A2172_A2341_5G_Product-mmWave-MPE_Simulation_Report_v1.0-withsimPDPlots

Model No	FCC ID:
A2172	BCG-E3542A
A2341	BCG-E3545A

Date of Simulation:
05/1/2020-09/10/2020
Location:
Apple Inc., Cupertino, CA, USA

Table of Contents

1 Introduction

This document provides an overview of the methodology used for MPE (averaged power density) 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 simulations and measurements 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 using measurements
- Brief review of the device configuration and operation, and detailed description of the simulation methodology and results

There are three antenna-arrays for mmWave (FR2) bands M0 (front facing), M1 (back facing), and M2 (side facing). Antenna arrays M0 and M2 operate with an EIRP approximately 12dB higher than antenna array M1. Only one antenna array is active at a time. The respective maximum output EIRP numbers are mentioned in the test report.

2 MPE Simulation Methodology

3D full-wave simulation is used to evaluate MPE (PD) for each bead from the antenna array. The following steps are followed to show the validity of the model used for MPE (PD) Simulations:

Figure 1. Flowchart of MPE simulation.

1) Import a CAD that represents the actual product into the simulation tool (Ansys HFSS).
2) Define material properties inside the product at 28 GHz and 39 GHz based on vendor inputs.
3) Solve the model using Ansys HFSS
4) Import the codebook for the antenna element. The codebook is generated at the 5G module.
    - Codebook shows the magnitude and phase of each antenna element, which determines each sector of the antenna array.
    - Codebook is generated to automate the simulation for different sectors.
5) Post-processing for the fields to get the averaged power density, which is MPE (PD).
    - The post-processing for MPE involves doing averaging of power density on the evaluating surface.
    - Averaging area is 4 cm^2.
    - Absolute power density is applied to derive MPE (PD) results.

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 in [1] 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.

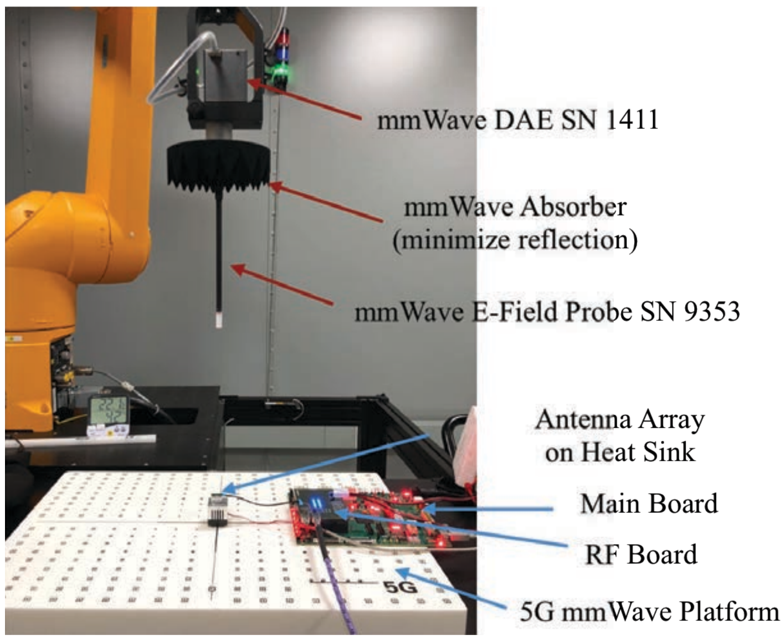


Figure 2. MPE measurement setup.

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.

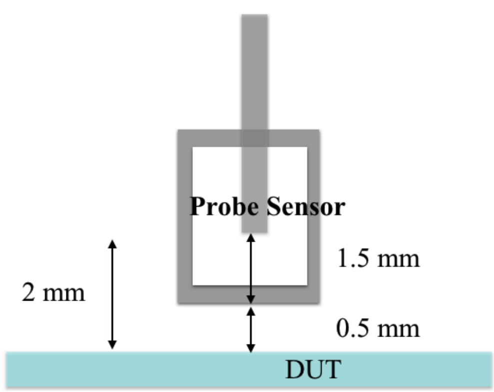


Figure 3. Sketch of the probe showing that the minimum measurable distance is 2 mm.

4 MPE (PD) Simulations

In 5G, MIMO antennas are designed to orient the beam to specific directions in order to improve link budgets. Most MIMOs 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, on the front, back, and side.

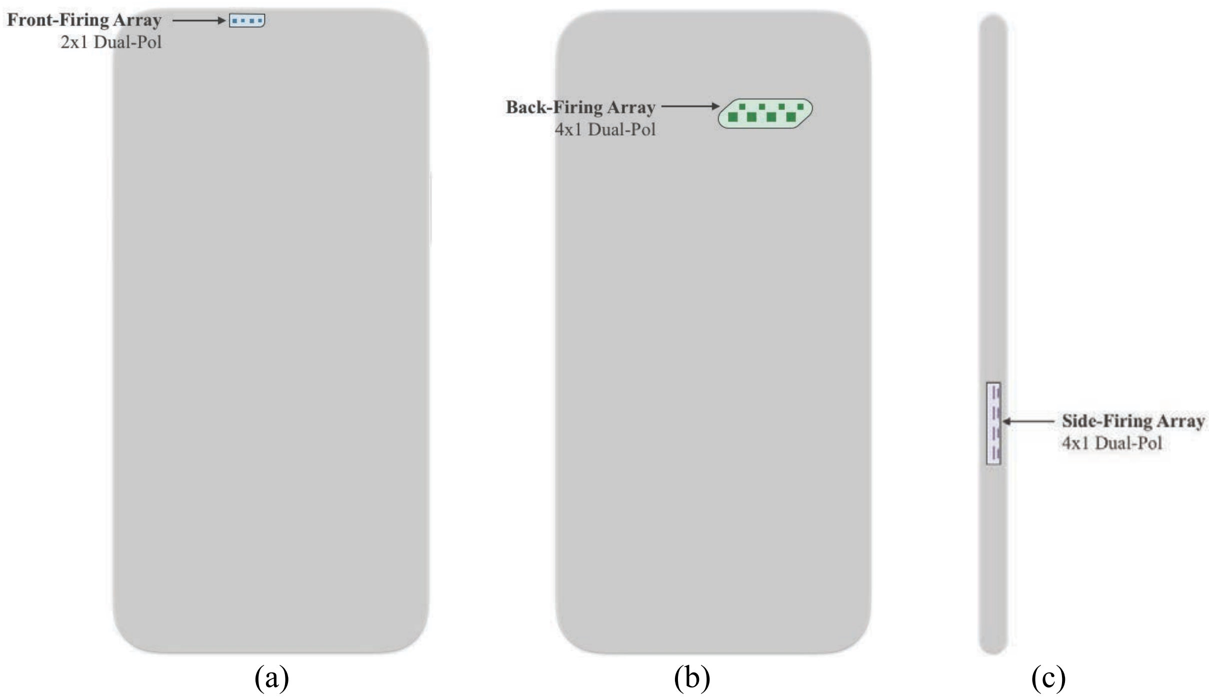


Figure 4. Schematic of the simulation mode, which consists of three 5G antenna arrays, (a) front view, (b) rear view and (c) side view.

The back-firing array consists of a 4x1 "high band"antenna array for n260, and a 4x1 "low band" array for n257 and n261. Both of the arrays are dual polarized.

The measurements and simulations are correlated across different evaluating surfaces 2 mm away from each DUT surface (drawn not to scale), as shown in **Error! Reference source not found.** below. Six surfaces will be evaluated, respectively: front, back, left, right, top and bottom. As Table 1 shows, for the three antenna modules, only the evaluating planes within 2.5 cm from the edges of the antenna modules will be considered. This does not apply to the front-to-back and back-to front conditions 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.

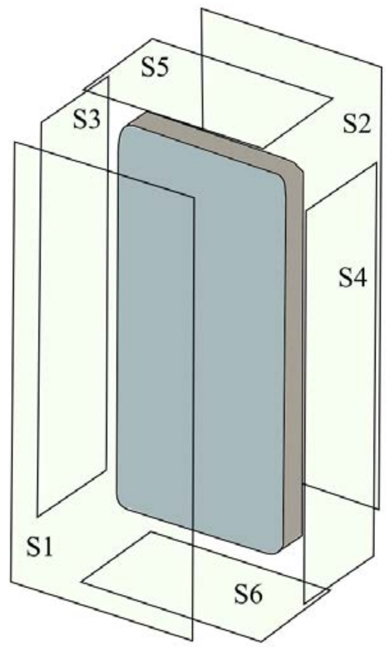


Figure 10. Evaluating surfaces for MPE (PD).

Table 1. PD Evaluation Planes

	Front (S1)	**Rear (S2)**	**Left from Front View (S3)**	**Right from Front View (S4)**	**Top (S5)**	**Bottom (S6)**
Side Module	**Yes (0.4 cm)**	**Yes (0.4 cm)**	No (7 cm)	**Yes (0 cm)**	No (8 cm)	No (4 cm)
Back Module	No (0.6 cm)	**Yes (0 cm)**	**Yes (0.8 cm)**	No (4 cm)	No (2.5 cm)	No (12 cm)
Front Module	**Yes (0 cm)**	**Yes (0.2 cm)**	No (2.6 cm)	No (4 cm)	**Yes (0.2 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:

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

$\vec{S}$ 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

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

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 cm^2. 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 11 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.

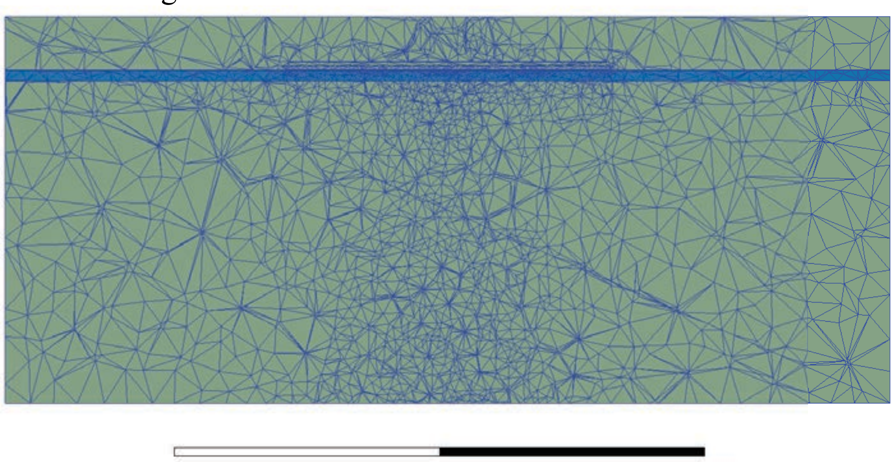


Figure 11. Example of the adaptive mesh technique (top view)

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 12 depicts, showing that a fine enough mesh is needed to guarantee that the simulation gives converged and correct results.

The first row in Figure 12 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 simulation, the mesh in the third row is applied to ensure an accurate result with the shortest processing time.

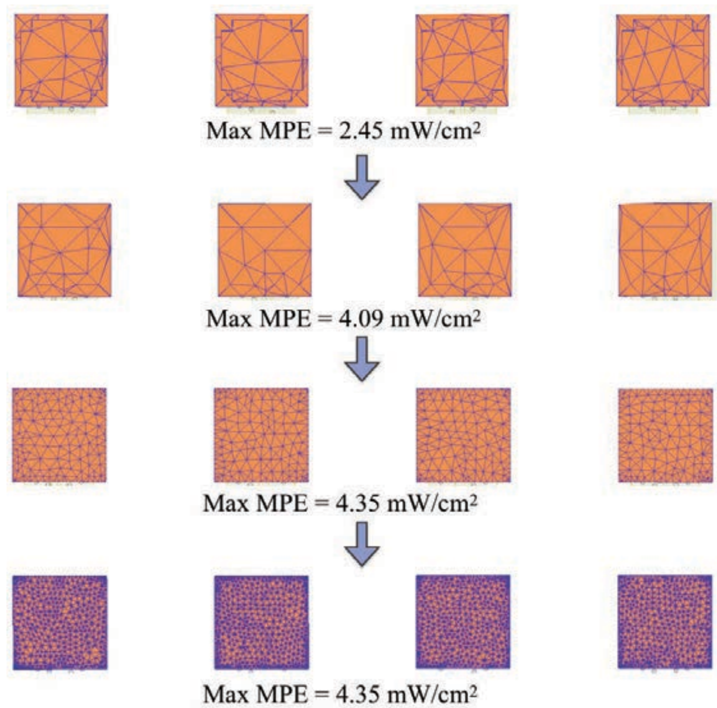


Figure 12. HFSS adaptive mesh shows that when the mesh is fine enough, MPE results will converge.

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 13 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.

Band	Beam_ID	Module	Ant_Group	Subarray	Ant_Type	Ant_Feed	Amplitude	Phase	Paired_With
257	0	0	0	1	PATCH	14	0	0	128
257	1	0	0	3	PATCH	11	0	0	129
257	2	1	0	5	PATCH	13	0	0	130
257	3	0	0	1	PATCH	14;9	0;0	180;281.25	131
257	4	0	0	1	PATCH	14;9	0;0	180;157.5	132
257	5	0	0	1	PATCH	14;9	0;0	180;78.75	133
257	6	0	0	3	PATCH	12;11	0;0	180;326.25	136
257	7	0	0	3	PATCH	12;11	0;0	180;168.75	134
257	8	0	0	3	PATCH	12;11	0;0	180;270	135
257	9	1	0	5	PATCH	10;9	0;0	180;146.25	139
257	10	1	0	5	PATCH	10;9	0;0	180;0	138
257	11	1	0	5	PATCH	13;14	0;0	180;33.75	137
257	12	0	0	1	PATCH	14;9	0;0	180;236.25	140
257	13	0	0	1	PATCH	14;9	0;0	180;123.75	141
257	14	0	0	3	PATCH	12;11	0;0	180;157.5	142
257	15	0	0	3	PATCH	12;11	0;0	180;236.25	143
257	16	1	0	5	PATCH	10;9	0;0	180;90	145
257	17	1	0	5	PATCH	10;9	0;0	180;247.5	144
257	18	0	0	1	PATCH	14;9;13;10	0;0;0;0	180;292.5;22.5;303.75	147
257	19	0	0	1	PATCH	14;9;13;10	0;0;0;0	180;202.5;247.5;101.25	146
257	20	0	0	1	PATCH	14;9;13;10	0;0;0;0	180;157.5;123.75;270	148
257	21	0	0	1	PATCH	14;9;13;10	0;0;0;0	180;101.25;0;135	149

Figure 13. 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. In some cases, there is an additional antenna flex cable (transmission lines) connecting the chip and antenna module. For example, as Figure 6 shows, there will be 16 RF lines connecting chip with antenna elements. Hence, the losses from the S-parameter (snp file) of the 16 RF lines (transmission lines) will also be determined through simulation, and a new codebook will be generated (simulation codebook) that properly models the excitation of the antenna elements in the array. The process is illustrated in Figure 14.

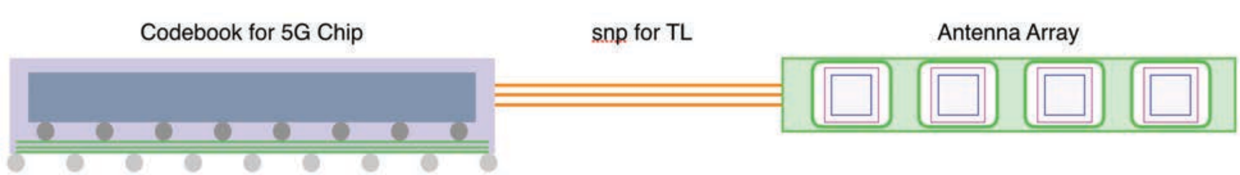


Figure 14. The process of excitation is from 5G chip to RF lines and to the antenna array

Averaging the Power Density for MPE (PD):

Spatial averaging is needed to determine the MPE values from power density simulation results over the 4 cm^2 area required by the FCC. Figure 15 illustrates how averaging is conducted inside the software.

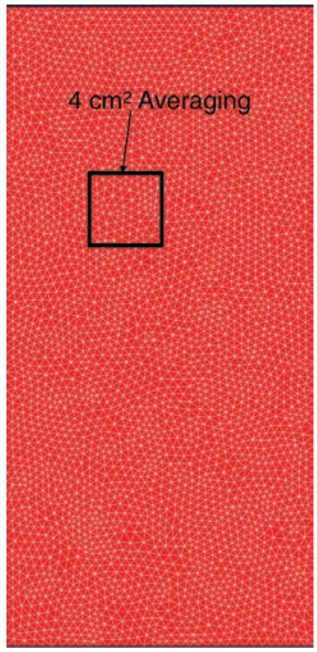


Figure 15. Averaging power density of 4cm^2 area to get MPE (PD) results.

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 1 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 1 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 1 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 1 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 1 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 1 as uncertainty with rectangular probability distribution.

Table 1 – Preliminary budget of the uncertainty contributions of the numerical algorithm for the validation- or testing-setup

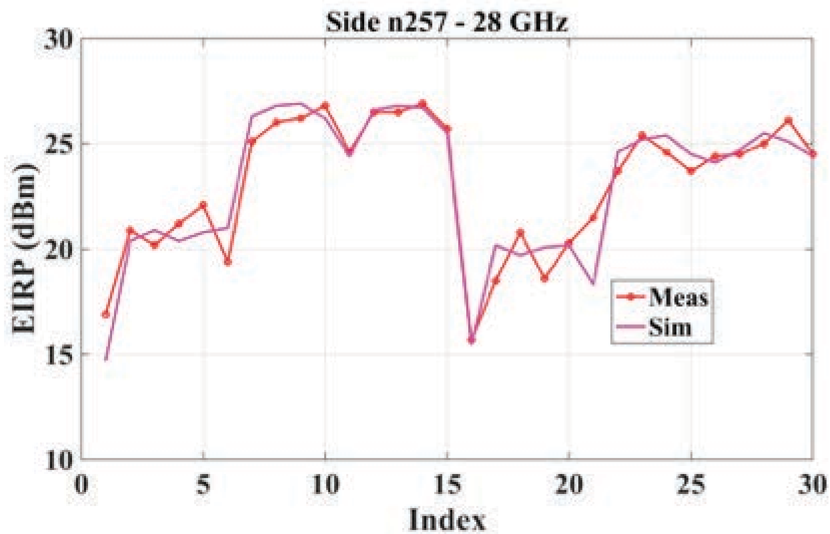
Uncertainty component	Subclause	Probability distribution	Divisor f(d, h)[1]	c_i [2]	Uncertainty %
Mesh resolution	5.1	Normal	1	1	0.5%
ABC	5.2	Normal	1	1	3%
Power budget	5.3	Normal	1	1	0.1%
Convergence	5.5	Rectangular	1,73	1	0.25%
DUT dielectrics	5.6	Normal	1	1	2.8%
Lossy conductors	5.7	Rectangular	1,73	1	0.8%
Combined standard uncertainty (k = 1)					7.45%

Note 1: The divisor is a function of the probability distribution and degrees of freedom (v_i and v_{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.

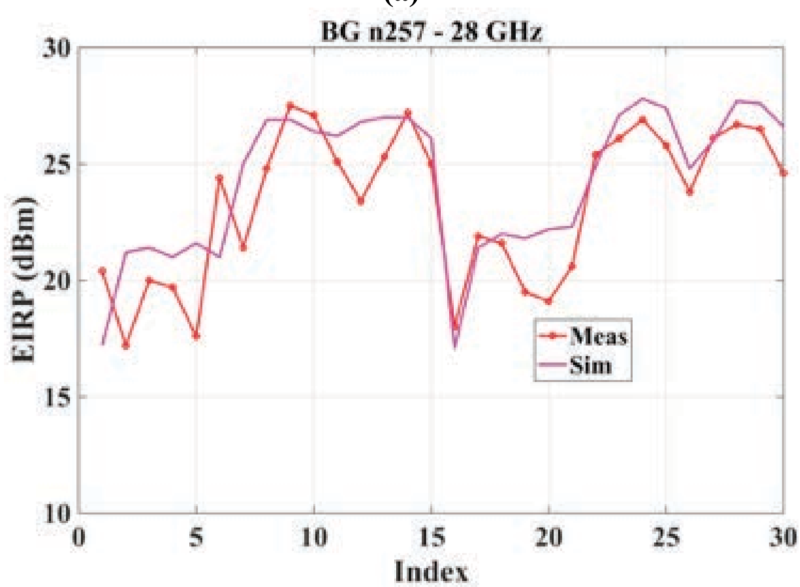
6 Simulation vs. Measurement

To validate the accuracy of the model, measured EIRP values for the three modules were compared to simulated EIRP for different beams. The comparison is shown in Figure 16 below. This shows very close correlation between measurements and simulation of max EIRP values.

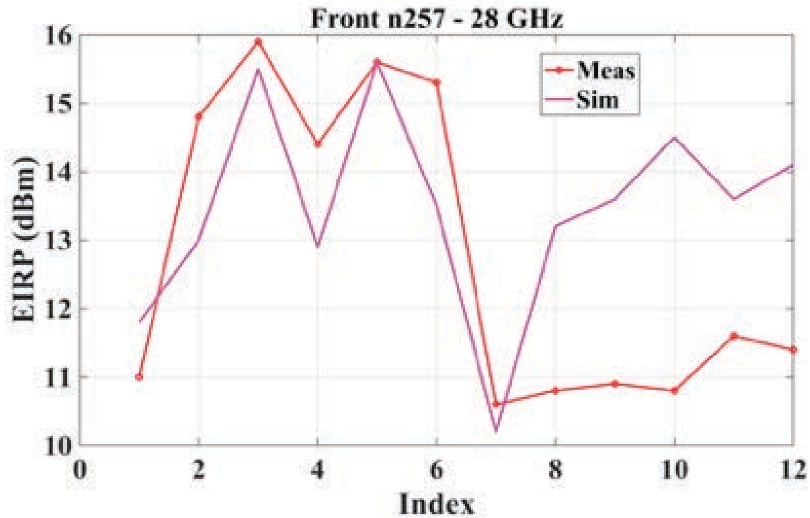
For MPE, the simulated and measured patterns for the worst case beam is shown in Figure 17.



(a)

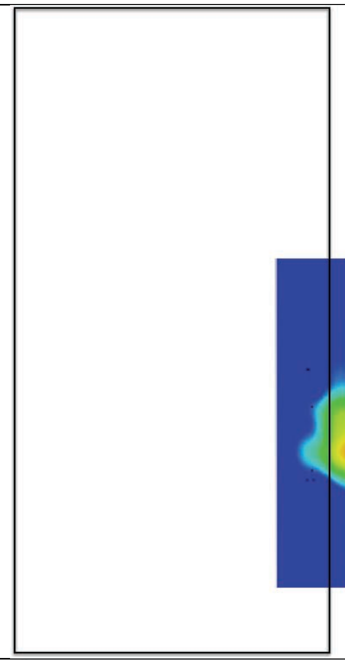
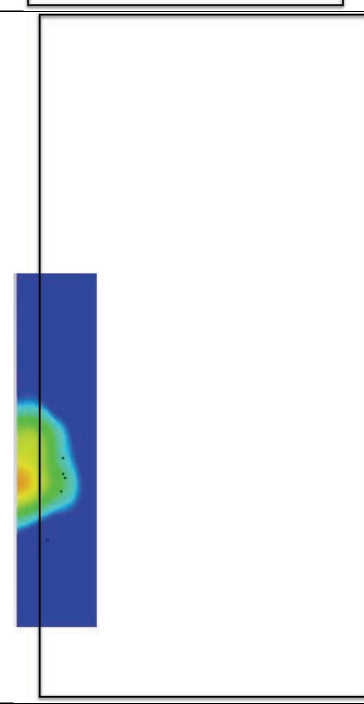


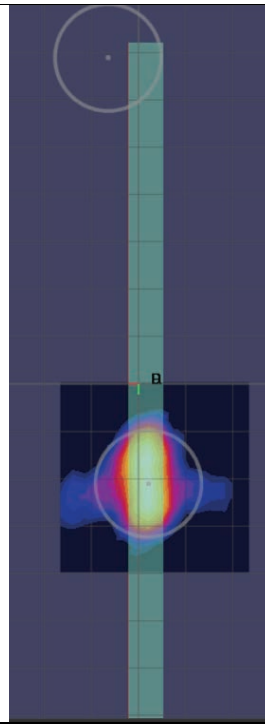
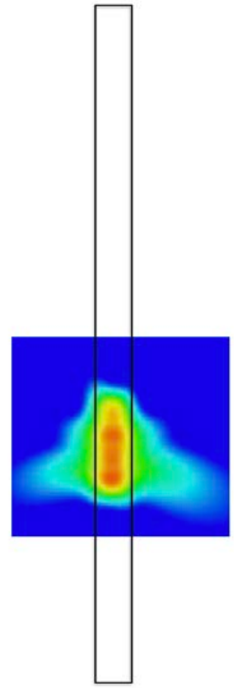
(b)



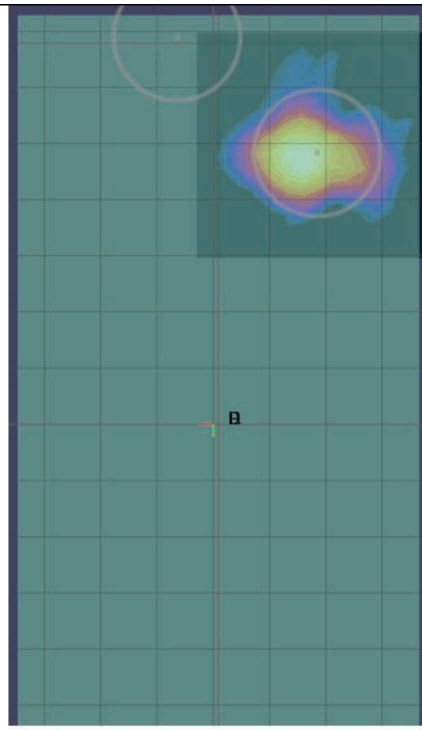
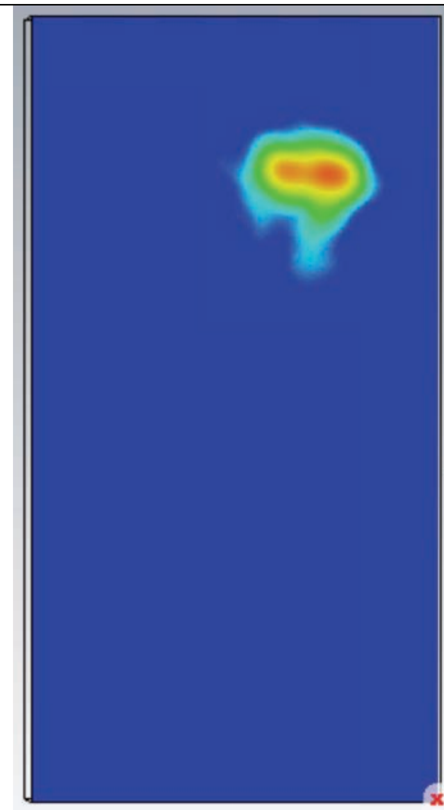
(c)

Figure 16. Simulated vs. Measured EIRP at 28 GHz for (a) side-firing antenna, (b) back-firing antenna, (c) front-firing antenna.

