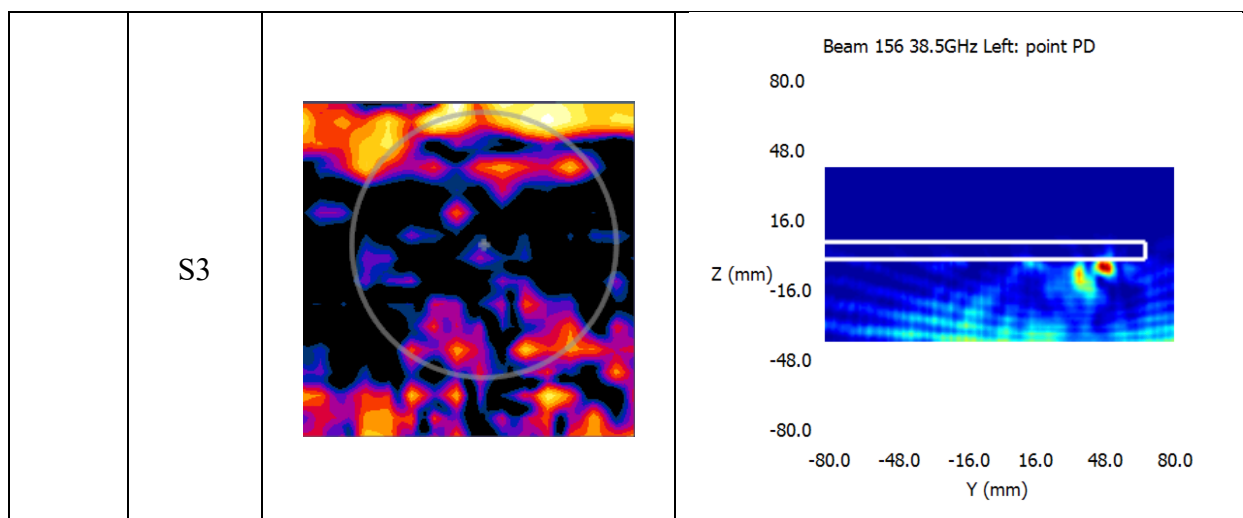
a) Side-Firing Array, n260

Beam ID	Surface	Measured Point PD	Simulated Point PD
161	S1		
	S2		

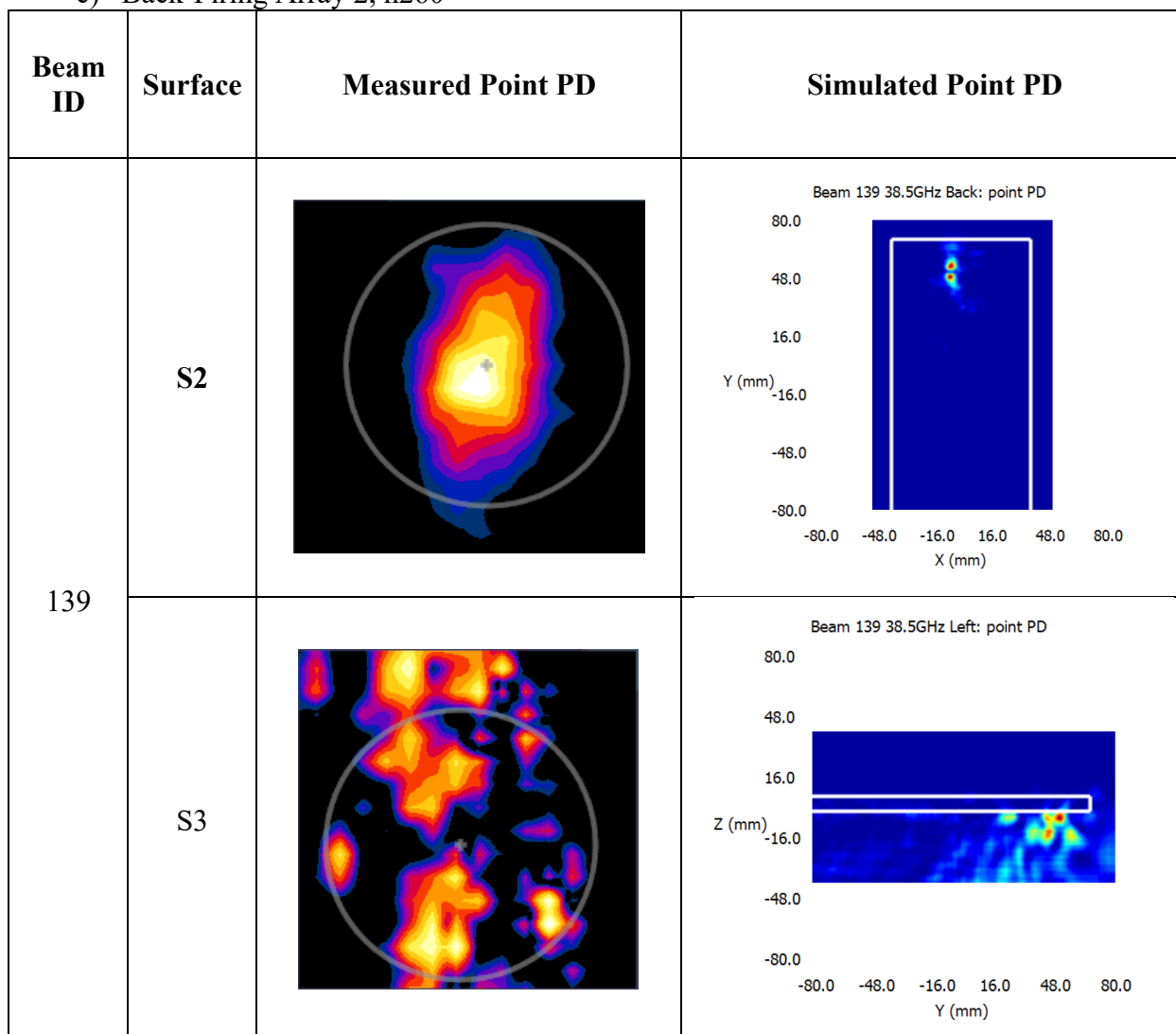


b) Back-Firing Array 1, n260





c) Back-Firing Array 2, n260



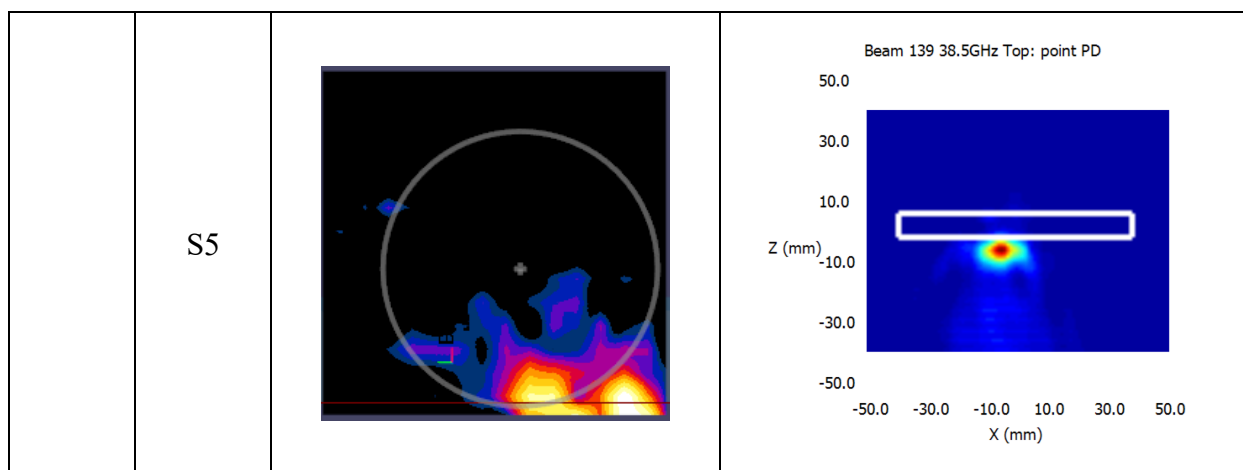


Figure 11. Simulated and measured point PD for different beams for n260.

Measured MPE and simulated MPE values for n260 are summarized below in Table 5, with unit mW/cm^2 . The difference between simulated and measured MPE values is in dB.

a) Side-Firing Array, n260

Beam ID	Ant Pol	Simulation (mW/cm^2)	Measurement (mW/cm^2)	Delta = Sim – Meas. (dB)
		S4	S4	S4
32	V	5.21	4.55	0.59
33	V	5.39	5.00	0.33
41	V	5.52	4.87	0.54
160	H	4.21	4.36	-0.15
161	H	4.74	5.41	-0.57
169	H	4.65	4.93	-0.25

b) Back-Firing Array 1, n260

Beam ID	Ant Pol	Simulation (mW/cm^2)	Measurement (mW/cm^2)	Delta = Sim – Meas. (dB)
		S2	S2	S2
28	V	3.73	2.99	0.96
37	V	3.51	3.00	0.68
38	V	3.86	3.15	0.88
156	H	4.39	4.24	0.15
165	H	4.23	4.08	0.16
166	H	4.36	4.14	0.22



c) Back-Firing Array 2, n260

Beam ID	Ant Pol	Simulation (mW/cm ²)	Measurement (mW/cm ²)	Delta = Sim – Meas. (dB)
		S2	S2	S2
11	V	0.97	1.02	-0.22
12	V	0.89	0.84	0.25
22	V	0.91	0.91	0.00
139	H	1.38	1.09	1.02
140	H	1.39	0.91	1.84
150	H	1.44	1.02	1.50

Table 5 - Simulated and measured n260 MPE (PD) at 2 mm away from DUT.



Appendix A: Worst Phase Derivation for Beam Pair

For beam pairs, since the relative phase between two beams is unknown, so finding the worst-case PD by sweeping the relative phase for all possible angles is required for conservative assessments.

