COLLEGE OF ENGINEERING

Plasma Electromagnetics using Dielectric Barrier Discharges

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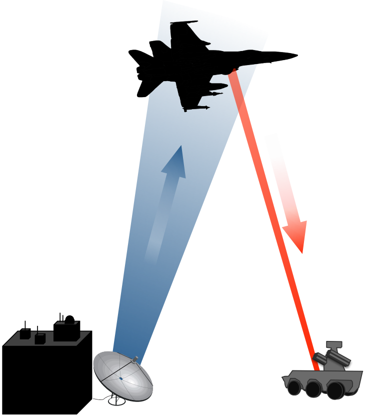
Motivation for Plasma Electromagnetics

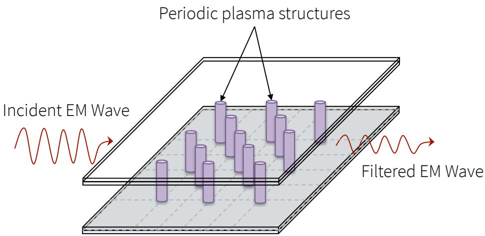
- Can control permittivity and refractive index of plasma by changing experimental conditions
- Plasma has no moving parts and high frequency response
- Adaptive optics for wavefront corrections
  - High-speed adaptive optics critical to aero-optic applications
  - Conrollable plasma index of refraction
- Plasma photonic crystals for adaptive filtering
  - Controllable periodic plasma structures
  - High-speed adaptive filtering for GHz-THz
  - Aircraft radar stealth

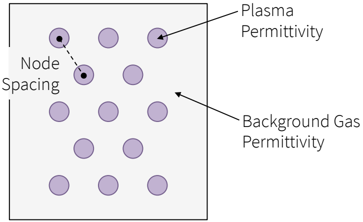


High-speed controllability of plasma makes it attractive for stealth and aero-optics.

Research Objectives

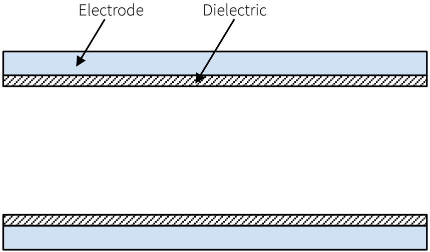
- Experimentally generate periodic plasma structures
- Spatially periodic dielectric
- Demonstrate dynamic control spacing of plasma structures
- Determine electron density of plasma columns
- Show that plasma photonic crystal can act as an adaptive filter for a range of probing frequencies





Current focus is to generate periodic plasma structures and show control over spaing.

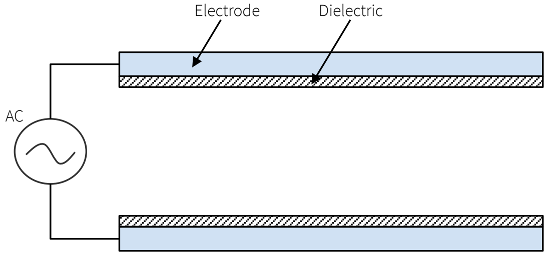
Dielectric Barrier Discharge (DBD)



- Two electrodes separated by dielectric material

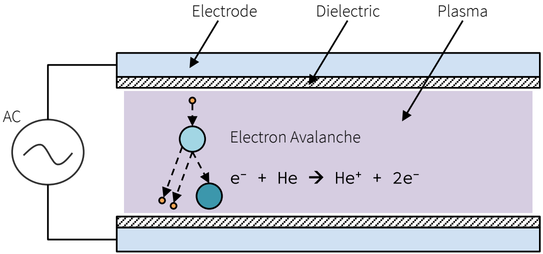
Dielectric Barrier Discharge (DBD)

FlowPAC



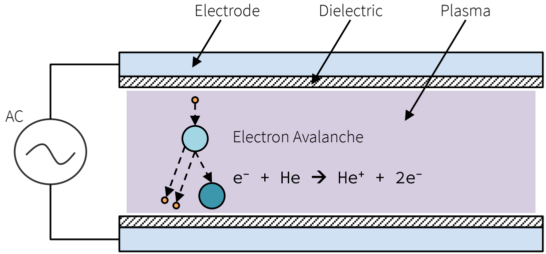
- Two electrodes separated by dielectric material
- Apply ac carrier signal (kV, kHz)

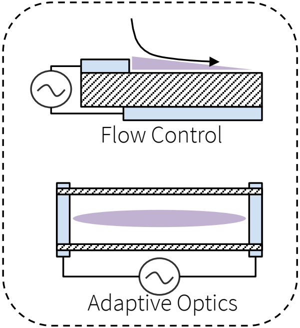
Dielectric Barrier Discharge (DBD)