Beam ID	Surface	Measured PD	Simulated PD
37	S1		
	S2		

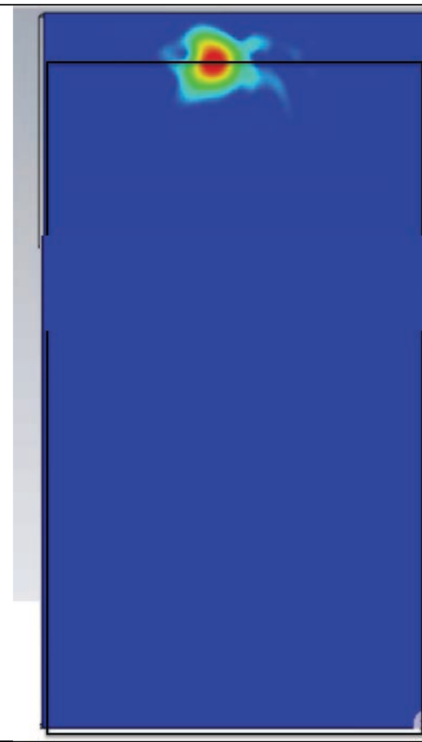
	S4		

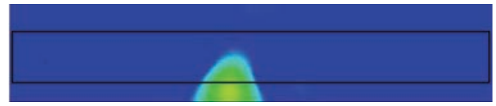
(a)
Measured MPE for side module at 2 mm, max MPE (PD) for measurement 6.9 mW/cm^2, and simulation is 11.73 mW/cm^2.

Beam ID	Surface	Measured PD	Simulated PD
151	S2		

	S3		

(b)
Measured MPE for back module at 2 mm, max MPE (PD) for measurement is 5.79 mW/cm^2, and simulation is 9.54 mW/cm^2.

Beam ID	Surface	Measured PD	Simulated PD
10	S1		
	S2		

	S5		

(c)
Measured MPE for front module at 2 mm, max MPE (PD) for measurement is 0.95 mW/cm^2, and simulation is 1.08 mW/cm^2.

Figure 17. Simulated and measured E-field and MPE (PD) at 2 mm away from DUT.

The above results demonstrate good correlation between the measurements and simulations. In Figure 16 and 17, both EIRP and MPE agree favorably between simulation and measurement.

Measured MPE and Simulated MPE values are summarized below in Table 2, with unit mW/cm^2.

Side Fire Array

Beam ID	Ant Pol	Simulation	Measurements	Delta = Sim – Meas. (dB)
		S4	**S4**	S4
27	V	**6.99**	**5**	1.46
28	V	**6.79**	**5.4**	0.99
30	V	**7.29**	**5.9**	0.92
36	V	**6.84**	**4.4**	1.92
37	V	**7.05**	**5.8**	0.85
154	H	**5.95**	**6.8**	-0.58
155	H	**7.58**	**6.8**	0.47
156	H	**7.00**	**6.9**	0.06
164	H	**7.29**	**6.3**	0.63
165	H	**6.92**	**6.7**	0.14

Back-fire Array

Beam ID	Ant Pol	Simulation	Measurements	Delta = Sim – Meas. (dB)
		S2	**S2**	S2
23	V	**6.33**	**5.06**	0.97
24	V	**6.84**	**4.13**	2.19
31	V	**4.68**	**3.44**	1.34
32	V	**5.17**	**4.29**	0.81
33	V	**6.67**	**4.9**	1.34
150	H	**5.44**	**5.4**	0.03
151	H	**4.45**	**5.57**	-0.97
153	H	**6.26**	**4.16**	1.77
160	H	**6.87**	**5.79**	0.74
161	H	**5.68**	**5.4**	0.22

Front-fire Array

Beam ID	Ant Pol	Simulation	Measurements	Delta = Sim – Meas. (dB)
		S1	**S1**	S1
9	V	**1.08**	**0.95**	0.56
139	H	**1.12**	**0.21**	7.27

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

Side Fire Array

Beam ID	Ant Pol	Simulation	Measurements	Delta = Sim – Meas. (dB)
		S4	**S4**	S4
27	V	**5.49**	**4.9**	0.49
28	V	**6.98**	**6.3**	0.45
29	V	**6.83**	**4.2**	2.11
36	V	**6.68**	**6.7**	-0.01
37	V	**7.36**	**5.0**	1.68
156	H	**6.26**	**4.4**	1.53

157	H	**5.42**	**4.2**	1.11
163	H	**4.53**	**4.0**	0.54
164	H	**5.94**	**4.2**	1.51
165	H	**6.38**	**4.1**	1.92

Back-fire Array

Beam ID	Ant Pol	Simulation	Measurements	Delta = Sim – Meas. (dB)
		S2	**S2**	S2
22	V	**5.19**	**5.0**	0.16
23	V	**4.51**	**5.0**	-0.45
24	V	**4.74**	**3.9**	0.85
31	V	**5.41**	**4.6**	0.70
33	V	**4.02**	**4.9**	-0.86
151	H	**4.29**	**4.6**	-0.30
152	H	**5.27**	**4.9**	0.32
159	H	**5.08**	**4.6**	0.43
160	H	**4.41**	**4.5**	-0.09
161	H	**4.56**	**5.1**	-0.49

Front-fire Array

Beam ID	Ant Pol	Simulation	Measurements	Delta = Sim – Meas. (dB)
		S1	**S1**	S1
18	V	**0.50**	**0.38**	1.19
137	H	**0.48**	**0.23**	3.20

Table 3 Simulated and measured n260 MPE (PD) at 2 mm away from DUT.

We note that measurement values consistently are a few dB lower than the simulations, demonstrating that the simulations provide conservative results. We suspect that this is largely due to the unavoidable coupling between the E-field probe and antenna when conducting measurements. To characterize the effect of measurement probe coupling, simulations and measurements at increasing distances from the DUT were compared. As is shown in Fig. 18, as the distance increases from 2 mm to 25 mm, the probe coupling effect decreases and the measurement results converge with the simulation results.

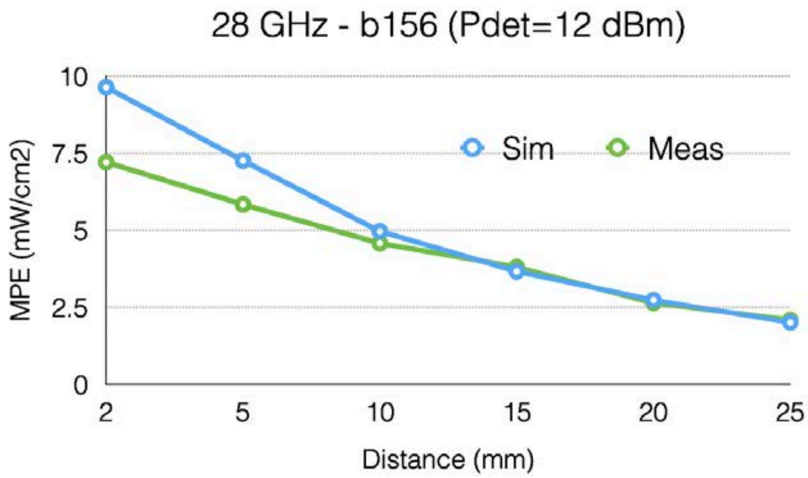


Figure 18. Simulation and measurement comparison with increasing distance from DUT.

7 Different Housing Simulations Using Same Antenna Arrays

For other phones with mmWave antenna modules, the antenna parts and glass case covering the antennas are the same for all phones; the only difference is the size of the phone. For mmWave antennas, both electric and magnetic fields are quite localized and there is negligible effect from different housing sizes. Therefore, we are requesting approval to use the same antenna and housing models to apply for all the phones.

Appendix A: Worst Phase Derivation for Beam Pair

For beam pairs, since the relative phase between two beams in 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 {Ex_a, Ey_a, Ez_a} and {Hx_a, Hy_a,Hz_a}, respectively; for beam pair which is ID b is {Ex_b,Ey_b,Ez_b} and {Hx_b,Hy_b,Hz_b}, respectively. The relative phase between beam a and b is θ, the combined E and H field after beam pairing is:

$$Ex\_pair\_i(\theta) = Ex\_a + Ex\_b \times e^{-j\omega\theta}$$
$$Ey\_pair\_i(\theta) = Ey\_a + Ey\_b \times e^{-j\omega\theta}$$
$$Ez\_pair\_i(\theta) = Ez\_a + Ez\_b \times e^{-j\omega\theta}$$

$$Hx\_pair\_i(\theta) = Hx\_a + Hx\_b \times e^{-j\omega\theta}$$
$$Hy\_pair\_i(\theta) = Hy\_a + Hy\_b \times e^{-j\omega\theta}$$
$$Hz\_pair\_i(\theta) = Hz\_a + Hz\_b \times e^{-j\omega\theta}$$

The combined PD can be calculated as:

$$PDx\_pair\_i(\theta) = Ey\_pair\_i(\theta) \times Hz\_pair\_i(\theta)^* - Ez\_pair\_i(\theta) \times Hy\_pair\_i(\theta)^*$$
$$PDy\_pair\_i(\theta) = Ez\_pair\_i(\theta) \times Hx\_pair\_i(\theta)^* - Ex\_pair\_i(\theta) \times Hz\_pair\_i(\theta)^*$$
$$PDz\_pair\_i(\theta) = Ex\_pair\_i(\theta) \times Hy\_pair\_i(\theta)^* - Ey\_pair\_i(\theta) \times Hx\_pair\_i(\theta)^*$$
$$PD(\theta) = \frac{1}{2}[(Re(PDx\_pair\_i(\theta)))^2 + (Re(PDy\_pair\_i(\theta)))^2 + (Re(PDz\_pair\_i(\theta)))^2]^{1/2}$$

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

Take side module as an example: at 28 GHz, beam 34 is paired with beam 160. By sweeping relative phase from 0 degree to 360 degree, it can be found that when θ = 315 degree, the combined PD is the worst case. Take θ = 0 degree as an example,

- θ = 0 degree, averaged PD = 19.05 mW/cm^2
- θ = 315 degree, averaged PD = 19.87 mW/cm^2

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 modules, at both band n261 and band n260. Table a), b), and c) show the results for n261, for side, back, and front modules, respectively; table d), e) and f) show the results for n260, for side, back, and front modules, respectively. The five worst-case beams per module per band are highlighted as red in the table.
These are preliminary results which will change as the hardware matures.

a) *Simulated PD (mW/cm²) at 4 cm² averaging for side module at n261.*

		4 cm² PD (mW/cm²) at 12 dBm per port, n261								
Module	Beam ID	LB			MB			HB		
		S1	S2	**S4**	S1	S2	**S4**	S1	S2	**S4**
Side	4	0.58	0.51	**1.67**	0.64	0.50	**1.72**	0.59	0.44	**1.74**
	5	0.52	0.49	**1.48**	0.60	0.51	**1.50**	0.52	0.40	**1.51**
	12	1.16	0.97	**3.23**	1.43	0.90	**3.26**	1.42	0.84	**3.61**
	13	1.35	1.18	**3.18**	1.47	1.23	**3.70**	1.46	1.13	**3.39**
	14	1.30	1.27	**3.41**	1.34	1.29	**3.41**	0.97	1.19	**3.58**
	19	1.37	1.10	**3.36**	1.57	1.26	**3.60**	1.63	1.15	**3.69**
	20	1.24	1.27	**3.41**	1.27	1.38	**3.63**	1.18	1.28	**3.54**
	26	3.06	2.95	**7.38**	4.06	2.73	**6.68**	4.16	2.35	**7.63**
	27	3.25	2.64	**6.21**	3.83	2.66	**6.99**	3.88	2.41	**6.77**
	28	3.00	2.71	**5.86**	3.32	2.98	**6.79**	3.27	2.84	**6.42**
	29	2.63	2.84	**6.99**	3.11	3.09	**7.33**	2.87	3.56	**7.27**
	30	2.45	2.73	**7.01**	2.37	3.15	**7.29**	2.22	3.28	**7.32**
	35	3.42	2.73	**6.77**	4.04	2.72	**7.18**	4.14	2.37	**7.23**
	36	3.05	2.61	**5.88**	3.55	2.76	**6.84**	3.54	2.53	**6.48**
	37	3.04	2.96	**6.44**	3.13	3.28	**7.05**	2.97	3.18	**6.86**
	38	2.84	2.96	**7.55**	2.42	3.19	**7.42**	2.54	3.20	**7.73**
	132	0.34	0.39	**1.39**	0.52	0.57	**1.84**	0.61	0.70	**1.99**
	133	0.29	0.32	**1.20**	0.40	0.45	**1.55**	0.45	0.55	**1.64**
	140	0.94	0.66	**2.80**	1.39	1.07	**3.11**	1.36	1.05	**4.12**
	141	0.79	0.83	**1.91**	1.29	1.28	**3.80**	1.54	1.52	**3.42**
	142	0.61	0.92	**3.02**	0.97	1.40	**3.37**	0.98	1.21	**4.13**
	147	0.92	0.69	**2.39**	1.33	0.98	**3.69**	1.43	1.10	**3.81**
	148	0.56	0.77	**2.70**	0.82	1.18	**3.81**	0.95	1.32	**4.08**
	154	2.24	1.65	**6.04**	3.25	2.47	**5.95**	3.21	2.00	**7.27**
	155	1.87	1.54	**4.22**	3.39	2.41	**7.58**	3.87	2.82	**7.27**
	156	1.45	1.64	**3.67**	2.12	2.45	**7.00**	2.58	2.86	**6.19**
	157	1.53	2.30	**5.29**	2.28	3.62	**7.30**	2.74	3.50	**7.63**
	158	1.48	2.17	**5.56**	2.06	2.83	**6.51**	1.96	2.59	**6.65**
	163	2.31	1.68	**5.73**	3.39	2.35	**7.65**	3.65	2.45	**7.78**
	164	1.87	1.51	**3.79**	2.62	2.10	**7.29**	3.06	2.57	**6.23**

	165	1.38	1.87	**4.02**	2.20	2.91	**6.92**	2.69	3.13	**7.01**
	166	1.62	2.42	**5.88**	2.29	3.26	**7.47**	2.20	2.83	**7.11**

b) Simulated PD (mW/cm^2) at 4 cm^2 averaging for back module at n261.

		4 cm^2 PD (mW/cm^2) at 12 dBm per port, n261								
Module	Beam ID	LB			MB			HB		
		S1	**S2**	S3	S1	**S2**	S3	S1	**S2**	S3
Back	0	x	**1.61**	0.13	x	**1.79**	0.11	x	**1.45**	0.06
	1	x	**1.23**	0.08	x	**1.46**	0.07	x	**1.20**	0.04
	6	x	**3.47**	0.44	x	**3.63**	0.62	x	**2.76**	0.44
	7	x	**3.22**	0.14	x	**3.67**	0.14	x	**3.63**	0.16
	8	x	**3.84**	0.06	x	**4.04**	0.05	x	**3.96**	0.08
	15	x	**3.19**	0.41	x	**3.35**	0.57	x	**2.63**	0.41
	16	x	**3.47**	0.17	x	**3.59**	0.17	x	**3.20**	0.10
	21	x	**4.61**	0.82	x	**4.99**	0.70	x	**5.56**	0.43
	22	x	**3.41**	0.87	x	**4.32**	0.97	x	**4.12**	0.60
	23	x	**6.28**	0.21	x	**6.33**	0.17	x	**5.99**	0.19
	24	x	**6.82**	0.13	x	**6.84**	0.33	x	**6.09**	0.16
	25	x	**5.84**	0.41	x	**7.00**	0.33	x	**5.62**	0.38
	31	x	**4.22**	0.89	x	**4.68**	0.92	x	**5.17**	0.51
	32	x	**5.04**	0.44	x	**5.17**	0.46	x	**5.08**	0.38
	33	x	**6.80**	0.41	x	**6.67**	0.14	x	**5.88**	0.13
	34	x	**6.38**	0.15	x	**7.18**	0.20	x	**5.78**	0.26
	128	x	**1.77**	0.17	x	**1.62**	0.11	x	**1.67**	0.09
	129	x	**1.78**	0.15	x	**1.69**	0.12	x	**1.19**	0.06
	134	x	**3.10**	0.41	x	**3.38**	0.34	x	**3.65**	0.26
	135	x	**3.10**	0.38	x	**3.65**	0.26	x	**3.80**	0.20
	136	x	**3.53**	0.86	x	**3.75**	0.60	x	**3.38**	0.37
	143	x	**3.01**	0.05	x	**3.39**	0.05	x	**3.83**	0.04
	144	x	**3.12**	0.68	x	**3.43**	0.48	x	**3.58**	0.33
	149	x	**4.09**	0.26	x	**4.40**	0.56	x	**5.44**	0.56
	150	x	**5.14**	0.14	x	**5.44**	0.15	x	**5.59**	0.06
	151	x	**7.02**	0.54	x	**4.45**	0.60	x	**4.96**	0.63
	152	x	**6.86**	1.72	x	**7.11**	1.23	x	**5.56**	0.77
	153	x	**6.10**	1.61	x	**6.26**	1.47	x	**5.12**	0.24
	159	x	**4.52**	0.41	x	**4.82**	0.43	x	**5.61**	0.34
	160	x	**6.29**	0.09	x	**6.87**	0.15	x	**5.43**	0.24
	161	x	**4.75**	1.45	x	**5.68**	1.01	x	**5.63**	0.56
	162	x	**7.25**	1.57	x	**6.53**	1.49	x	**5.38**	0.83

c) Simulated PD (mW/cm^2) at 4 cm^2 averaging for front module at n261.

		4 cm^2 PD (mW/cm^2) at 12 dBm per port, n261								
Module	Beam ID	LB			MB			HB		
		S1	S2	S5	**S1**	S2	S5	**S1**	S2	S5
Front	2	**0.42**	0.13	0.12	**0.43**	0.13	0.17	**0.58**	0.09	0.19
	3	**0.30**	0.08	0.07	**0.37**	0.07	0.08	**0.32**	0.06	0.10
	9	**0.69**	0.36	0.20	**1.08**	0.31	0.24	**1.15**	0.15	0.23
	10	**0.71**	0.25	0.23	**1.00**	0.23	0.58	**1.34**	0.17	0.54
	11	**0.61**	0.46	0.15	**0.95**	0.30	0.33	**1.12**	0.14	0.28
	17	**0.73**	0.22	0.24	**1.02**	0.22	0.49	**1.35**	0.17	0.56
	18	**0.60**	0.43	0.20	**0.91**	0.28	0.45	**1.20**	0.14	0.43
	130	**0.41**	0.12	0.09	**0.42**	0.10	0.09	**0.51**	0.10	0.07
	131	**0.30**	0.08	0.07	**0.34**	0.07	0.06	**0.35**	0.07	0.06
	137	**0.52**	0.34	0.12	**0.51**	0.32	0.13	**0.79**	0.27	0.12
	138	**0.51**	0.35	0.12	**0.56**	0.32	0.14	**0.80**	0.27	0.14
	139	**0.75**	0.29	0.13	**1.12**	0.29	0.18	**1.22**	0.12	0.19
	145	**0.51**	0.35	0.12	**0.56**	0.32	0.14	**0.80**	0.27	0.14
	146	**0.82**	0.24	0.14	**1.19**	0.29	0.18	**1.29**	0.12	0.16

d) Simulated PD (mW/cm²) at 4 cm² averaging for side module at n260.

		4 cm² PD (mW/cm²) at 11 dBm per port, n260								
Module	Beam ID	LB			MB			HB		
		S1	S2	**S4**	S1	S2	**S4**	S1	S2	**S4**
Side	4	0.43	0.32	**1.67**	0.36	0.49	**1.74**	0.22	0.59	**1.83**
	5	0.30	0.28	**1.10**	0.30	0.32	**1.19**	0.15	0.20	**1.20**
	12	0.53	0.29	**2.82**	0.53	0.42	**2.28**	0.63	0.58	**2.72**
	13	1.04	0.64	**3.29**	1.24	0.82	**3.68**	1.02	0.81	**3.72**
	14	0.91	0.48	**3.19**	0.87	0.58	**3.20**	0.90	0.53	**3.30**
	19	1.00	0.41	**3.29**	0.81	0.53	**3.07**	0.71	0.52	**3.14**
	20	1.19	0.77	**3.22**	1.03	0.70	**3.54**	0.99	0.65	**3.93**
	26	1.41	0.70	**4.85**	1.11	0.85	**3.94**	1.19	1.04	**4.60**
	27	2.19	1.19	**5.52**	1.75	1.31	**5.49**	1.08	1.17	**5.07**
	28	2.71	1.89	**6.80**	2.34	1.87	**6.98**	2.26	1.40	**7.44**
	29	2.30	1.32	**6.07**	2.36	1.64	**6.83**	1.91	1.06	**6.64**
	30	1.31	0.70	**5.44**	1.19	0.64	**4.37**	1.46	0.98	**4.72**
	35	1.47	0.66	**5.35**	1.09	0.66	**4.24**	1.45	0.97	**4.65**
	36	2.42	1.44	**6.13**	2.46	1.76	**6.68**	1.90	1.56	**6.10**
	37	2.41	1.69	**6.49**	2.47	1.77	**7.36**	2.03	1.19	**7.44**
	38	1.77	0.80	**5.67**	1.93	1.04	**6.06**	1.92	1.01	**6.04**
	132	0.39	0.37	**1.65**	0.32	0.42	**1.59**	0.31	0.39	**1.38**
	133	0.28	0.31	**1.01**	0.25	0.32	**1.06**	0.24	0.25	**1.02**
	140	0.67	0.65	**3.05**	0.53	0.53	**2.59**	0.51	0.57	**2.51**
	141	0.91	0.89	**3.01**	0.88	0.97	**3.19**	0.79	0.80	**3.00**
	142	0.63	0.55	**3.21**	0.59	0.65	**2.52**	0.68	0.63	**2.47**
	147	0.56	0.68	**3.26**	0.80	0.64	**2.82**	0.69	0.71	**3.04**
	148	0.85	0.82	**2.90**	0.85	0.85	**2.89**	0.73	0.75	**2.86**
	154	1.26	1.12	**5.48**	1.10	1.14	**4.95**	1.05	0.93	**4.80**
	155	1.22	1.37	**5.63**	1.41	1.26	**5.09**	1.20	1.32	**4.80**
	156	1.41	1.30	**6.03**	1.25	1.42	**6.26**	1.40	1.27	**5.93**
	157	1.05	1.06	**4.81**	1.22	1.61	**5.42**	0.99	1.07	**4.41**
	158	0.89	0.91	**5.42**	1.11	0.93	**4.89**	1.20	1.29	**5.55**
	163	1.32	1.19	**4.87**	1.26	1.11	**4.53**	0.97	0.88	**4.18**
	164	1.50	1.63	**6.16**	1.65	1.29	**5.94**	1.58	1.27	**5.61**
	165	1.27	1.22	**5.59**	1.41	1.51	**6.38**	1.33	1.18	**5.38**
	166	1.27	1.09	**4.78**	1.16	1.20	**4.30**	1.10	1.10	**4.08**

e) Simulated PD (mW/cm^2) at 4 cm^2 averaging for back module at n260.