Assuming E-field and H-field for beam ID a are $\{E_x_a, E_y_a, E_z_a\}$ and $\{H_x_a, H_y_a, H_z_a\}$, respectively; for beam pair which is ID b is $\{E_x_b, E_y_b, E_z_b\}$ and $\{H_x_b, H_y_b, H_z_b\}$, respectively. The relative phase between beam a and b is θ , the combined E and H field after beam pairing is:

$$E_{x_pair_i}(\theta) = E_{x_a} + E_{x_b} \times e^{-j\omega\theta}$$

$$E_{y_pair_i}(\theta) = E_{y_a} + E_{y_b} \times e^{-j\omega\theta}$$

$$E_{z_pair_i}(\theta) = E_{z_a} + E_{z_b} \times e^{-j\omega\theta}$$

$$H_{x_pair_i}(\theta) = H_{x_a} + H_{x_b} \times e^{-j\omega\theta}$$

$$H_{y_pair_i}(\theta) = H_{y_a} + H_{y_b} \times e^{-j\omega\theta}$$

$$H_{z_pair_i}(\theta) = H_{z_a} + H_{z_b} \times e^{-j\omega\theta}$$

The combined PD can be calculated as:

$$PD_{x_pair_i}(\theta) = E_{y_pair_i}(\theta) \times H_{z_pair_i}(\theta)^* - E_{z_pair_i}(\theta) \times H_{y_pair_i}(\theta)^*$$

$$PD_{y_pair_i}(\theta) = E_{z_pair_i}(\theta) \times H_{x_pair_i}(\theta)^* - E_{x_pair_i}(\theta) \times H_{z_pair_i}(\theta)^*$$

$$PD_{z_pair_i}(\theta) = E_{x_pair_i}(\theta) \times H_{y_pair_i}(\theta)^* - E_{y_pair_i}(\theta) \times H_{x_pair_i}(\theta)^*$$

$$PD(\theta) = \frac{1}{2}[(\text{Re}(PD_{x_pair_i}(\theta)))^2 + (\text{Re}(PD_{y_pair_i}(\theta)))^2 + (\text{Re}(PD_{z_pair_i}(\theta)))^2]^{1/2}$$

Sweep θ from 0 degree to 360 degree to find the worst case beam pair.