- Two electrodes separated by dielectric material
- Apply ac carrier signal (kV, kHz)
- Electric field generates electron avalanche, partially ionizes gas

Dielectric Barrier Discharge (DBD)

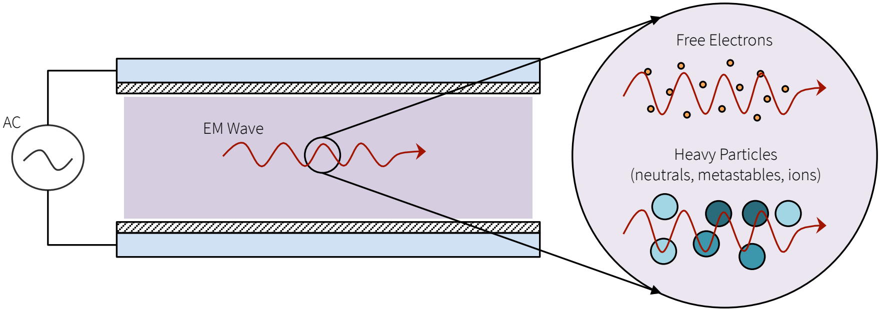




- Two electrodes separated by dielectric material
- Apply ac carrier signal (kV, kHz)
- Electric field generates electron avalanche, partially ionizes gas
- DBD allows for highly adaptable geometries

Investigate DBD geometries for electromagnetic control of optics and microwaves.

Dielectric Barrier Discharge (DBD)

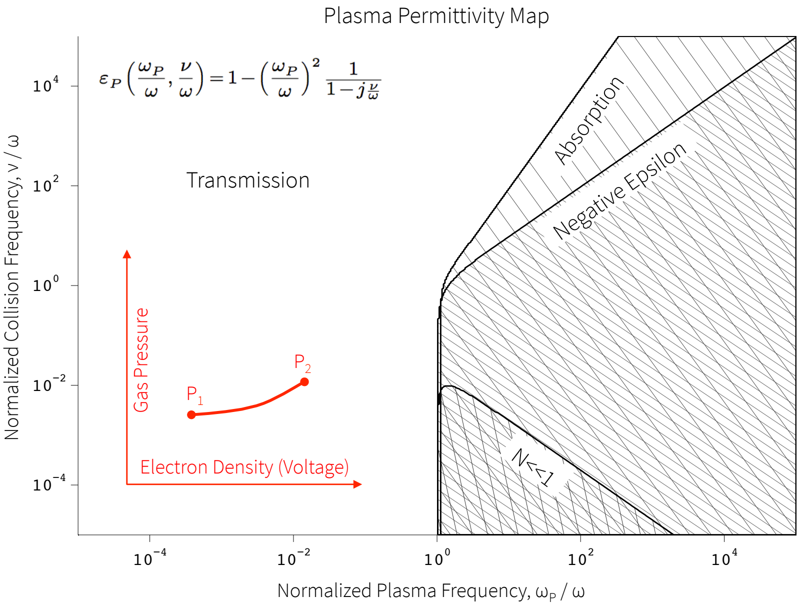


(Plasma permittivity) $$\varepsilon_P\left(\frac{\omega_P}{\omega}, \frac{\nu}{\omega}\right) = 1 - \left(\frac{\omega_P}{\omega}\right)^2 \frac{1}{1 - j\frac{\nu}{\omega}}$$

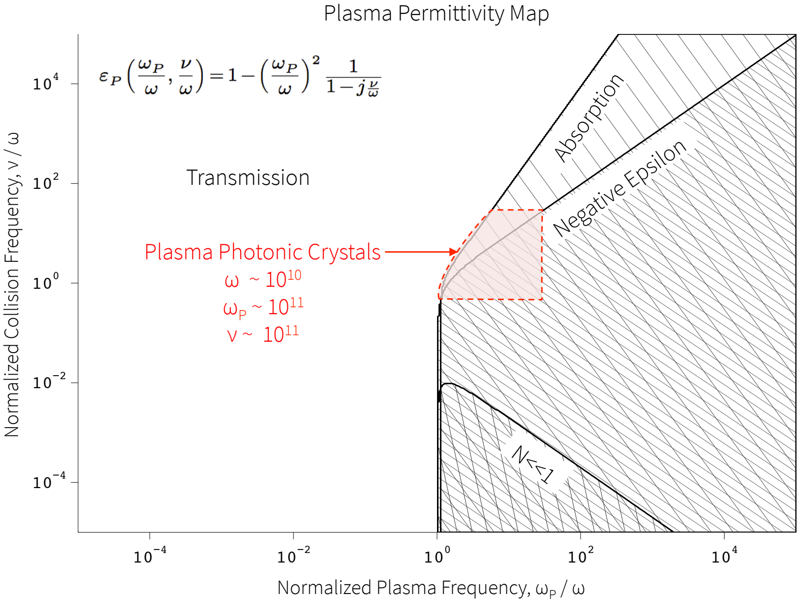
- Plasma frequency ω_P is a function of electron density, controllable by applied voltage
- Electron-neutral collision frequency ν is a function of gas pressure

Use voltage and gas pressure to control permittivity of plasma.

