Synthesis and Control of Coherent Structures in Low Temperature Plasmas for Reconfigurable Electromagnetic Devices: Self-organized Plasma Lattice Metamaterial

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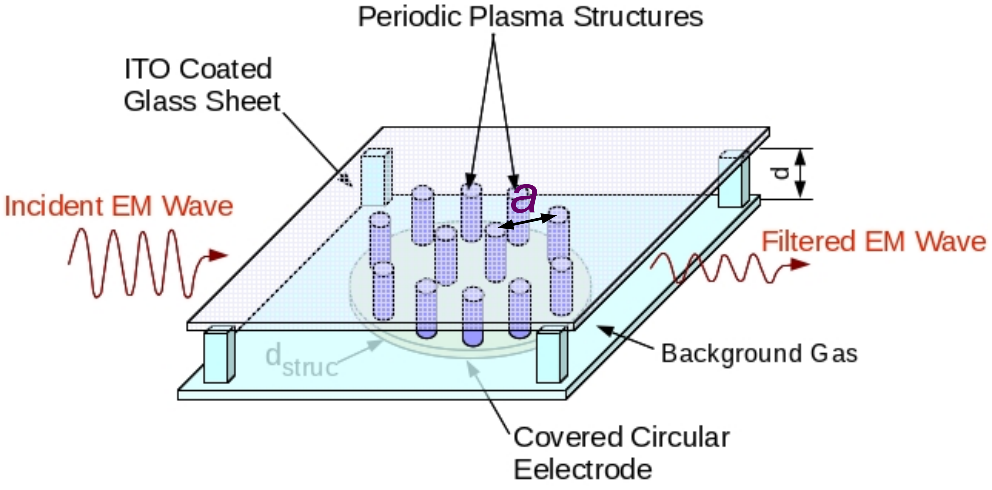
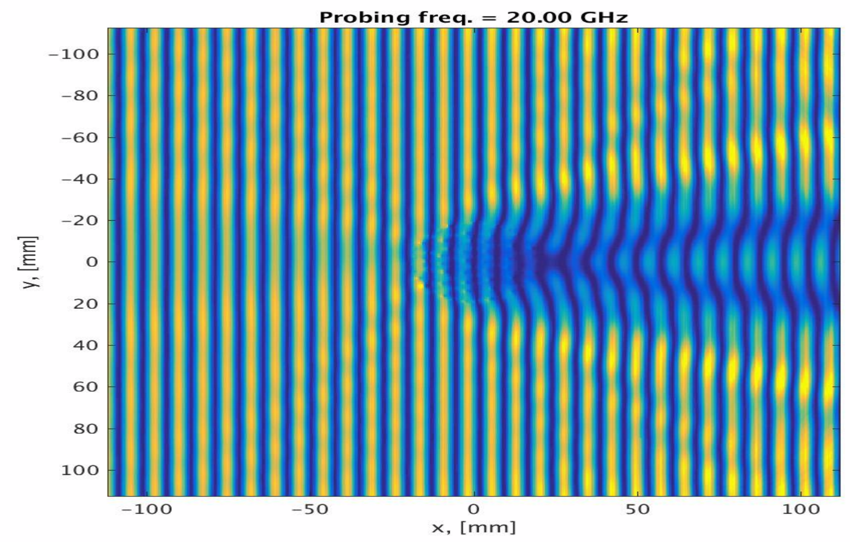
Research Objectives

- Experimentally generate spatially periodic plasma lattice structures in air
  - Exploit charge instability between electrodes separated by a double dielectric layer
- Demonstrate dynamic control of plasma lattice spacing, *a*
  - Document dependence on gas pressure (P_s), gap distance (d), and input power
- Experimentally determine EM wave transmittance under different plasma lattice conditions

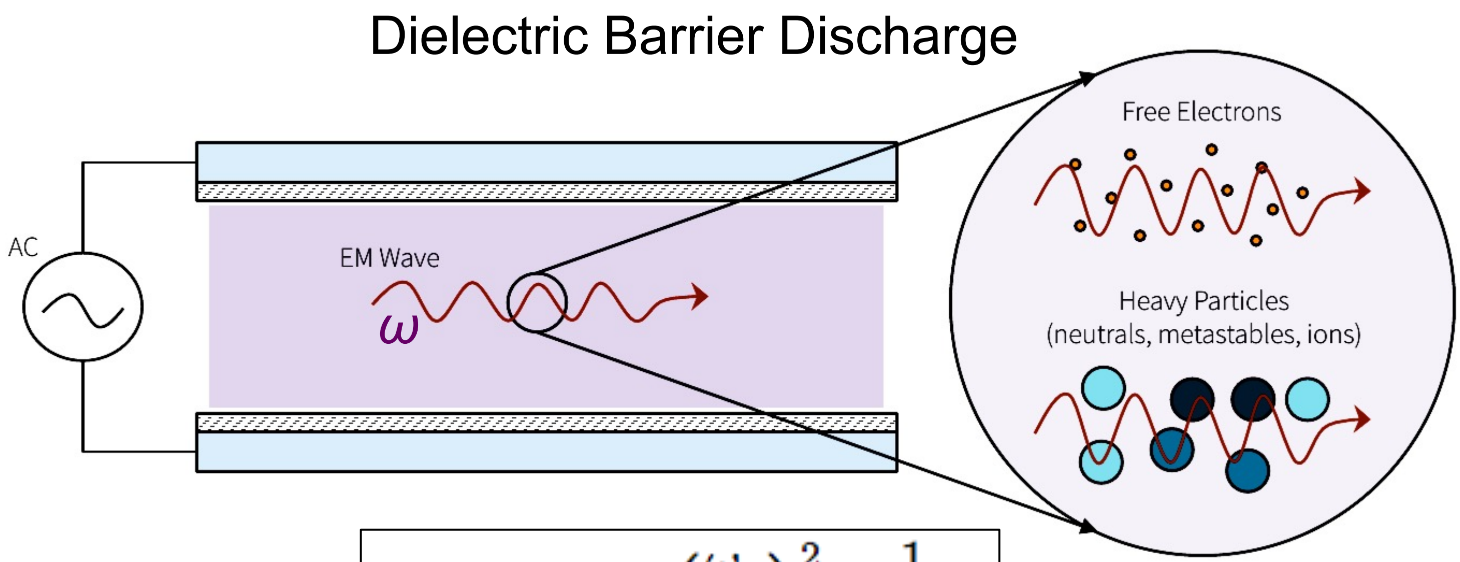


Research Objectives

- Incorporate experimentally derived plasma lattice into EM wave simulation to determine predicted transmittance characteristics
- Compare EM transmittance obtained from experiments to EM wave simulation predictions
  - Independent variables: P_s and n_e
- Use validated simulation to project EM transmittance to target 70Ghz probing frequency



Approach: Plasma Permittivity Control



Plasma Permittivity: $$\epsilon_p(\omega) = 1 - \left(\frac{\omega_p}{\omega}\right)^2 \frac{1}{1 - i\frac{\nu}{\omega}}$$

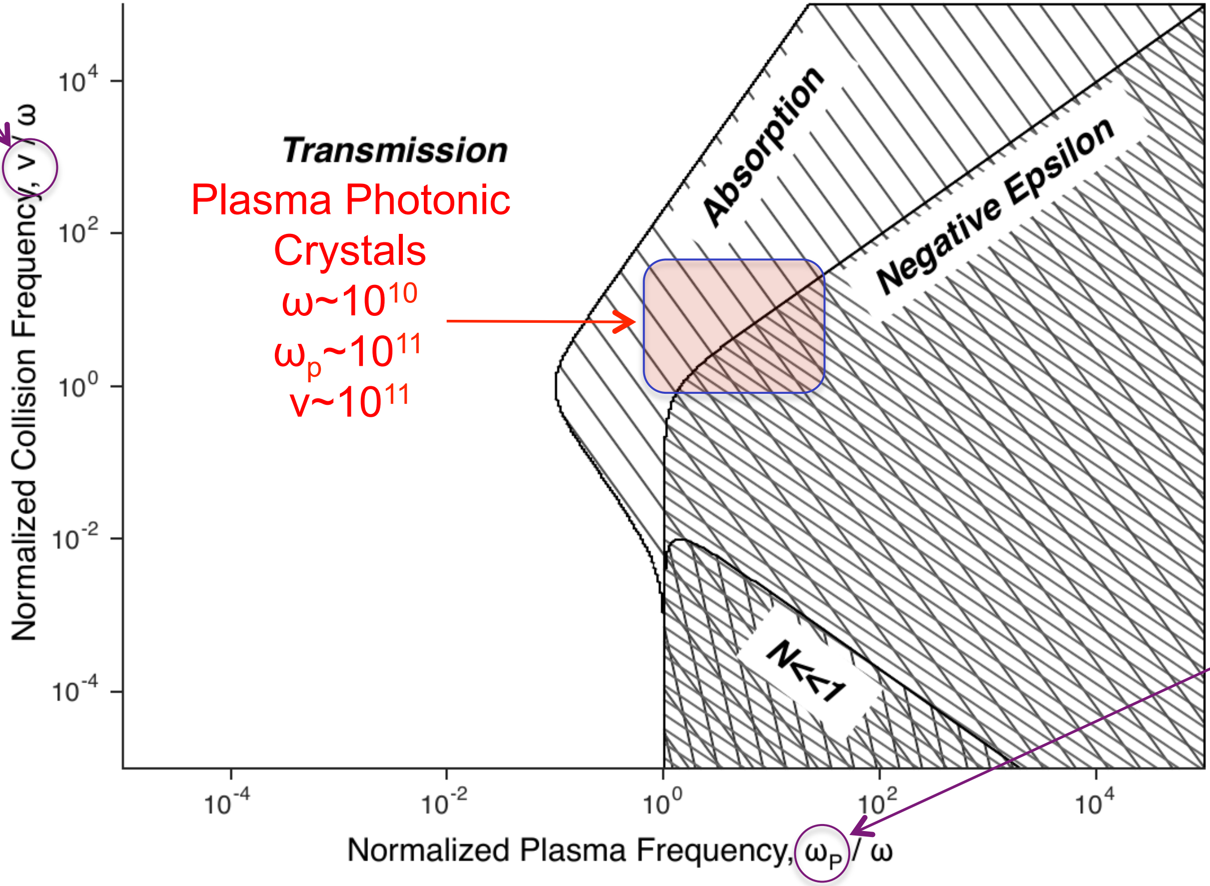
- Plasma frequency, ω_p, is a function of electron density, which is controllable by the applied voltage.
- Electron-neutrals collision frequency, v , is a function of the gas pressure.
- The combination control the plasma permittivity.

Approach: Plasma Permittivity Regimes

Razier (1991)

v=(3.9e9 $s^{-1}Torr^{-1}$)P_s

$$\epsilon_p(\omega) = 1 - \left(\frac{\omega_p}{\omega}\right)^2 \frac{1}{1 - i\frac{\nu}{\omega}}$$