Take side array as an example: at 28 GHz, beam 32 is paired with beam 160. By sweeping relative phase from 0 degree to 360 degree, it can be found that when $\theta = 135$ degree, the combined PD is the worst case. Take $\theta = 0$ degree as an example,

- $\theta = 0$ degree, averaged PD = 19.07 mW/cm²
- $\theta = 135$ degree, averaged PD = 20.62 mW/cm²



Appendix B: 4 cm² Averaging PD and Scaling Factor

4 cm² Averaging PD: The following tables show the simulated PD results for all three different arrays, at band n258, n261 and band n260. Table a), b), and c) show the results for n258, for side array, back array 1, and back array 2, respectively; table d), e), and f) show the results for n261, for side array, back array 1, and back array 2, respectively; table g), h) and i) show the results for n260, for side array, back array 1, and back array 2, respectively.

a) Simulated PD (mW/cm²) at 4 cm² averaging for side array at n258.

Module ID	Beam ID 1	Beam ID 2	4 cm ² PD (mW/cm ²) at 12 dBm per port, n258								
			LB			MB			HB		
1			S1	S2	S4	S1	S2	S4	S1	S2	S4
Side Array	2		0.35	0.38	1.28	0.59	0.49	2.00	0.47	0.51	1.94
	5		0.74	0.71	2.59	0.52	0.58	2.11	0.68	0.47	2.23
	14		1.54	1.09	4.19	1.08	0.87	3.61	1.76	1.14	4.86
	15		1.60	1.40	4.71	1.36	1.14	4.07	1.77	1.19	4.93
	16		0.81	1.18	3.48	1.34	1.74	5.21	1.22	1.21	4.58
	17		0.71	1.05	2.82	0.82	0.94	3.18	1.00	1.47	4.46
	24		0.83	0.47	2.40	1.48	1.02	4.21	1.55	1.01	4.40
	25		0.94	0.85	2.81	1.22	1.14	3.88	1.18	1.42	4.30
	26		0.75	1.05	2.85	0.89	0.99	3.28	1.03	1.51	4.46
	32		2.60	1.75	7.15	2.63	2.13	8.08	3.91	2.48	10.20
	33		2.96	1.83	7.43	3.16	2.17	8.48	3.52	2.00	8.84
	34		2.21	2.01	6.78	2.56	2.16	7.82	2.57	2.14	8.04
	35		1.71	2.46	6.66	2.66	3.38	9.42	2.42	2.99	9.10
	36		1.36	2.22	6.31	2.41	3.09	9.11	2.60	3.45	9.96
	41		2.94	1.88	7.61	3.02	2.28	8.67	3.99	2.33	9.93
	42		2.60	1.84	7.03	2.89	2.06	8.02	3.05	2.02	8.43
	43		1.84	2.25	6.44	2.56	2.86	8.56	2.30	2.34	7.76
	44		1.57	2.46	6.72	2.64	3.41	9.64	2.60	3.44	10.04
	130		0.23	0.23	0.88	0.30	0.30	1.27	0.61	0.55	2.44
	133		0.17	0.20	0.81	0.50	0.43	2.04	0.49	0.50	2.02
	142		0.34	0.78	2.07	0.72	0.84	2.93	1.04	1.20	4.49
	143		0.59	0.82	2.55	0.86	0.92	3.20	1.26	1.40	4.58
	144		0.66	0.41	1.95	0.70	0.62	2.33	1.36	1.03	4.07
	145		0.56	0.46	2.06	0.67	0.61	2.43	1.27	1.00	4.41
	152		0.33	0.75	1.99	0.77	0.93	2.99	1.08	1.32	4.36
	153		0.76	0.56	2.42	0.93	0.88	3.26	1.28	1.12	4.20
	154		0.80	0.45	2.52	1.02	0.90	3.55	1.23	1.02	4.32
	160		1.05	2.05	5.02	2.16	2.06	6.63	3.06	3.50	10.45
	161		0.85	1.77	4.52	1.49	1.88	5.63	1.88	2.57	7.52
	162		1.19	0.99	3.92	1.51	1.20	4.90	1.99	1.50	6.76
	163		1.58	1.00	4.75	1.90	1.32	5.36	2.42	1.66	7.01
	164		1.92	0.86	4.90	1.98	2.12	6.38	3.40	2.82	9.67
	169		0.96	2.20	5.14	1.86	2.27	6.54	2.40	3.37	9.12



	170		0.96	1.29	4.10	1.32	1.39	4.98	1.90	1.92	7.16
	171		1.36	0.98	4.25	1.70	1.20	4.98	2.10	1.46	6.54
	172		1.95	1.02	5.16	2.11	1.75	6.11	3.12	2.26	8.51
	2	130	1.02	1.04	3.39	1.27	1.03	4.04	1.32	1.15	4.52
	5	133	1.14	1.17	3.99	1.30	1.28	4.51	1.48	1.11	4.60
	14	142	2.26	1.93	6.04	2.59	1.65	6.59	3.60	2.44	9.11
	15	143	3.02	3.10	8.93	2.85	2.66	8.30	3.71	3.14	10.26
	16	144	1.76	1.58	5.33	2.65	2.64	7.44	3.30	2.56	8.54
	17	145	2.23	1.55	6.19	2.22	2.31	5.79	3.42	3.72	9.15
	24	152	1.59	1.92	5.65	3.44	2.99	9.08	3.98	3.21	9.32
	25	153	1.60	1.59	5.14	1.87	2.16	6.86	2.37	2.77	8.13
	26	154	1.64	1.90	5.22	1.79	2.56	7.05	2.35	3.40	8.72
	32	160	5.27	5.96	15.05	7.54	6.67	17.33	10.80	9.32	22.41
	33	161	5.10	5.67	16.01	6.78	6.06	17.87	7.57	6.48	18.71
	34	162	4.80	3.78	13.44	5.44	4.10	15.00	6.14	4.27	16.56
	35	163	5.33	4.56	13.95	6.77	6.94	17.71	6.98	6.61	17.00
	36	164	5.54	3.99	13.02	6.80	8.61	18.01	9.60	10.18	21.06
	41	169	5.48	6.35	16.34	7.81	7.15	19.11	9.82	8.61	21.72
	42	170	4.80	4.63	14.72	5.62	4.61	15.95	6.48	4.94	17.91
	43	171	5.02	3.82	13.19	6.16	5.55	16.32	6.21	4.98	15.32
	44	172	5.82	4.77	14.34	7.26	8.31	18.82	8.78	8.91	20.29

b) Simulated PD (mW/cm²) at 4 cm² averaging for back array 1 at n258.