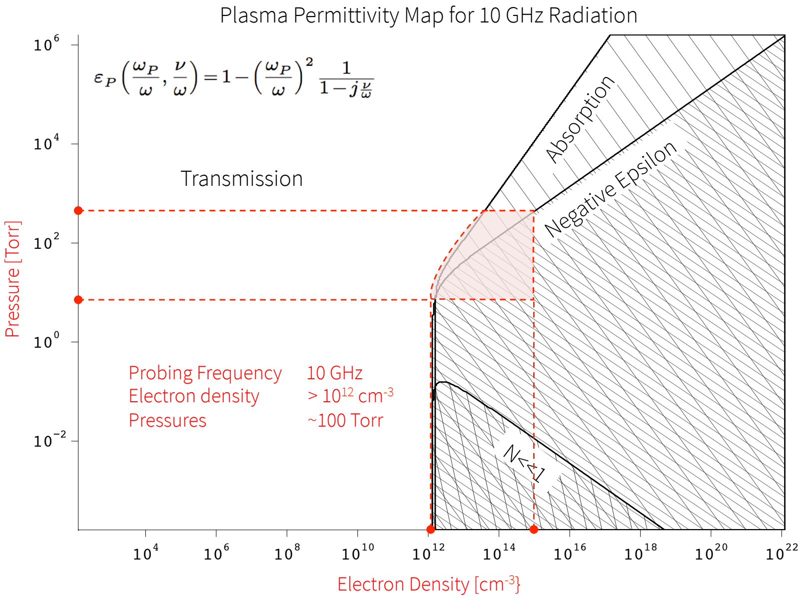
Plasma Permittivity Map



Plasma Permittivity Map



Plasma Permittivity Map

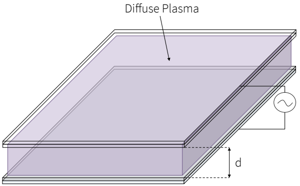


Experimental Approach

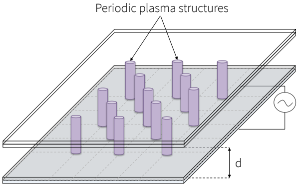
FlowPAC

- Parallel plate electrodes and dielectrics
- Plasma regime dependent on
  - Gas pressure
  - Gap distance
  - Carrier voltage and frequency
- Plasma charge instability produces stationary, naturally spaced plasma structures
- Applied voltage changes natural spacing
- Adaptive plasma photonic crystal
- Requires sufficient electron density for absorption

Diffuse Regime

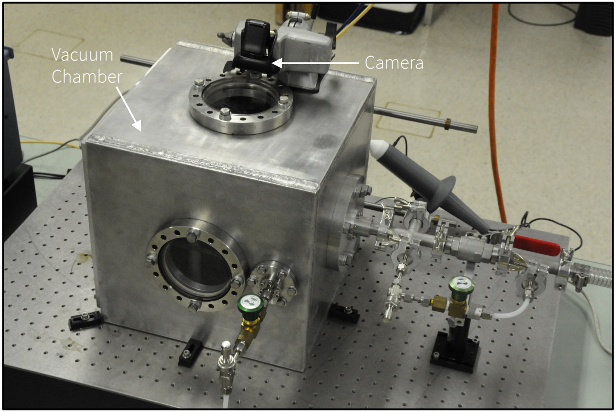


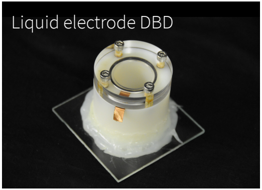
Instability Regime

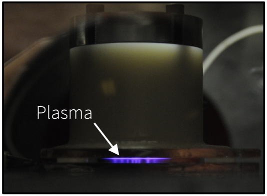


Plasma produces structures of periodic permittivity with adaptable spacing.