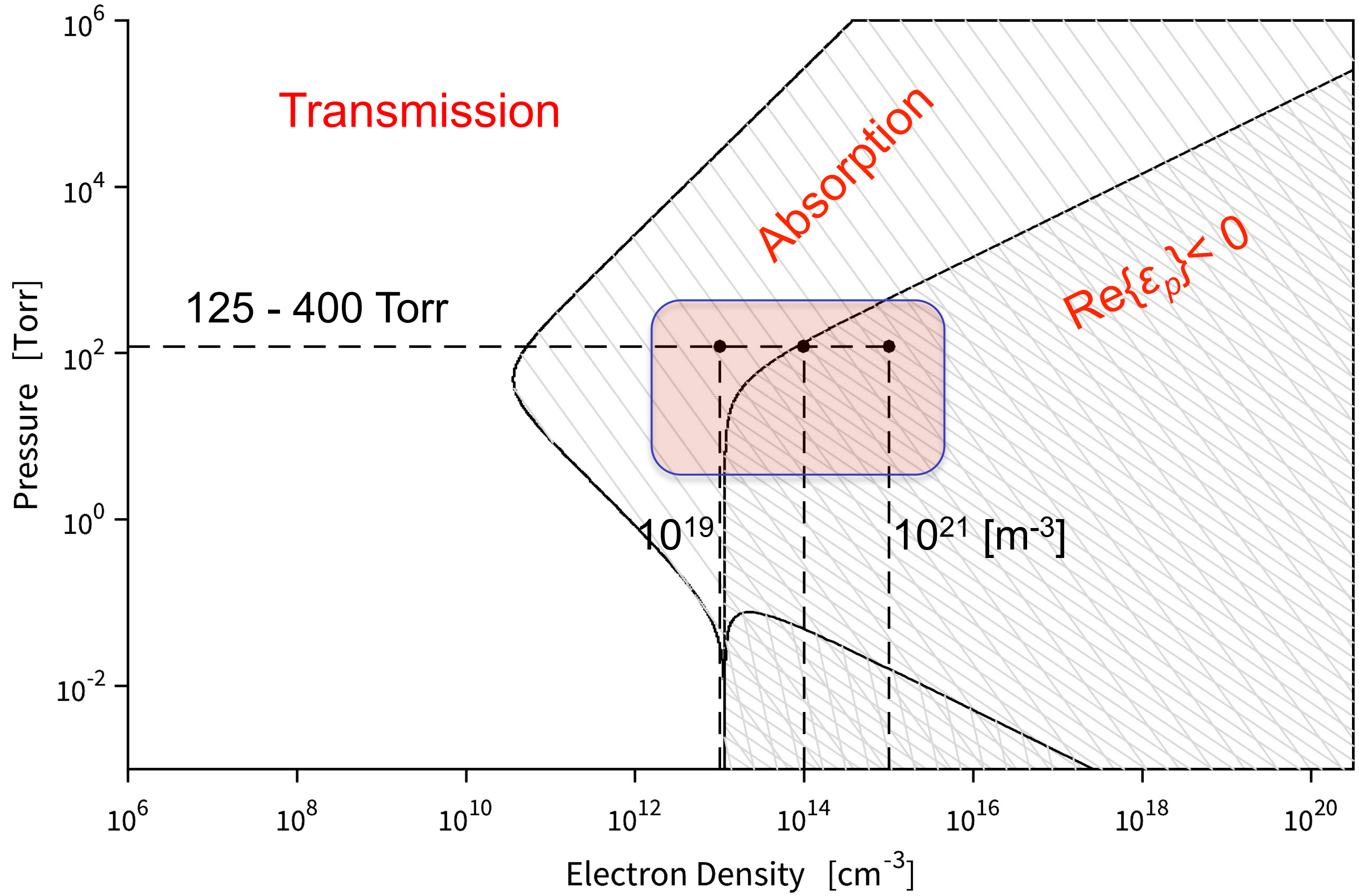
$$\omega_p = \sqrt{\frac{n_e q^2}{m \epsilon_0}}$$

Approach: Plasma Permittivity Control

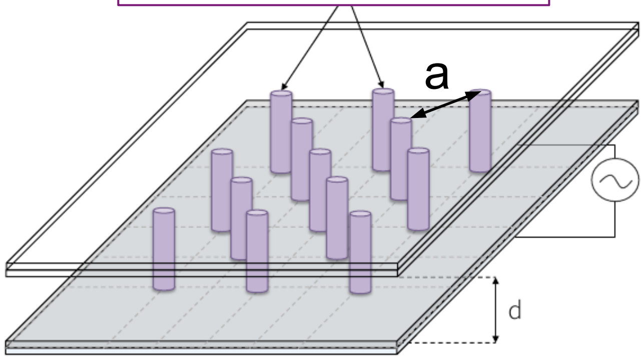
$\omega/2\pi$=20GHz

$$\epsilon_p(\omega) = 1 - \left(\frac{\omega_p}{\omega}\right)^2 \frac{1}{1 - i\frac{\nu}{\omega}}$$

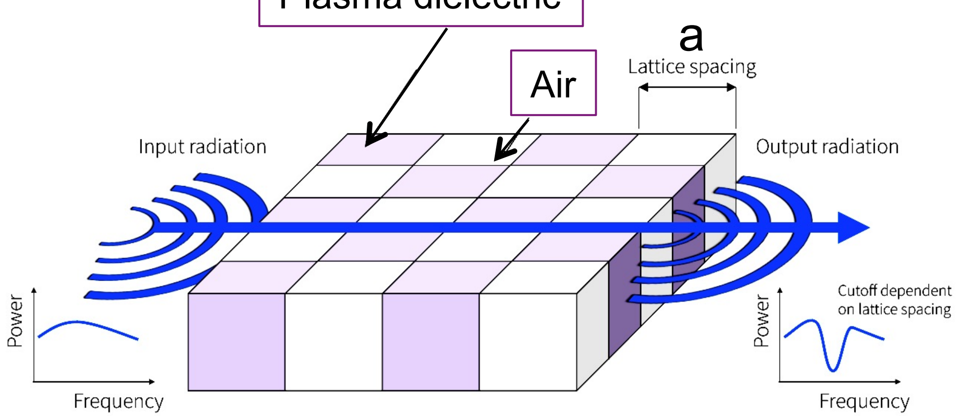
Air



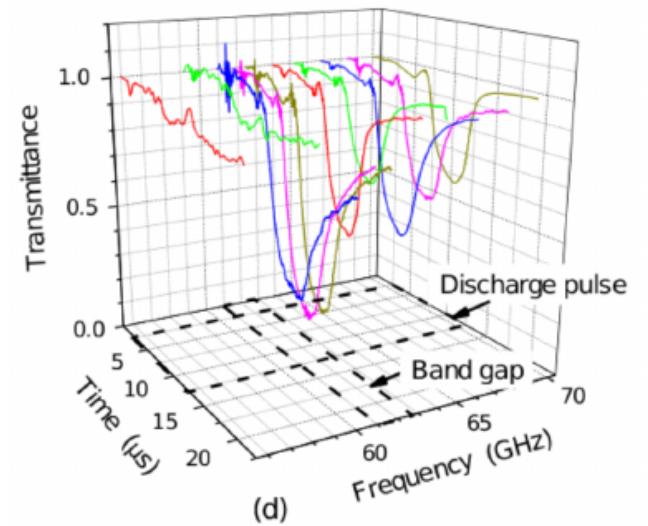
Approach: Plasma Lattice



- Plasma charge instability* produces stationary, naturally spaced plasma lattice structure. (*Callegari et al., 2014)
- Forms a periodic dielectric in 2-D.
- Lattice spacing determines propagation characteristics: frequency cut-off, photonic band gap.