4 cm ² PD (mW/cm ²) at 12 dBm per port, n258											
Module ID	Beam ID 1	Beam ID 2	LB			MB			HB		
0			S1	S2	S3	S1	S2	S3	S1	S2	S3
Back Array 1	0		x	1.89	0.09	x	1.84	0.09	x	1.46	0.11
	3		x	1.95	0.18	x	2.13	0.15	x	1.72	0.12
	6		x	2.85	0.26	x	2.72	0.25	x	2.59	0.31
	7		x	4.26	0.38	x	4.30	0.31	x	3.68	0.27
	8		x	4.54	0.11	x	4.36	0.09	x	3.26	0.14
	9		x	3.12	0.32	x	3.41	0.42	x	2.67	0.37
	18		x	3.51	0.48	x	4.09	0.43	x	3.31	0.40
	19		x	4.53	0.21	x	4.25	0.17	x	3.72	0.12
	20		x	3.81	0.15	x	3.90	0.22	x	2.92	0.23
	27		x	5.34	1.37	x	6.10	1.26	x	5.58	1.46
	28		x	8.18	1.51	x	7.96	1.18	x	6.35	0.68
	29		x	8.55	0.36	x	7.53	0.32	x	6.60	0.19
	30		x	9.42	0.11	x	8.41	0.08	x	7.21	0.17
	31		x	6.59	0.28	x	6.16	0.37	x	3.91	0.48
	37		x	6.60	1.57	x	7.28	1.47	x	6.19	1.31
	38		x	8.59	0.93	x	7.44	0.72	x	6.72	0.48
	39		x	9.36	0.16	x	8.28	0.19	x	6.68	0.12
	40		x	8.82	0.16	x	8.07	0.14	x	6.22	0.33



	128		x	1.78	0.19	x	1.83	0.17	x	1.54	0.12
	131		x	1.91	0.36	x	2.04	0.26	x	1.53	0.18
	134		x	3.78	1.00	x	3.72	0.80	x	2.70	0.39
	135		x	4.34	0.77	x	3.96	0.51	x	2.92	0.14
	136		x	3.61	0.14	x	3.96	0.07	x	3.35	0.21
	137		x	4.13	0.22	x	4.19	0.30	x	2.77	0.19
	146		x	3.10	0.51	x	2.99	0.50	x	2.62	0.27
	147		x	4.10	0.74	x	3.88	0.60	x	3.68	0.44
	148		x	3.53	0.12	x	4.00	0.19	x	3.26	0.36
	155		x	8.50	2.84	x	9.28	2.74	x	5.50	1.08
	156		x	7.98	1.56	x	7.26	1.17	x	5.58	0.52
	157		x	6.51	0.38	x	6.23	0.54	x	5.96	0.44
	158		x	6.89	0.06	x	7.25	0.14	x	6.68	0.16
	159		x	8.23	0.08	x	9.75	0.11	x	5.96	0.32
	165		x	8.86	2.33	x	8.32	1.61	x	5.48	0.81
	166		x	7.05	0.96	x	6.47	0.58	x	5.76	0.41
	167		x	6.52	0.27	x	6.45	0.26	x	6.15	0.22
	168		x	7.59	0.07	x	8.27	0.17	x	6.93	0.20
	0	128	x	3.95	0.40	x	4.19	0.31	x	3.21	0.29
	3	131	x	4.08	0.62	x	4.43	0.55	x	3.53	0.34
	6	134	x	7.06	1.87	x	7.00	1.07	x	5.62	0.76
	7	135	x	9.11	1.28	x	8.78	0.94	x	6.96	0.49
	8	136	x	8.64	0.29	x	8.71	0.20	x	6.91	0.58
	9	137	x	8.76	0.65	x	8.20	0.90	x	6.38	0.78
	18	146	x	7.02	1.40	x	8.11	1.21	x	6.64	0.79
	19	147	x	8.34	1.15	x	7.73	0.70	x	7.28	0.67
	20	148	x	7.71	0.34	x	8.19	0.58	x	6.31	0.95
	27	155	x	16.74	5.86	x	16.74	5.00	x	13.41	3.54
	28	156	x	17.84	4.04	x	17.22	3.22	x	12.56	1.56
	29	157	x	15.58	0.78	x	14.60	0.80	x	13.79	0.91
	30	158	x	16.95	0.19	x	16.89	0.23	x	15.02	0.56
	31	159	x	17.94	0.50	x	17.70	0.68	x	11.63	1.23
	37	165	x	18.01	4.84	x	17.78	4.50	x	13.03	2.64
	38	166	x	16.54	2.03	x	14.90	1.26	x	12.96	0.90
	39	167	x	16.53	0.60	x	15.60	0.75	x	13.63	0.52
	40	168	x	17.45	0.26	x	17.60	0.32	x	14.89	0.71

c) Simulated PD (mW/cm²) at 4 cm² averaging for back array 2 at n258.