Experimental Setup



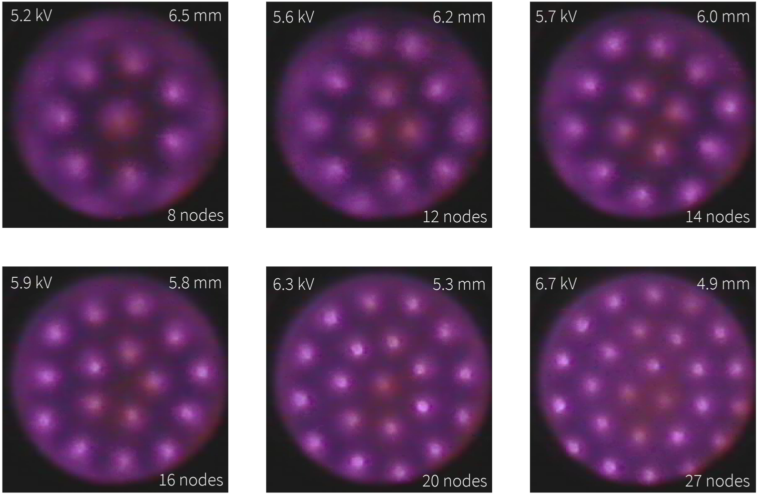




Use liquid electrode DBD geometry to generate plasma within a vacuum chamber.

Voltage Effect on Plasma Structures

FlowPAC



Increasing voltage decreases the spacing between plasma nodes.

Image Analysis

FlowPAC

- Image processing determines:
  1. Node location
  2. Plasma radius
  3. Node spacing
- Identify bad nodes and edges
- Limited pixel resolution, can improve imaging system

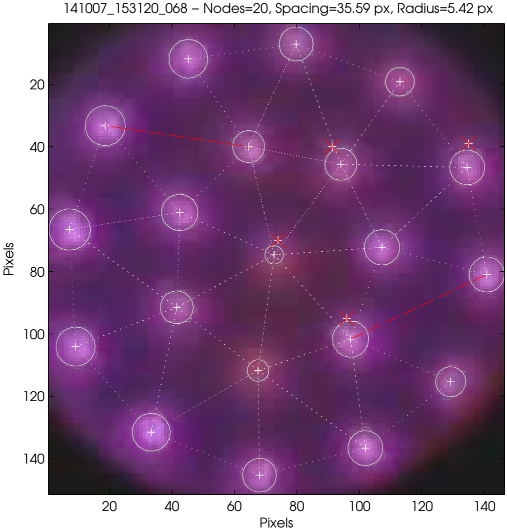
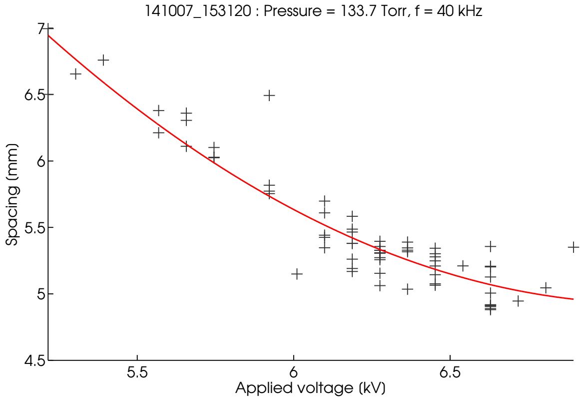


Image processing determines average plasma structure spacing at each voltage.

Experimental Results

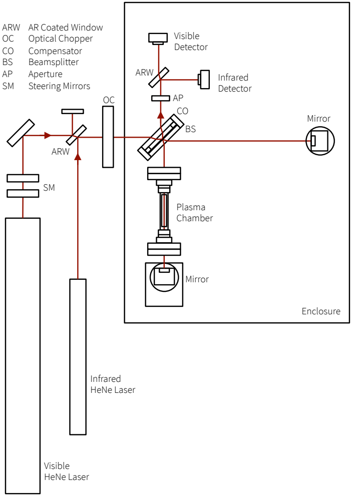


- Preliminary results show clear trend between voltage and spacing
- Is electron density sufficient for absorption?

Results demonstrate experimental control of plasma periodic spacing.

Measuring Plasma Electron Density

- Previously measured electron density for different DBD geometry
- Michelson interferometer, helium neon lasers at 633nm and 3.39μm
- Dual wavelengths isolate effects of electron density and gas heating
- Plasma placed in one arm of interferometer
- Interference indicates phase difference between both arms

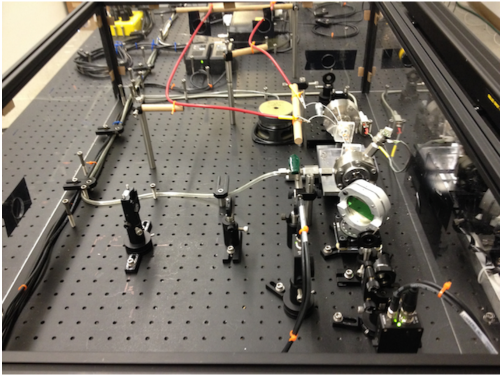


Dual wavelength interferometer provides non-invasive simultaneous measurement of plasma and heavy densities.