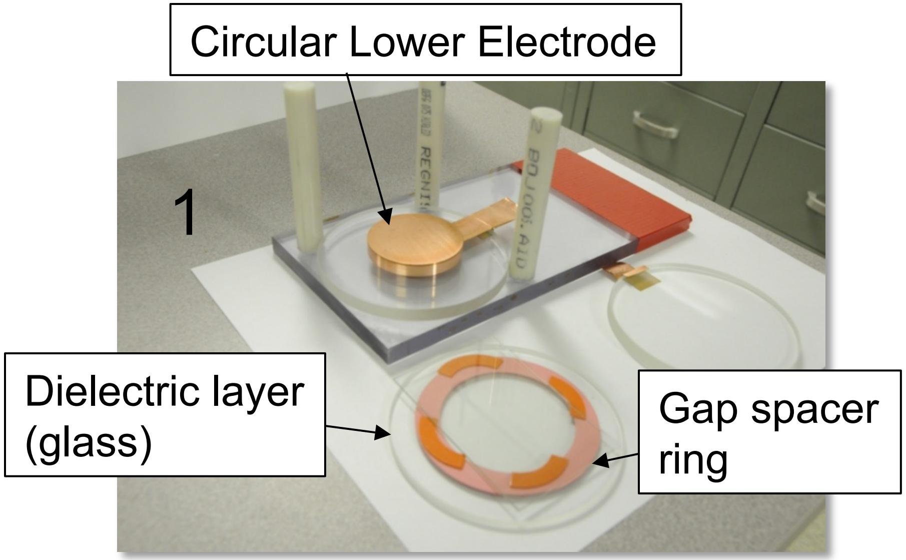


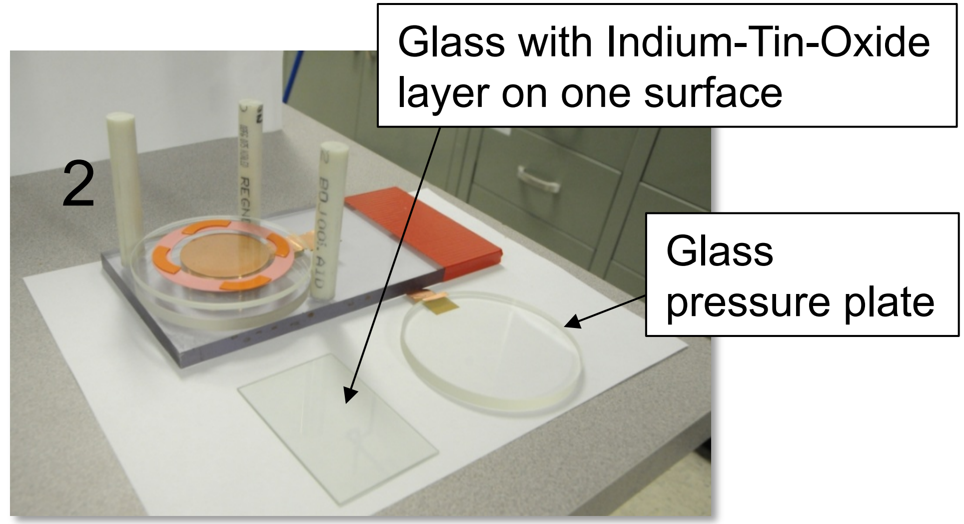
Simplified rectilinear lattice

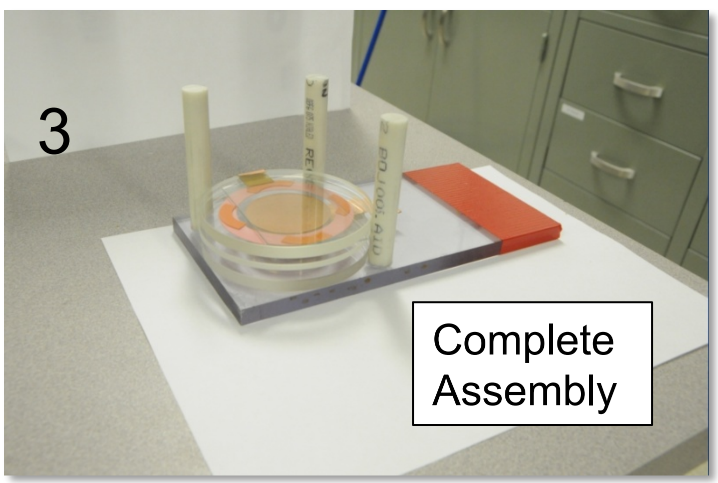


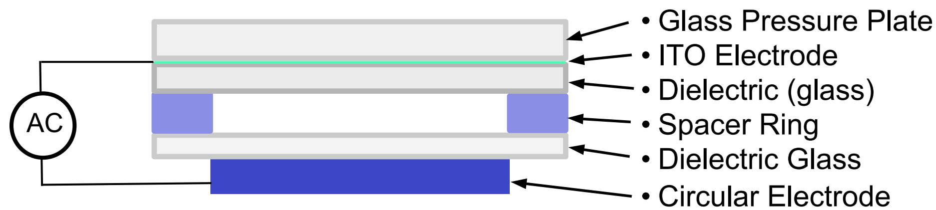
Sakai & Tachibana. 2012

Plasma Lattice Device



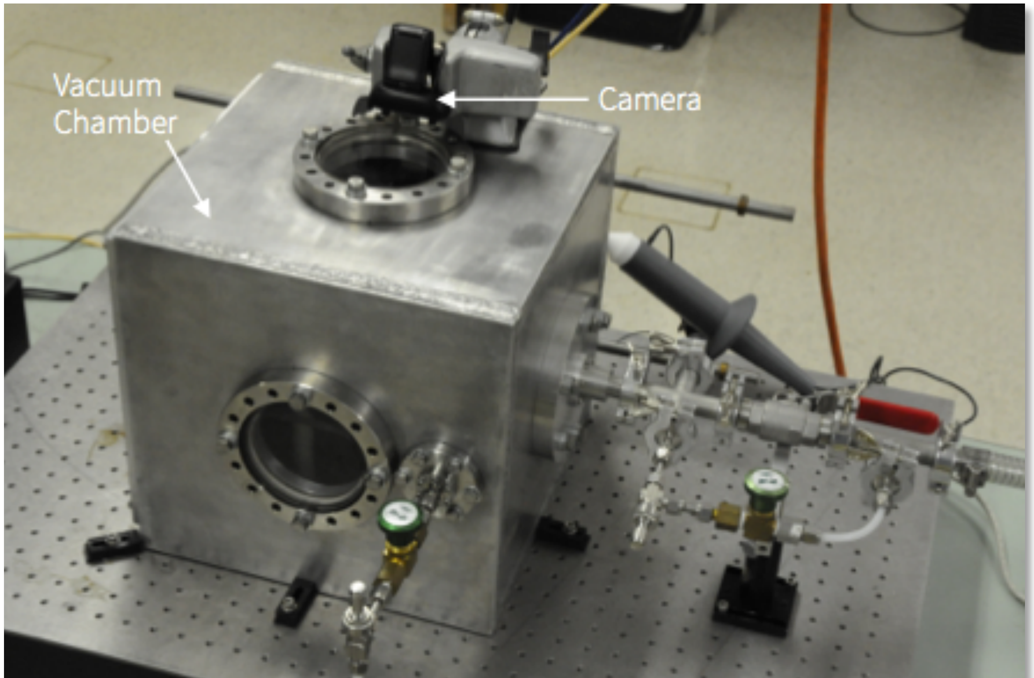


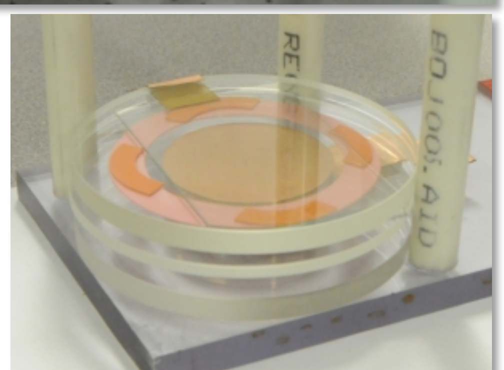




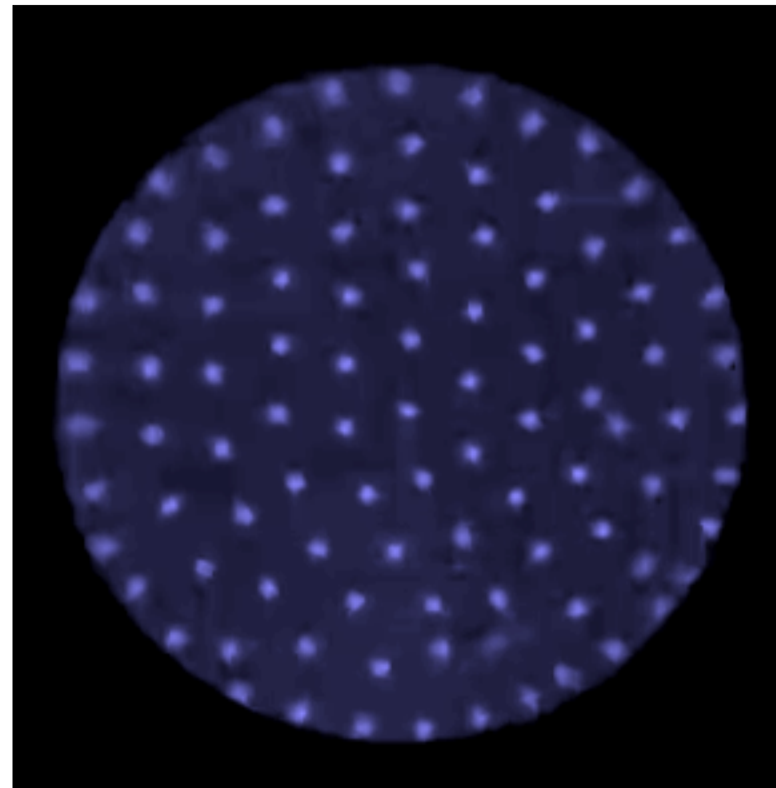
Assembly Schematic

Plasma Lattice Structure

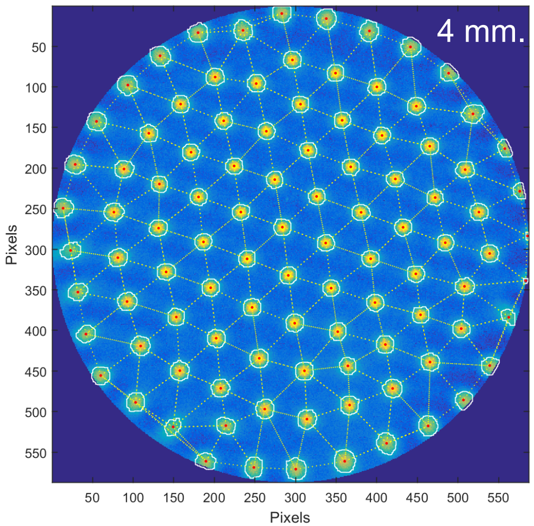


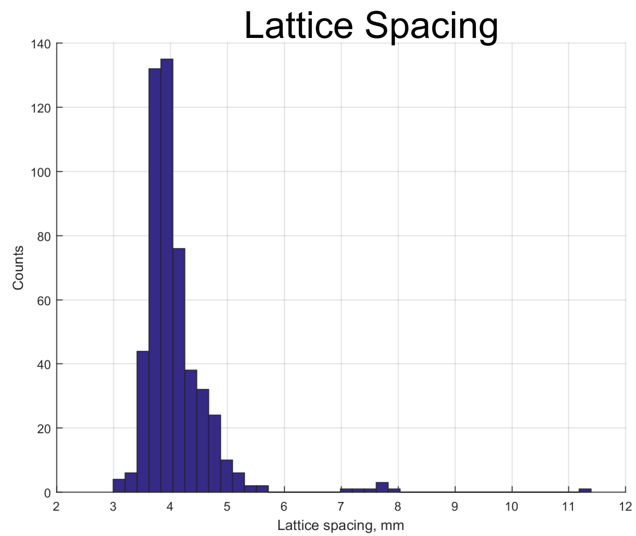


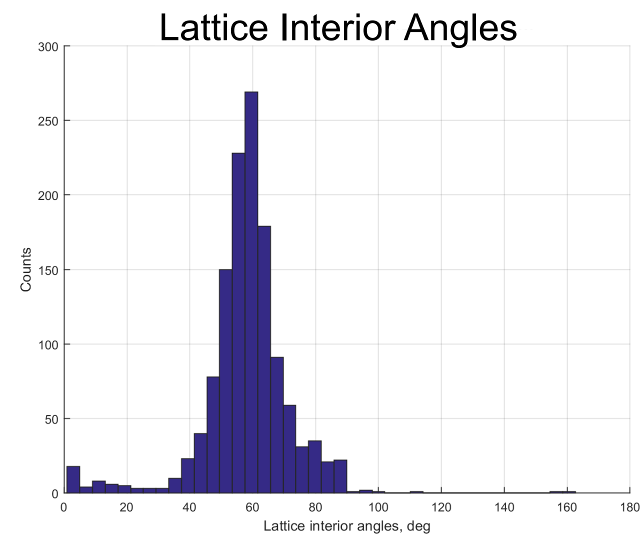
Effect of Voltage

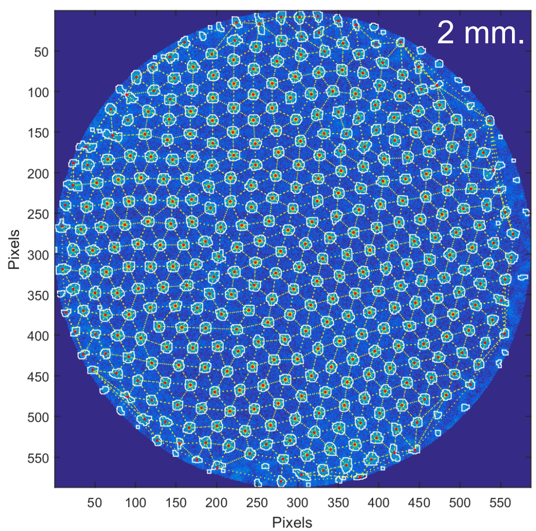


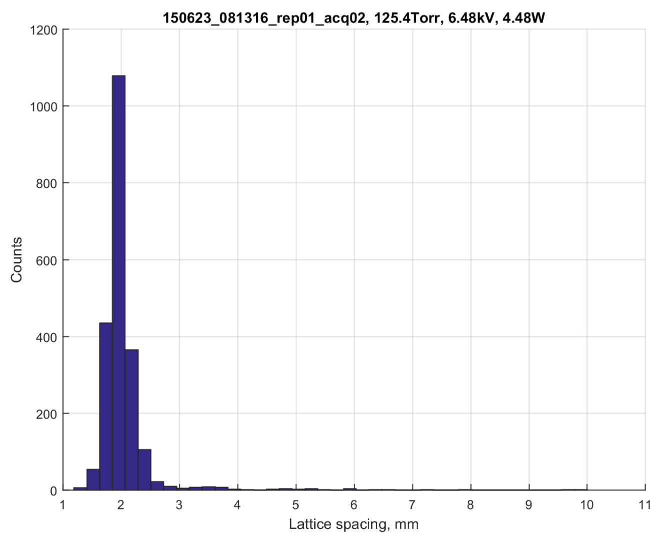
Lattice Analysis: Node Locations, Radii and Spacing