		4 cm^2 PD (mW/cm^2) at 11 dBm per port, n260								
Module	Beam ID	LB			MB			HB		
		S1	**S2**	S3	S1	**S2**	S3	S1	**S2**	S3
Back	0	x	**1.52**	0.14	x	**1.69**	0.17	x	**1.56**	0.19
	1	x	**1.23**	0.10	x	**1.27**	0.11	x	**1.20**	0.12
	6	x	**3.02**	0.17	x	**3.01**	0.29	x	**2.64**	0.40
	7	x	**2.88**	0.51	x	**2.91**	0.40	x	**2.65**	0.36
	8	x	**2.67**	0.52	x	**2.63**	0.68	x	**2.60**	0.55
	15	x	**3.26**	0.14	x	**3.17**	0.13	x	**2.63**	0.19
	16	x	**2.64**	0.57	x	**2.70**	0.60	x	**2.66**	0.52
	21	x	**3.79**	0.17	x	**3.69**	0.44	x	**4.72**	0.55
	22	x	**5.30**	0.54	x	**5.19**	0.40	x	**4.66**	0.21
	23	x	**4.49**	0.33	x	**4.51**	0.32	x	**4.07**	0.48
	24	x	**5.04**	0.60	x	**4.74**	0.95	x	**4.61**	0.82
	25	x	**3.64**	0.94	x	**4.82**	1.25	x	**4.03**	0.98
	31	x	**4.19**	0.24	x	**5.41**	0.29	x	**4.57**	0.25
	32	x	**4.84**	0.49	x	**4.99**	0.36	x	**4.87**	0.30
	33	x	**3.78**	0.59	x	**4.02**	0.98	x	**3.96**	0.98
	34	x	**5.07**	0.65	x	**4.79**	1.00	x	**4.60**	0.92
	128	x	**1.66**	0.16	x	**1.64**	0.13	x	**1.51**	0.14
	129	x	**1.19**	0.11	x	**1.37**	0.09	x	**1.32**	0.11
	134	x	**2.88**	0.24	x	**2.63**	0.35	x	**2.40**	0.21
	135	x	**3.12**	0.10	x	**2.98**	0.13	x	**2.71**	0.10
	136	x	**3.27**	0.62	x	**3.15**	0.49	x	**2.80**	0.48
	143	x	**3.33**	0.24	x	**3.24**	0.16	x	**3.18**	0.19
	144	x	**3.21**	0.54	x	**3.09**	0.44	x	**2.68**	0.41
	149	x	**5.28**	0.38	x	**5.33**	0.33	x	**4.94**	0.44
	150	x	**5.34**	0.33	x	**5.10**	0.21	x	**4.81**	0.25
	151	x	**5.72**	0.17	x	**4.29**	0.16	x	**4.26**	0.30
	152	x	**4.28**	0.70	x	**5.27**	0.51	x	**4.69**	0.29
	153	x	**4.56**	0.86	x	**4.24**	0.48	x	**3.70**	0.52
	159	x	**5.32**	0.40	x	**5.08**	0.40	x	**4.67**	0.55
	160	x	**5.54**	0.24	x	**4.41**	0.21	x	**4.57**	0.24
	161	x	**5.23**	0.46	x	**4.56**	0.38	x	**4.06**	0.41
	162	x	**4.35**	0.79	x	**4.10**	0.49	x	**4.64**	0.40

f) Simulated PD (mW/cm^2) at 4 cm^2 averaging for front module at n260.

		4 cm^2 PD (mW/cm^2) at 11 dBm per port, n260								
Module	Beam ID	LB			MB			HB		
		S1	S2	S5	**S1**	S2	S5	**S1**	S2	S5
Front	2	**0.23**	0.04	0.06	**0.20**	0.05	0.06	**0.23**	0.06	0.06
	3	**0.17**	0.03	0.04	**0.16**	0.03	0.04	**0.17**	0.04	0.04
	9	**0.48**	0.11	0.13	**0.55**	0.12	0.10	**0.43**	0.13	0.08
	10	**0.44**	0.13	0.23	**0.43**	0.19	0.20	**0.39**	0.07	0.17
	11	**0.54**	0.15	0.22	**0.52**	0.09	0.21	**0.45**	0.09	0.16
	17	**0.43**	0.09	0.18	**0.45**	0.20	0.14	**0.40**	0.11	0.13
	18	**0.52**	0.16	0.24	**0.50**	0.10	0.22	**0.44**	0.08	0.16
	130	**0.27**	0.07	0.04	**0.27**	0.06	0.05	**0.30**	0.04	0.05
	131	**0.19**	0.05	0.04	**0.20**	0.04	0.03	**0.21**	0.02	0.02
	137	**0.58**	0.11	0.09	**0.48**	0.12	0.13	**0.66**	0.12	0.13
	138	**0.40**	0.13	0.09	**0.53**	0.08	0.11	**0.60**	0.05	0.11
	139	**0.68**	0.15	0.10	**0.40**	0.10	0.12	**0.46**	0.05	0.15
	145	**0.37**	0.11	0.07	**0.55**	0.08	0.11	**0.66**	0.05	0.11
	146	**0.45**	0.15	0.10	**0.50**	0.08	0.11	**0.53**	0.04	0.11

Scaling factor calculation: The following tables show the scaling factor results for all three different modules, at both band n261 and band n260. The scaling factor is defined as the MPE internal design limit (0.6 mW/cm^2) divided by the simulated averaged power density. Table a), b), and c) show the results for n261, for side, back, and front modules, respectively; table d), e) and f) show the results for n260, for side, back, and front modules, respectively.
In the tables below, the values reported represent the scaled factors for low-band, mid-band and high-band results (S_LB, S_MB, and S_HB, respectively) and the scaling factor S is the most restrictive of the three band-specific values. These are preliminary results which will change as the hardware matures.

a) *Scaling factor for side module n261*

Beam ID	S_LB	S_MB	S_HB	S
4	0.36	0.35	0.34	0.34
5	0.41	0.40	0.40	0.40
12	0.19	0.18	0.17	0.17
13	0.19	0.16	0.18	0.16
14	0.18	0.18	0.17	0.17
19	0.18	0.17	0.16	0.16
20	0.18	0.17	0.17	0.17
26	0.08	0.09	0.08	0.08
27	0.10	0.09	0.09	0.09
28	0.10	0.09	0.09	0.09
29	0.09	0.08	0.08	0.08
30	0.09	0.08	0.08	0.08
35	0.09	0.08	0.08	0.08
36	0.10	0.09	0.09	0.09
37	0.09	0.09	0.09	0.09
38	0.08	0.08	0.08	0.08
132	0.43	0.33	0.30	0.30
133	0.50	0.39	0.37	0.37
140	0.21	0.19	0.15	0.15
141	0.31	0.16	0.18	0.16
142	0.20	0.18	0.15	0.15
147	0.25	0.16	0.16	0.16
148	0.22	0.16	0.15	0.15
154	0.10	0.10	0.08	0.08
155	0.14	0.08	0.08	0.08
156	0.16	0.09	0.10	0.09
157	0.11	0.08	0.08	0.08
158	0.11	0.09	0.09	0.09
163	0.10	0.08	0.08	0.08
164	0.16	0.08	0.10	0.08
165	0.15	0.09	0.09	0.09
166	0.10	0.08	0.08	0.08

b) Scaling factor for back module n261

Beam ID	S_LB	S_MB	S_HB	S
0	0.37	0.34	0.41	0.34
1	0.49	0.41	0.50	0.41
6	0.17	0.17	0.22	0.17
7	0.19	0.16	0.17	0.16
8	0.16	0.15	0.15	0.15
15	0.19	0.18	0.23	0.18
16	0.17	0.17	0.19	0.17
21	0.13	0.12	0.11	0.11
22	0.18	0.14	0.15	0.14
23	0.10	0.09	0.10	0.09
24	0.09	0.09	0.10	0.09
25	0.10	0.09	0.11	0.09
31	0.14	0.13	0.12	0.12
32	0.12	0.12	0.12	0.12
33	0.09	0.09	0.10	0.09
34	0.09	0.08	0.10	0.08
128	0.34	0.37	0.36	0.34
129	0.34	0.36	0.50	0.34
134	0.19	0.18	0.16	0.16
135	0.19	0.16	0.16	0.16
136	0.17	0.16	0.18	0.16
143	0.20	0.18	0.16	0.16
144	0.19	0.17	0.17	0.17
149	0.15	0.14	0.11	0.11
150	0.12	0.11	0.11	0.11
151	0.09	0.13	0.12	0.09
152	0.09	0.08	0.11	0.08
153	0.10	0.10	0.12	0.10
159	0.13	0.12	0.11	0.11
160	0.10	0.09	0.11	0.09
161	0.13	0.11	0.11	0.11
162	0.08	0.09	0.11	0.08

c) Scaling factor for front module n261

Beam ID	S_LB	S_MB	S_HB	S
2	1.43	1.40	1.03	1.03
3	2.00	1.62	1.88	1.62
9	0.87	0.56	0.52	0.52
10	0.85	0.60	0.45	0.45
11	0.98	0.63	0.54	0.54
17	0.82	0.59	0.44	0.44
18	1.00	0.66	0.50	0.50
130	1.46	1.43	1.18	1.18
131	2.00	1.76	1.71	1.71
137	1.15	1.18	0.76	0.76
138	1.18	1.07	0.75	0.75
139	0.80	0.54	0.49	0.49
145	1.18	1.07	0.75	0.75
146	0.73	0.50	0.47	0.47

d) Scaling factor for side module n260

Beam ID	S_LB	S_MB	S_HB	S
4	0.36	0.34	0.33	0.33
5	0.55	0.50	0.50	0.50
12	0.21	0.26	0.22	0.21
13	0.18	0.16	0.16	0.16
14	0.19	0.19	0.18	0.18
19	0.18	0.20	0.19	0.18
20	0.19	0.17	0.15	0.15
26	0.12	0.15	0.13	0.12
27	0.11	0.11	0.12	0.11
28	0.09	0.09	0.08	0.08
29	0.10	0.09	0.09	0.09
30	0.11	0.14	0.13	0.11
35	0.11	0.14	0.13	0.11
36	0.10	0.09	0.10	0.09
37	0.09	0.08	0.08	0.08
38	0.11	0.10	0.10	0.10
132	0.36	0.38	0.43	0.36
133	0.59	0.57	0.59	0.57
140	0.20	0.23	0.24	0.20
141	0.20	0.19	0.20	0.19
142	0.19	0.24	0.24	0.19
147	0.18	0.21	0.20	0.18
148	0.21	0.21	0.21	0.21
154	0.11	0.12	0.13	0.11
155	0.11	0.12	0.13	0.11
156	0.10	0.10	0.10	0.10
157	0.12	0.11	0.14	0.11
158	0.11	0.12	0.11	0.11

163	0.12	0.13	0.14	0.12
164	0.10	0.10	0.11	0.10
165	0.11	0.09	0.11	0.09
166	0.13	0.14	0.15	0.13

e) *Scaling factor for back module n260*

Beam ID	S_LB	S_MB	S_HB	S
0	0.39	0.36	0.38	0.36
1	0.49	0.47	0.50	0.47
6	0.20	0.20	0.23	0.20
7	0.21	0.21	0.23	0.21
8	0.22	0.23	0.23	0.22
15	0.18	0.19	0.23	0.18
16	0.23	0.22	0.23	0.22
21	0.16	0.16	0.13	0.13
22	0.11	0.12	0.13	0.11
23	0.13	0.13	0.15	0.13
24	0.12	0.13	0.13	0.12
25	0.16	0.12	0.15	0.12
31	0.14	0.11	0.13	0.11
32	0.12	0.12	0.12	0.12
33	0.16	0.15	0.15	0.15
34	0.12	0.13	0.13	0.12
128	0.36	0.37	0.40	0.36
129	0.50	0.44	0.45	0.44
134	0.21	0.23	0.25	0.21
135	0.19	0.20	0.22	0.19
136	0.18	0.19	0.21	0.18
143	0.18	0.19	0.19	0.18
144	0.19	0.19	0.22	0.19
149	0.11	0.11	0.12	0.11
150	0.11	0.12	0.12	0.11
151	0.10	0.14	0.14	0.10
152	0.14	0.11	0.13	0.11
153	0.13	0.14	0.16	0.13
159	0.11	0.12	0.13	0.11
160	0.11	0.14	0.13	0.11
161	0.11	0.13	0.15	0.11
162	0.14	0.15	0.13	0.13

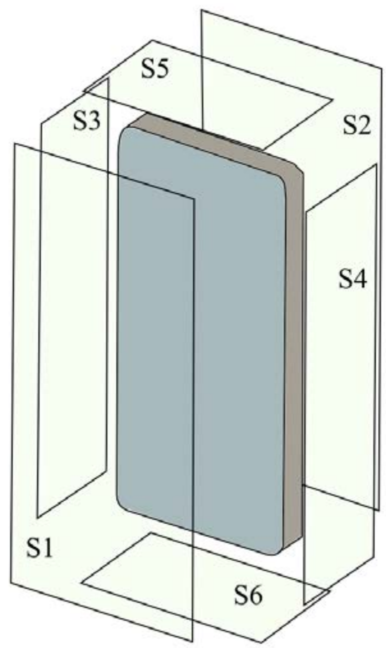
f) *Scaling factor for front module n260*

Beam ID	S_LB	S_MB	S_HB	S
2	2.61	3.00	2.61	2.61
3	3.53	3.75	3.53	3.53
9	1.25	1.09	1.40	1.09
10	1.36	1.40	1.54	1.36
11	1.11	1.15	1.33	1.11
17	1.40	1.33	1.50	1.33

18	1.15	1.20	1.36	1.15
130	2.22	2.22	2.00	2.00
131	3.16	3.00	2.86	2.86
137	1.03	1.25	0.91	0.91
138	1.50	1.13	1.00	1.00
139	0.88	1.50	1.30	0.88
145	1.62	1.09	0.91	0.91
146	1.33	1.20	1.13	1.13

Appendix C: Simulated PD Distribution Plots

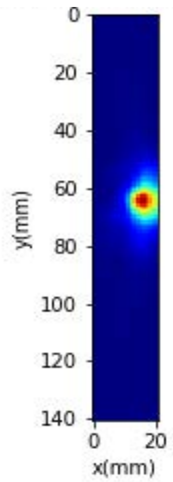
The evaluating planes are illustrated in the figure below. All PD distribution plots are normalized to its own maximum value.

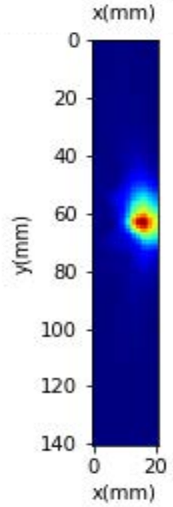


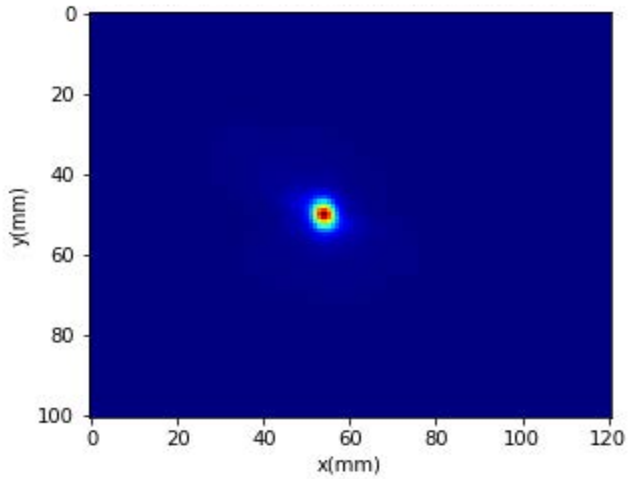
	Front (S1)	Rear (S2)	Left from Front View (S3)	Right from Front View (S4)	Top (S5)	Bottom (S6)
Side Module	**Yes (0.4 cm)**	**Yes (0.4 cm)**	No (7 cm)	**Yes (0 cm)**	No (8 cm)	No (4 cm)
Back Module	No (0.6 cm)	**Yes (0 cm)**	**Yes (0.8 cm)**	No (4 cm)	No (2.5 cm)	No (12 cm)
Front Module	**Yes (0 cm)**	**Yes (0.2 cm)**	No (2.6 cm)	No (4 cm)	**Yes (0.2 cm)**	No (12 cm)

Normalized power density plots for all the Beam IDs across S1, S2 and S4 evaluation planes for the side-firing antenna array are shown below.