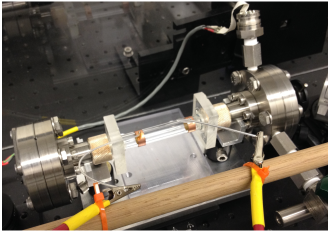
Experimental Setup

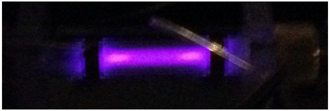
FlowPAC

Dual Wavelength Interferometer



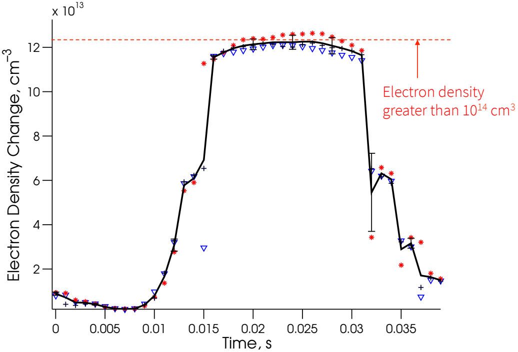
Cylindrical DBD





Experiment measured electron density of a cylindrical DBD geometry.

Electron Density Measurements



- Electron density 10^{14} cm^{-3} sufficient for absorption up to 100 GHz
- Different geometry but suggests feasibility for plasma photonic crystal DBD geometry

DBD electron density sufficient for absorption at 100 GHz.

Summary and Future Work

FlowPAC

- Seek to develop adaptive plasma photonic crystal
- Vacuum chamber experiments demonstrate adjustable plasma spacing
- Electron density measurements show that the plasma will likely be an absorbing medium
- Further investigate effects of voltage, pressure, frequency, gas
- Use data in FDTD simulations to investigate electromagnetic response
- Probe the plasma with spectrum analyzer to directly measure electromagnetic response

Questions and Comments?

Appendix

Determining the Absorbing Boundary

- Plasma complex susceptibility

$$1+\chi=\varepsilon_P=1-\left(\frac{\omega_P}{\omega}\right)^2\frac{1}{1-j\frac{\nu}{\omega}}$$

- Index of refraction and absorption coefficient

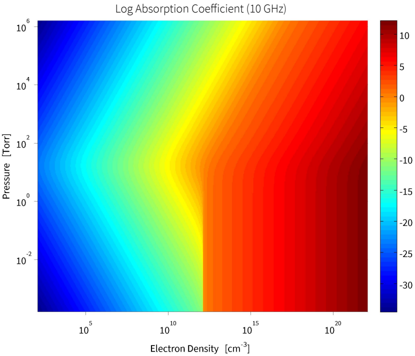
$$\beta-j\frac{1}{2}\alpha = k_0\left(1+\chi\right)^{1/2} = \frac{\omega}{c_0}\sqrt{\varepsilon_P}$$

- Plasma absorption coefficient

$$\alpha = -2\frac{\omega}{c_0}\Im\left(\sqrt{\varepsilon_P}\right)$$

- Wave is attenuated by $|\exp\left(-jkz\right)|^2 = \exp\left(-\alpha z\right)$

- Use $\alpha \geq 1$ threshold value to create boundary



B.E.A. Saleh and M.C. Teich, Fundamentals of Photonics (Wiley, 1991).

Determining Electron Density

- The measured plasma induced phase shift represented with

$$\Delta\phi = \frac{4\pi L}{\lambda}\left(\frac{-q^2\lambda^2\Delta n_e}{8\pi^2\epsilon_0 c^2 m} + \left(A + \frac{B}{\lambda^2}\right)\frac{\Delta n_h}{n_{h0}}\right)$$

- Form linear system of equations

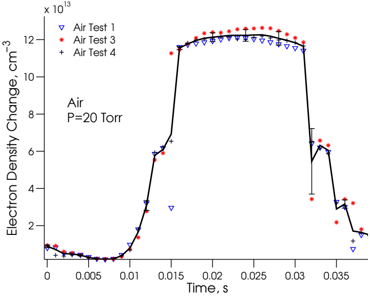
$$\underbrace{\frac{1}{4\pi L}\begin{bmatrix}\Delta\phi_{\lambda_1,j}\\ \Delta\phi_{\lambda_2,j}\end{bmatrix}}_{\text{Measurements}} = \underbrace{\begin{bmatrix}\frac{-q^2\lambda_1}{8\pi^2 c^2\epsilon_0 m} & \frac{A}{n_{h0}\lambda_1}+\frac{B}{n_{h0}\lambda_1^3}\\ \frac{-q^2\lambda_2}{8\pi^2 c^2\epsilon_0 m} & \frac{A}{n_{h0}\lambda_2}+\frac{B}{n_{h0}\lambda_2^3}\end{bmatrix}}_{\text{Constants}}\underbrace{\begin{bmatrix}\Delta n_{e,j}\\ \Delta n_{h,j}\end{bmatrix}}_{\text{Unknowns}}$$