4 cm ² PD (mW/cm ²) at 12 dBm per port, n258											
Module ID	Beam ID 1	Beam ID 2	LB			MB			HB		
0			S2	S3	S5	S2	S3	S5	S2	S3	S5
Back Array 2	1		0.66	0.04	0.07	1.31	0.06	0.11	0.86	0.05	0.07
	4		0.90	0.03	0.06	1.18	0.07	0.09	1.19	0.12	0.07



	10		1.56	0.06	0.12	2.55	0.20	0.14	2.36	0.27	0.15
	11		1.82	0.01	0.14	2.86	0.08	0.16	1.87	0.11	0.12
	12		1.47	0.06	0.16	2.34	0.07	0.26	1.48	0.07	0.15
	13		1.54	0.12	0.22	2.37	0.15	0.27	1.96	0.19	0.18
	21		1.74	0.04	0.13	2.75	0.15	0.14	2.21	0.21	0.13
	22		1.60	0.03	0.14	2.58	0.05	0.22	1.47	0.04	0.14
	23		1.50	0.10	0.19	2.30	0.11	0.28	1.70	0.12	0.16
	129		0.80	0.02	0.10	1.28	0.08	0.15	1.28	0.10	0.16
	132		1.33	0.04	0.18	0.92	0.04	0.14	0.85	0.04	0.04
	138		1.80	0.06	0.13	2.00	0.16	0.21	1.95	0.13	0.12
	139		2.46	0.04	0.41	2.39	0.11	0.50	2.01	0.07	0.16
	140		2.55	0.03	0.46	2.44	0.09	0.50	2.07	0.06	0.17
	141		2.30	0.06	0.44	2.24	0.06	0.38	2.18	0.12	0.25
	149		1.91	0.06	0.20	2.07	0.15	0.30	1.90	0.10	0.11
	150		2.37	0.04	0.38	2.34	0.12	0.48	1.98	0.08	0.15
	151		2.38	0.05	0.46	2.30	0.06	0.41	2.17	0.11	0.24
	1	129	1.65	0.07	0.18	2.92	0.21	0.29	2.61	0.15	0.29
	4	132	2.42	0.10	0.35	2.31	0.13	0.29	2.74	0.18	0.15
	10	138	3.74	0.20	0.35	4.90	0.53	0.41	5.08	0.49	0.34
	11	139	4.86	0.05	0.81	5.83	0.22	0.77	5.31	0.25	0.42
	12	140	4.39	0.14	0.74	5.56	0.30	0.90	4.94	0.12	0.38
	13	141	3.89	0.21	0.64	5.38	0.34	0.68	5.11	0.24	0.58
	21	149	4.14	0.13	0.50	5.14	0.44	0.44	5.07	0.42	0.35
	22	150	4.57	0.11	0.73	5.54	0.22	0.85	4.86	0.13	0.34
	23	151	3.96	0.18	0.67	5.48	0.30	0.76	5.11	0.17	0.51

d) Simulated PD (mW/cm²) at 4 cm² averaging for side array at n261.

Module ID	Beam ID 1	Beam ID 2	4 cm ² PD (mW/cm ²) at 12 dBm per port, n261								
			LB			MB			HB		
1			S1	S2	S4	S1	S2	S4	S1	S2	S4
Side Array	2		0.63	0.54	2.32	0.62	0.61	2.44	0.53	0.43	2.00
	5		0.64	0.67	2.61	0.73	0.51	2.52	0.49	0.30	1.60
	14		1.18	0.70	3.48	1.75	1.24	5.00	1.30	0.62	3.26
	15		1.26	1.00	3.68	1.86	1.26	5.16	1.24	0.51	2.91
	16		1.53	1.59	5.12	1.53	1.37	4.95	0.95	0.84	3.04
	17		0.68	0.80	2.99	1.07	1.44	4.59	0.87	0.93	3.89
	24		1.30	0.85	3.72	1.26	0.88	4.19	1.33	1.02	4.33
	25		1.14	1.30	4.02	1.68	1.29	5.04	1.20	0.74	3.28
	26		1.43	1.67	5.20	1.38	1.30	4.80	0.92	0.92	3.35
	32		2.22	1.62	6.59	3.07	2.49	9.07	2.99	2.00	8.16
	33		3.17	2.06	8.24	3.66	2.31	9.44	2.55	1.48	6.52
	34		2.27	2.01	6.86	2.77	2.34	8.63	1.97	1.39	5.92
	35		2.36	3.00	8.36	2.80	3.18	9.68	1.93	2.20	6.86
	36		2.04	2.66	7.82	2.46	2.77	8.68	2.07	2.22	7.16
	41		2.99	2.04	8.40	3.72	2.60	10.12	2.92	1.76	7.53
	42		2.56	1.89	7.16	3.04	2.24	8.81	2.12	1.38	6.07



	43		2.10	2.40	7.14	2.70	2.67	8.72	1.90	1.67	6.09
	44		2.49	3.22	9.06	2.79	3.36	10.09	2.14	2.59	7.75
	130		0.35	0.38	1.59	0.58	0.50	2.25	0.66	0.55	2.46
	133		0.45	0.41	1.85	0.62	0.66	2.73	0.39	0.45	1.66
	142		0.88	0.95	3.28	1.43	1.21	5.11	0.88	1.02	4.01
	143		0.83	0.86	2.97	1.36	1.24	4.55	0.96	1.07	3.64
	144		0.88	0.86	3.05	1.42	1.19	4.48	1.37	0.88	3.87
	145		0.83	0.96	3.04	1.54	1.34	4.90	1.37	1.09	4.17
	152		0.79	0.75	3.42	1.11	0.92	4.68	0.93	1.14	4.67
	153		1.03	1.04	3.64	1.23	1.20	4.24	1.29	1.13	4.27
	154		0.99	0.97	3.60	1.26	1.36	4.80	1.27	1.16	4.21
	160		2.07	1.63	5.77	3.45	2.56	9.52	1.73	2.20	6.82
	161		2.09	2.05	6.66	2.79	2.93	9.06	1.79	2.52	7.36
	162		1.70	1.48	5.50	2.16	1.96	7.42	1.79	1.69	6.26
	163		2.22	1.64	6.20	2.70	2.26	8.00	2.42	1.74	6.75
	164		1.94	2.51	7.02	3.16	3.29	9.96	2.74	2.29	7.77
	169		2.28	1.84	6.38	3.52	2.82	9.96	1.78	2.42	7.20
	170		1.62	1.65	5.55	2.18	2.24	7.60	1.73	1.95	6.48
	171		1.94	1.44	5.72	2.21	1.86	7.26	1.94	1.61	6.23
	172		2.16	2.15	6.84	3.12	2.96	9.48	2.79	2.05	7.58
	2	130	1.32	1.23	4.79	1.45	1.46	5.07	1.41	1.22	4.67
	5	133	1.47	1.42	5.39	1.74	1.35	5.32	1.18	1.09	3.95
	14	142	3.42	2.03	7.94	5.00	3.14	10.92	3.30	2.05	7.60
	15	143	3.30	2.00	7.90	4.72	3.02	10.33	3.19	1.82	7.01
	16	144	3.67	2.89	8.83	4.37	3.35	10.16	3.53	2.41	7.14
	17	145	2.10	2.87	6.72	3.78	4.28	9.95	3.40	3.23	7.98
	24	152	3.40	2.34	8.53	3.85	2.60	9.44	3.35	3.48	8.87
	25	153	2.40	2.32	6.98	3.40	2.33	8.83	2.84	1.90	7.19
	26	154	3.65	4.23	10.81	3.99	4.35	10.05	3.30	3.43	8.42
	32	160	7.05	4.86	14.97	10.60	7.65	20.62	7.49	6.89	15.87
	33	161	8.30	6.16	19.90	9.66	7.64	20.45	6.19	5.85	14.17
	34	162	5.36	4.64	16.08	5.84	4.91	17.29	4.24	3.18	11.99
	35	163	6.74	7.22	18.52	8.06	8.32	19.47	6.74	5.95	14.44
	36	164	5.93	8.82	18.52	8.64	10.09	20.00	7.76	7.54	15.65
	41	169	8.12	5.94	18.32	11.09	8.27	21.62	7.06	6.58	15.62
	42	170	6.08	4.90	16.62	6.84	5.55	17.82	4.62	4.12	12.36
	43	171	5.57	5.34	16.10	6.36	5.98	17.04	5.36	4.33	12.86
	44	172	6.98	9.03	20.26	9.05	10.36	21.78	7.91	7.57	16.26