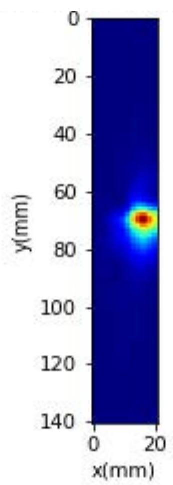
Power Density Plots for Beam ID: 4

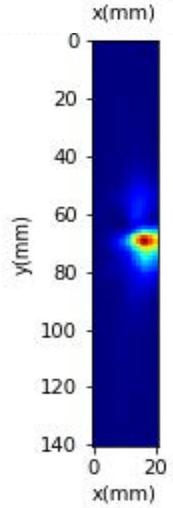


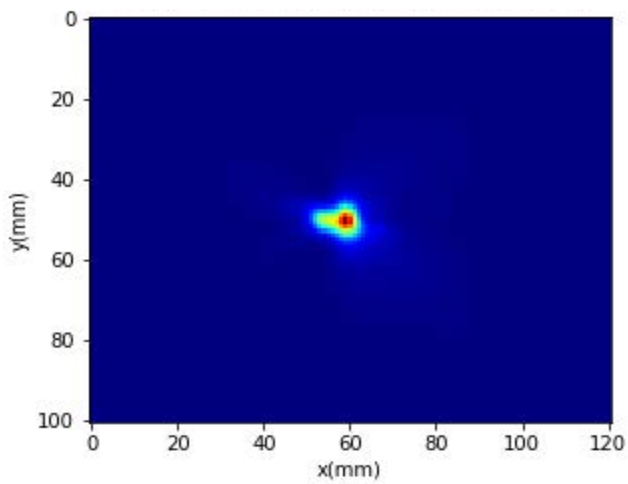




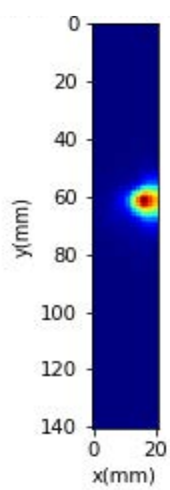
Power Density Plots for Beam ID: 12

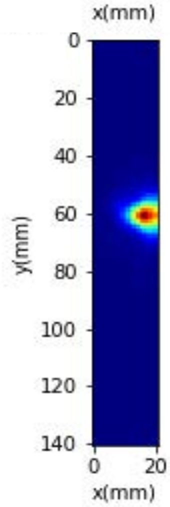


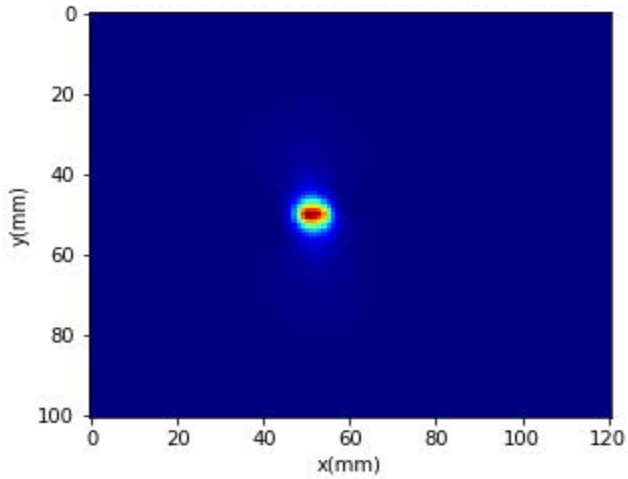




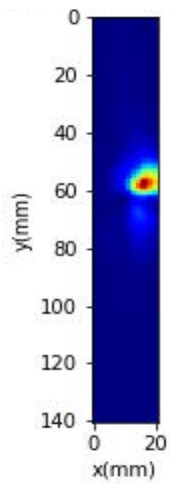
Power Density Plots for Beam ID: 13

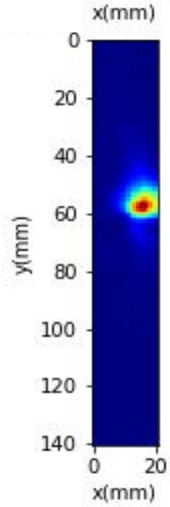


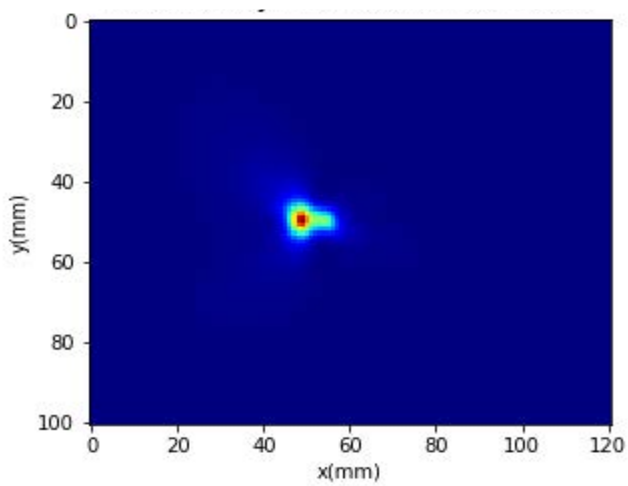




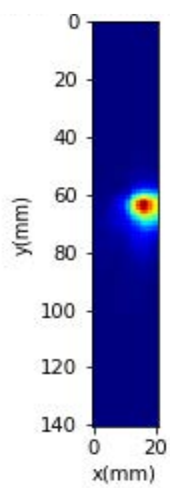
Power Density Plots for Beam ID: 14

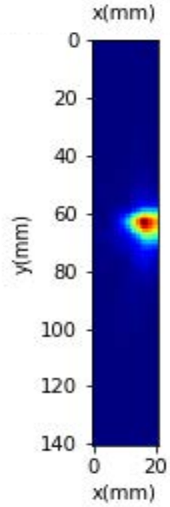


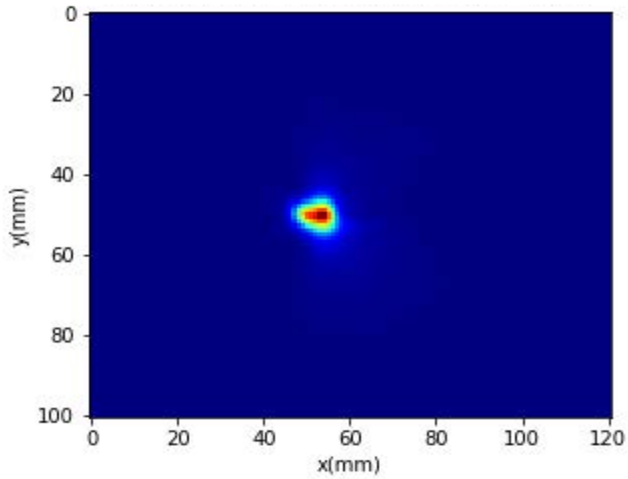




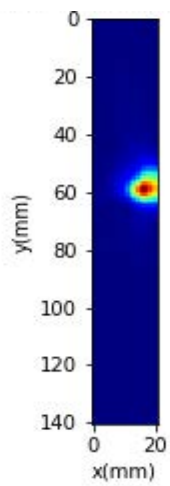
Power Density Plots for Beam ID: 19

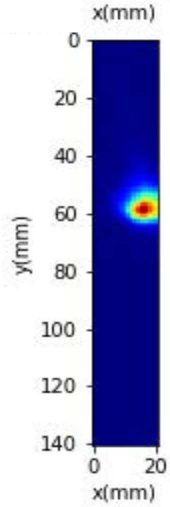


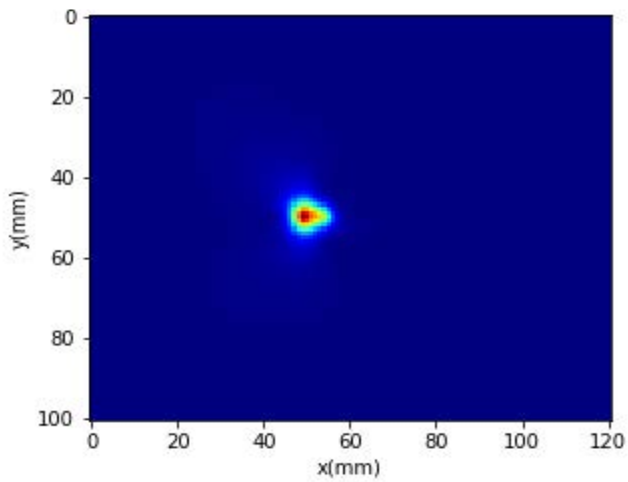




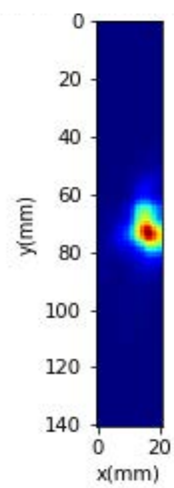
Power Density Plots for Beam ID: 20

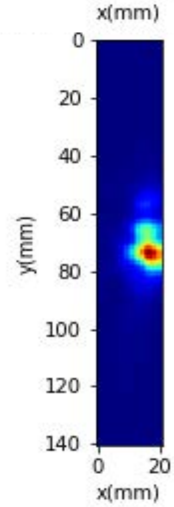


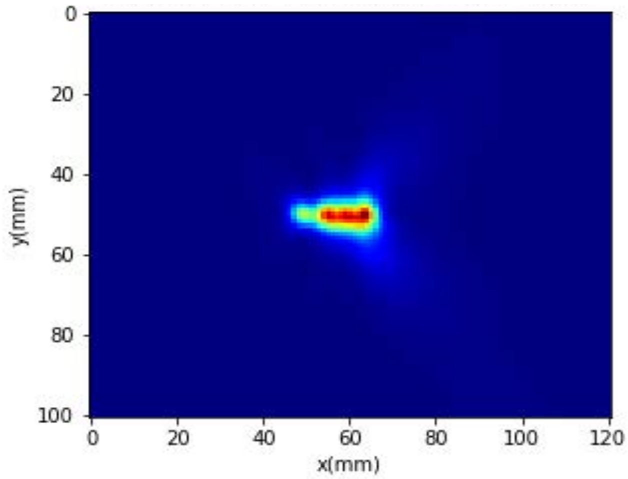




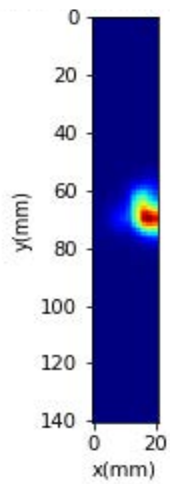
Power Density Plots for Beam ID: 26

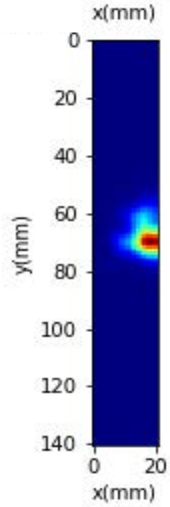


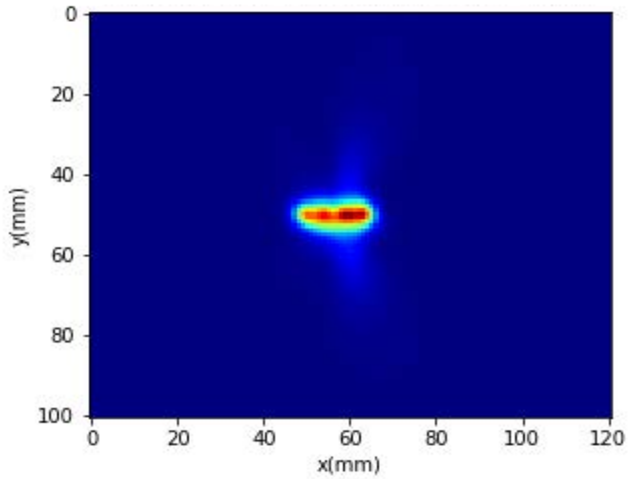




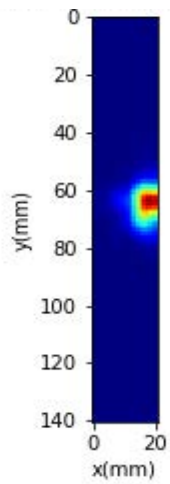
Power Density Plots for Beam ID: 27

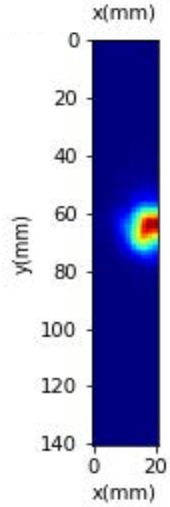


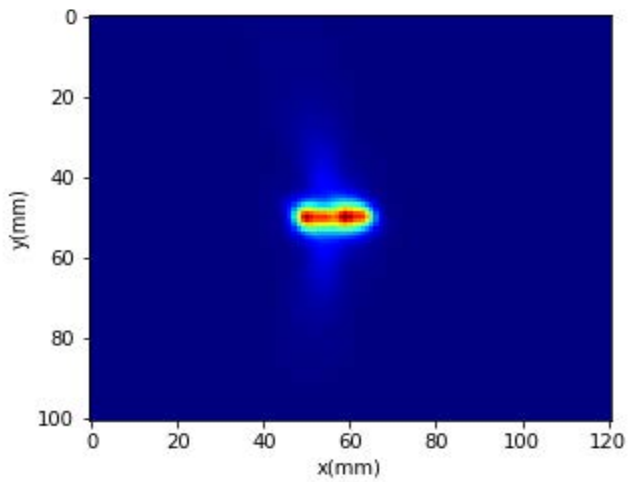




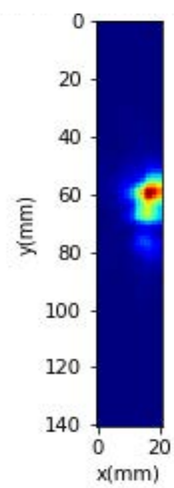
Power Density Plots for Beam ID: 28

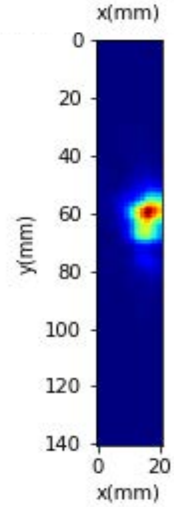


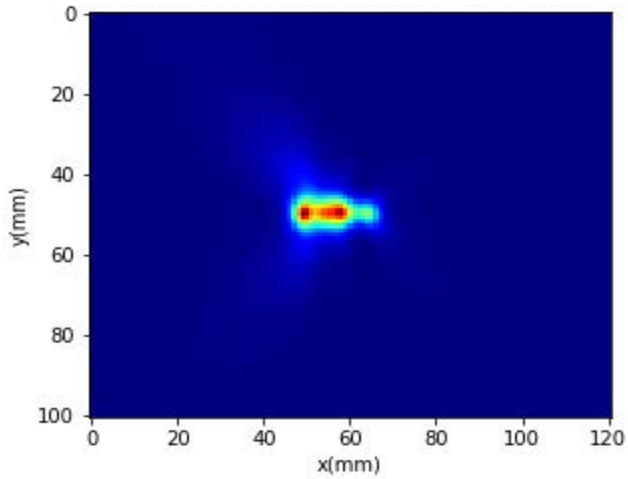




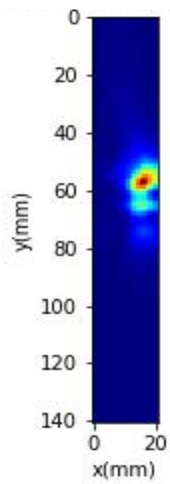
Power Density Plots for Beam ID: 29

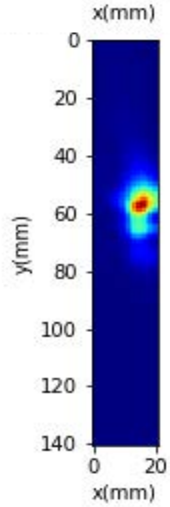


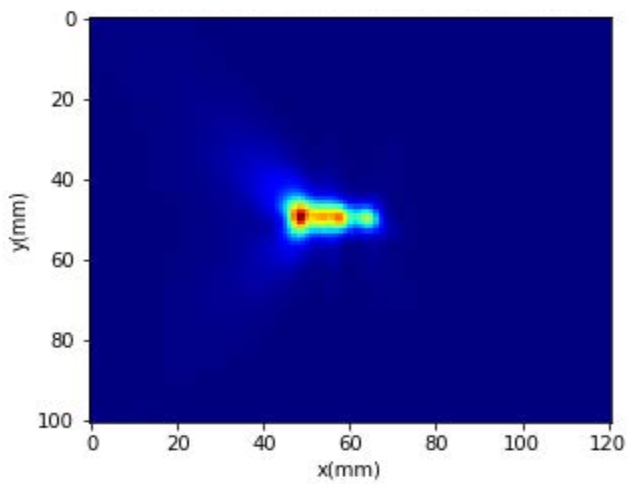




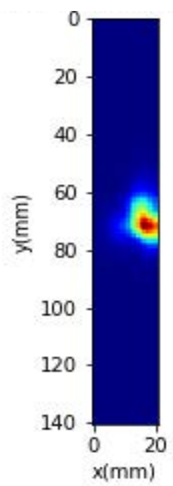
Power Density Plots for Beam ID: 30

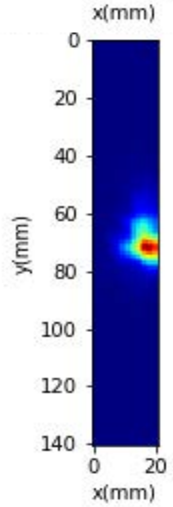


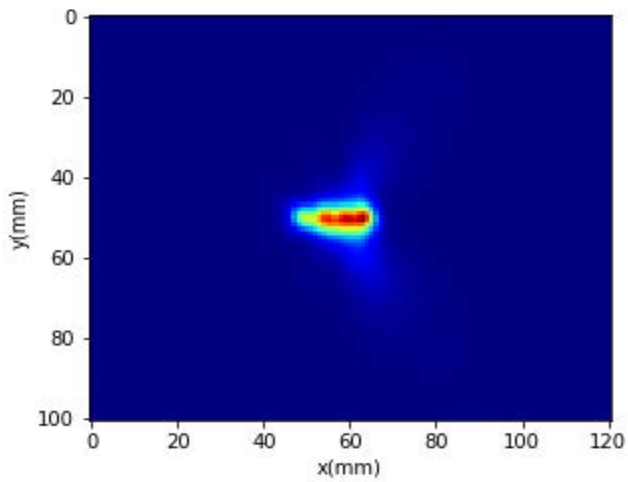




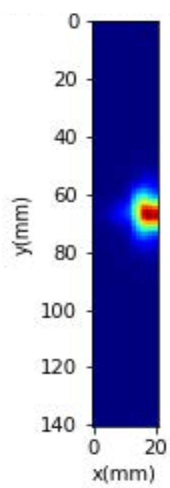
Power Density Plots for Beam ID: 35

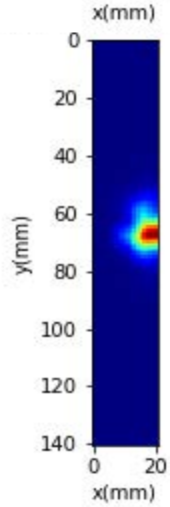


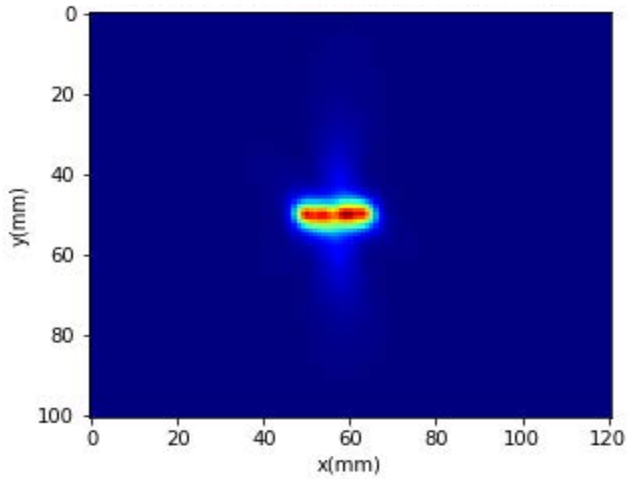




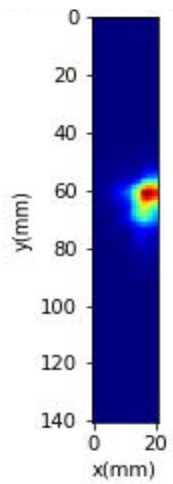
Power Density Plots for Beam ID: 36

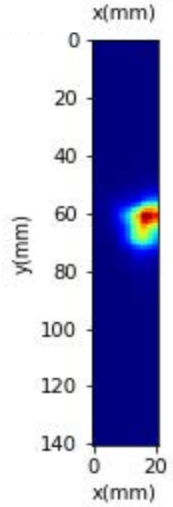


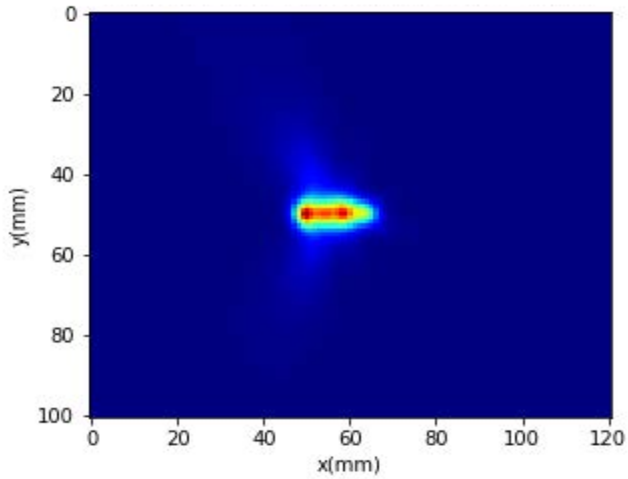




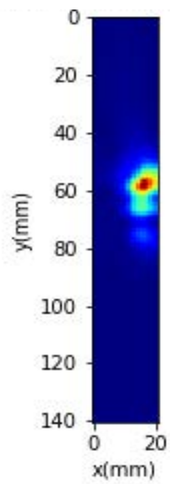
Power Density Plots for Beam ID: 37

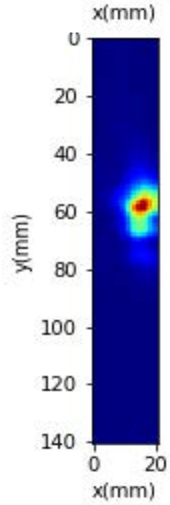


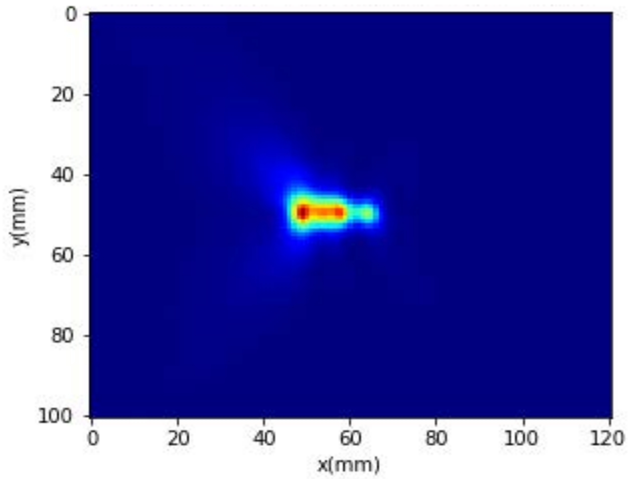




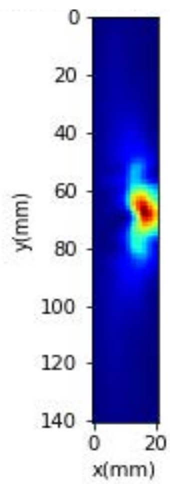
Power Density Plots for Beam ID: 38

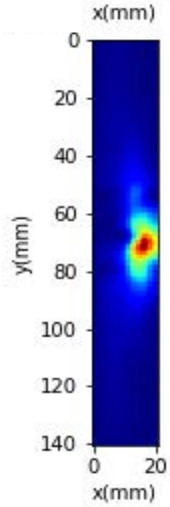


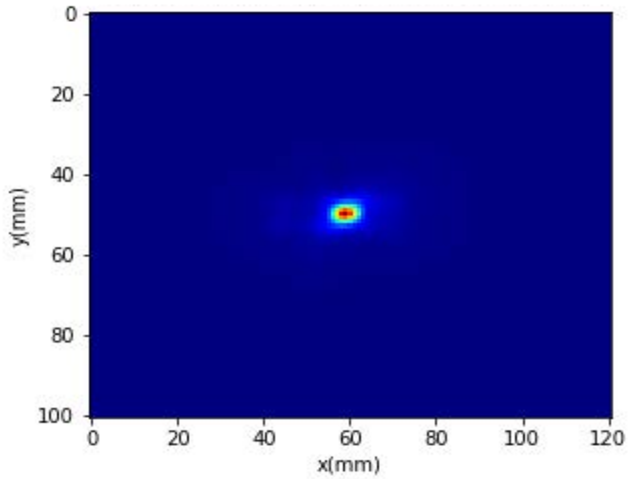