- Determine Δn_e and Δn_h using constrained least-squares solver

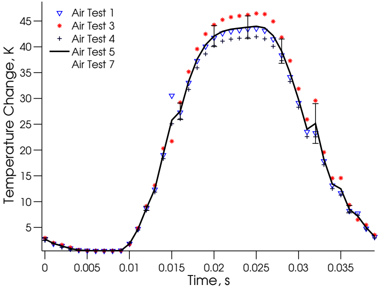
Phase measurements at each wavelength are used to set up a system of equations to solve for the electron and heavy particle densities.

Electron and Temperature Profiles

Electron Density Profile

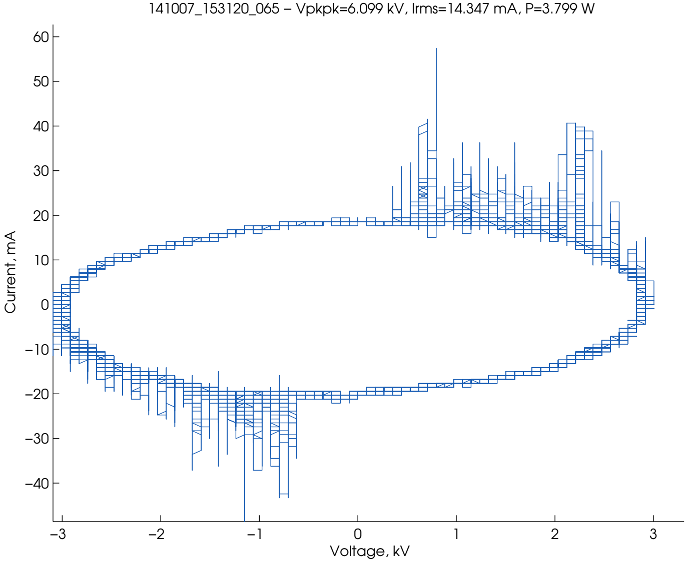


Temperature Profile

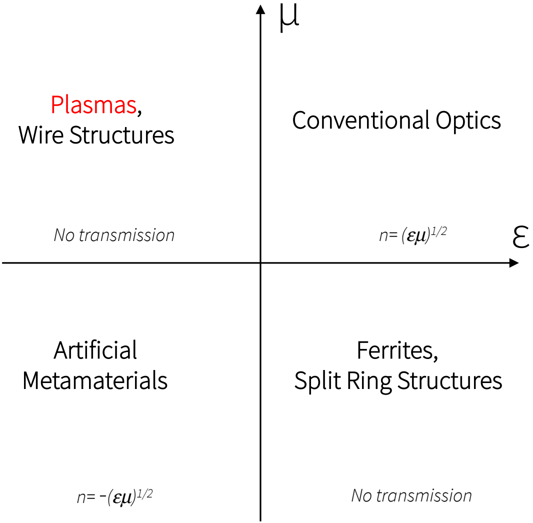


DBD Power Cycle

FlowPAC



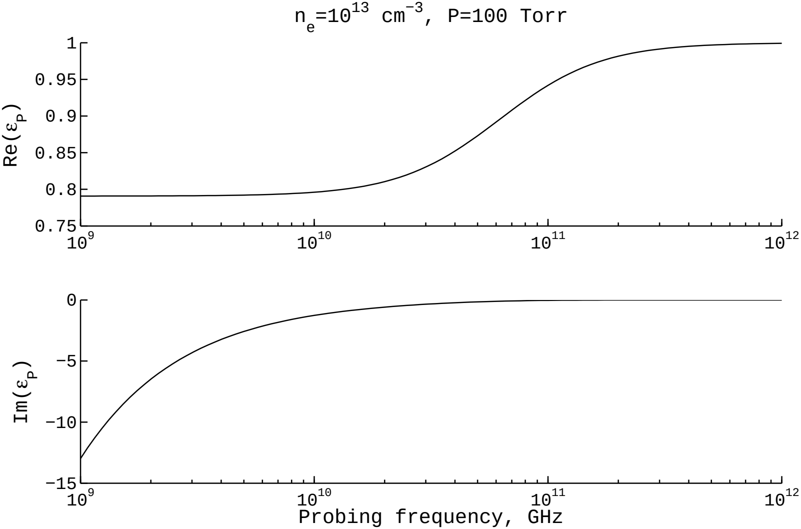
Permittivity and Permeability



Reproduced from Kumar, R., Plasma as a Metamaterial, Lambert Academic Publishing, 2011.