e) Simulated PD (mW/cm²) at 4 cm² averaging for back array 1 at n261.

Module ID	Beam ID 1	Beam ID 2	4 cm ² PD (mW/cm ²) at 12 dBm per port, n261								
			LB			MB			HB		
0			S1	S2	S3	S1	S2	S3	S1	S2	S3
Back Array 1	0		x	1.99	0.13	x	1.69	0.15	x	1.46	0.10
	3		x	1.49	0.09	x	1.37	0.07	x	1.20	0.07



	6		x	2.58	0.29	x	2.40	0.30	x	2.75	0.26
	7		x	4.26	0.49	x	3.66	0.46	x	2.88	0.22
	8		x	3.54	0.05	x	2.99	0.05	x	2.78	0.08
	9		x	3.32	0.34	x	2.79	0.38	x	2.28	0.19
	18		x	3.88	0.57	x	3.52	0.58	x	2.49	0.25
	19		x	3.31	0.14	x	2.82	0.08	x	3.04	0.10
	20		x	3.48	0.05	x	2.86	0.14	x	2.38	0.14
	27		x	6.12	1.33	x	5.78	1.45	x	4.85	0.75
	28		x	7.36	0.78	x	6.16	0.65	x	6.15	0.33
	29		x	7.00	0.20	x	6.42	0.24	x	6.25	0.13
	30		x	8.12	0.08	x	6.78	0.17	x	6.19	0.17
	31		x	7.52	0.40	x	4.86	0.46	x	3.61	0.47
	37		x	7.59	1.35	x	5.81	0.92	x	5.74	0.59
	38		x	7.23	0.40	x	6.51	0.41	x	6.14	0.15
	39		x	7.24	0.24	x	6.26	0.18	x	6.40	0.13
	40		x	8.28	0.24	x	6.15	0.33	x	4.81	0.36
	128		x	1.85	0.20	x	1.42	0.20	x	1.31	0.12
	131		x	1.43	0.12	x	1.18	0.08	x	1.31	0.06
	134		x	2.86	0.51	x	2.41	0.28	x	2.49	0.21
	135		x	3.93	0.89	x	3.44	0.64	x	3.33	0.40
	136		x	3.76	0.14	x	2.73	0.06	x	2.89	0.04
	137		x	3.99	0.05	x	3.00	0.08	x	2.39	0.14
	146		x	3.44	0.57	x	2.69	0.28	x	2.58	0.20
	147		x	3.89	0.66	x	3.60	0.48	x	3.22	0.31
	148		x	3.90	0.08	x	3.25	0.12	x	2.56	0.08
	155		x	8.25	2.62	x	5.57	1.19	x	5.23	0.85
	156		x	7.31	1.17	x	5.31	0.76	x	5.61	0.43
	157		x	6.05	0.40	x	5.37	0.40	x	5.45	0.26
	158		x	6.19	0.12	x	5.51	0.16	x	5.38	0.14
	159		x	7.66	0.20	x	6.16	0.22	x	5.14	0.19
	165		x	8.70	2.04	x	5.62	0.89	x	5.63	0.82
	166		x	6.28	0.80	x	5.26	0.44	x	5.58	0.29
	167		x	6.22	0.42	x	5.52	0.31	x	5.44	0.21
	168		x	6.50	0.11	x	5.75	0.14	x	5.54	0.11
	0	128	x	4.07	0.43	x	3.41	0.44	x	2.98	0.30
	3	131	x	3.11	0.23	x	2.66	0.17	x	2.76	0.15
	6	134	x	6.37	0.92	x	5.20	0.67	x	5.84	0.50
	7	135	x	9.02	1.69	x	7.72	1.38	x	6.46	0.70
	8	136	x	7.44	0.25	x	6.14	0.15	x	6.19	0.16
	9	137	x	7.81	0.48	x	6.59	0.57	x	5.08	0.39
	18	146	x	7.65	1.52	x	7.14	0.99	x	5.80	0.60
	19	147	x	6.69	0.88	x	5.96	0.58	x	5.85	0.40
	20	148	x	7.41	0.17	x	6.46	0.35	x	5.12	0.28
	27	155	x	16.01	4.72	x	12.25	2.89	x	11.26	1.88
	28	156	x	14.96	2.25	x	12.34	1.38	x	12.25	0.81



	29	157	x	13.67	0.79	x	12.70	0.70	x	12.38	0.43
	30	158	x	15.14	0.28	x	13.03	0.46	x	12.82	0.40
	31	159	x	15.71	0.83	x	12.80	0.99	x	9.22	0.81
	37	165	x	17.33	4.36	x	13.40	2.30	x	12.02	1.60
	38	166	x	13.84	1.14	x	12.29	0.94	x	12.32	0.47
	39	167	x	14.62	0.89	x	12.91	0.70	x	12.64	0.42
	40	168	x	15.01	0.49	x	13.00	0.71	x	11.21	0.69

f) Simulated PD (mW/cm²) at 4 cm² averaging for back array 2 at n261.