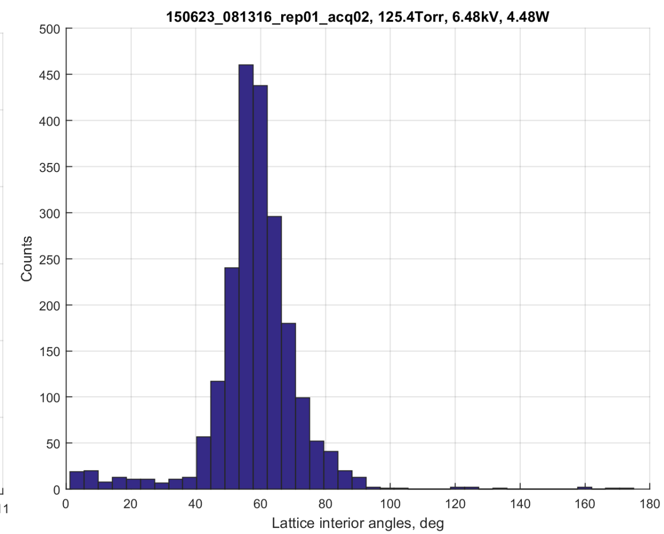






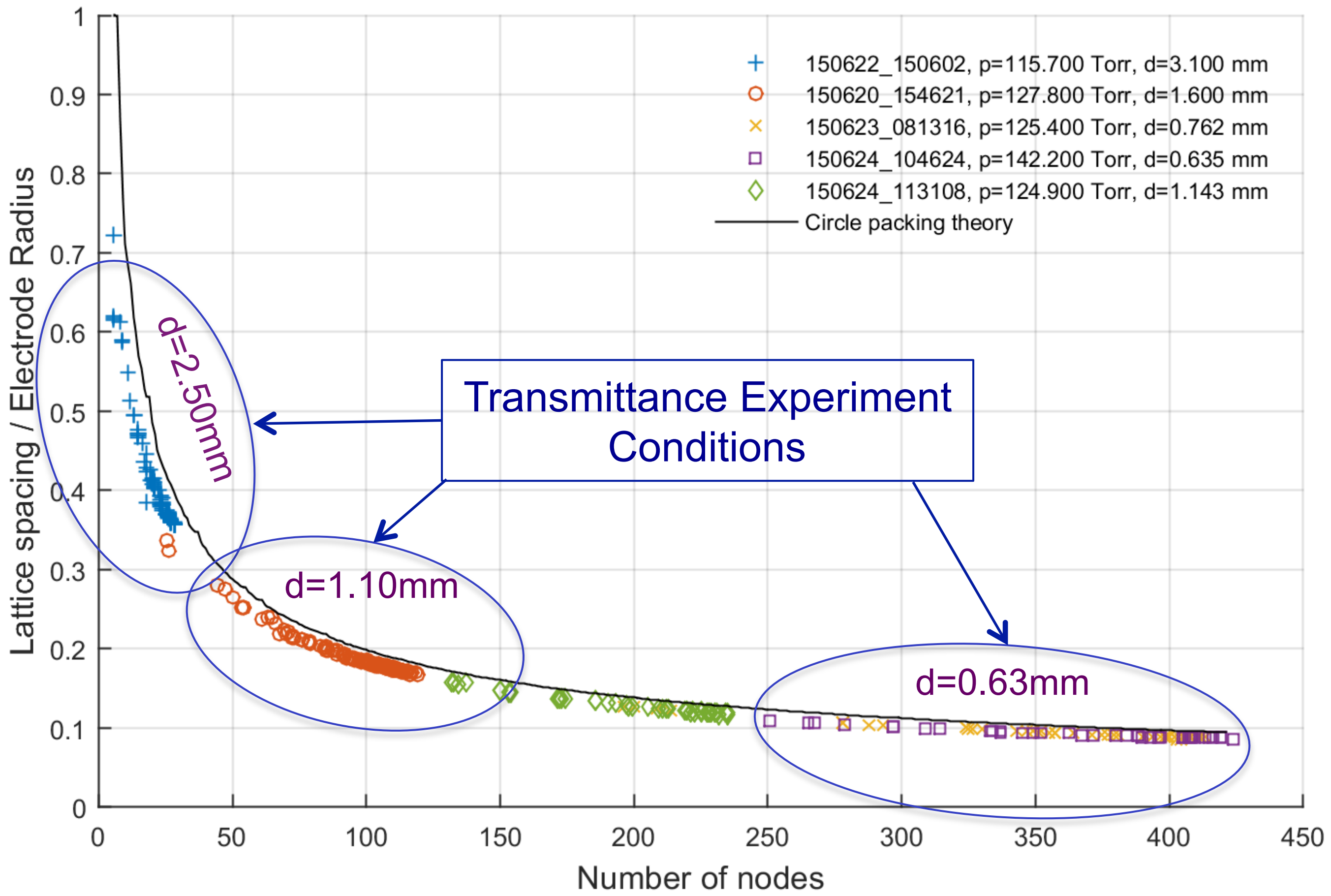




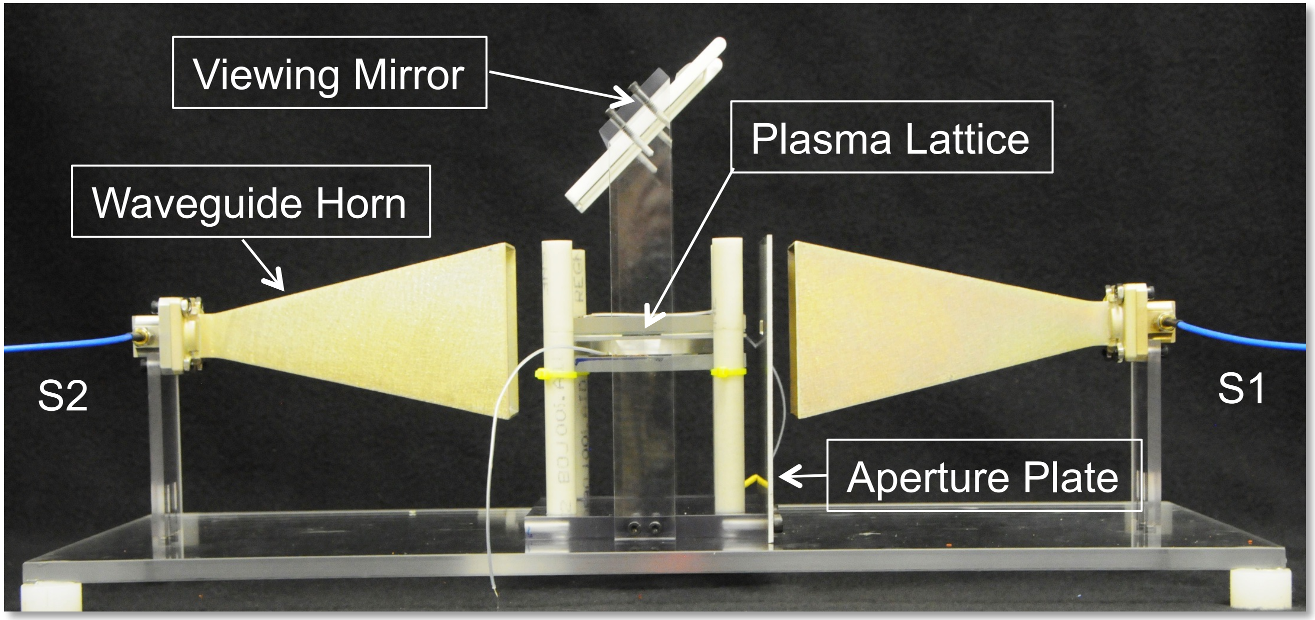


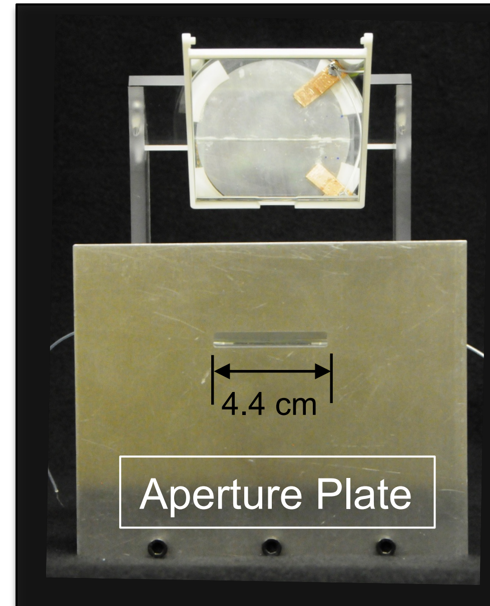
Predictive Plasma Lattice Control

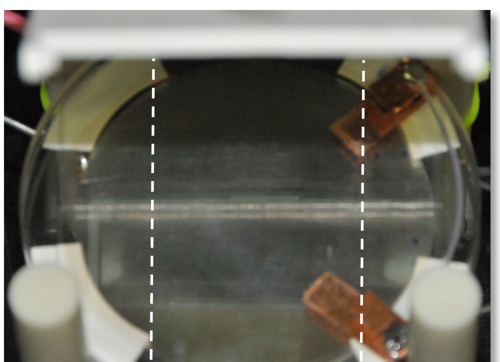
Follows Circle Packing Theory



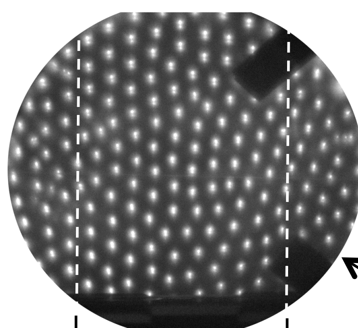
EM Wave Experimental Setup







TE mode

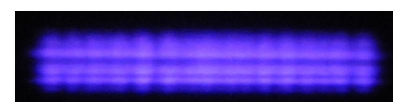


B/W Camera Mirror View

D=7cm ($4.7\lambda_{20GHz}$)

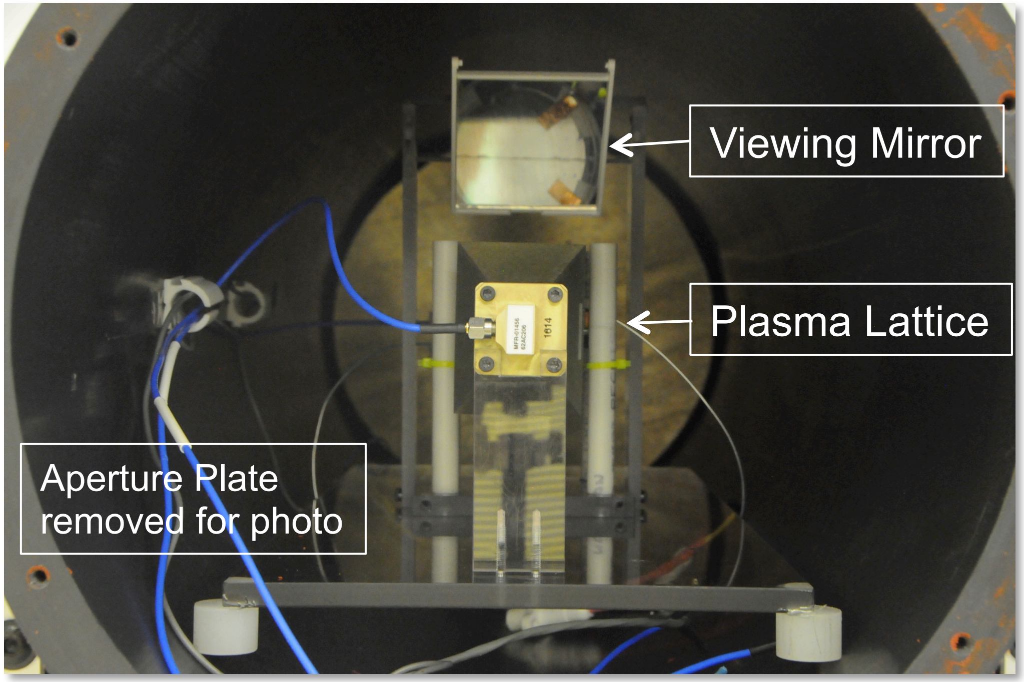
4.4 cm

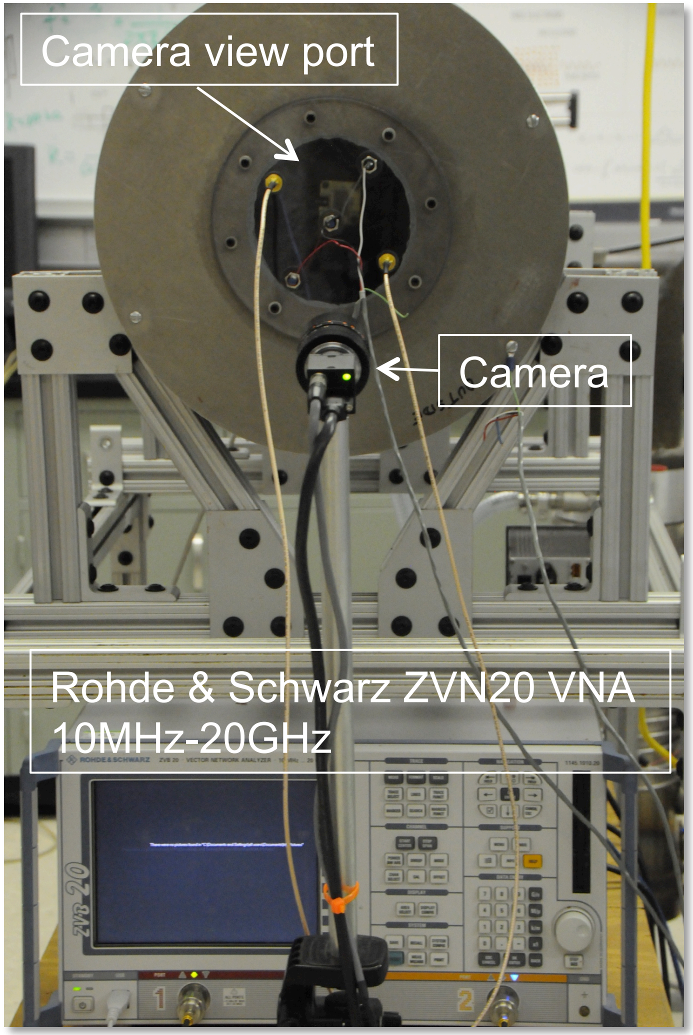
Aperture View



TE mode

EM Wave Experimental Setup





- Experimental setup placed in cylindrical pressure vessel
- Vacuum-rated electrical pass-through connectors for plasma power, and S1 and S2 analyzer signals.