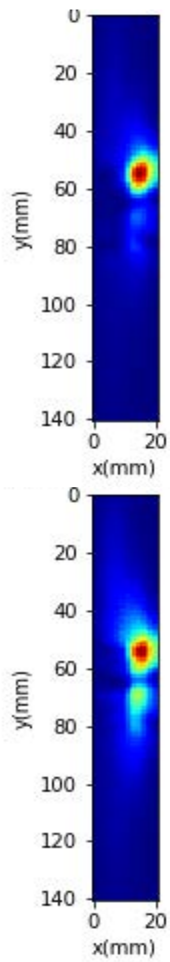
Power Density Plots for Beam ID: 132

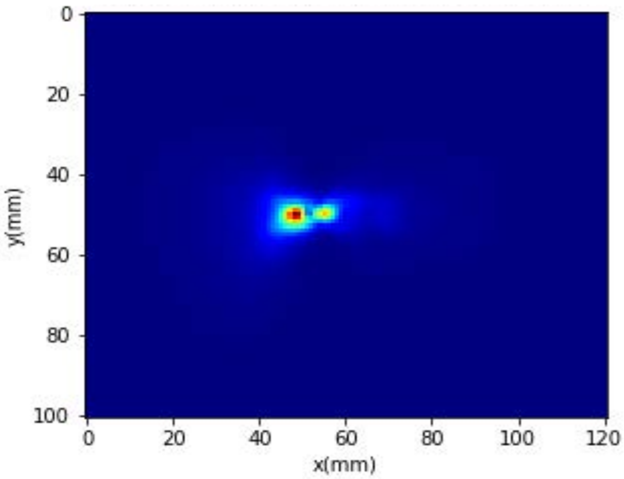




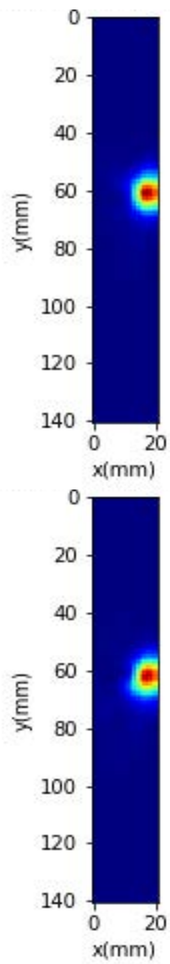


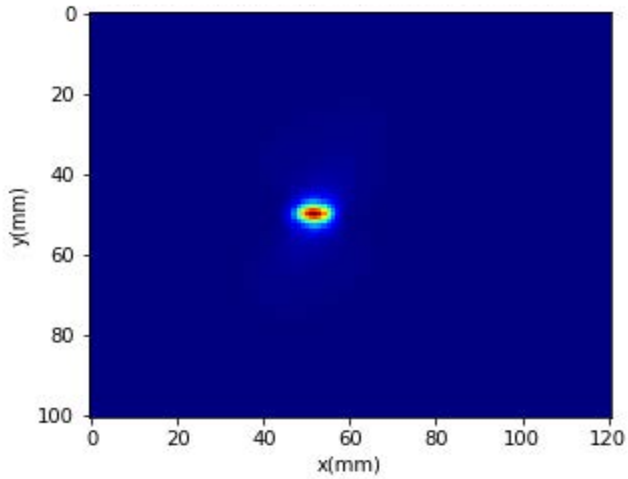
Power Density Plots for Beam ID: 140



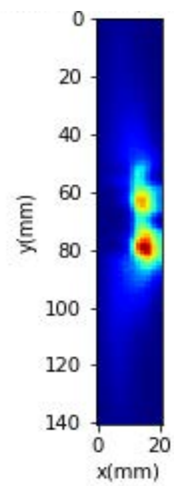


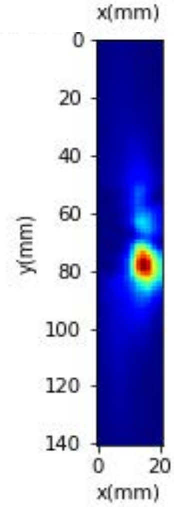
Power Density Plots for Beam ID: 141

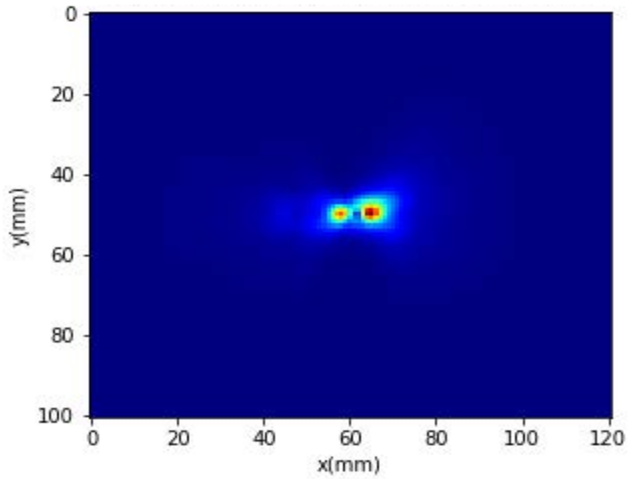




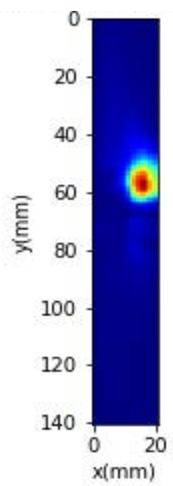
Power Density Plots for Beam ID: 142

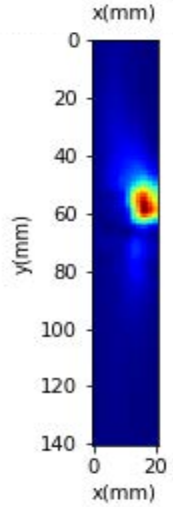


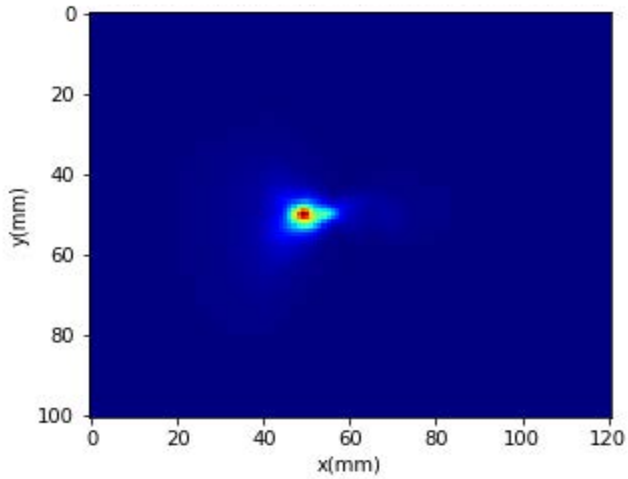




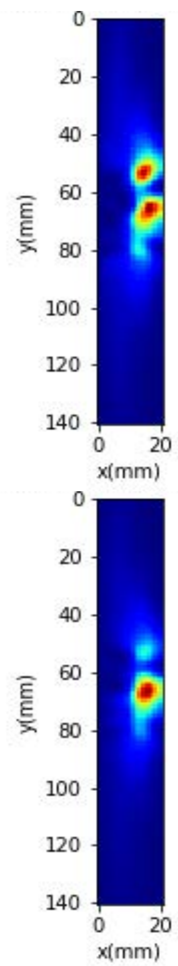
Power Density Plots for Beam ID: 147

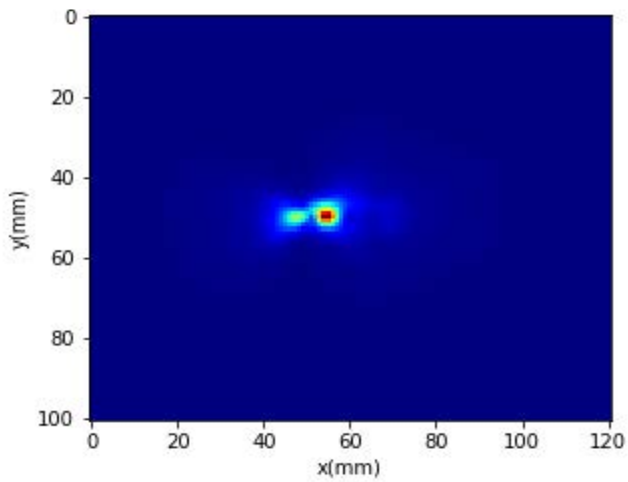




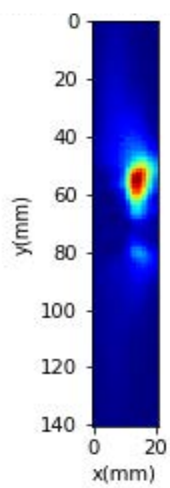


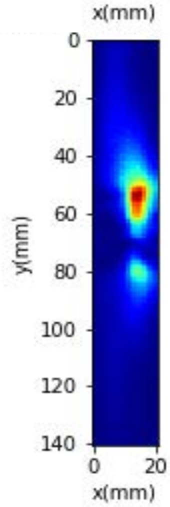
Power Density Plots for Beam ID: 148

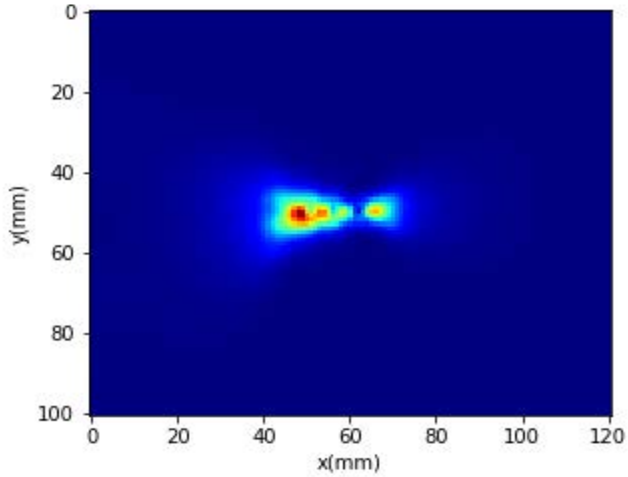




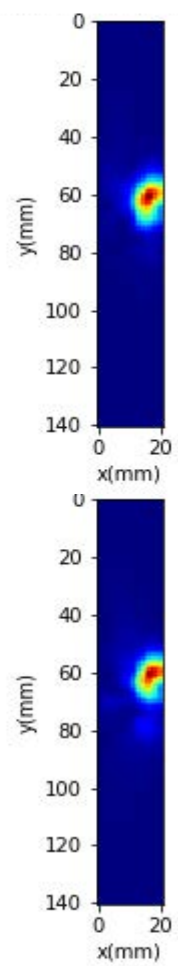
Power Density Plots for Beam ID: 154

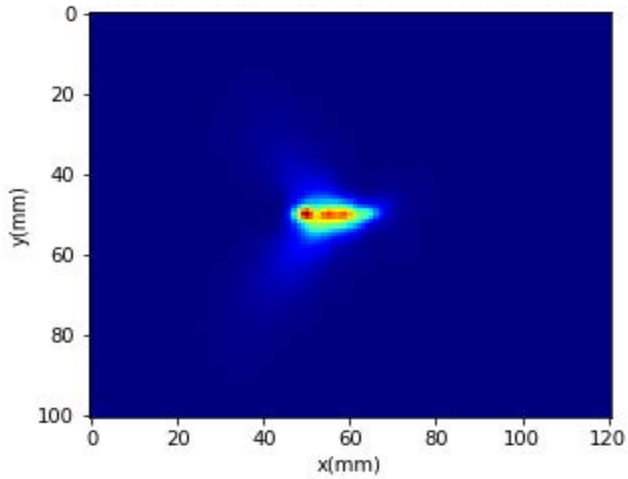




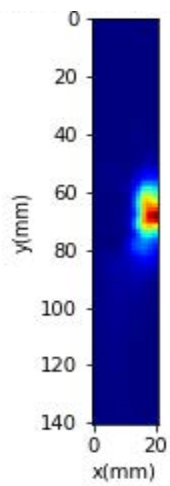


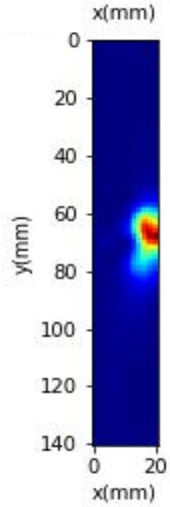
Power Density Plots for Beam ID: 155

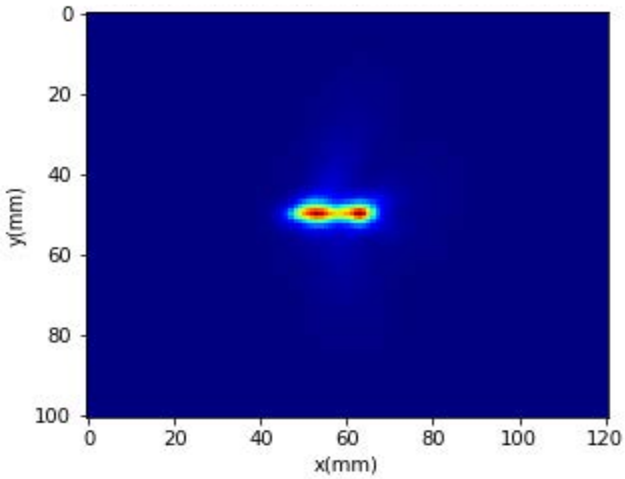




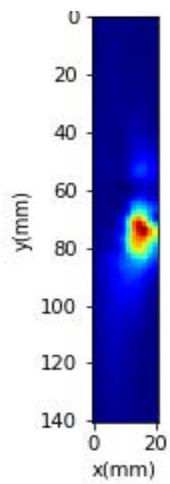
Power Density Plots for Beam ID: 156

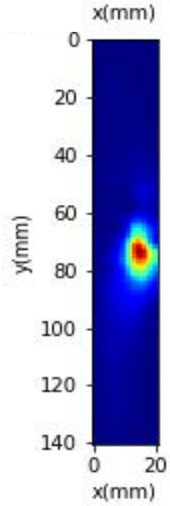


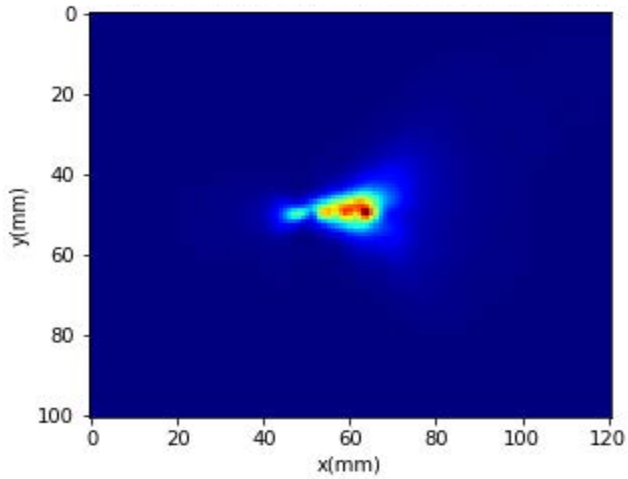




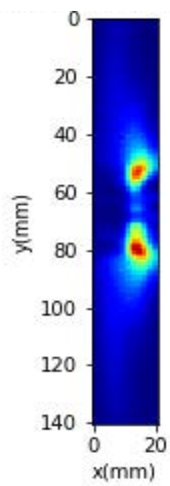
Power Density Plots for Beam ID: 157

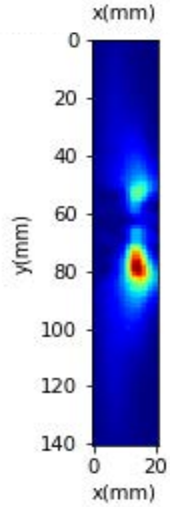


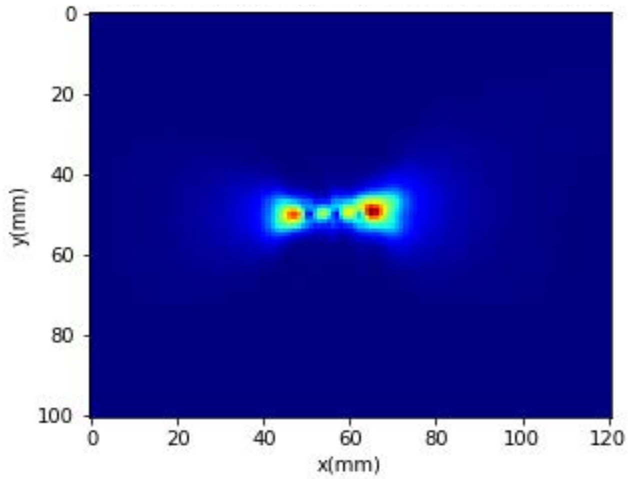




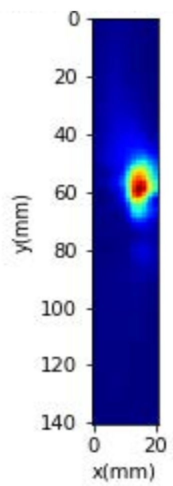
Power Density Plots for Beam ID: 158

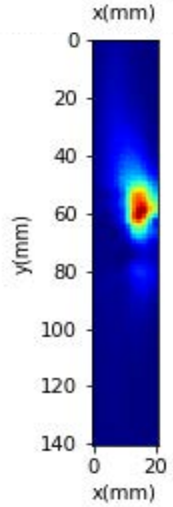


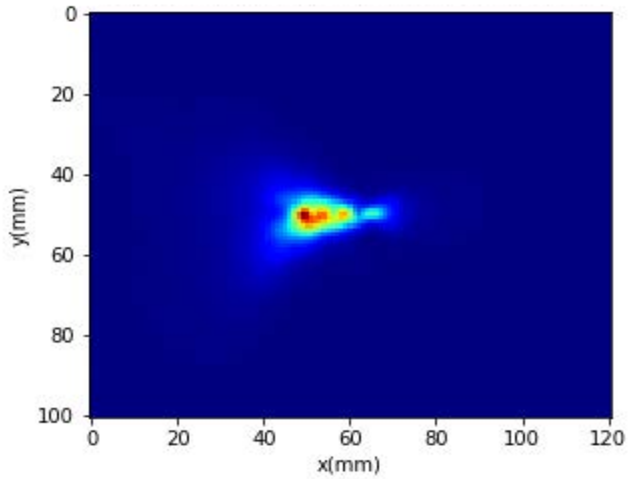




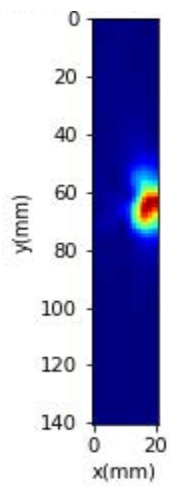
Power Density Plots for Beam ID: 163

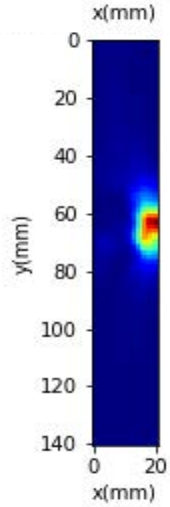


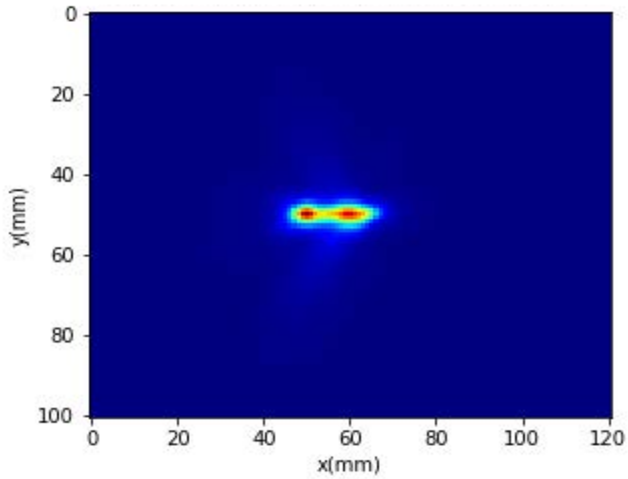




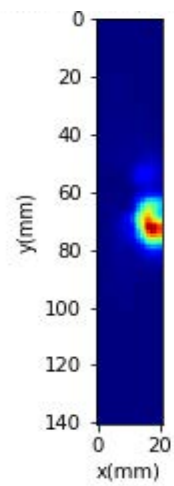
Power Density Plots for Beam ID: 164

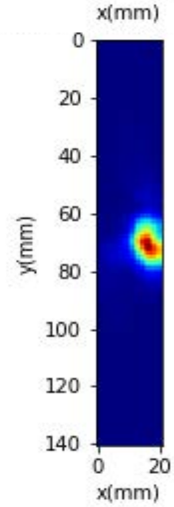


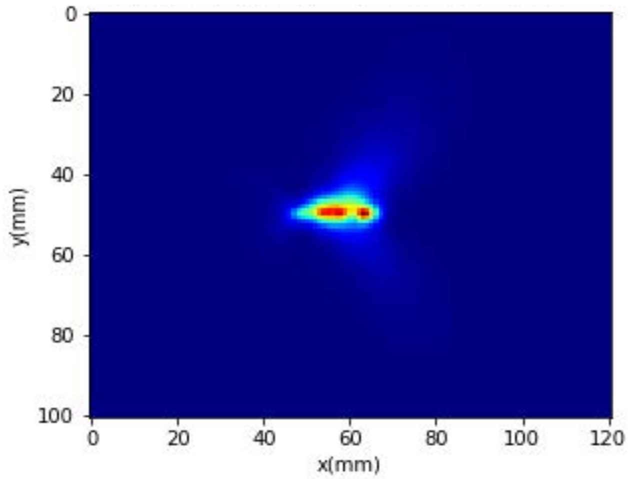




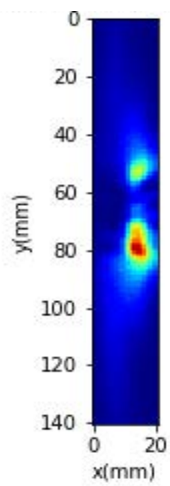
Power Density Plots for Beam ID: 165

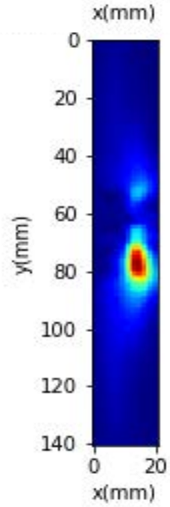


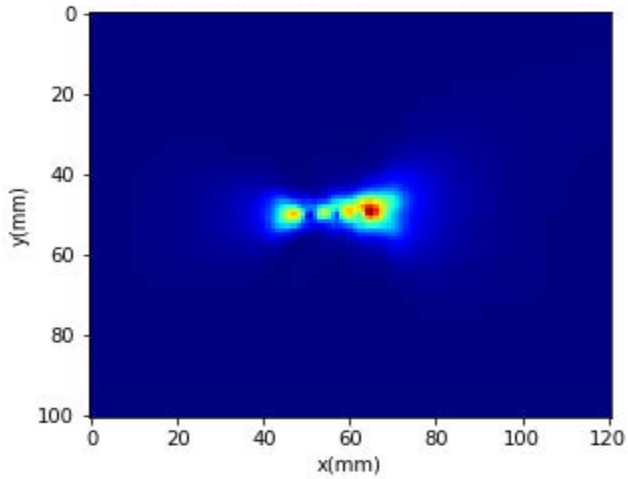




Power Density Plots for Beam ID: 166

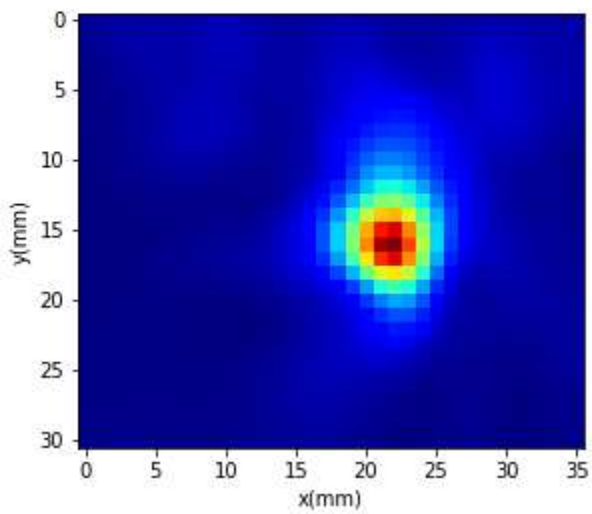


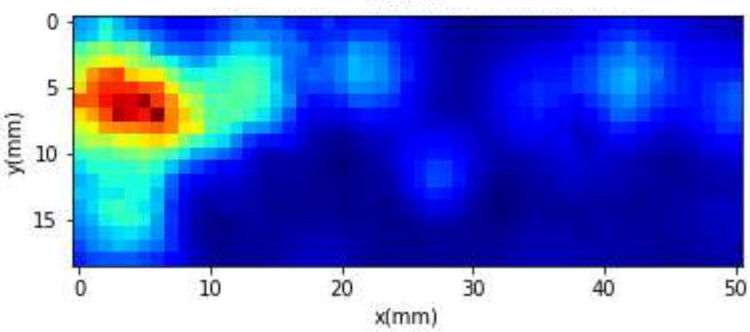




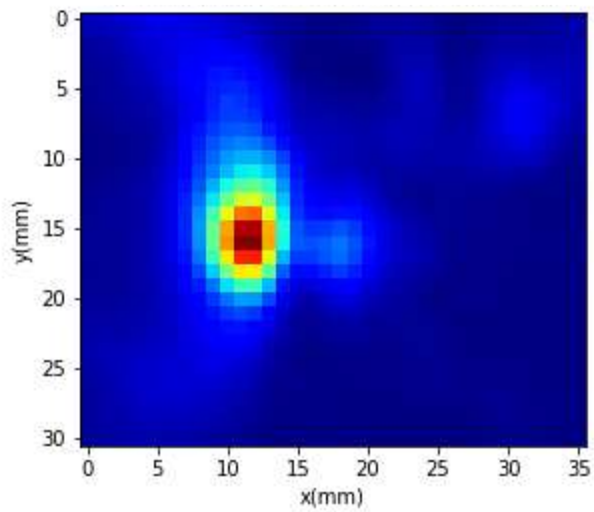
Normalized power density plots for all the Beam IDs across S2 and S3 evaluation planes for the back-firing antenna array are shown below.