4 cm ² PD (mW/cm ²) at 12 dBm per port, n261											
Module ID	Beam ID 1	Beam ID 2	LB			MB			HB		
0			S2	S3	S5	S2	S3	S5	S2	S3	S5
Back Array 2	1		1.40	0.05	0.10	0.77	0.04	0.07	0.44	0.02	0.04
	4		0.76	0.06	0.04	1.28	0.09	0.09	0.80	0.07	0.06
	10		2.42	0.12	0.12	2.12	0.17	0.18	1.20	0.13	0.10
	11		2.17	0.04	0.16	1.69	0.04	0.18	1.01	0.06	0.11
	12		1.88	0.10	0.16	1.74	0.06	0.19	1.10	0.04	0.14
	13		2.00	0.20	0.18	2.12	0.21	0.21	1.37	0.11	0.09
	21		2.40	0.06	0.14	1.92	0.10	0.16	1.07	0.10	0.10
	22		1.96	0.06	0.17	1.64	0.03	0.19	1.03	0.04	0.13
	23		1.90	0.14	0.16	1.93	0.12	0.22	1.24	0.06	0.12
	129		0.96	0.08	0.09	0.86	0.04	0.11	0.85	0.05	0.11
	132		1.11	0.06	0.14	0.92	0.04	0.07	1.12	0.04	0.14
	138		2.34	0.23	0.18	1.55	0.10	0.12	2.02	0.12	0.27
	139		2.02	0.06	0.41	1.75	0.05	0.19	1.94	0.07	0.22
	140		1.98	0.06	0.40	1.79	0.04	0.20	1.94	0.06	0.24
	141		1.90	0.14	0.20	1.94	0.12	0.25	1.93	0.05	0.39
	149		2.23	0.18	0.28	1.49	0.10	0.10	1.98	0.12	0.19
	150		1.98	0.06	0.40	1.79	0.04	0.20	1.94	0.06	0.24
	151		1.77	0.09	0.27	1.93	0.09	0.26	1.89	0.04	0.35
	1	129	2.68	0.21	0.23	1.84	0.13	0.23	1.62	0.09	0.16
	4	132	2.34	0.16	0.19	2.89	0.15	0.23	2.23	0.15	0.21
	10	138	5.18	0.42	0.39	4.30	0.38	0.34	3.45	0.32	0.38
	11	139	5.40	0.17	0.62	4.78	0.12	0.41	3.97	0.17	0.49
	12	140	5.00	0.28	0.60	4.74	0.13	0.50	3.72	0.11	0.46
	13	141	4.41	0.39	0.39	4.65	0.27	0.74	3.44	0.19	0.49
	21	149	5.46	0.28	0.51	4.42	0.28	0.37	3.66	0.27	0.33
	22	150	5.19	0.22	0.60	4.75	0.09	0.45	3.87	0.12	0.50
	23	151	4.71	0.36	0.43	4.76	0.19	0.70	3.49	0.12	0.51

g) Simulated PD (mW/cm²) at 4 cm² averaging for side array at n260.

4 cm ² PD (mW/cm ²) at 11 dBm per port, n260											
Module ID	Beam ID 1	Beam ID 2	LB			MB			HB		



1			S1	S2	S4	S1	S2	S4	S1	S2	S4
Side Array	2		0.45	0.09	1.02	0.55	0.21	1.47	0.41	0.26	1.28
	5		0.22	0.40	1.10	0.40	0.33	1.36	0.48	0.23	1.37
	14		0.78	0.31	2.01	0.82	0.36	2.31	0.72	0.49	2.41
	15		0.70	0.63	2.15	0.74	0.79	2.73	0.95	0.58	2.81
	16		0.73	0.36	2.12	0.98	0.32	2.48	0.69	0.47	2.18
	17		0.40	0.52	1.70	0.78	0.65	2.91	0.77	0.59	2.71
	24		0.66	0.61	2.07	0.77	0.79	2.94	1.05	0.57	3.00
	25		0.74	0.56	2.29	0.77	0.64	2.68	0.73	0.54	2.30
	26		0.41	0.38	1.79	0.59	0.50	2.21	0.60	0.72	2.69
	32		1.32	0.58	3.37	1.47	0.71	4.29	1.72	0.97	4.85
	33		1.53	1.05	4.29	1.61	1.30	5.26	1.96	0.92	5.15
	34		1.48	1.14	4.52	1.72	1.35	5.38	1.63	0.99	4.64
	35		0.96	0.81	3.37	1.32	0.65	4.25	0.91	1.10	3.88
	36		1.03	0.93	3.12	1.62	1.19	4.79	1.48	1.03	4.80
	41		1.45	0.79	3.89	1.47	0.87	4.57	1.80	0.89	4.77
	42		1.48	1.10	4.32	1.69	1.53	5.58	1.89	1.09	5.27
	43		1.22	1.00	3.95	1.62	0.87	4.74	1.18	0.88	3.81
	44		1.01	0.96	3.17	1.55	1.10	4.51	1.36	1.24	4.52
	130		0.25	0.33	1.11	0.33	0.37	1.46	0.36	0.27	1.37
	133		0.55	0.22	1.54	0.52	0.29	1.66	0.34	0.13	1.08
	142		0.80	0.30	2.25	1.00	0.49	3.03	0.70	0.43	2.30
	143		0.70	0.47	2.18	0.83	0.59	2.70	0.59	0.42	2.00
	144		0.71	0.60	2.54	0.46	0.71	2.33	0.84	0.53	2.73
	145		0.85	0.26	2.21	0.98	0.54	3.08	0.77	0.41	2.45
	152		0.48	0.75	2.33	0.51	0.45	2.03	0.59	0.41	2.28
	153		0.84	0.48	2.47	0.40	0.68	2.14	0.83	0.55	2.70
	154		0.55	0.75	2.55	0.49	0.64	2.34	0.79	0.47	2.60
	160		0.97	1.11	3.58	1.20	1.07	4.24	1.32	0.75	4.04
	161		1.24	1.19	4.34	1.25	0.91	4.27	0.95	0.75	3.45
	162		1.52	0.95	4.58	1.23	1.22	4.60	1.64	0.97	5.00
	163		1.64	0.70	4.29	1.22	0.82	4.11	1.28	0.79	4.26
	164		1.35	1.24	4.03	1.66	1.30	5.12	1.79	0.94	4.61
	169		0.91	1.14	3.72	1.00	0.67	3.70	0.78	0.65	3.25
	170		1.45	1.00	4.37	1.25	1.28	4.72	1.38	0.92	4.47
	171		1.59	0.82	4.58	1.02	1.06	4.14	1.50	0.91	4.72
	172		1.64	1.02	4.29	1.63	1.13	4.84	1.64	1.00	4.60
	2	130	0.90	0.58	2.54	0.97	0.67	3.04	0.99	0.63	2.92
	5	133	0.85	0.79	3.05	1.24	0.66	3.36	0.96	0.55	2.76
	14	142	1.20	0.65	3.73	1.28	1.06	4.54	1.12	1.08	4.62
	15	143	1.84	1.49	5.31	1.96	1.66	6.12	1.72	1.19	5.30
	16	144	1.45	1.24	5.05	1.64	1.07	5.40	1.90	1.03	5.53
	17	145	1.25	1.11	4.40	2.19	1.38	6.52	1.75	1.12	6.06
	24	152	1.31	1.45	4.64	1.30	1.16	4.89	1.81	1.11	5.46
	25	153	1.88	1.35	5.31	1.38	1.34	5.11	1.75	1.29	5.26
	26	154	1.14	1.19	4.98	1.23	0.94	4.90	1.60	1.33	5.41
	32	160	2.16	2.13	8.33	2.59	2.41	9.44	2.69	2.34	9.62