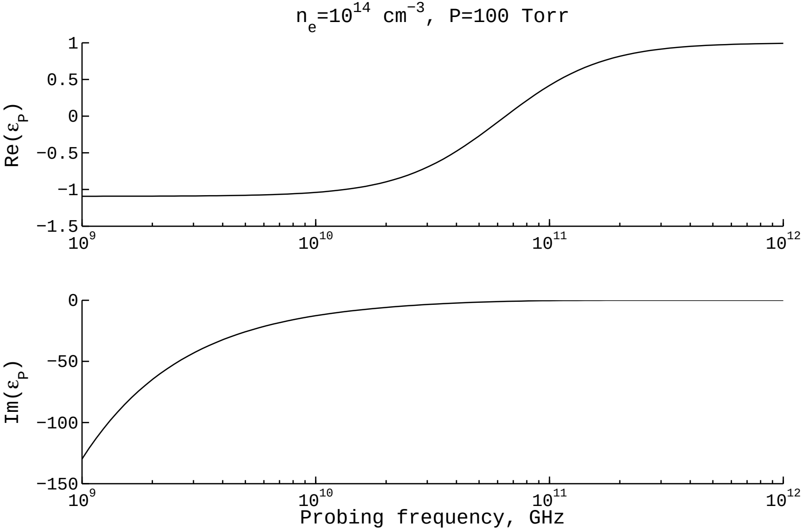
Plasma Permittivity (10^{13} cm^{-3})

FlowPAC

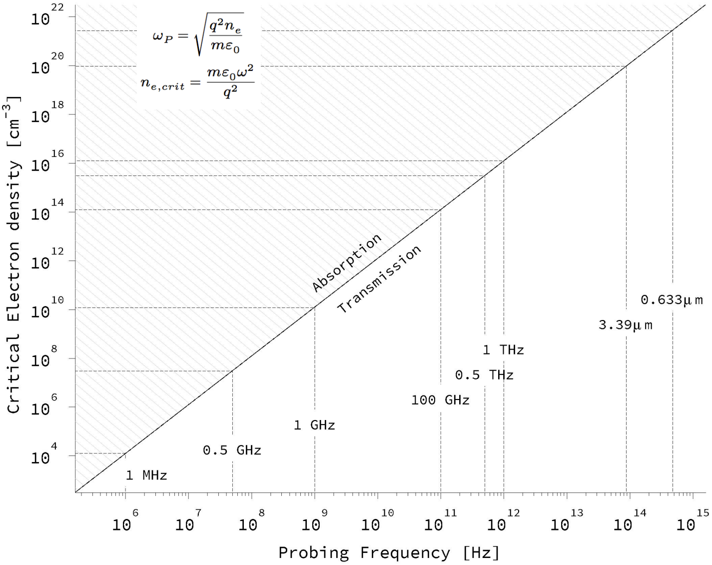


Plasma Permittivity (10^{14} cm^{-3})