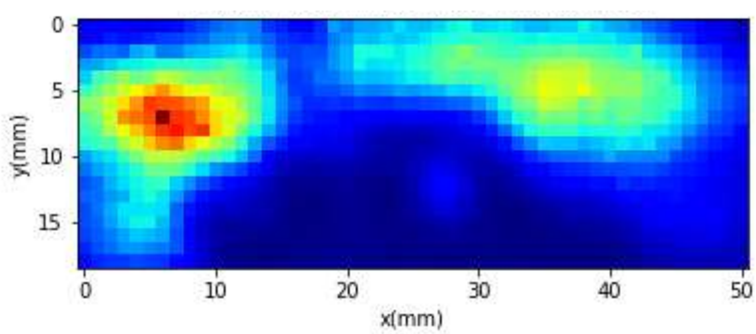
Power Density Plots for Beam ID: 0



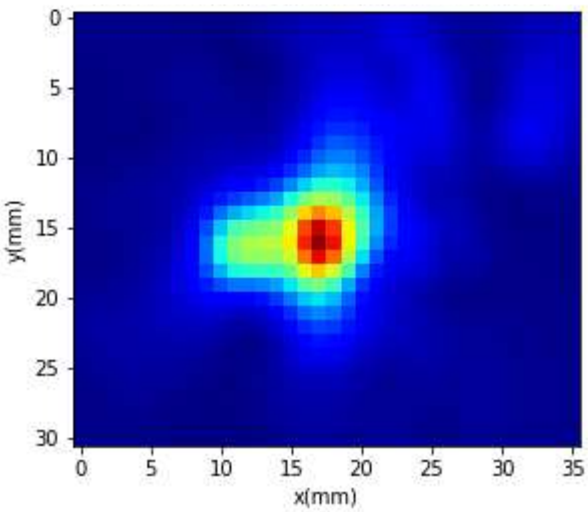


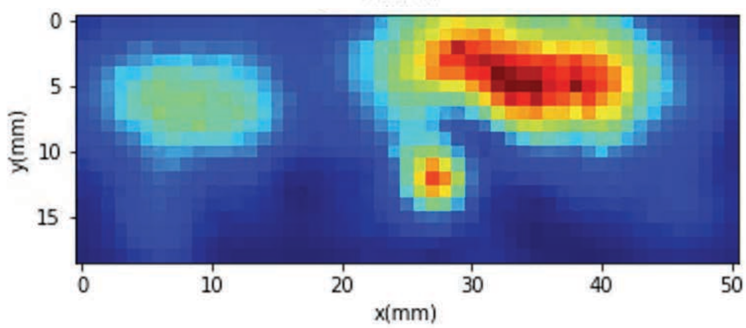
Power Density Plots for Beam ID: 6



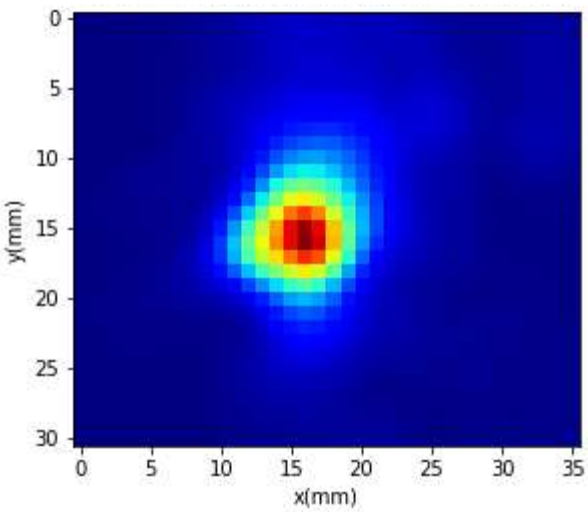


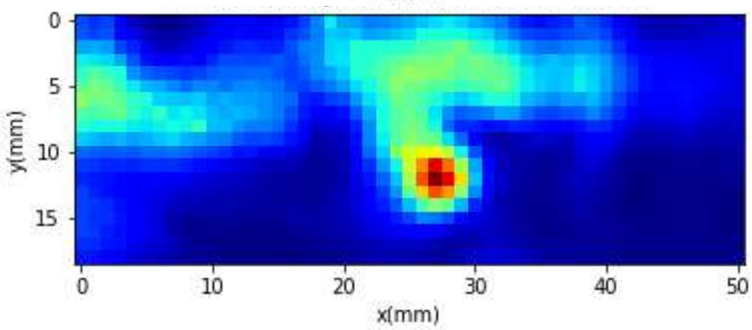
Power Density Plots for Beam ID: 7



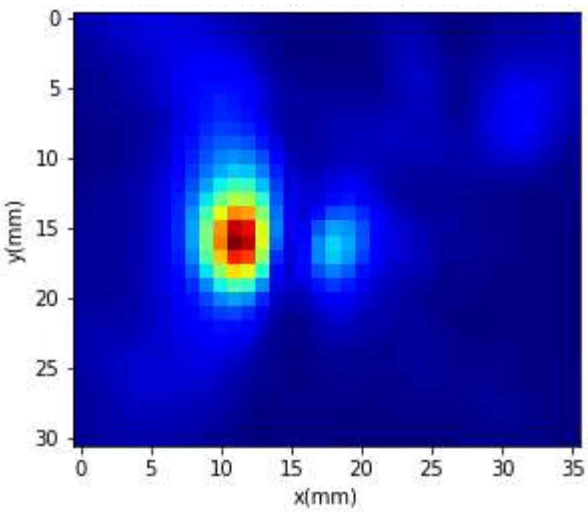


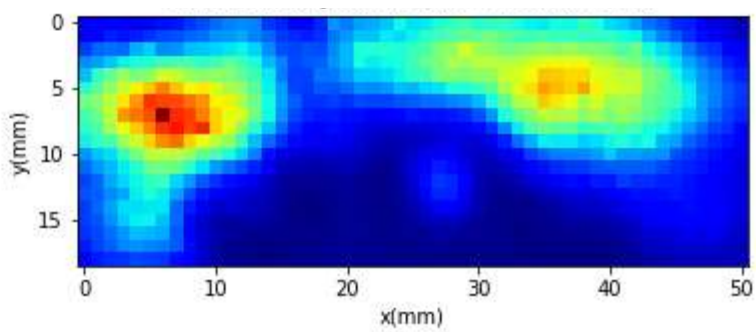
Power Density Plots for Beam ID: 8



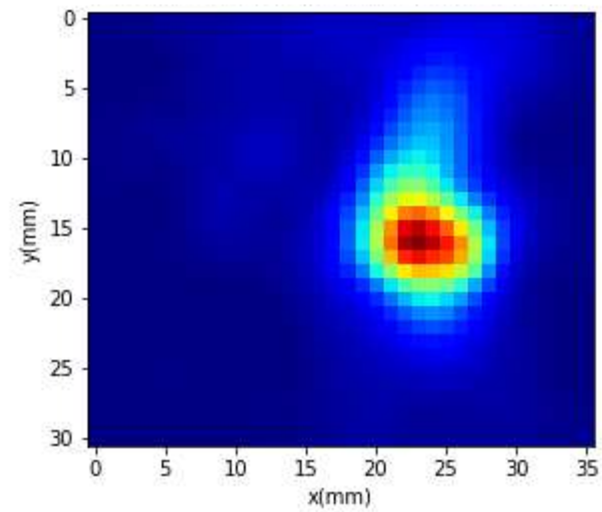


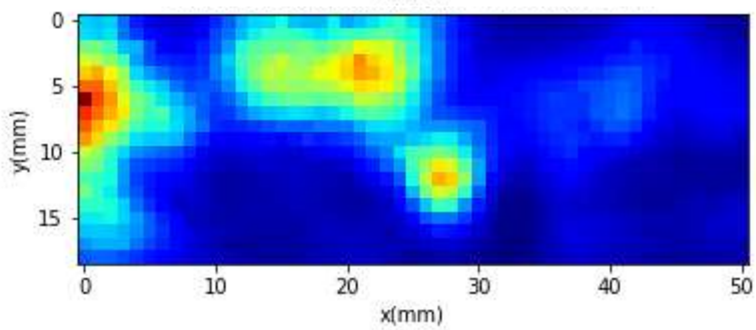
Power Density Plots for Beam ID: 15



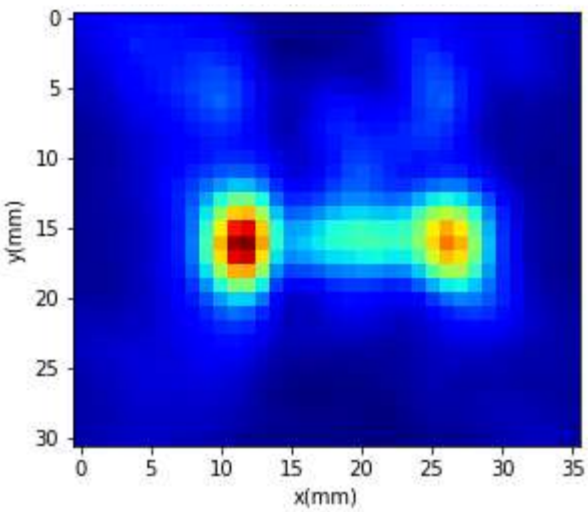


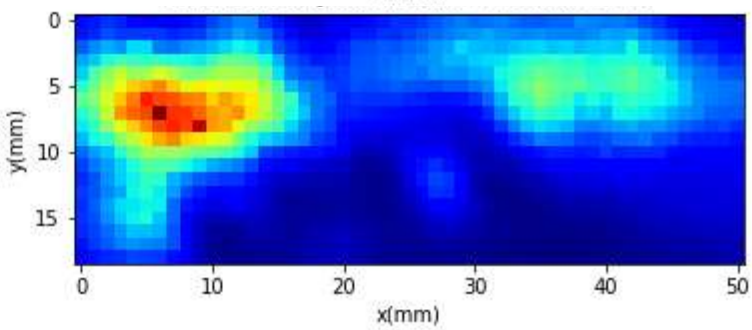
Power Density Plots for Beam ID: 16



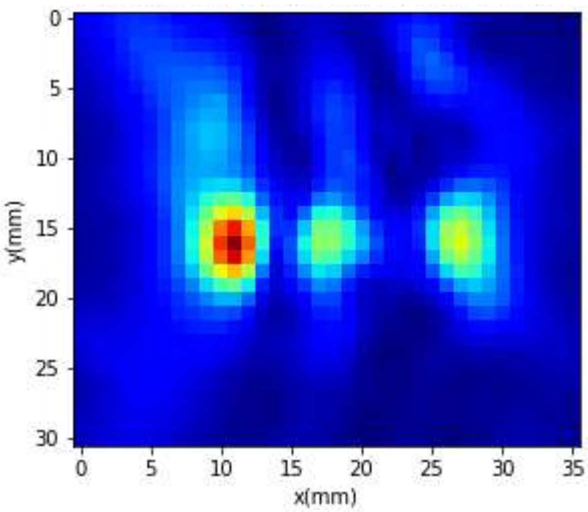


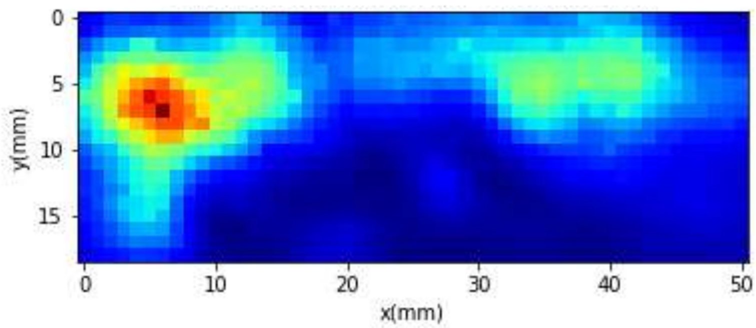
Power Density Plots for Beam ID: 21



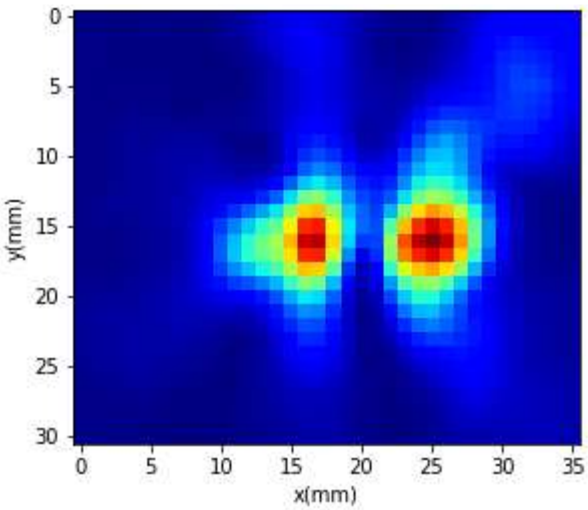


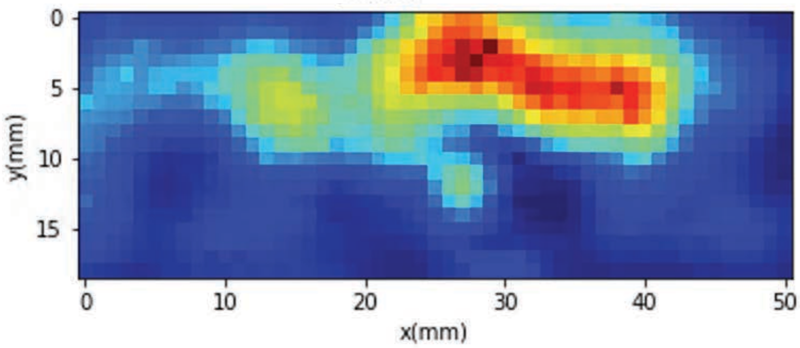
Power Density Plots for Beam ID: 22



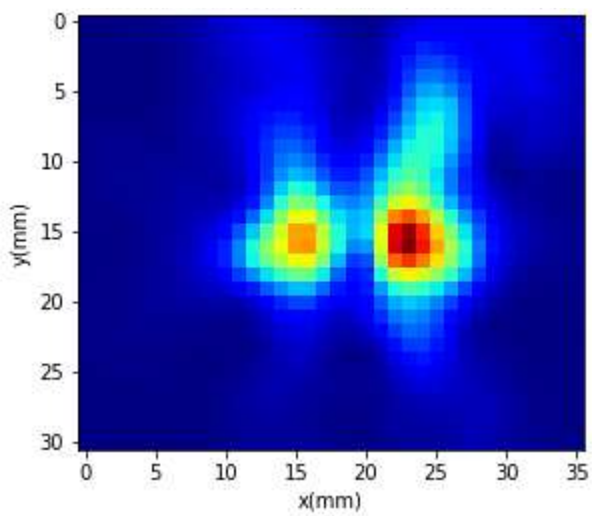


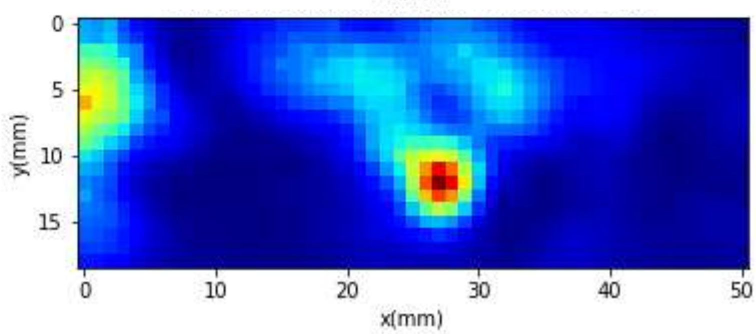
Power Density Plots for Beam ID: 23


y(mm)
x(mm)
0
5
10
15
20
25
30
35

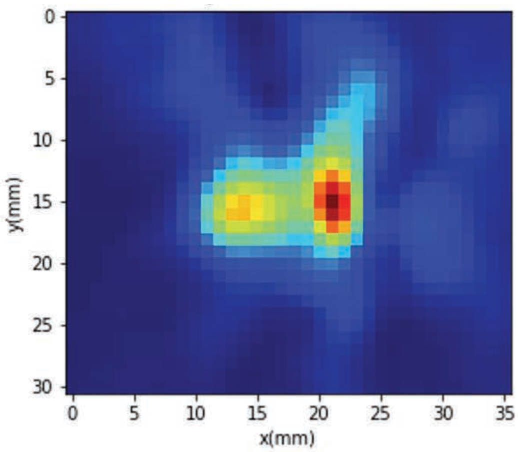

y(mm)
x(mm)
0
5
10
15
20
30
40
50

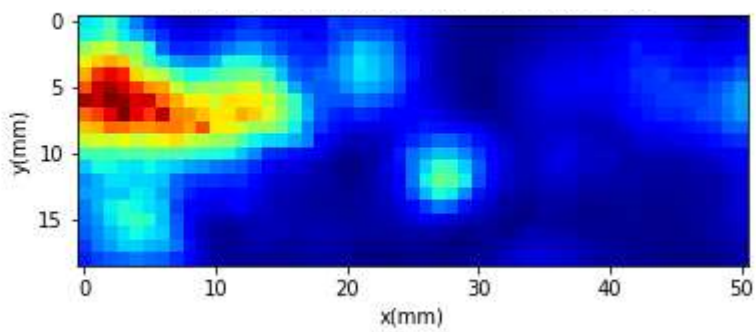
Power Density Plots for Beam ID: 24



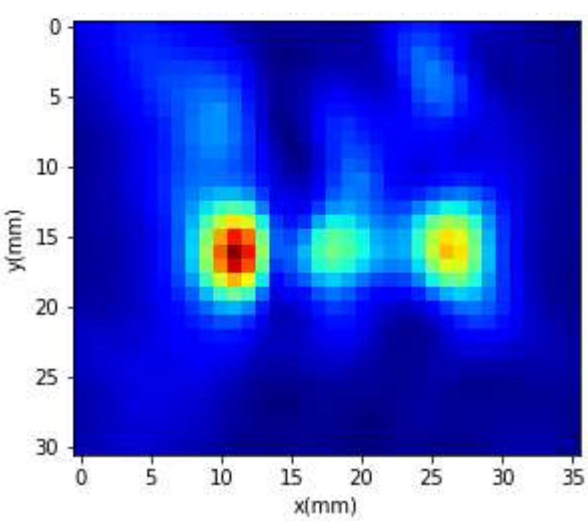


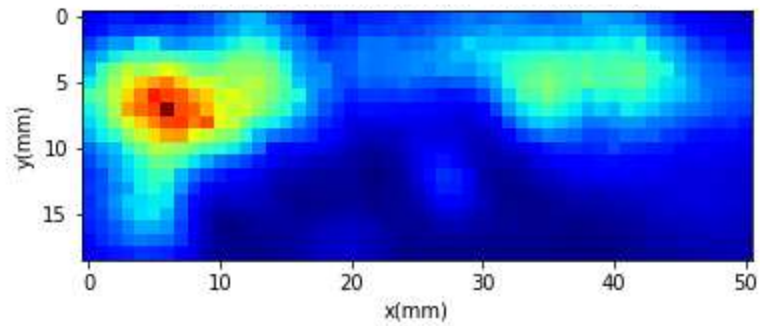
Power Density Plots for Beam ID: 25



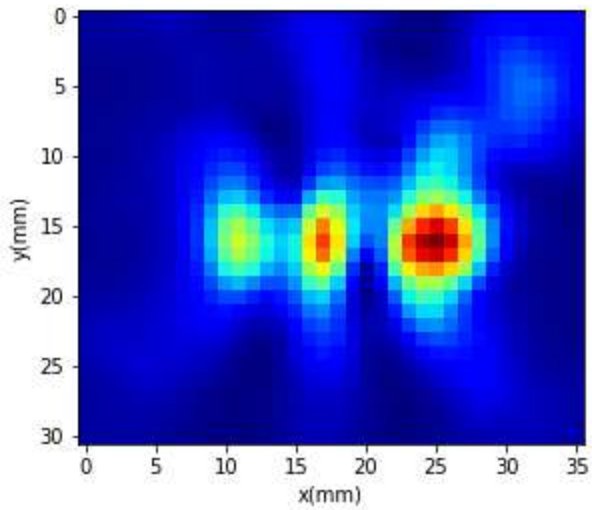


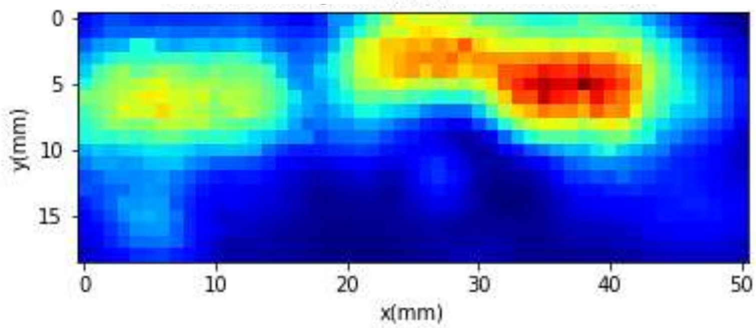
Power Density Plots for Beam ID: 31



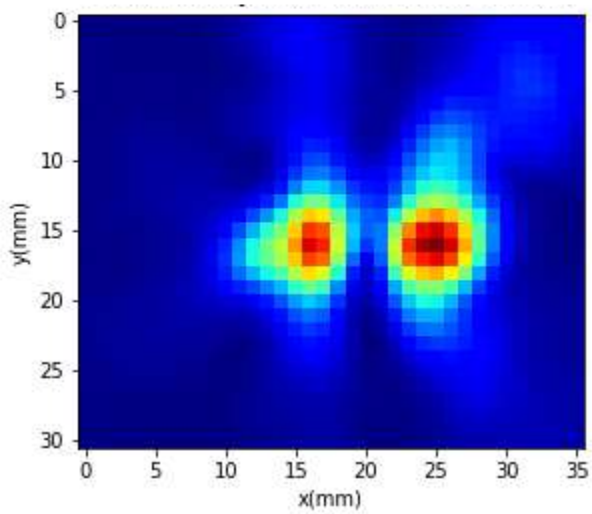


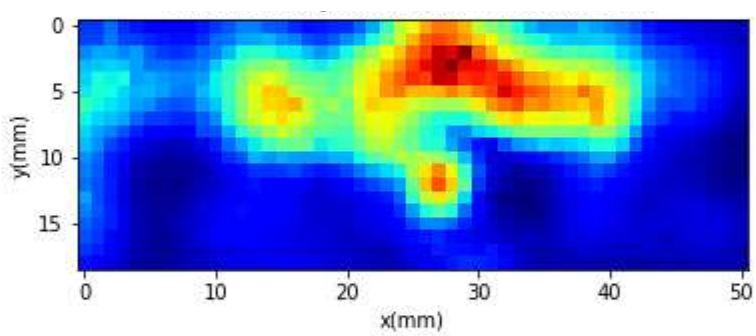
Power Density Plots for Beam ID: 32



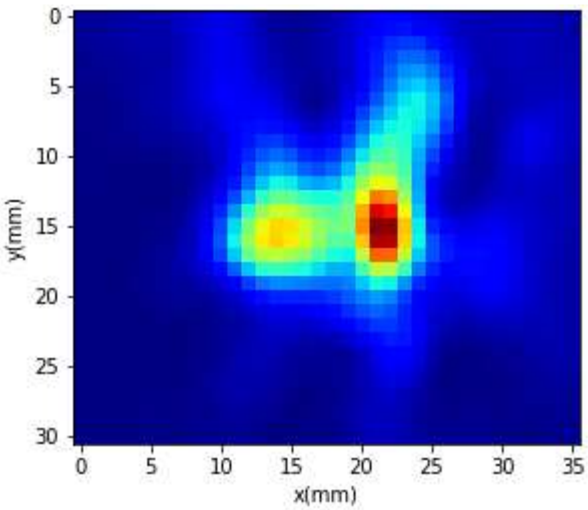


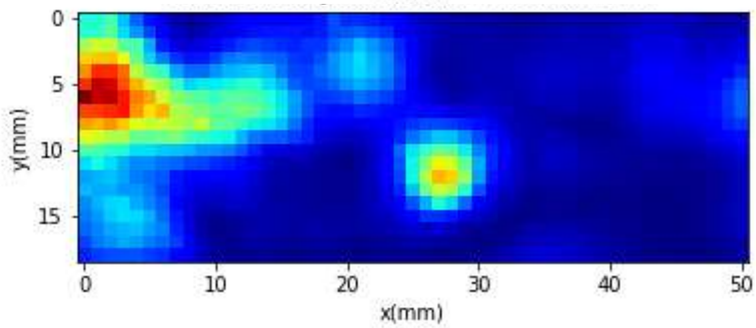
Power Density Plots for Beam ID: 33



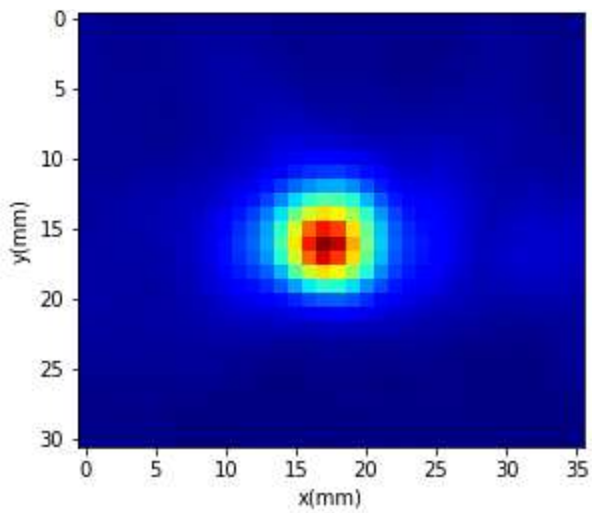


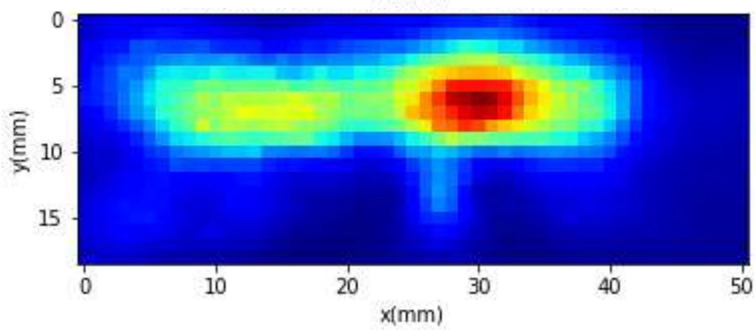
Power Density Plots for Beam ID: 34



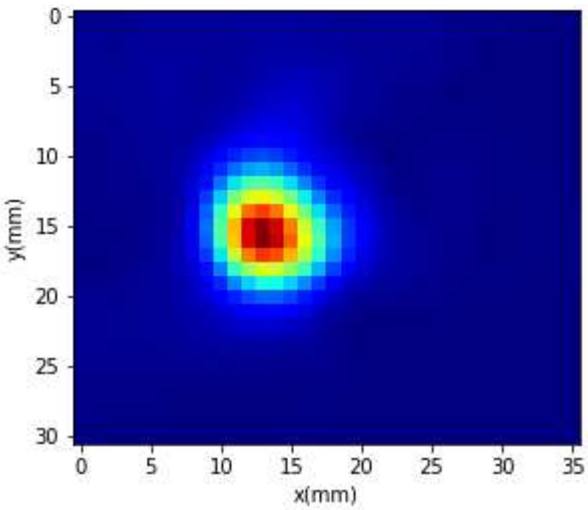