Experimental Conditions

d (mm)	Static Pressure, P_s (Torr)					Power Gain
2.50	125	200	250	300	400	22-56
1.10	-	200	-	300	400	35-80
0.62	-	-	-	-	400	46-72

- Plasma AC frequency = 54kHz
- Data Acquisition:
  - Sequence of Plasma Lattice Off, On, Off
  - 1001pts. S_{21}: 17.5 - 20GHz
  - Plasma Lattice Image

Plasma Lattice Images: P_s=400Torr

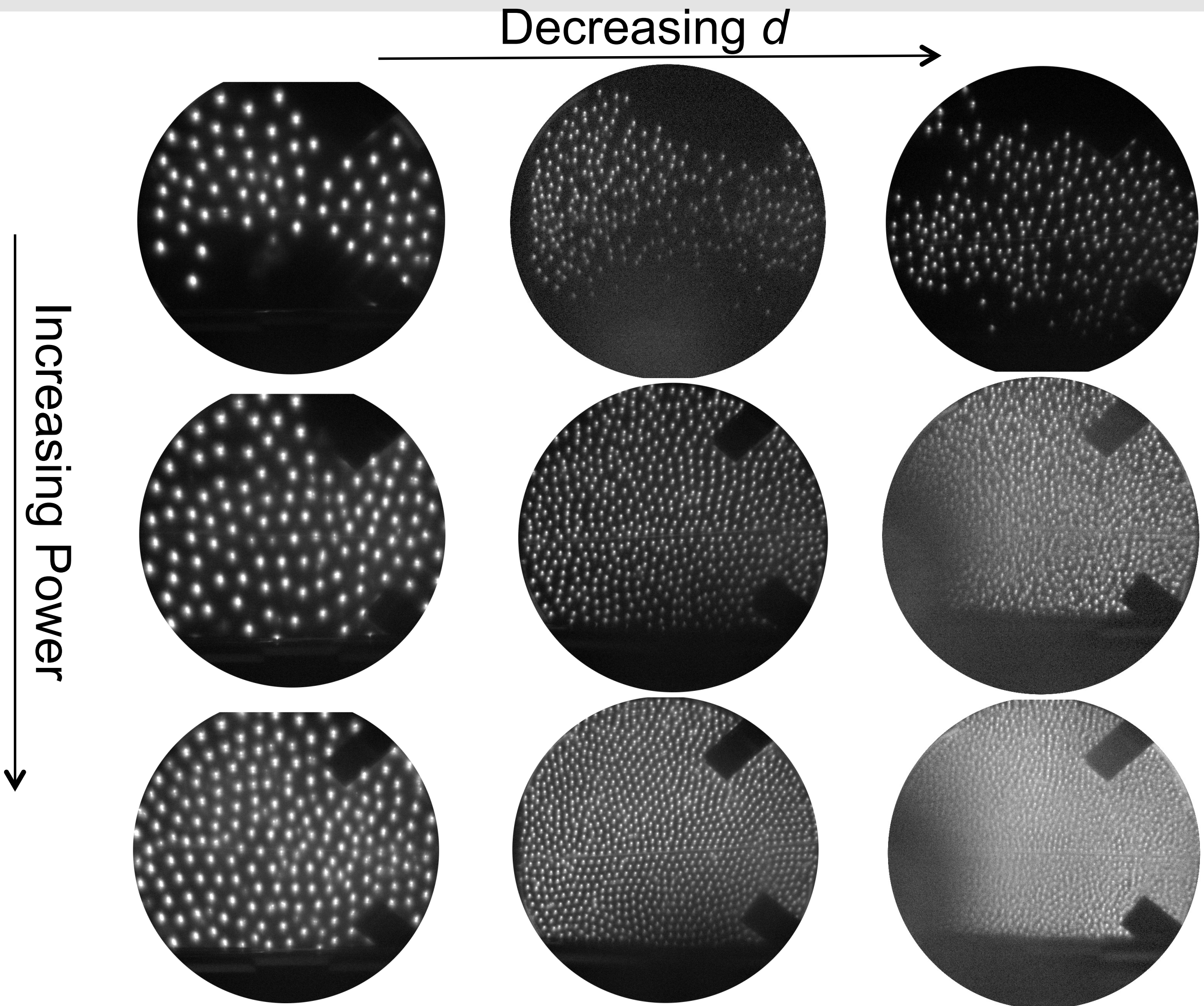
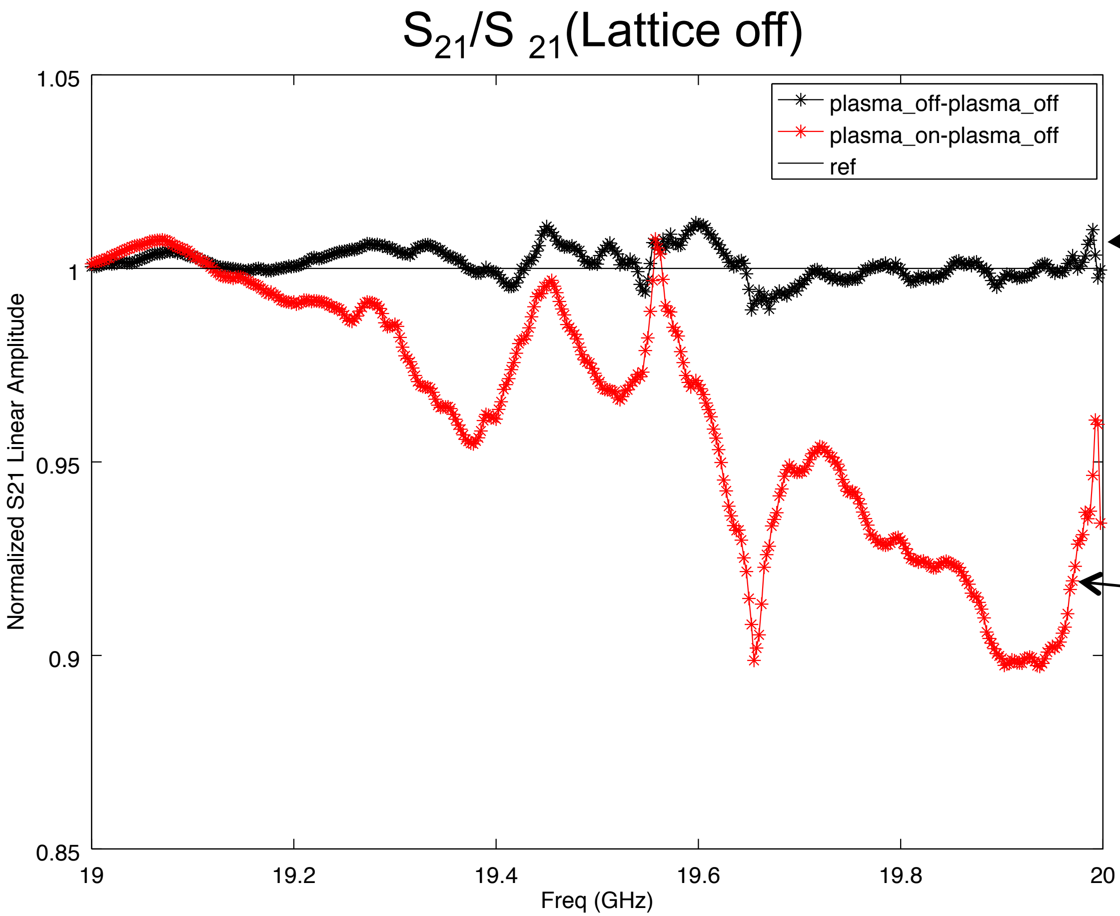


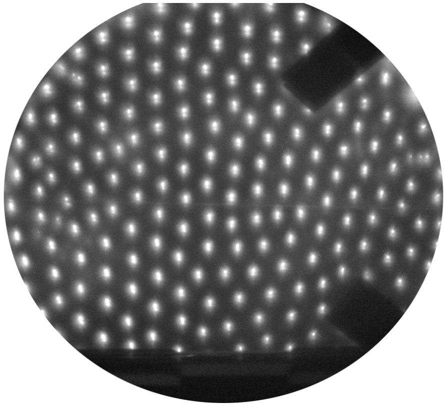
Image Analysis

Plasma Lattice: P_s=400Torr, $\omega/2\pi$=20GHz									
Power Gain	d=2.50(mm)			d=1.11(mm)			d=0.63(mm)		
	a (mm)	λ/a	$\omega a/2\pi c$	a (mm)	λ/a	$\omega a/2\pi c$	a (mm)	λ/a	$\omega a/2\pi c$
Min.	4.7	3.2	0.31	3.2	4.7	0.21	3.0	5.0	0.20
Mid.	4.2	3.6	0.28	2.4	6.2	0.16	2.1	7.1	0.14
Max.	4.6	3.3	0.31	2.0	7.5	0.13	1.6	9.4	0.11

- Metamaterial: $\lambda/a \approx 10$
- Phototonic Crystal: $\lambda/a \approx 1$
- Band Gap (Sakai et al., 2005): $\omega a/2\pi c \approx 0.5$