	33	161	3.61	3.08	10.86	3.56	2.60	11.52	2.99	2.32	10.06
	34	162	4.23	2.64	11.08	3.56	2.89	10.96	3.96	2.50	10.28
	35	163	2.65	2.34	8.06	2.91	1.87	9.15	2.51	2.02	9.39
	36	164	2.00	2.22	8.21	3.22	2.58	11.11	3.72	2.23	11.08
	41	169	2.86	2.56	9.22	3.02	1.86	9.73	2.71	2.04	8.94
	42	170	4.05	2.74	10.81	3.70	3.72	12.28	3.53	2.59	11.02
	43	171	3.55	2.30	9.18	2.92	2.16	9.42	2.98	2.09	9.45
	44	172	2.15	2.31	8.24	3.27	2.70	10.14	3.33	1.96	10.56

h) Simulated PD (mW/cm²) at 4 cm² averaging for back array 1 at n260.

4 cm ² PD (mW/cm ²) at 11 dBm per port, n260											
Module ID	Beam ID 1	Beam ID 2	LB			MB			HB		
0			S1	S2	S3	S1	S2	S3	S1	S2	S3
Back Array 1	0		x	1.24	0.11	x	0.92	0.13	x	0.96	0.08
	3		x	1.08	0.05	x	0.96	0.05	x	0.80	0.05
	6		x	2.24	0.20	x	1.81	0.20	x	1.59	0.15
	7		x	2.14	0.14	x	1.98	0.10	x	1.58	0.07
	8		x	2.52	0.19	x	1.82	0.24	x	1.89	0.28
	9		x	2.35	0.38	x	1.68	0.30	x	1.74	0.25
	18		x	1.97	0.09	x	1.76	0.09	x	1.56	0.07
	19		x	2.54	0.09	x	1.96	0.16	x	1.88	0.22
	20		x	2.41	0.33	x	1.69	0.29	x	1.80	0.27
	27		x	4.23	0.62	x	3.63	0.44	x	2.99	0.20
	28		x	4.22	0.08	x	3.64	0.12	x	3.23	0.16
	29		x	4.55	0.23	x	3.63	0.28	x	3.12	0.25
	30		x	4.20	0.31	x	3.21	0.25	x	3.05	0.57
	31		x	3.71	0.68	x	3.12	0.66	x	3.12	0.58
	37		x	4.24	0.23	x	3.51	0.10	x	3.01	0.06
	38		x	4.57	0.13	x	3.91	0.31	x	3.34	0.27
	39		x	4.15	0.24	x	3.26	0.32	x	2.99	0.35
	40		x	3.97	0.50	x	3.11	0.51	x	3.08	0.62
	128		x	1.48	0.09	x	1.33	0.08	x	1.20	0.09
	131		x	1.16	0.06	x	1.09	0.06	x	0.95	0.06
	134		x	2.49	0.27	x	2.30	0.23	x	1.96	0.25
	135		x	2.28	0.12	x	1.82	0.05	x	1.58	0.04
	136		x	2.76	0.11	x	2.66	0.12	x	2.16	0.16
	137		x	2.93	0.28	x	2.61	0.26	x	2.25	0.28
	146		x	2.72	0.30	x	2.43	0.21	x	2.14	0.21
	147		x	2.66	0.08	x	2.61	0.07	x	2.11	0.10
	148		x	2.92	0.26	x	2.63	0.24	x	2.24	0.27
	155		x	4.67	0.65	x	3.91	0.57	x	3.48	0.57
	156		x	4.91	0.48	x	4.29	0.22	x	3.78	0.10
	157		x	4.61	0.07	x	4.42	0.06	x	3.49	0.12
	158		x	4.88	0.23	x	4.22	0.33	x	3.67	0.54
	159		x	4.56	0.57	x	4.14	0.58	x	3.96	0.73
	165		x	4.75	0.80	x	3.93	0.53	x	3.54	0.29