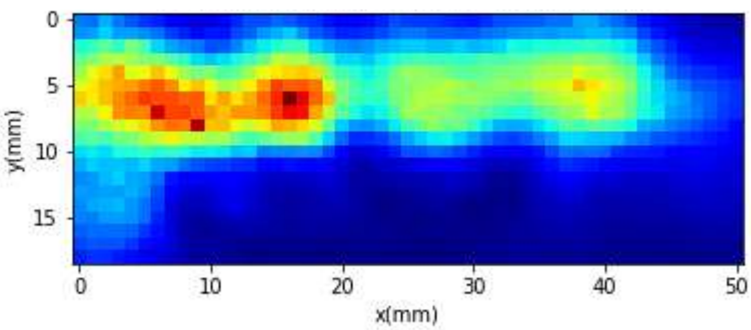
Power Density Plots for Beam ID: 128



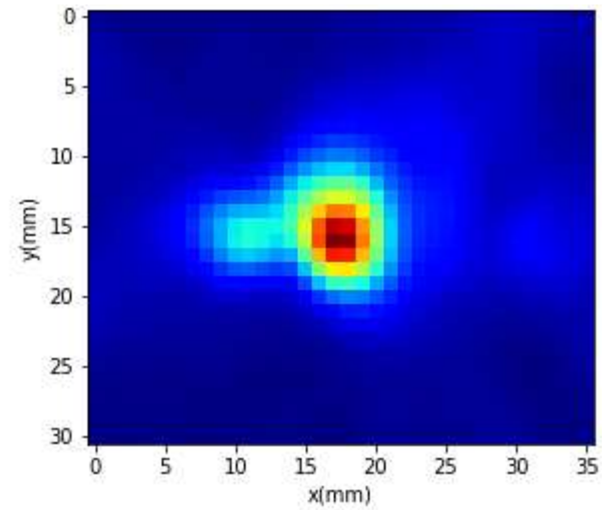


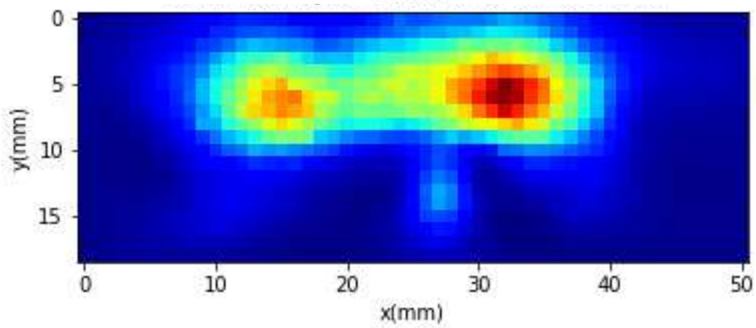
Power Density Plots for Beam ID: 134



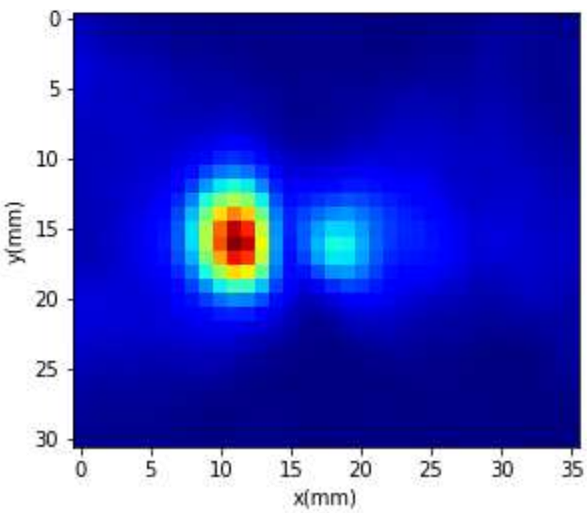


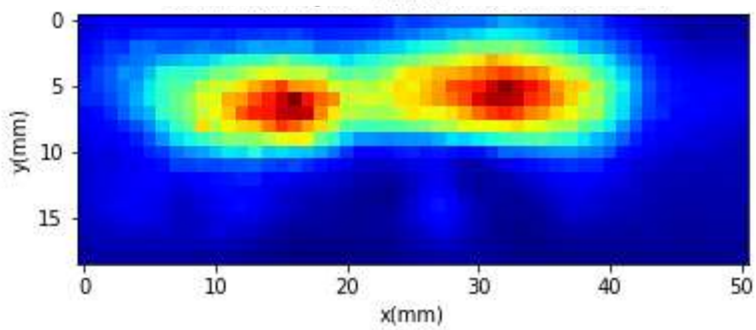
Power Density Plots for Beam ID: 135



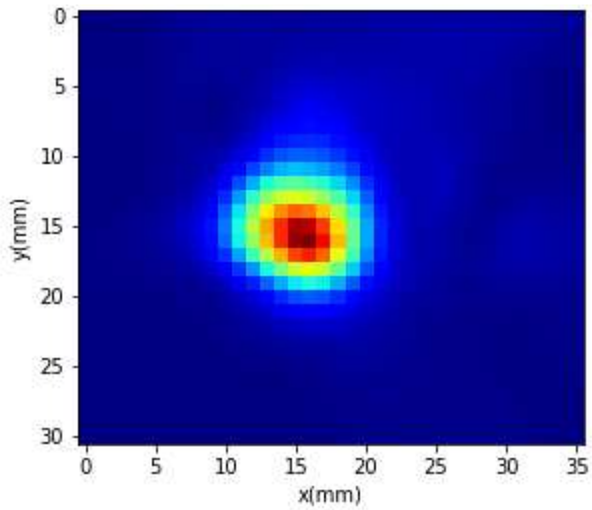


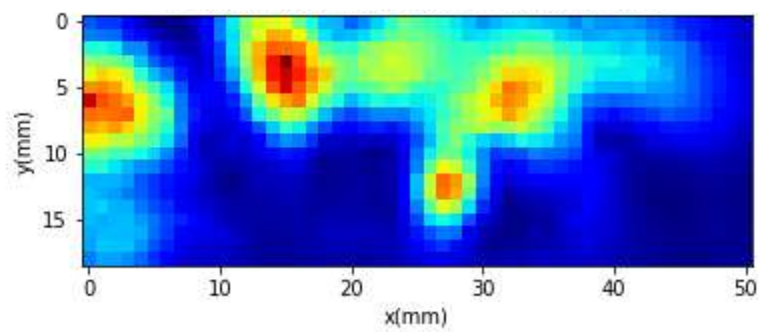
Power Density Plots for Beam ID: 136



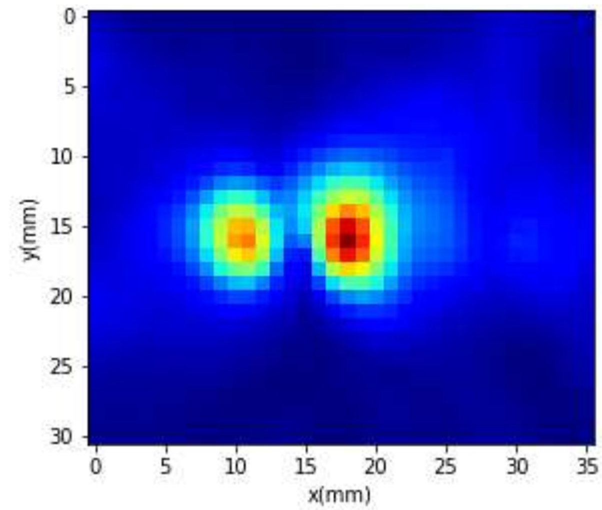


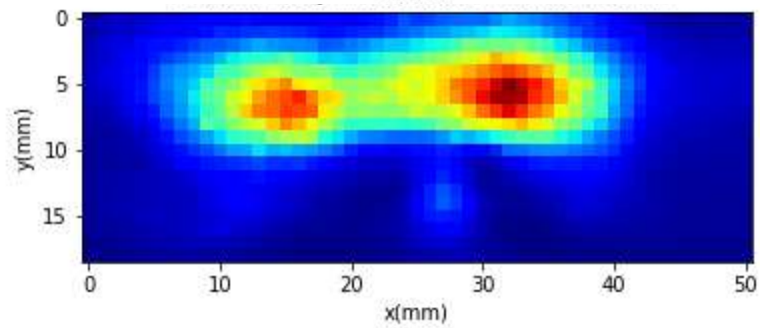
Power Density Plots for Beam ID: 143



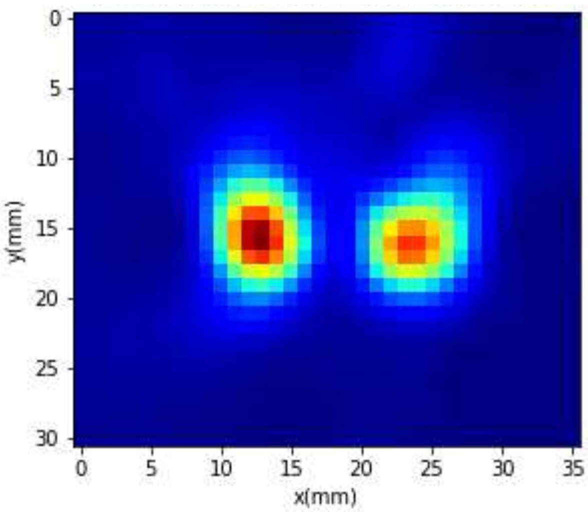


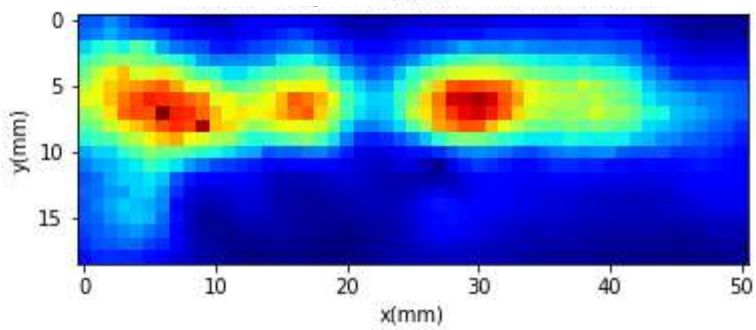
Power Density Plots for Beam ID: 144



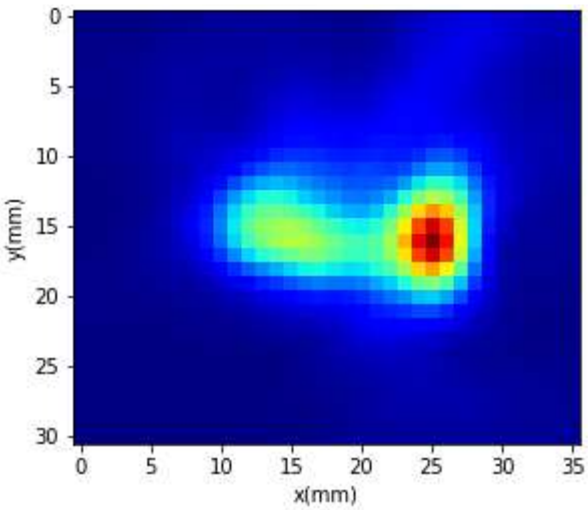


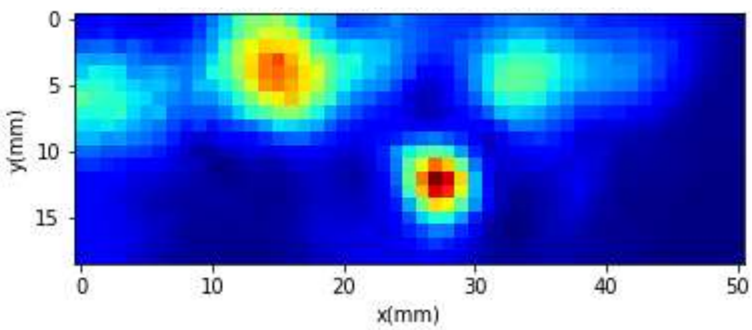
Power Density Plots for Beam ID: 149



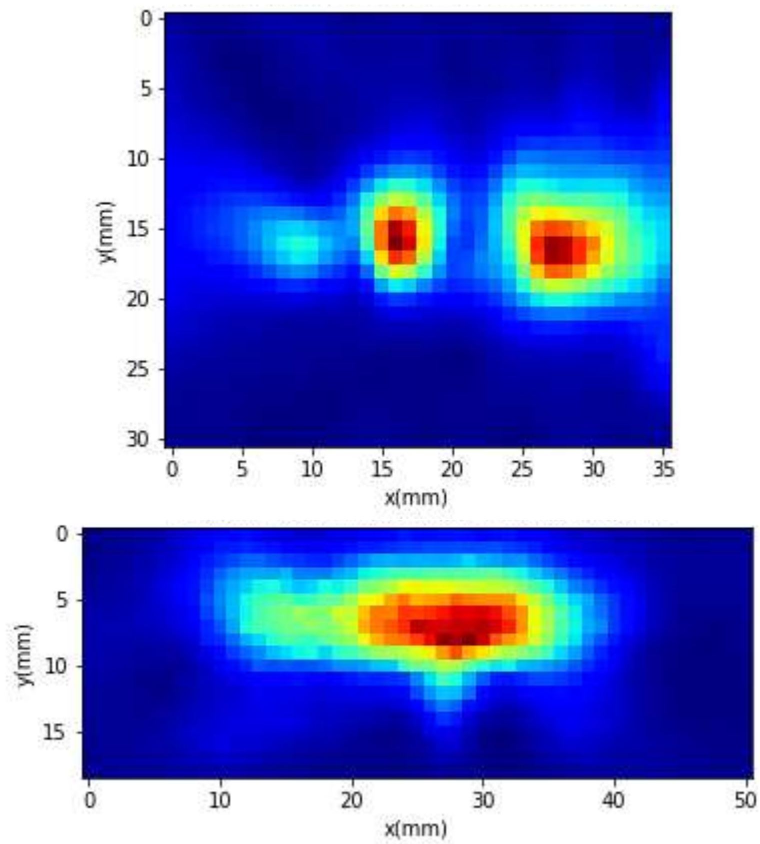


Power Density Plots for Beam ID: 150

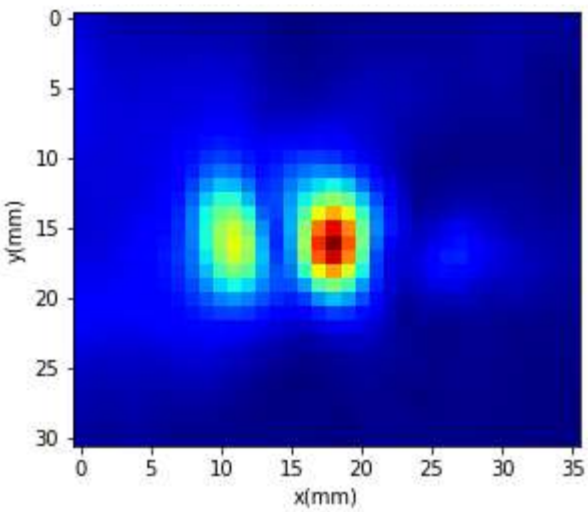


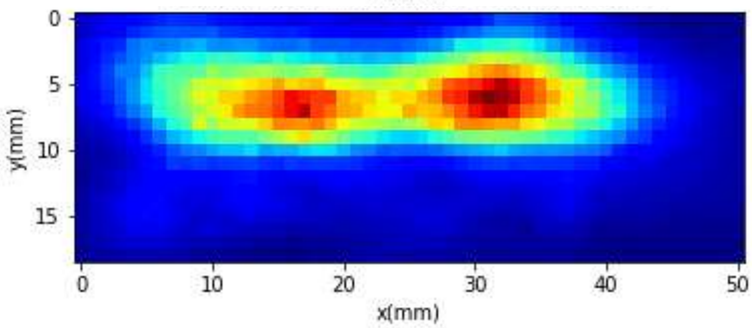


Power Density Plots for Beam ID: 151

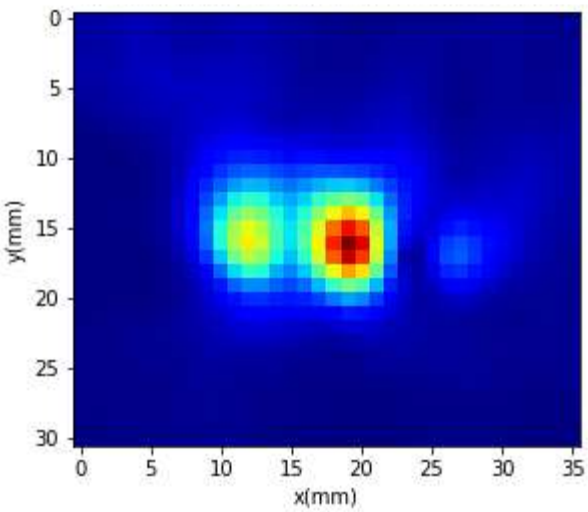


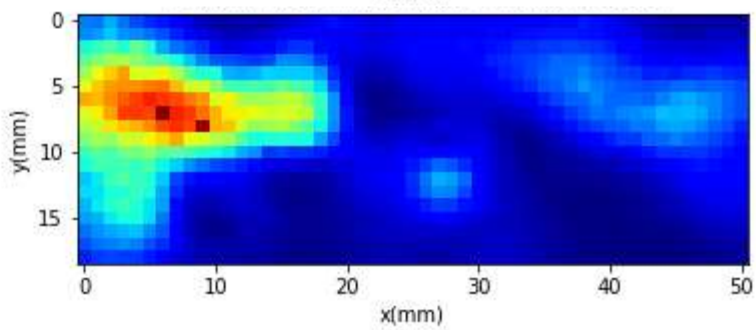
Power Density Plots for Beam ID: 152



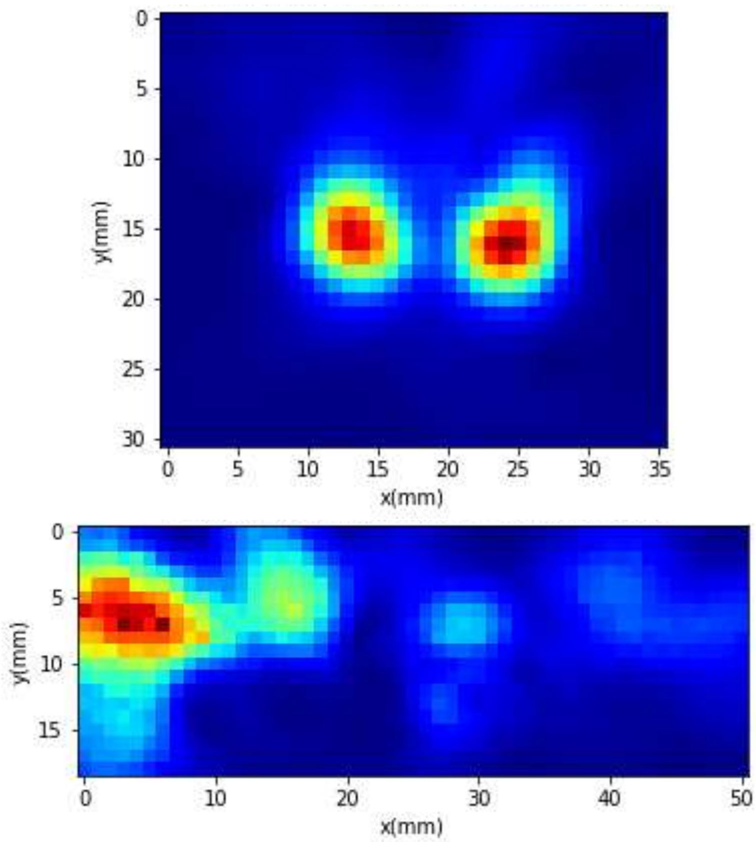


Power Density Plots for Beam ID: 153

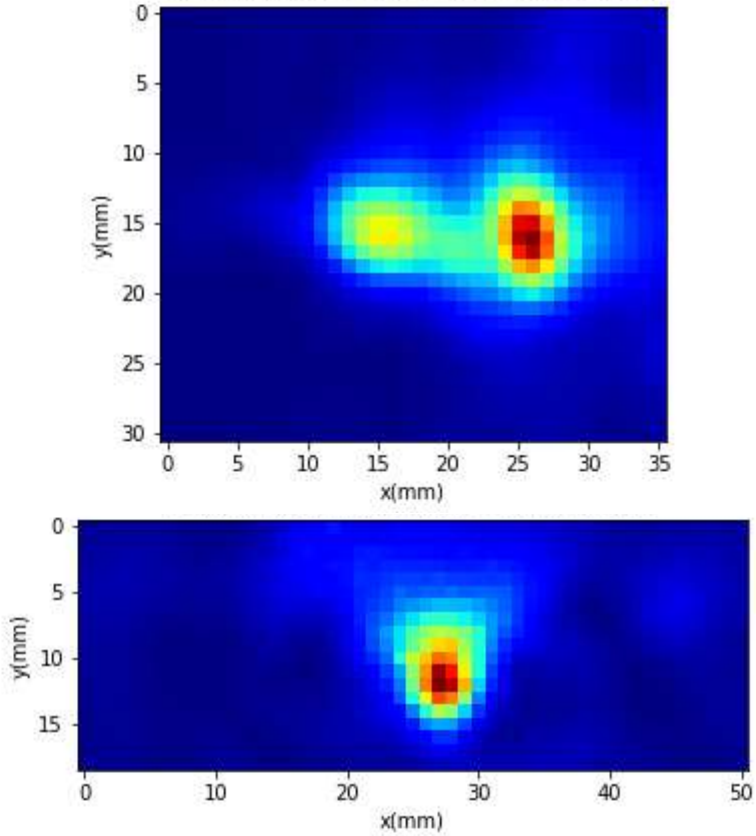




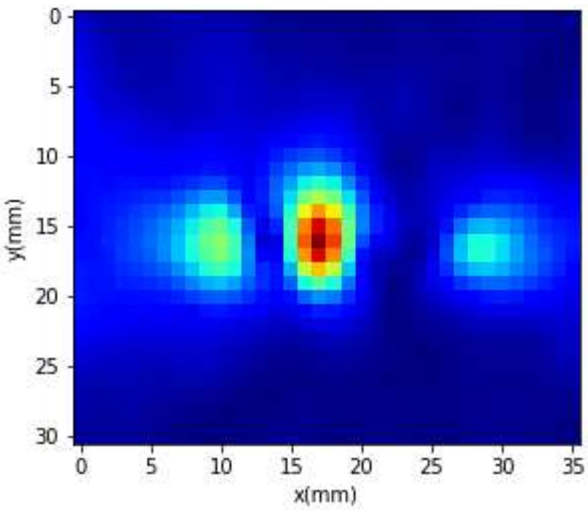
Power Density Plots for Beam ID: 159

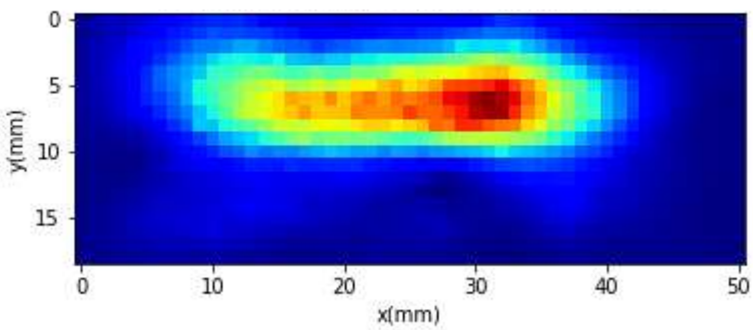


Power Density Plots for Beam ID: 160

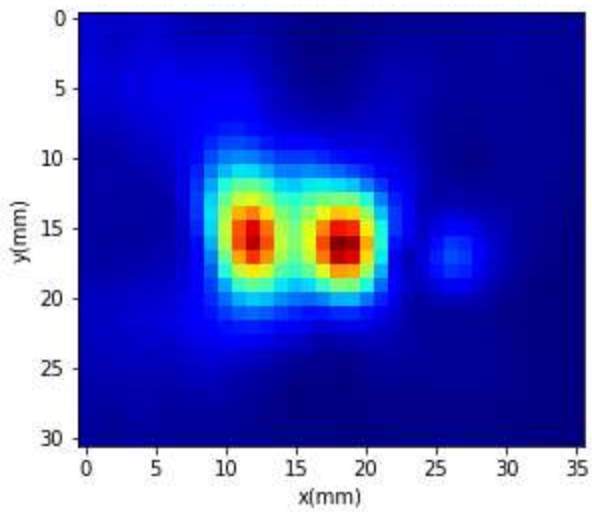


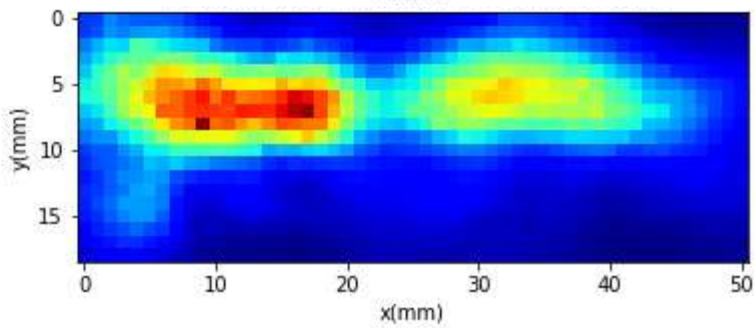
Power Density Plots for Beam ID: 161





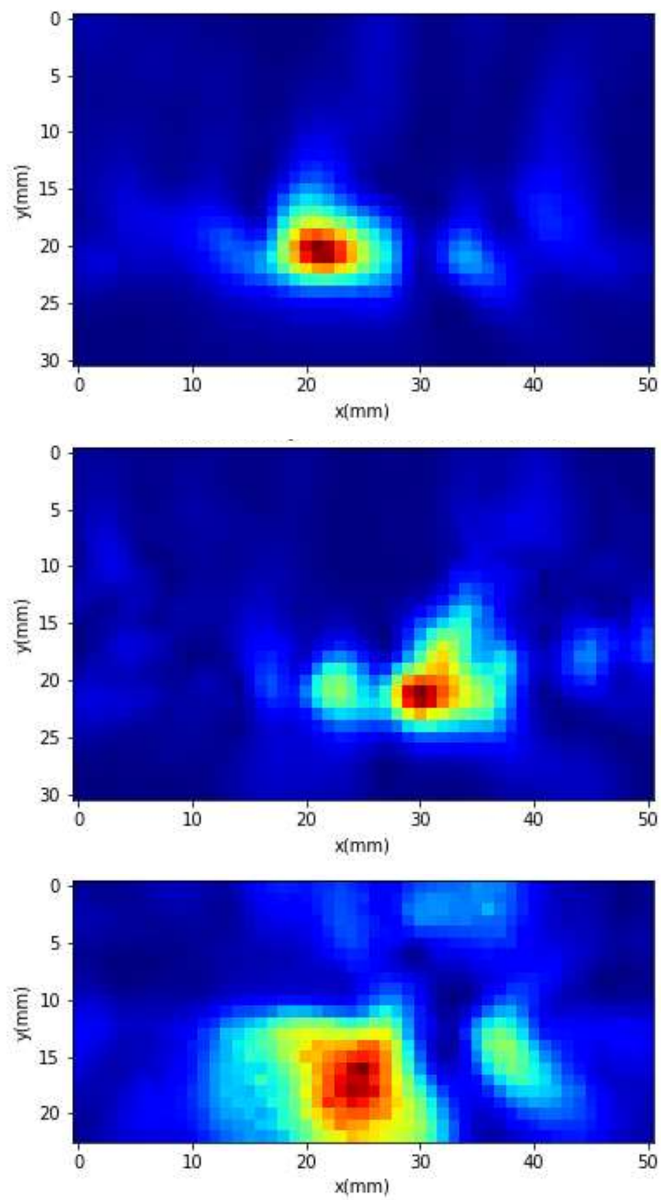
Power Density Plots for Beam ID: 162



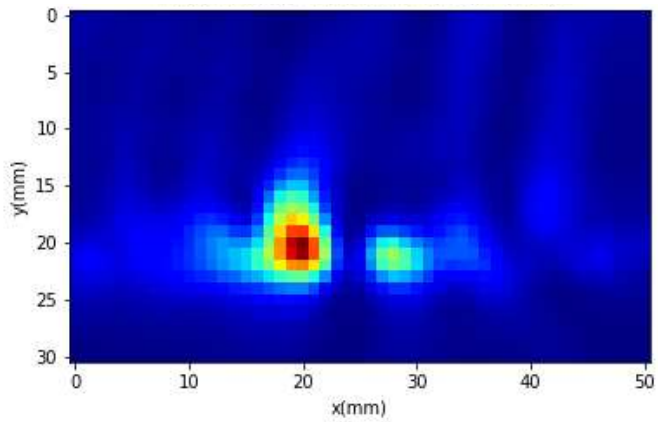


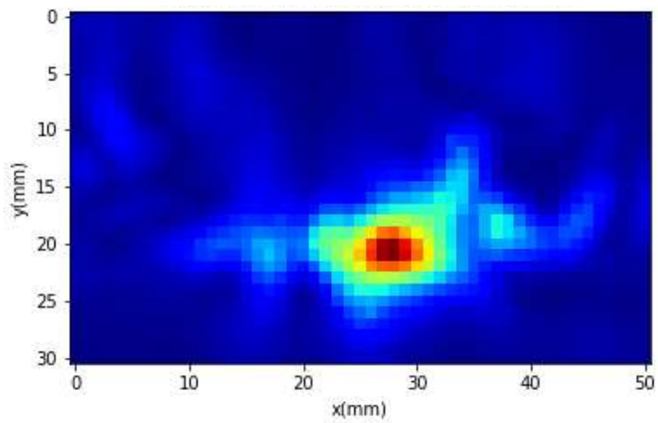
Normalized power density plots for all the Beam IDs across S1, S2 and S5 evaluation planes for the front-firing antenna array are shown below.