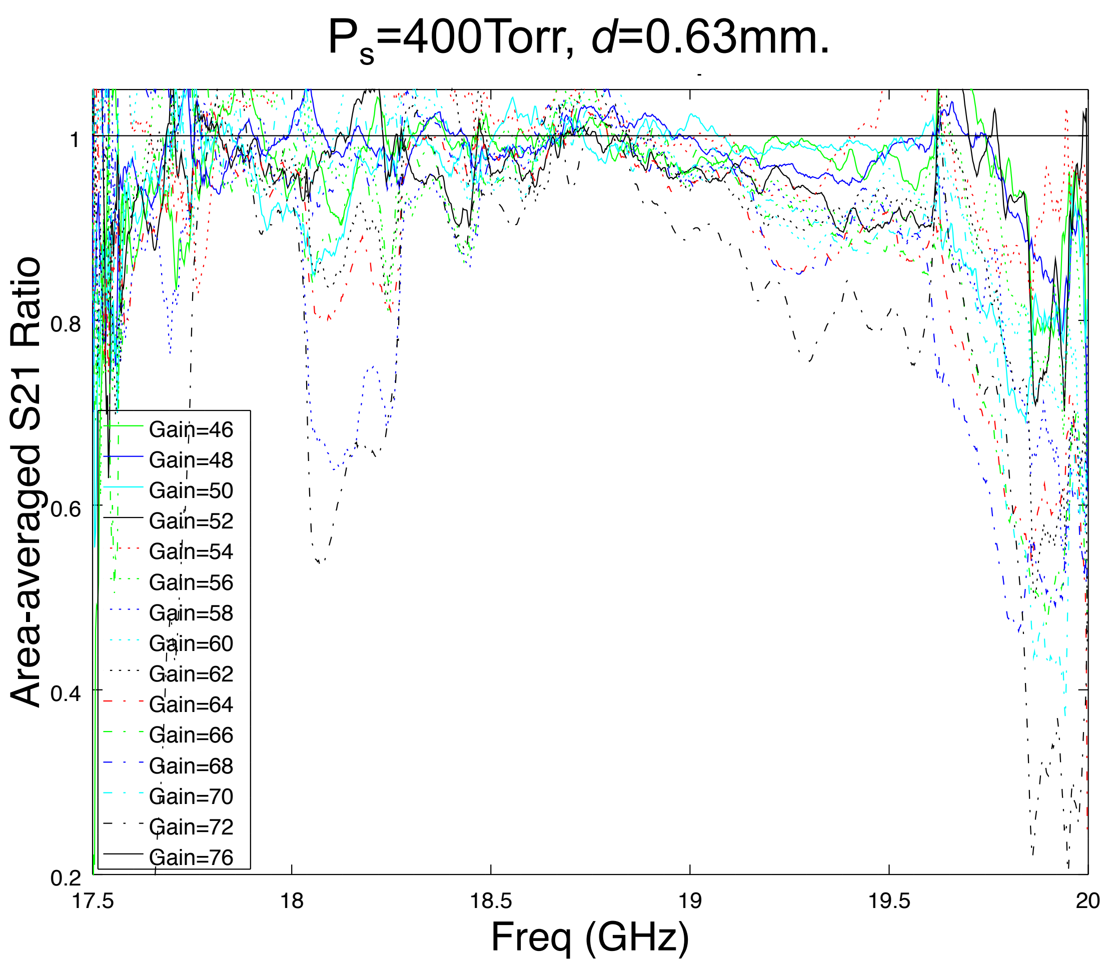
Sample S_{21} Transmittance Spectra



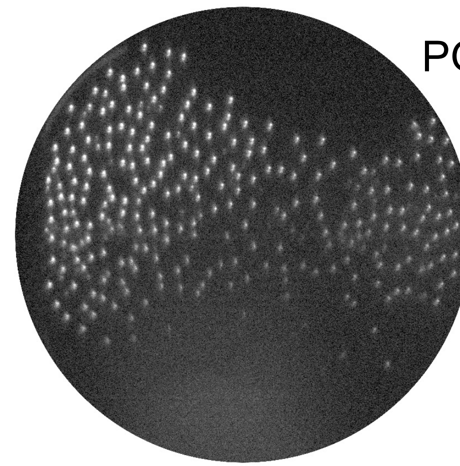


d=2.5mm., P_s=250Torr

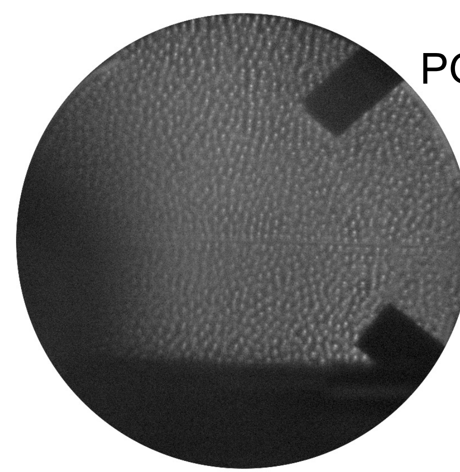
S_{21} Transmittance Spectra



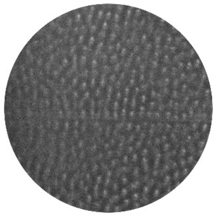
PG:46



PG:72

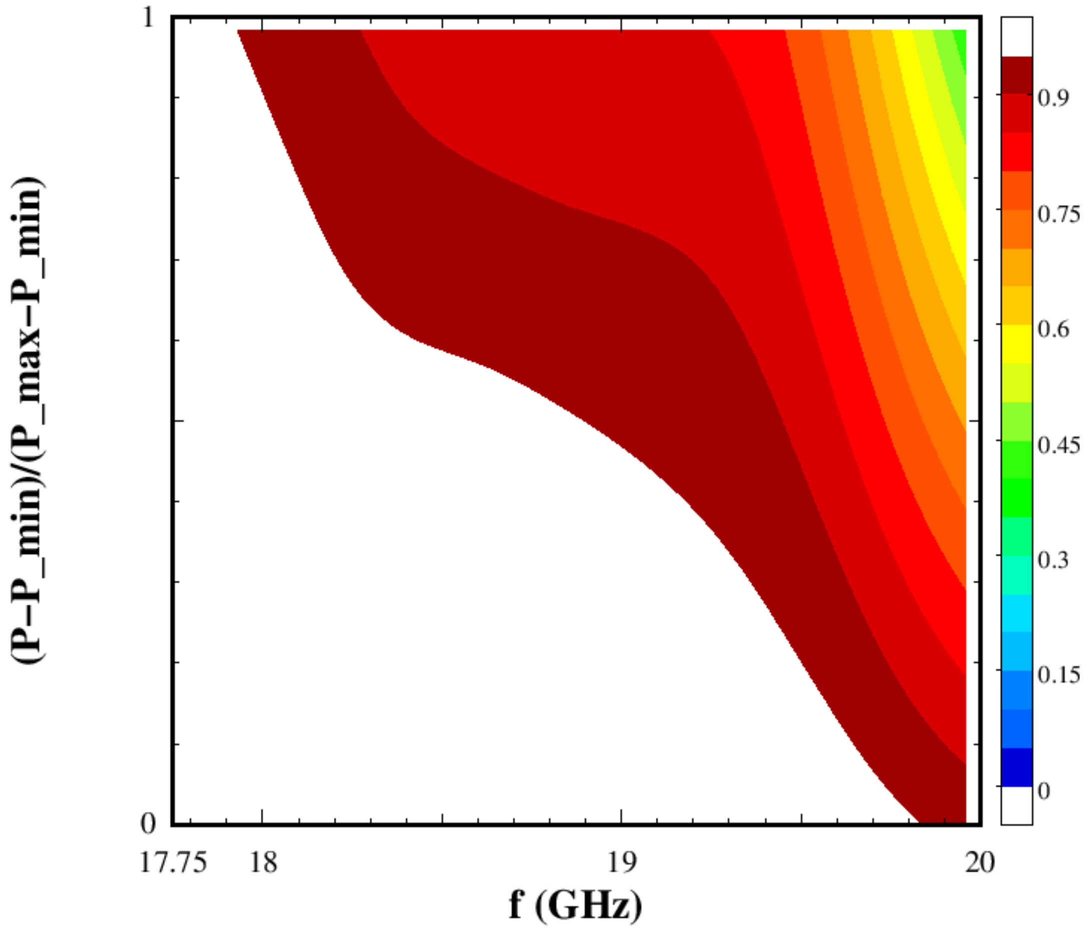


S_{21} Transmittance Spectra



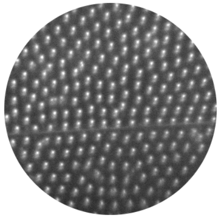
a (mm)	λ/a	ωa/ 2πc
3.0	5.0	0.20
2.1	7.1	0.14
1.6	9.4	0.11

P_s=400Torr, d=0.63mm.



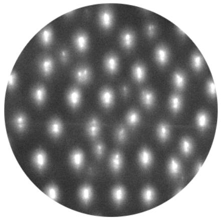
S_{21} Transmittance Spectra

a (mm)	λ/a	ωa/2πc
3.2	4.7	0.21
2.4	6.2	0.16
2.0	7.5	0.13

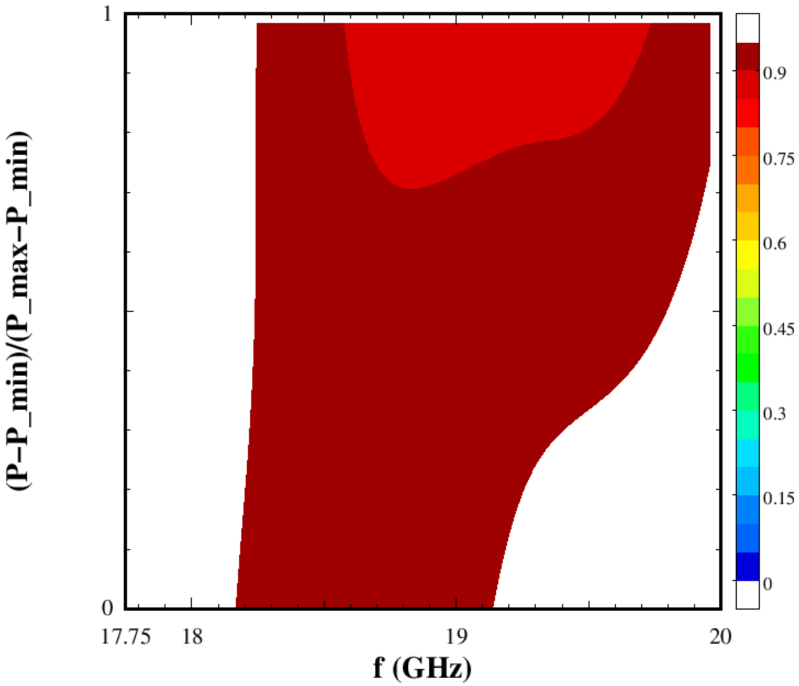


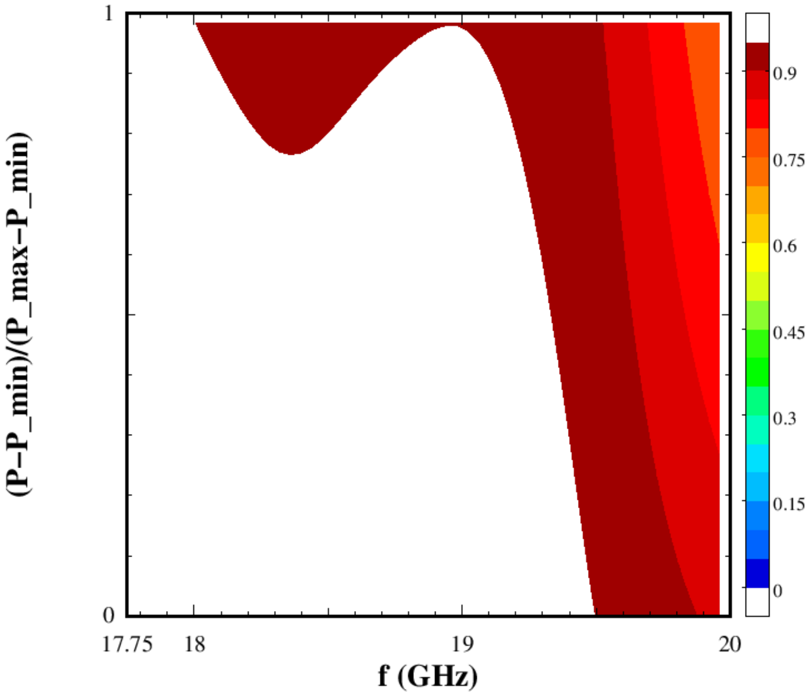
P_s=400Torr, *d*=1.1mm.

a (mm)	λ/a	ωa/2πc
4.7	3.2	0.31
4.2	3.6	0.28
4.6	3.3	0.31



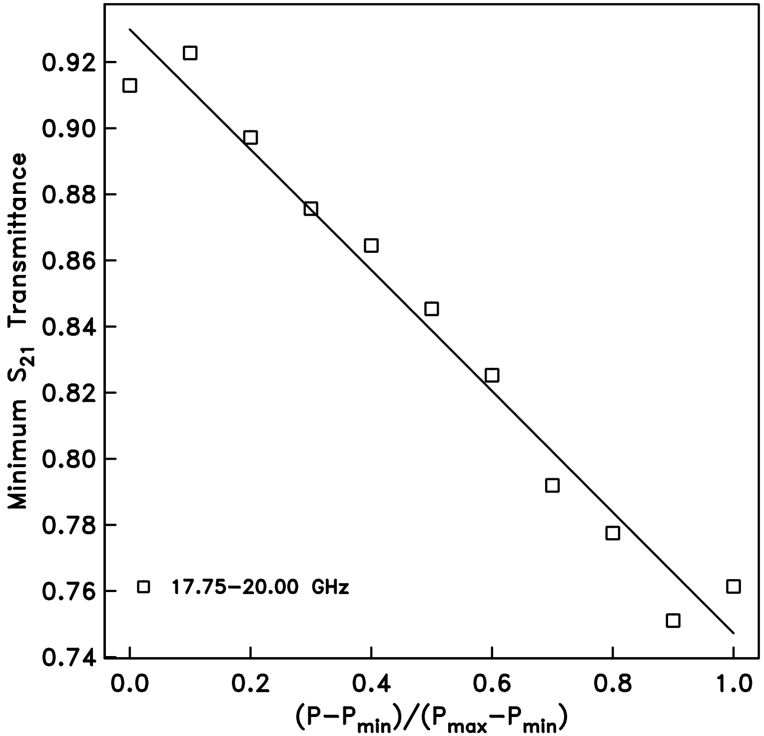
P_s=400Torr, *d*=2.50mm.





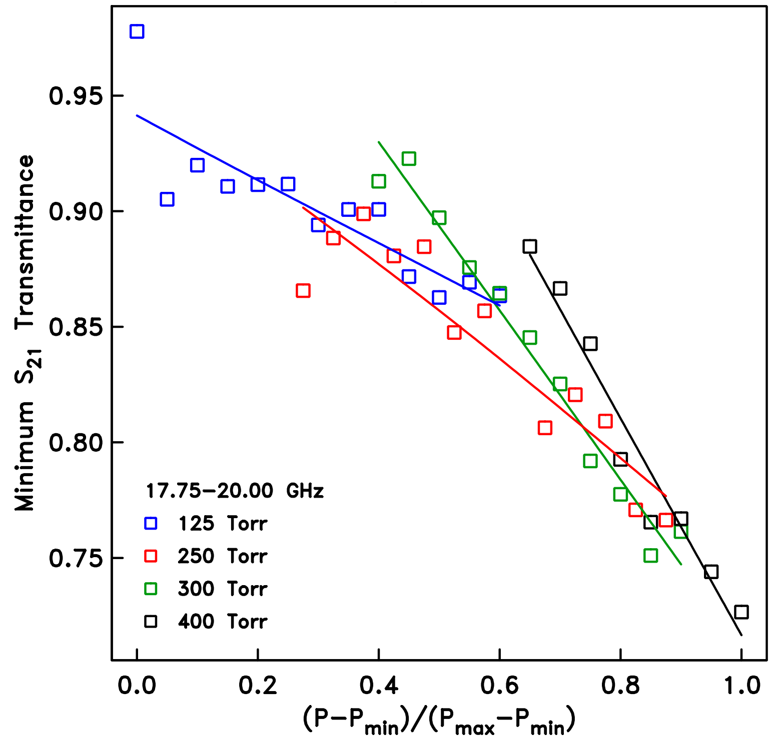
Effect of Power on Minimum S_{21} Transmittance

P_s=300Torr, *d*=2.50mm.