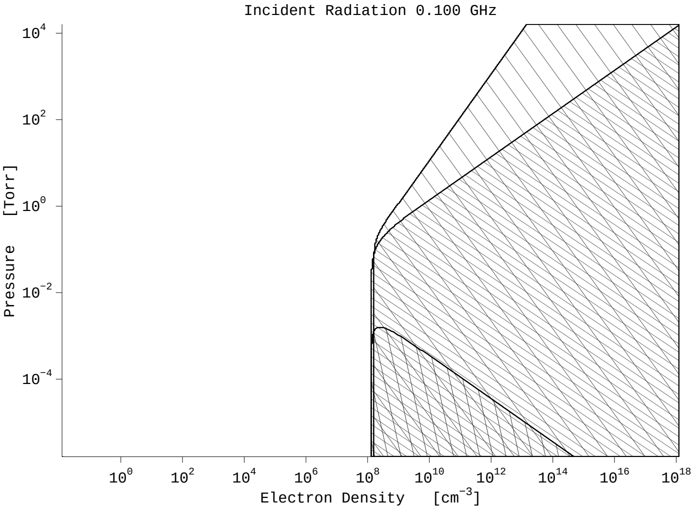
FlowPAC



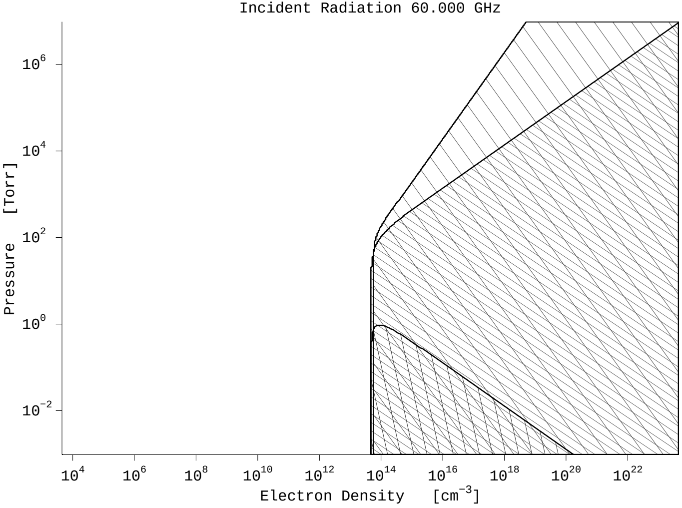
Electron Density and Frequency



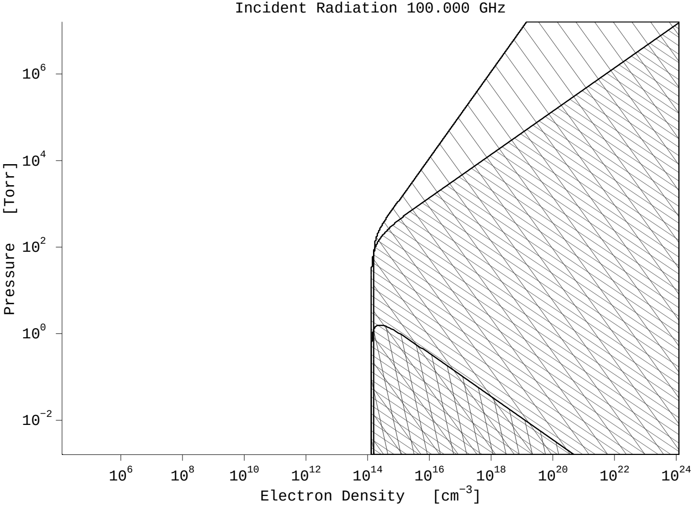
100 MHz Permittivity Map



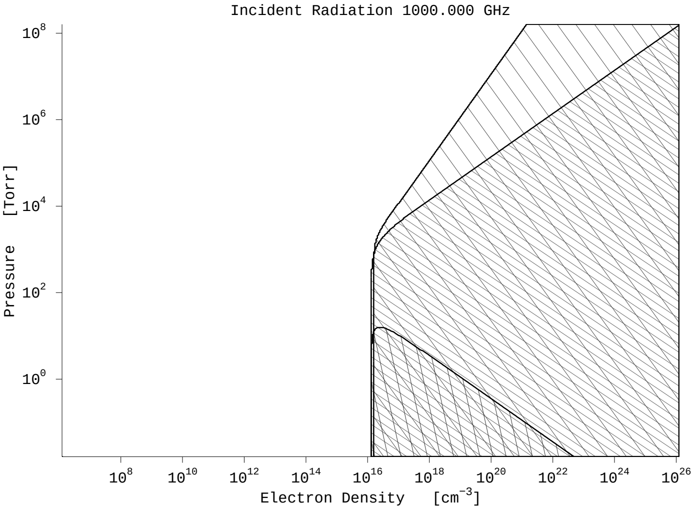
60 GHz Permittivity Map



100 GHz Permittivity Map

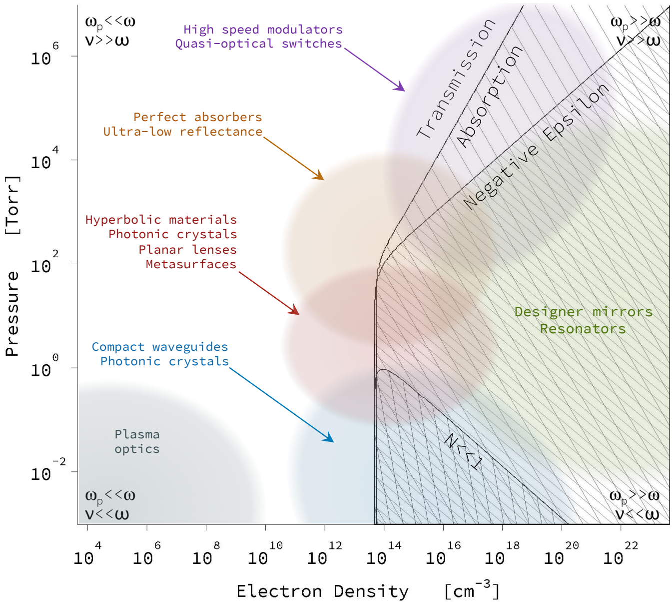


1 THz Permittivity Map



60 GHz Permittivity Map

FlowPAC ND



1 GHz Permittivity Map