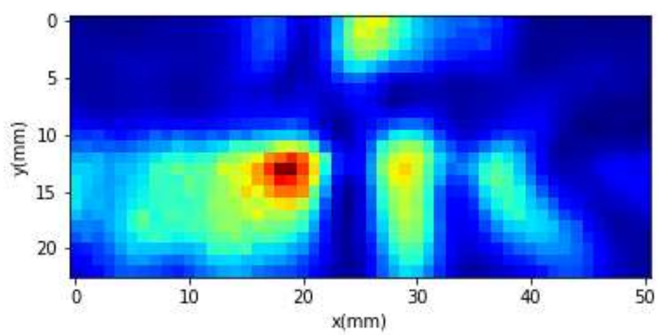
Power Density Plots for Beam ID: 2



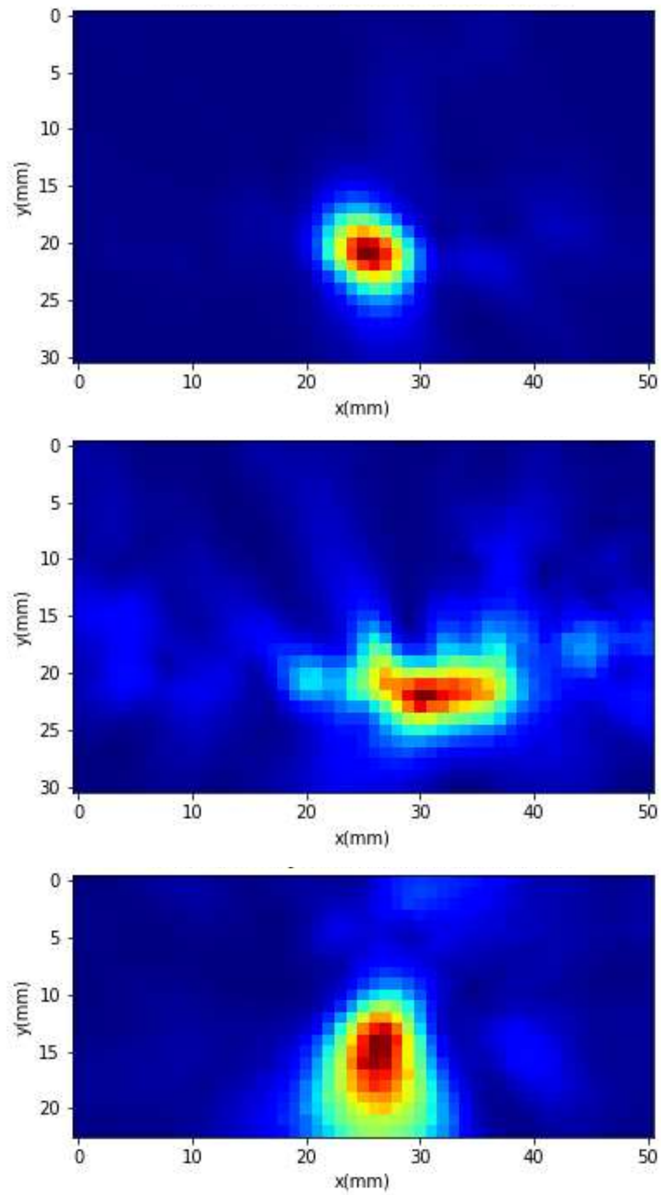
Power Density Plots for Beam ID: 9



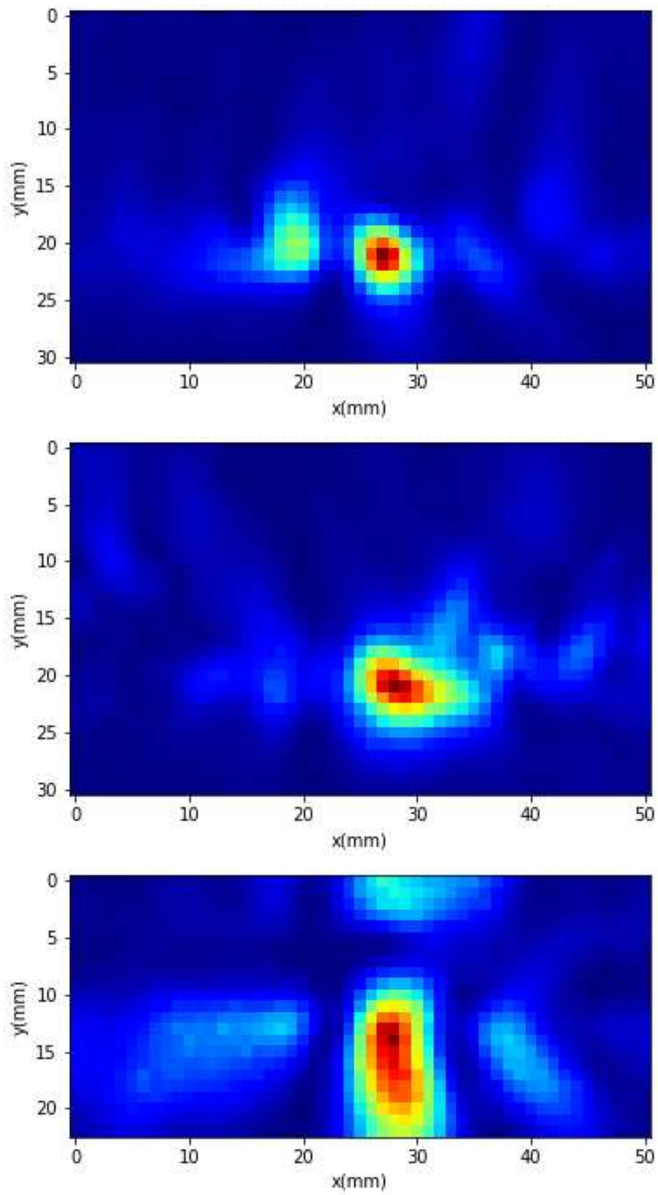




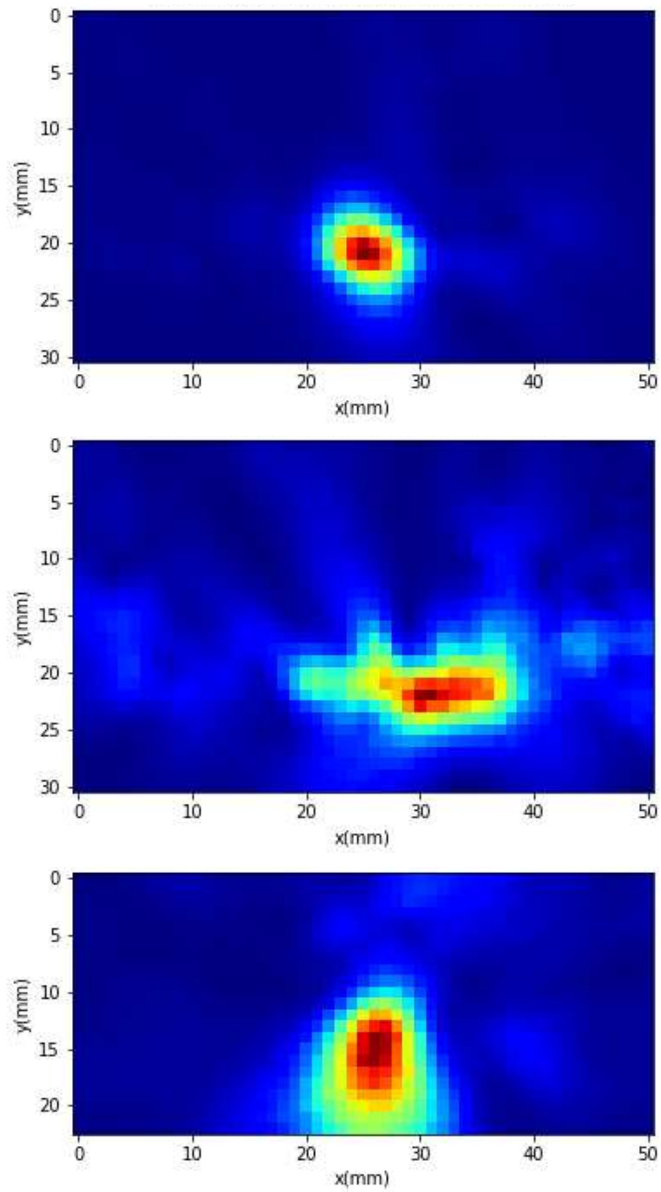
Power Density Plots for Beam ID: 10



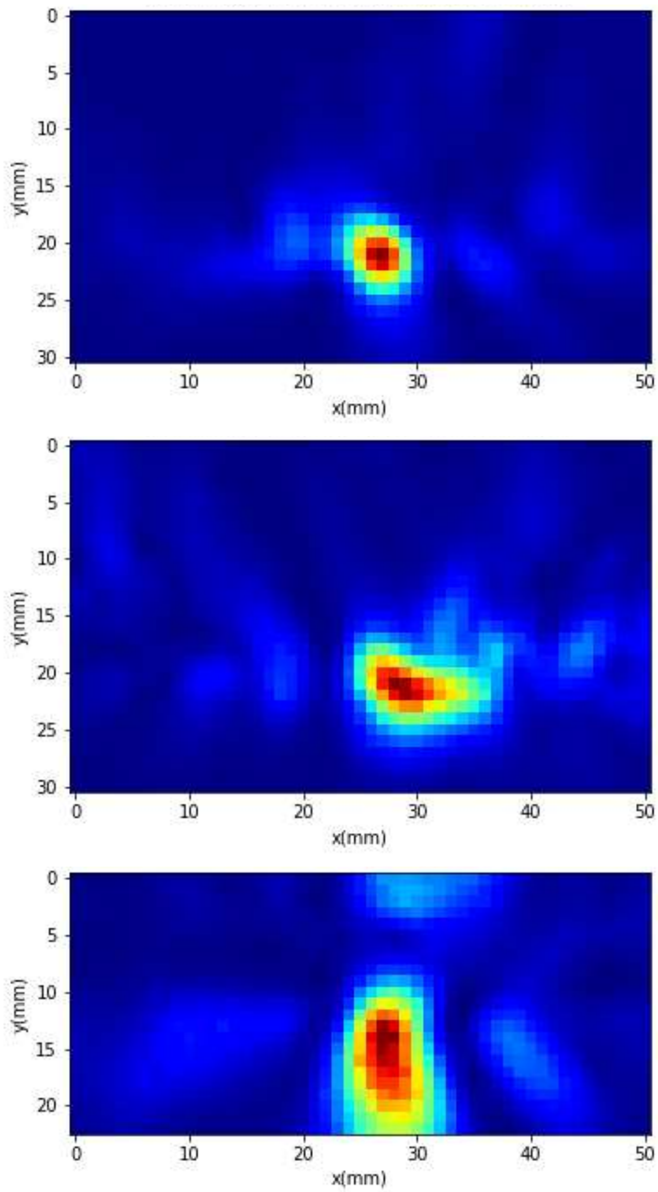
Power Density Plots for Beam ID: 11



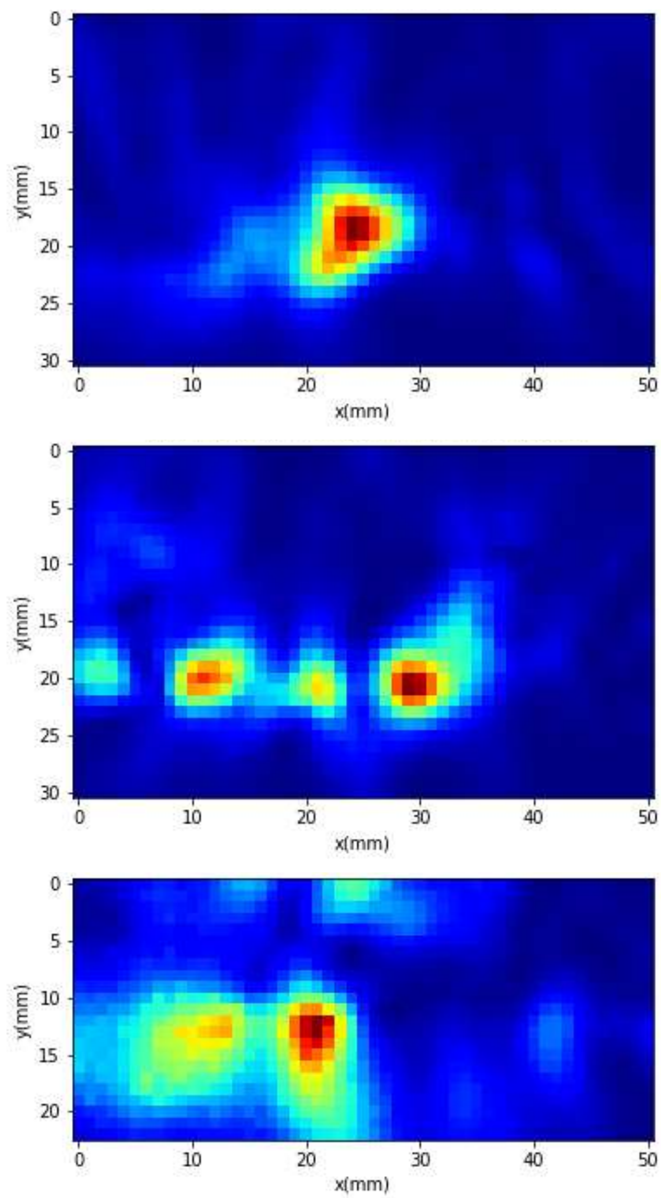
Power Density Plots for Beam ID: 17



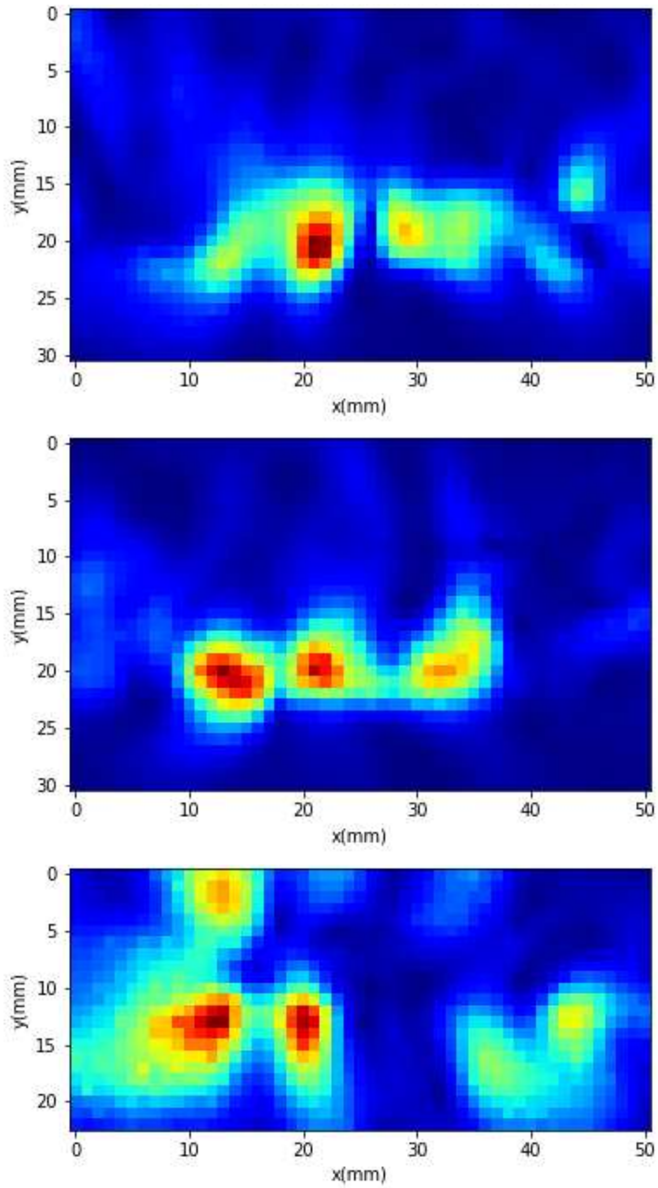
Power Density Plots for Beam ID: 18



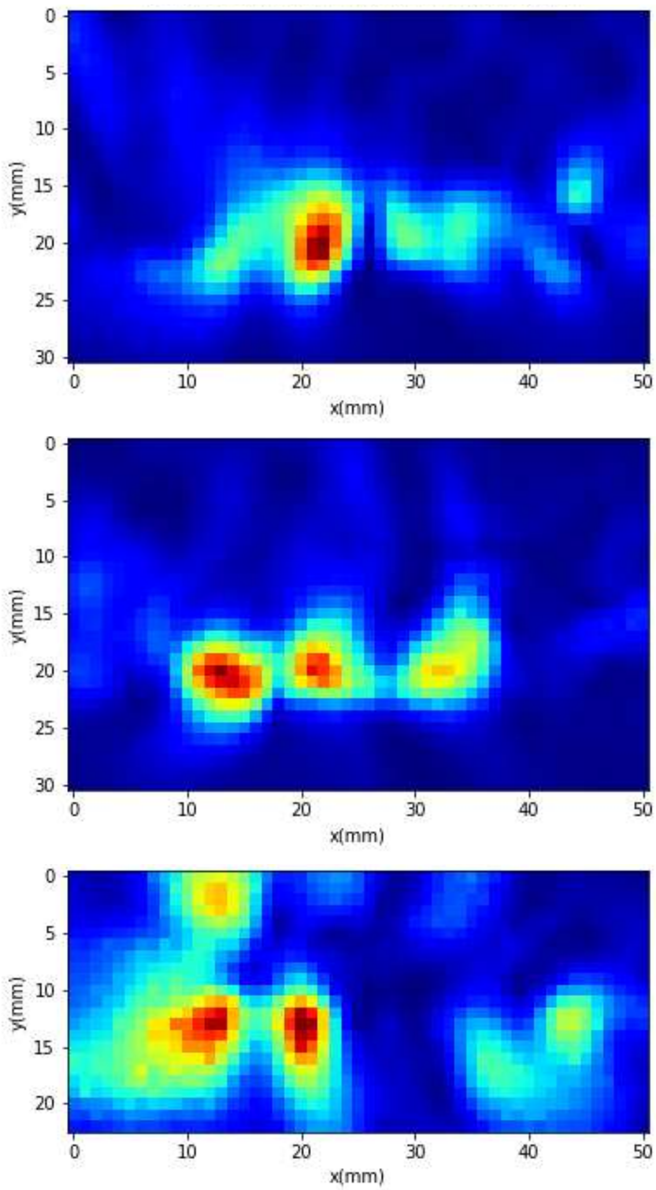
Power Density Plots for Beam ID: 130



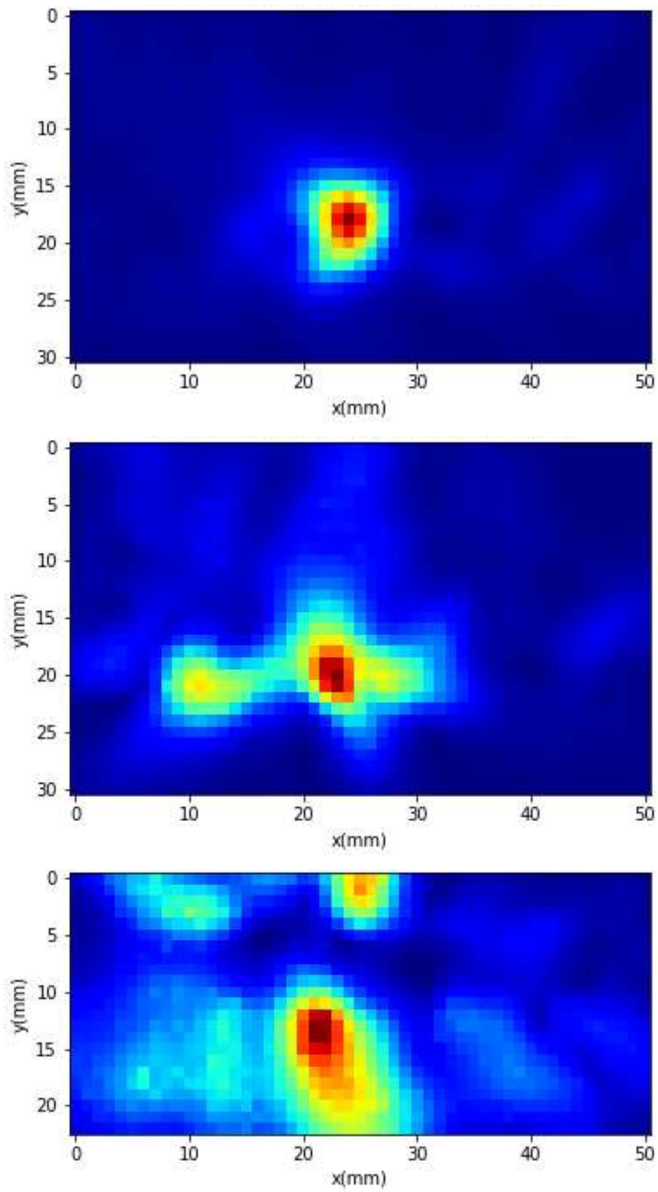
Power Density Plots for Beam ID: 137



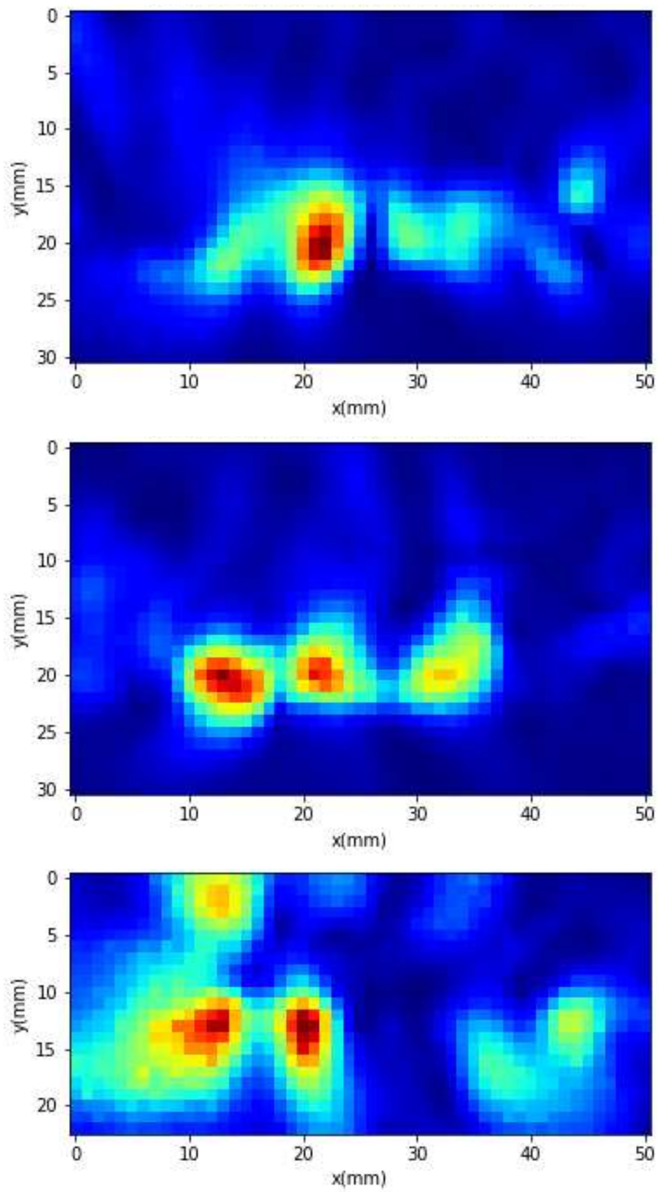
Power Density Plots for Beam ID: 138



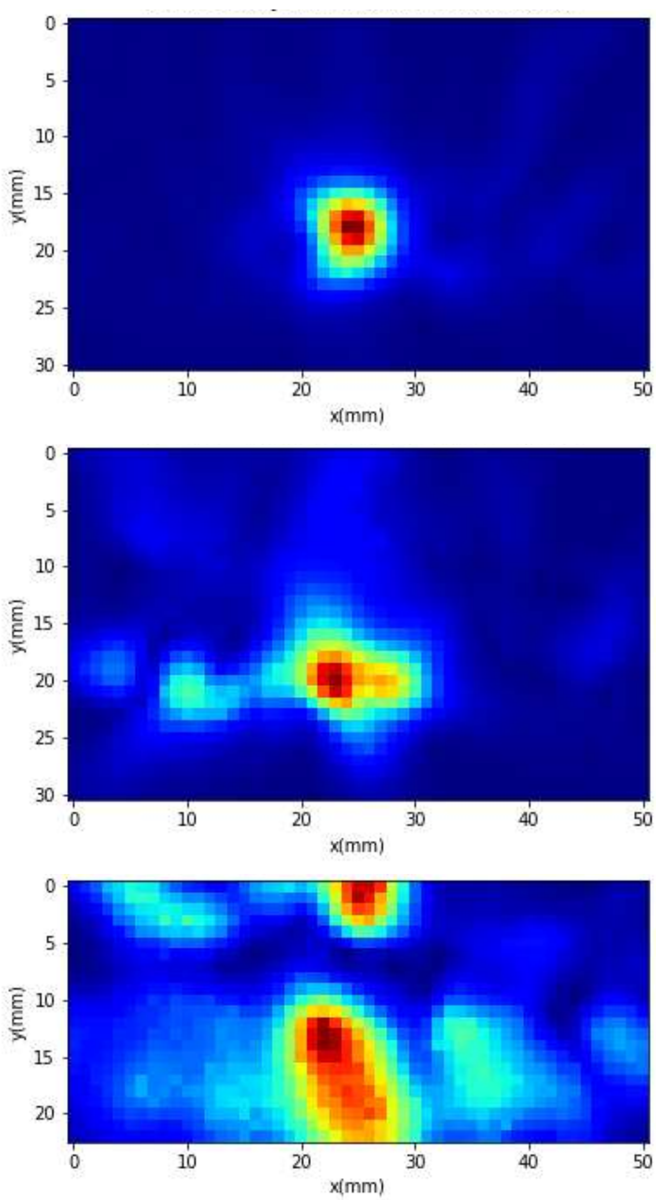
Power Density Plots for Beam ID: 139



Power Density Plots for Beam ID: 145



Power Density Plots for Beam ID: 146


y(mm)
0
5
10
15
20
25
30
0
10
20
30
40
50
x(mm)
y(mm)
0
5
10
15
20
25
30
0
10
20
30
40
50
x(mm)
y(mm)
0
5
10
15
20
0
10
20
30
40
50
x(mm)