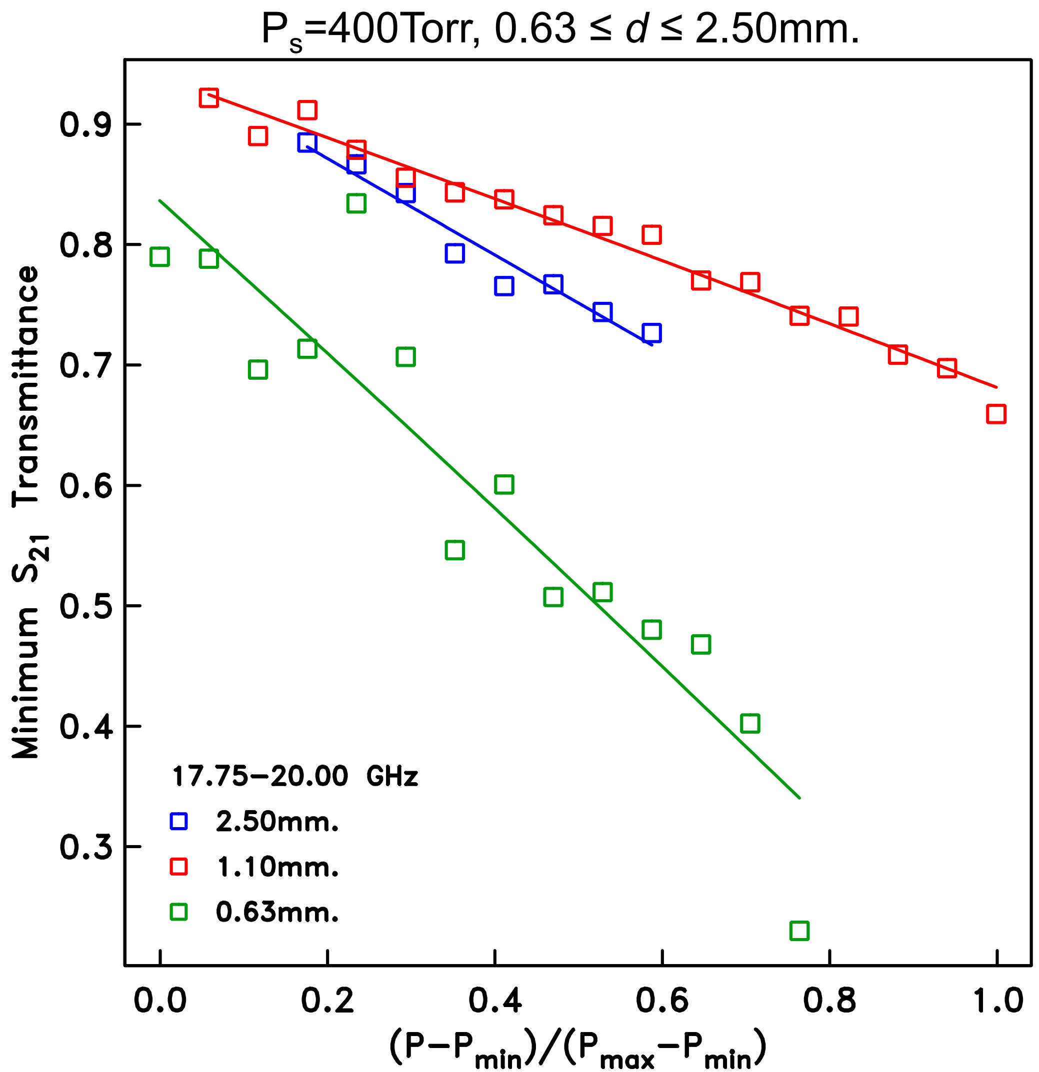
Normalized Power

d=2.50mm., 125 ≤ Ps ≤ 400Torr



Normalized Power

Effect of Gap on S_{21} Minimum Transmittance



EM Wave Simulation

- Simulation of a 2-D plasma photonic crystal subject to planar electromagnetic wave fronts of a specific probing frequency

- Utilized MIT open-source (Meep) software that solves Maxwell's equations at each time step to realize the electromagnetic field at discrete spatial locations through an implementation of a finite-difference time-domain (FDTD) method.

- Dispersive materials are defined in Meep using a Lorentz-Drude model

$$\epsilon(\omega) = \epsilon_\infty + \sum_{m=1}^{N} \frac{\sigma_m \Omega_m^2}{\Omega_m^2 - \omega^2 + i\nu\omega}$$

Where ε_∞ is the frequency-independent permittivity, N is the number of resonance frequencies, Ω_m is a resonance frequency, σ_m is the strength associated with that frequency, and v is the electron elastic collision frequency.

Meep: Plasma Column Permittivity

- Permittivity, ε_p, of each plasma column given by the dispersive relation

$$\epsilon_p(\omega) = 1 - \left(\frac{\omega_p}{\omega}\right)^2 \frac{1}{1 - i\frac{\nu}{\omega}}$$

  where ω is the probing frequency, and ω_p is the plasma frequency and v is the electron elastic collision frequency.

- The plasma frequency is defined as $\omega_p = \sqrt{\frac{n_e q^2}{m \epsilon_0}}$

  where n_e is the electron density, q is the electron charge, m is electron mass, and ε_0 is the free-space permittivity. Based on Razier (1991), v=(3.9e9 s^{-1}Torr^{-1})P_s

- For the Meep parameters, we equate two forms of the permittivity, namely

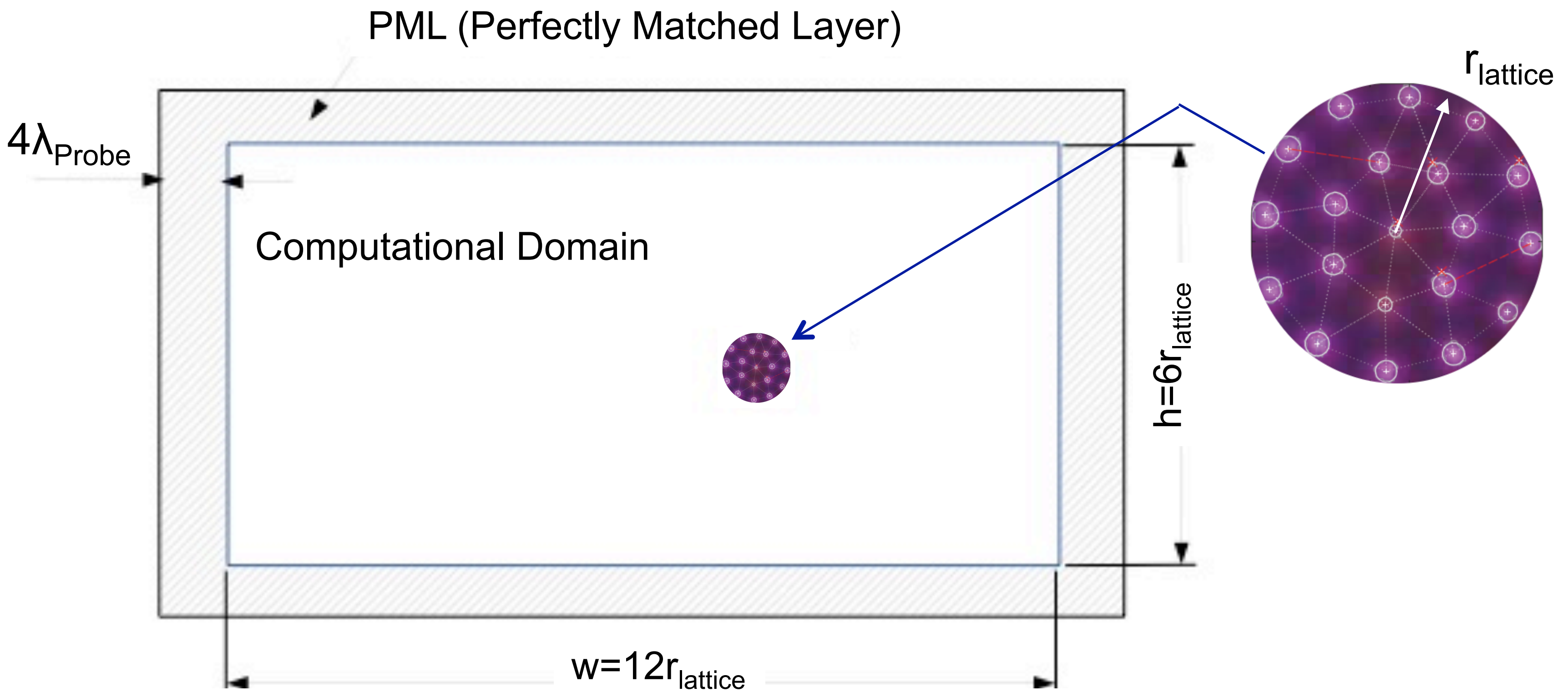
$$\epsilon(\omega) = \epsilon_\infty + \sum_{m=1}^{N} \frac{\sigma_m \Omega_m^2}{\Omega_m^2 - \omega^2 + i\nu\omega} = 1 + \frac{\omega_p^2}{-\omega^2 + i\nu\omega}$$

  then ε_∞=1 and N=1.

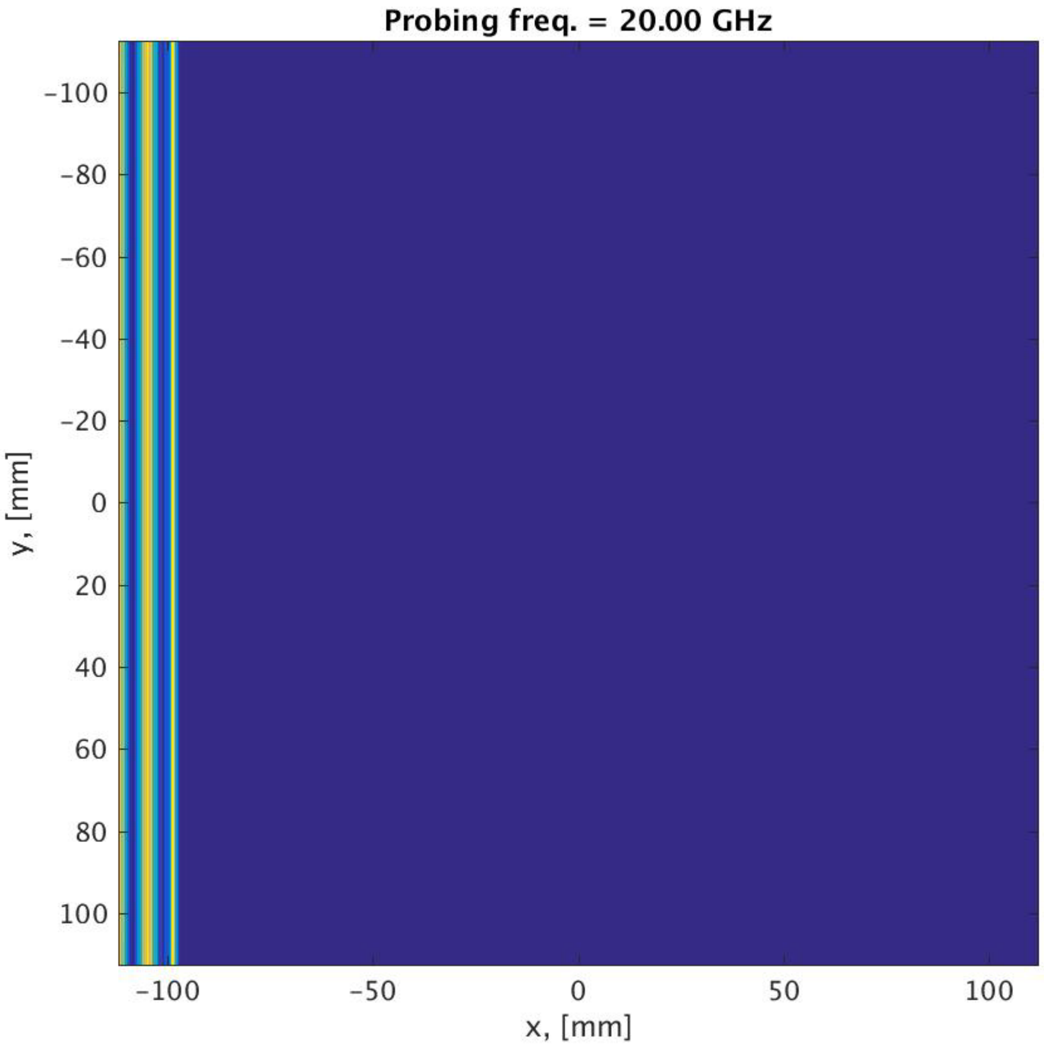
- To achieve the best representation of the plasma material, Ω_m<<1 which requires that $\sigma_m=(\omega_p)^2/(\Omega_m)^2$. *Used* $\Omega_m = 0.0001$.

EM Wave Simulation

- Computational domain consists of rectangular region $12r_{lattice}$ by 6 $r_{lattice}$
- A non-reflecting PML perimeter of width $4\lambda_{Probe}$ surrounds the domain
- Plasma grating patterns from the experiments are inset in computational domain

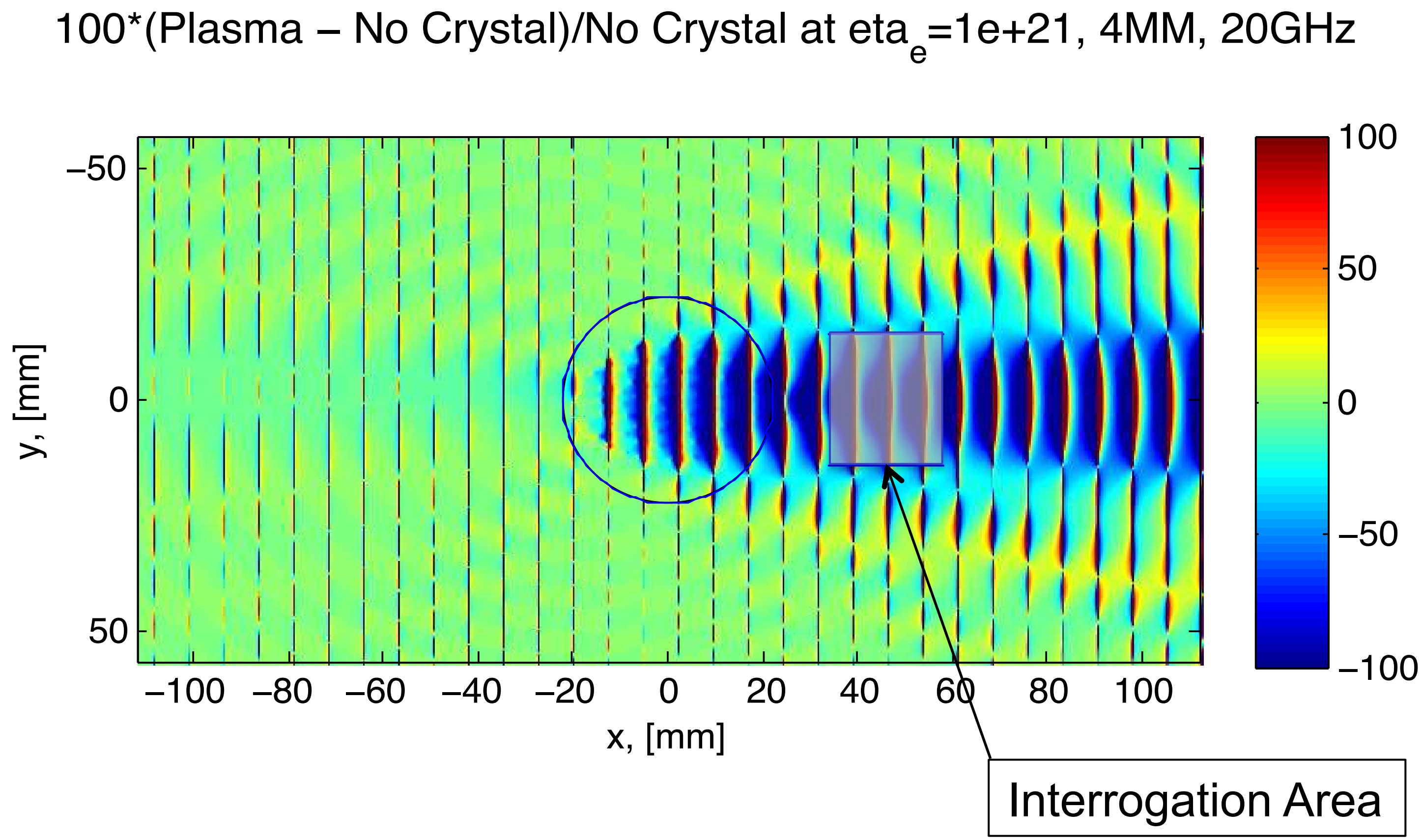


Simulation: 400 Torr, a=4mm, n_e=1e^{21}m^{-3}



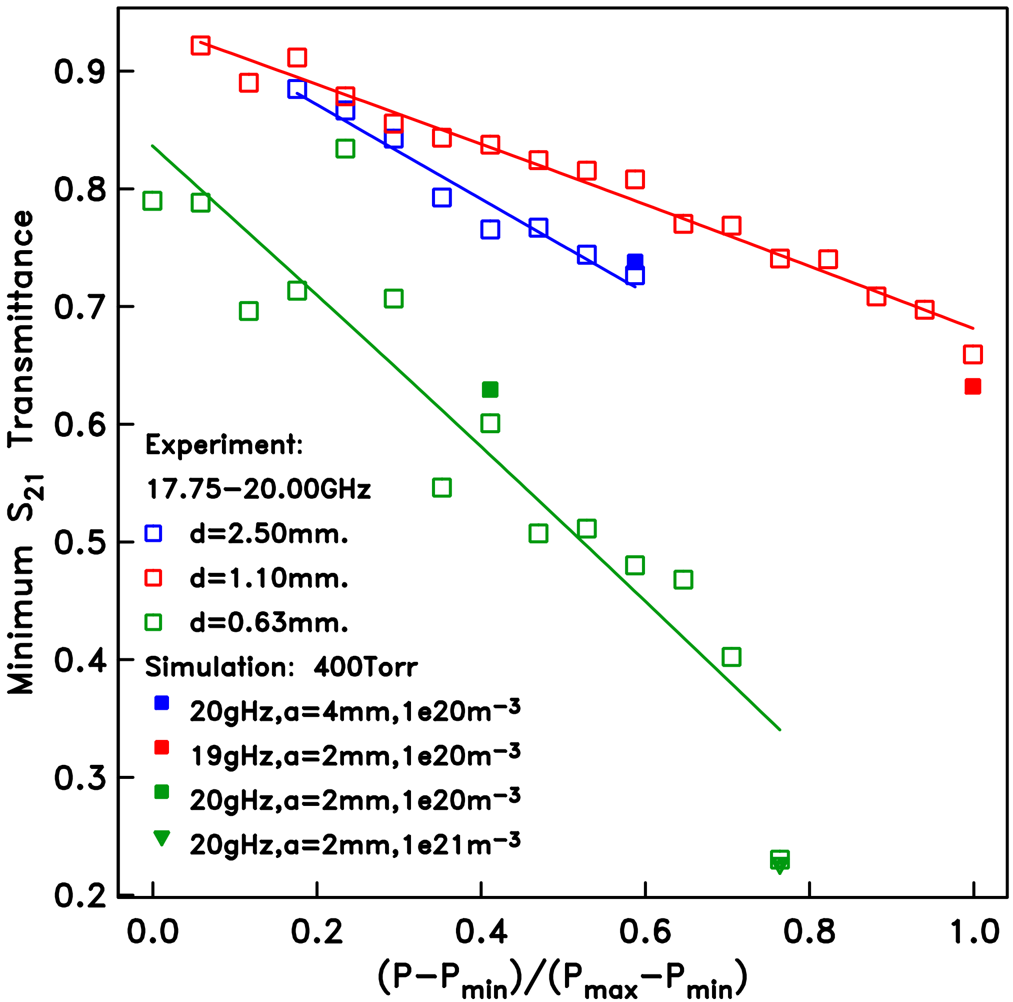
Wave Energy

Simulation: 400 Torr, a=4mm, n_e=1e^{21}m^{-3}

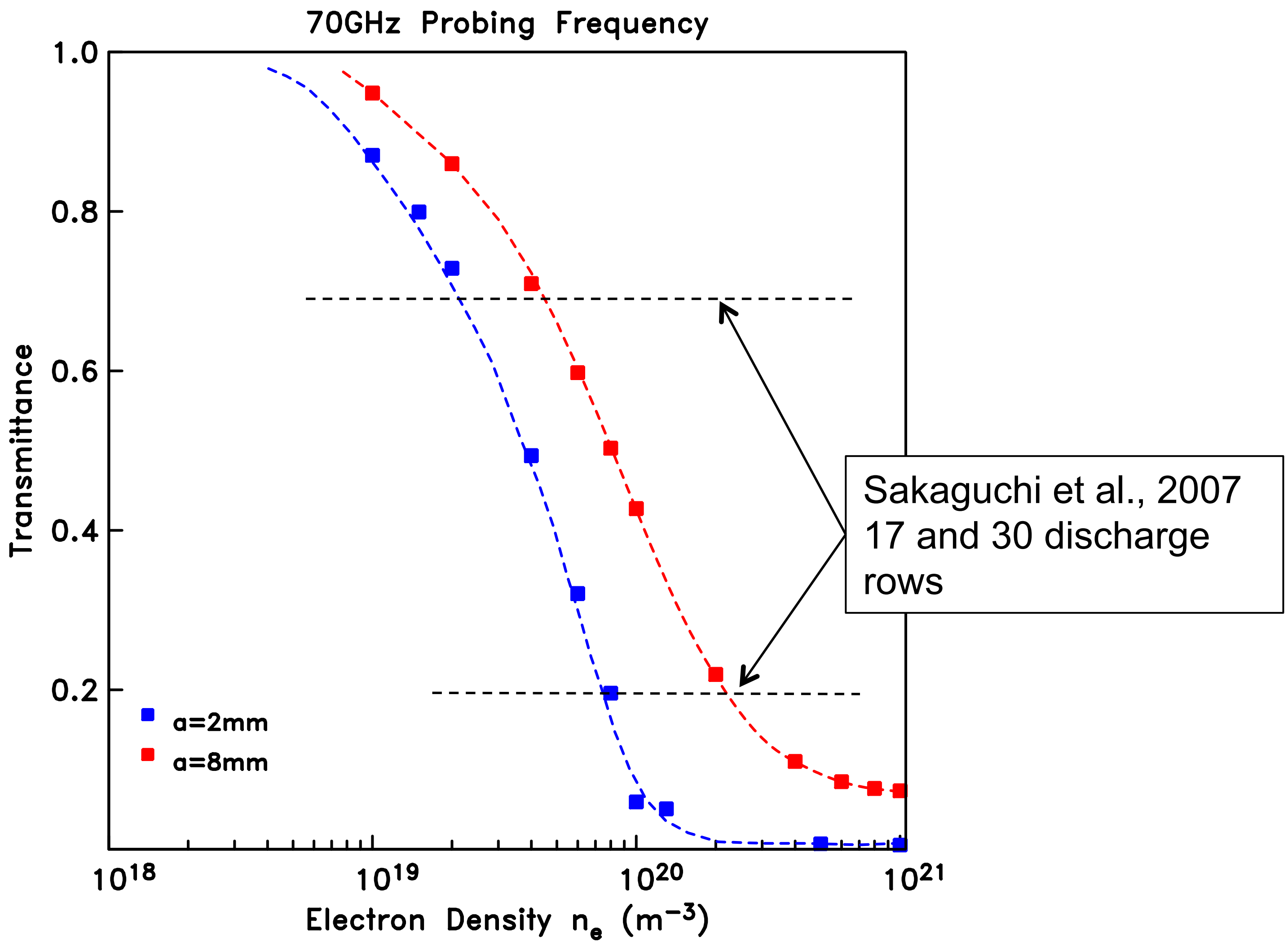


Simulation Results

P_s=400Torr, 0.63 ≤ d ≤ 2.50mm.



Simulation Projection



a (mm)	λ/a	*ωa/ 2πc*
2	2.15	0.47
8	0.54	1.87

Summary

- Demonstrated dynamic control of plasma lattice structures with different lattice spacings, *a*.
- Performed EM wave transmittance experiments for probing frequencies up to 20GHz.
- Experiments demonstrated effects of P_s, *d*, and power on S21 transmittance.
- Results indicated a narrow frequency band S21 attenuation.
- Largest S21 attenuation occurred with highest P_s were $\lambda/a = \mathcal{O}10$
- The largest attenuation was comparable to other non-configurable plasma lattices in the literature, e.g. Sakaguchi et al., 2007.
- EM wave simulations performed on experiment-based plasma lattice configurations produced transmittance values that were in good agreement with the experiments.
    - Indicates validity of the simulation to predict effect at higher probing frequencies.

Way Forward

- Perform EM wave transmittance experiments at higher probing frequencies (~70GHz).
  - Acquire a 70GHz Vector Network Analyzer and matched components.
- Repeat transmittance measurements at the higher probing frequencies that include off-axis locations.
  - Seek wave energy changes in the $\Gamma - M$ direction that is a characteristic of a photonic crystal.
- Perform further comparisons to the EM wave simulations.
- Generate band diagrams for a range of lattice spacing and electron densities derived from the experiments. Correlate these to the experimental observations.
- Investigate charge instability lattice control approaches that include:
  - Silicon dielectric with surface layer doping patterns
  - Real-time UV patterns projected on the glass dielectric

Wave Guides and Conduits

Way Forward

- Even at the current probing frequencies, with our control over the plasma, we are in a position to look at photonic crystals where the columns can have positive, negative or 0 permittivity.
- This is quite unique and we think, not realizable with non-configurable plasma lattices in the literature such as that of Sakaguchi et al.